VI International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2013
K.-U.Bletzinger, B. Kröplin and E. Oñate (Eds)

TESTING OF FULL-SCALE CONFINED INFLATABLE FOR THE PROTECTION OF TUNNELS

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Key words: Confined Inflatable Structure, Flooding, Leakage Rate, and Tunnel

1 INTRODUCTION

There are approximately 337 highway tunnels and 211 rail transit tunnels in the United States; many of these tunnels are beneath bodies of water.[1] Every day, more than 11.3 million passengers in 35 metropolitan areas and 22 states use some form of rail transit, either commuter, heavy, or light rail.[2] It is well known that man-made or natural disasters can significantly disrupt the functionality of critical transportation infrastructure. Some examples in the United States include the 1992 Chicago freight tunnel flood;[3] the 2003 flooding of the Midtown Tunnel in Virginia caused by Hurricane Isabel;[4] and the 2012 flooding of New York City, when Hurricane Sandy caused seven subway tunnels under the East River to flood and remain inoperable for several days.[5] Tunnel safety and integrity is a subject of special concern, not only because tunnels are of difficult and limited accessibility, but also because most of the potential threats (e.g. fires, flooding, or noxious substances) compromise the integrity of entire connecting system as the threat can spread along it.[6]

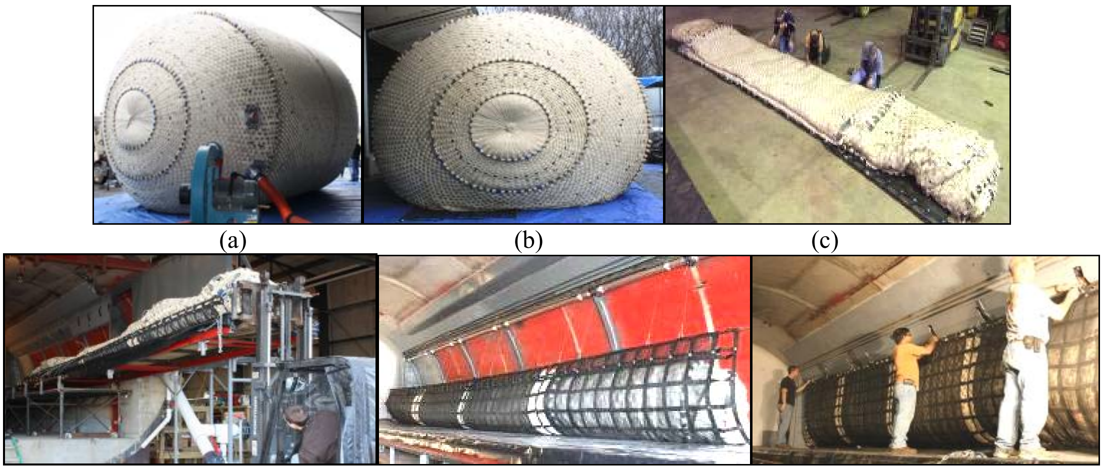
Conventional emergency sealing systems are not always installed or operational during the occurrence of extraordinary events, prompting the evaluation of alternative solutions, such as inflatable plugs.[7-10] An inflatable plug can seal off and protect an underground system by stopping hazards, such as smoke or flooding. Unlike floodgates, an inflatable plug is fast-deploying, relatively inexpensive, and can be quickly installed in a small space in an existing tunnel or conduit. The concept was demonstrated in 2008 in the Washington D.C. Metro system with promising results.[7, 9] This work describes additional full scale testing performed between late 2011 and 2012 for the development of confined inflatable structures for the protection of tunnels completed at West Virginia University.[10]

2 PREPARATION OF THE INFLATABLE PLUG

The inflatable plug used for tests at full scale consists of a cylinder with two hemispherical end-caps. The cylinder has a diameter of 194.48 inches (4.939 meters [m]) and a length of 182.70 inches (4.641 m). Each hemispherical end-cap has a radius of 97.24 inches (2.469 m). The membrane of the plug consists of a three-layer system comprised of an internal bladder, an intermediate fabric restraint, and an external webbing restraint. The bladder is the innermost layer of the construction and is in direct contact with the fluid used for inflation and pressurization. The function of the fabric restraint is to act as a middle layer and protect the bladder. The inner bladder and fabric restraint layers are oversized with respect of the webbing restraint in order to minimize membrane stresses generated by the internal pressure. The outermost layer is a macro fabric comprised of woven webbings designed to undertake the membrane stresses generated by the pressurization. Structurally, the outer layer is the most important while the two inner layers contribute to the watertightness and add to the mass and material volume of the plug. The macro fabric of the outer layer consists of a plain weave pattern of Vectran® webbings of 2 inches (0.05 m) in width. Two aluminum fittings are also integrated into the membrane. One functions as either air or water filling port, and the other one only as air release port. The total weight of the plug is approximately 2,100 lbs (953 kg).

An important geometric characteristic of the plug is the length of the cylindrical portion. It was selected based on friction tests run at coupon level on samples of Vectran webbing as well as on small-scale prototypes subjected to induced slippage over concrete surfaces, which can be encountered in typical tunnel sections.

To prepare the inflatable plug for the tests, the following steps were performed: a) Unconstrained inflation for integration of handling and holding mesh; b) Controlled deflation; c) Folding of the inflatable; d) Transportation and placement of folded plug inside the mockup tunnel; e) Storing of folded plug in the container; f) Connection of release mechanism and closing of container door. Figure 1 illustrates these steps.



(a) (b) (c)

(d) (e) (f)

Figure 1: Overview of plug preparation procedure for full-scale testing: (a) Unconstrained inflation; (b) Controlled deflation; (c) Folding; (d) Transportation and placement inside tunnel; (e) Storing in the container; (f) Connection of releasing mechanism.

3 FULL-SCALE TEST SETUP

The inflation system for full-scale tests was designed to operate with air during the initial inflation and then with water for full pressurization of the inflatable. It was designed also to provide enough water flow to simulate flooding and to recirculate water during the tests so that the entire test operation could be stabilized and measurements could be made from a self-contained water reservoir. Figure 2 shows a schematic of the inflation system showing major components and their function. The testing system consisted of a 50-foot-long (15.24 m) by 16.2-foot-diameter (4.94 m) steel structure and concrete-lined tunnel mockup specially built to replicate a typical rail tunnel section. The initial inflation and positioning of the plug required a high capacity air blower. An 85,000 gallon (321,760 liters) tank provided water for plug pressurization and flooding simulation. Three high-capacity diesel pumps were used for different functions: The water inflation pump was used to pump water from the tank to the inflated plug, replacing the air used for deployment and initial inflation; the flood simulation pump was used to fill the cavity left between the plug and the tunnel end-cap; and the water recirculation pump was used to pump leaking water collected in a dump tank, returning it to the main water tank. A smaller electrical pump and a pressure regulator were used to control the plug pressure while the tunnel pressure was regulated by changing the pumping speed of the flood simulation pump.

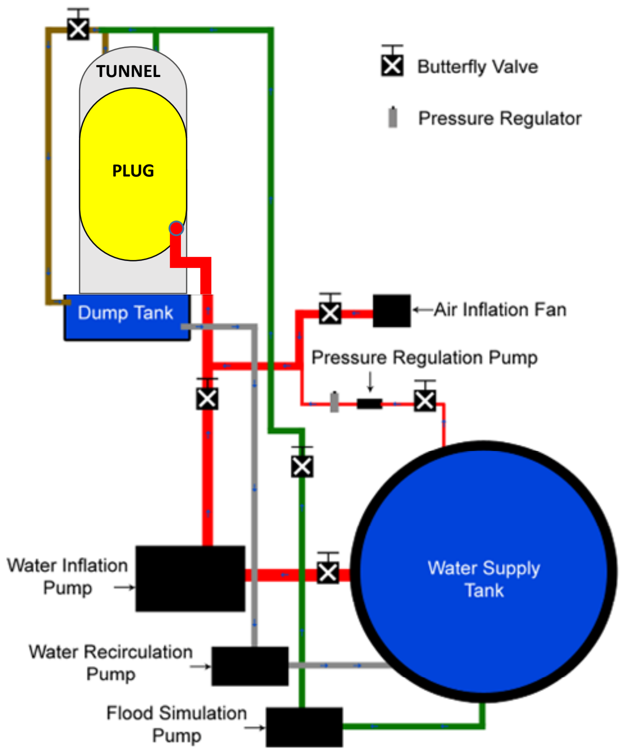


Figure 2: Schematic of the flooding simulation system used for full-scale tests.

4 TEST PROCEDURE

The testing procedure consisted of six major steps: 1) Deployment of the plug; 2) Inflation with air; 3) Filling of the plug with water and subsequent pressurization; 4) Tunnel flooding; 5) Stabilization of pressures; and finally, 6) Depressurization and plug removal. The plug deployment and air inflation were automatically controlled, but the water fill was done manually for both the plug and tunnel.

Step 1: Upon successful container door opening, the release system of the holding mesh was activated to deploy the plug.

Step 2: The initial deployment was followed by air inflation using a blower running at 1,800 standard cubic feet per minute (scfm). The inflation continued until reaching a nominal pressure of 0.25 pounds per square inch gauge (psig) (1.72 kilo Pascal [kPa]). When the plug was fully inflated, a constant pressure of 0.25 psig (1.72 kPa) was maintained by the control software. Visual inspection of the plug sealing was then conducted and documented through photographs of the front of the plug and remote video of the rear of the plug.

Step 3: Once visual inspection indicated proper inflation, the blower was turned off and isolated from the rest of the piping system. The main tank valve was opened, allowing water to fill the piping system. Then, the water inflation pump was turned on and the plug filling commenced. During the filling process, air contained in the plug was allowed to escape and the pressure was maintained at approximately 3 psig (20.68 kPa). As the water neared the top of the plug and the air within the plug was purged by the water, a valve installed in the air release port of the plug was adjusted to complete the removal of air. When all air was removed, the small electric pump was turned on and the pressure regulator set to maintain a 17 psig (117.21 kPa) plug pressure to ensure proper system operation.

Step 4: Tunnel fill started with the activation of the flood simulation pump. Tunnel flood pressure was maintained through the diesel throttle adjustment of the pump in order to reach and maintain a nominal pressure of 11.6 psig (79.98 kPa).

Step 5: During the tunnel fill and pressurization, the plug pressure was maintained at a nominal pressure of 17 psig (117.21 kPa) through continuous adjustment of the pressure regulator. As the dump tank water level reached the top, the water recirculation pump was cycled to remove the water accumulated within the dump tank as needed. Plug and tunnel pressures were maintained for the test duration. Measurements of leakage rates were performed during this step.

Step 6: Upon completion of the test, the flood simulation pump was turned off and the tunnel water was allowed to drain to the dump tank through natural leakage around the plug. The plug pressure was maintained at a minimum of 6 psig (41.37 kPa) differential from the tunnel pressure during this step to ensure that the plug did not move. After the tunnel was empty, the plug was depressurized and water was allowed to drain into the dump tank. After the plug was completely deflated, it was removed from the tunnel and prepared for another test.

A total of ten tests were executed. Seven of them consisted of only deployment followed by air inflation at 0.25 psig (1.72 kPa). The remaining three consisted of deployment, air inflation, plug pressurization, and flooding simulation.

5 RESULTS

5.1 Deployment

The deployment consisted of the following steps: First, the container door was fully opened; second, the releasing mechanism of the holding mesh was activated; third, the holding mesh along with the plug fell by gravity to unroll the plug. Figure 3 shows an example of the sequence of door opening and initial deployment of a surrogate plug, which was used for initial trials and adjustments of the process.

Figure 3: Sequence of container door opening and initial deployment.

5.2 Air Inflation

For the air inflation step, the blower was programmed to provide air flow depending on the stage of inflation. The inflation process consisted of three stages: 1) Initial inflation at 2,800 revolutions per minute (rpm) for approximately three minutes or until the plug pressure reached 0.25 psig (1.72 kPa); 2) Reduction of blower speed to 1400 rpm for approximately one minute or until the plug pressure reached and stabilized at 0.25 psig (1.72 kPa); 3) Maintain blower speed at 1400 rpm in order to keep the plug pressure constant at 0.25 psig (1.72 kPa). These three stages resulted in flows of approximately 1,000 scfm, 400 scfm, and 60 scfm, respectively. Figure 4 shows the sequence of air inflation and Figure 5 illustrates the variation of blower speed and plug pressure.

Figure 4: Sequence of air inflation.

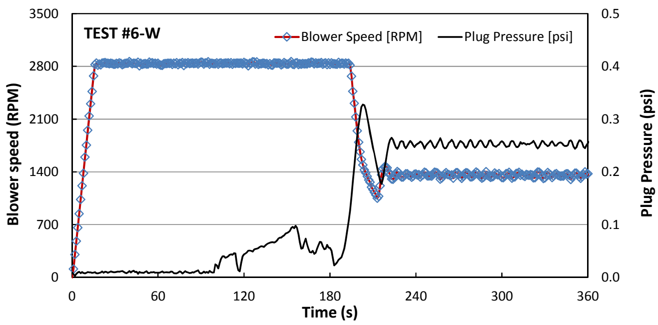


Figure 5: Variation of blower speed and plug pressure.

5.3 Evaluation of Conformity

The global conformity of the plug to the tunnel section was evaluated visually at the end of the initial inflation. The global conformity was considered acceptable when there were not significant distortions on the surface of plug and when the longitudinal horizontal axis of the plug was approximately parallel to the longitudinal and horizontal axis of the tunnel. In most of the tests the concentric circles of the spherical end-cap leaned slightly towards the container side, but did not affect the overall level of global conformity. Figure 6 shows examples of global conformity obtained after the initial inflation with air.

The local conformity was evaluated by visual inspection of critical locations, such as transitions and changes of angles in the perimeter of the tunnel section. Thorough visual inspection of these zones was performed. Local conformity of the plug to the tunnel perimeter was considered acceptable when there were no evident signs of material bridging, visible gaps, or local distortions. The absence of these anomalies was verified before proceeding with the flooding simulations. Close-up views of local contact after initial inflation with air are shown in Figure 7.

The quality of sealing was also tested during the three flooding simulations. During these three tests, different levels of leakage were observed. Particularly on the container side (location E in Figure 7), at the line of longitudinal attachment of the holding mesh to the tunnel, and in the proximity of the container floor, the plug did not seal well. This source of leakage was preliminary attributed to the presence of bridging material that created an opening at the base of the container, allowing leakage of water as illustrated in Figure 12.

Figure 6: Examples of global conformity.

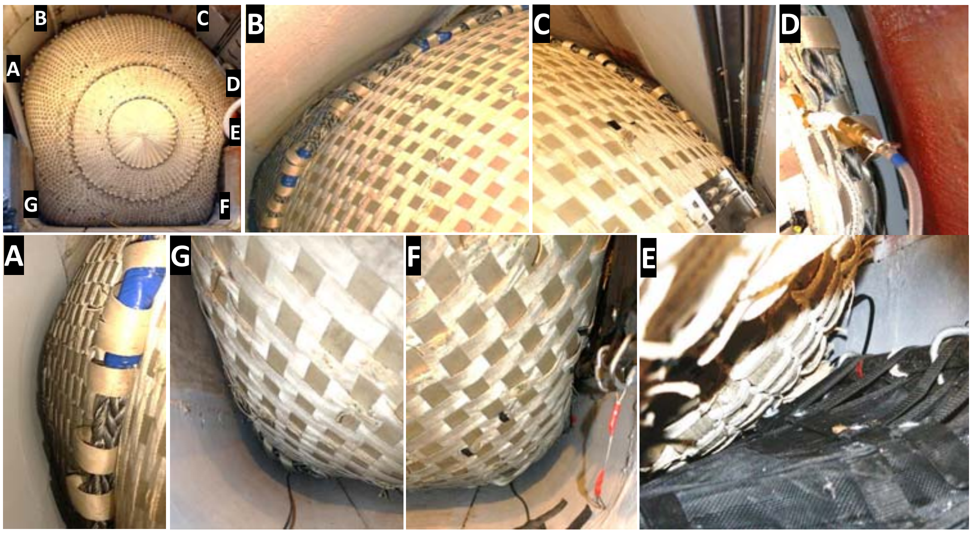


Figure 7: Evaluation of local conformity: Clockwise close-up views of critical locations.

5.4 Pressurization

Once the plug was inflated and the evaluation of conformity completed, the test continued with water pressurization of the plug. The process of filling the plug consisted of pumping nearly 1,100 gallons per minute (gpm) (4,164 liters/min) of water into the plug at the same time that air was released through a snorkel pipe located inside the plug. This process took approximately 35 minutes until all air inside the plug was replaced by approximately 35,000 gallons (132,489 liters) of water. Once the plug was completely full, the water inflation pump was substituted with a smaller electric pump for fine tuning and stabilization of the plug pressure at 17 psig (117.21 kPa). An example of the initial plug pressurization process is illustrated in Figure 8. The fluctuations of pressure seen during the filling process are due to the discrete release of air executed manually in order to avoid excessive air pressure in the upper part of the plug.

When the plug pressure was stabilized, the flood simulation pump was turned on to initiate the tunnel filling process for flooding simulation. The estimated volume of the cavity between the plug and the tunnel end-cap was 12,000 gallons (45,424 liters), and filling of this cavity took approximately eight minutes at a pumping rate of approximately 1,500 gpm (5678 liters/min). Once the cavity was full, the same pump was used to stabilize and maintain the tunnel pressure at 11.6 psig (79.98 kPa). The tunnel filing and pressurization process can be seen in the initial slope of the tunnel pressures plotted in Figures 8 and 9. When both the plug and tunnel pressures reached the target values, they were maintained approximately constant for 35 to 40 minutes for evaluation of the leakage rate. Note in Figure 9 the fluctuations of the plug pressure induced by fluctuations of the tunnel pressure. These fluctuations required continuous adjustment of the plug pressure regulator to reestablish a constant plug pressure.

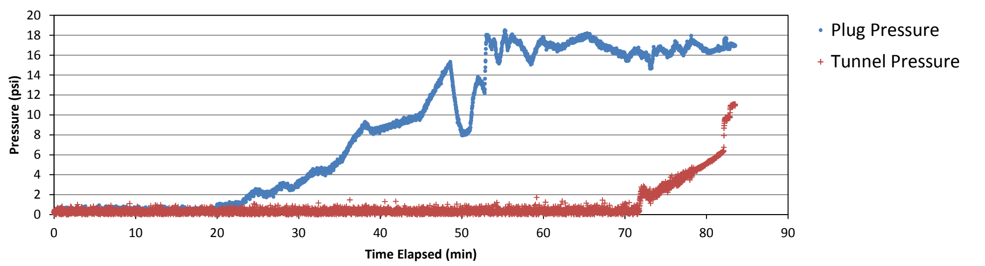


Figure 8: Plug and tunnel initial pressurization.

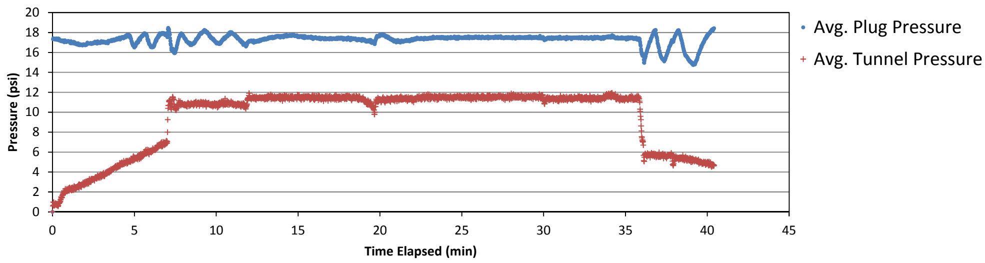


Figure 9: Stabilized plug and tunnel pressures.

5.5 Evaluation of axial stability

The stability of the plug was verified by continuous monitoring of the axial movement of the plug during the tunnel pressurization. The relative axial movement was measured by a laser range meter pointing horizontally to the tip of the plug for the duration of the entire pressurization sequence. An example of the measurements is illustrated in Figure 10. Results showed that the plug practically did not move when it was subjected to the selected testing pressures. From Figure 10, it is seen that the axial displacement ranged from 0 to 0.05 inches (0 to 1.27 millimeters) during the flooding simulation. Similar results were obtained for the other two flooding tests.

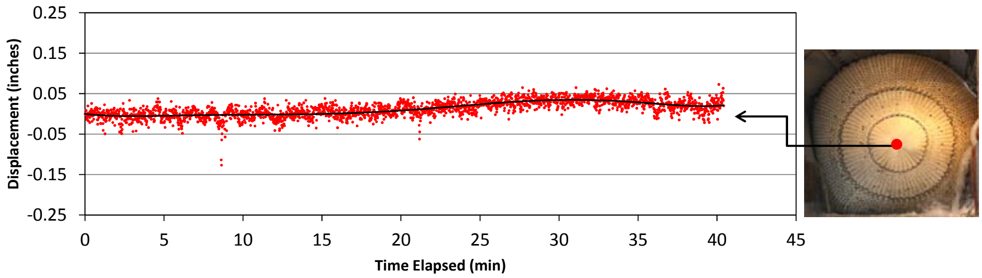


Figure 10: Plug tip horizontal displacement during flood simulation.

5.6 Evaluation of leakage rate

The water leakage originated from the non-uniform local contact between the external surface of the plug and the inner surface of the tunnel. Leaking water was collected in a dump tank placed in front of the tunnel mockup. The tank was allowed to fill while an ultrasonic depth gauge measured the change of the water level. The change in the water level, along with the known volume of the dump tank, was used to estimate the leakage rate. Once the tank was full, the water recirculation pump was turned on to drain the tank until it was nearly empty. Then, the pump was shut off, allowing the tank to fill again. This process of filling and draining of the dump tank was repeated at least ten times in order to have multiple readings for computation of the leakage rate. An example of recorded data for evaluation of leakage is shown in Figure 11. A summary of leakage rates collected from three flooding simulations is presented in Table 1.

Results summarized in Table 1 show that the average leakage of all tests was approximately 568 gpm (2,150 liters/minute). During execution of the flooding tests, it was noted that the majority of the leakage came from the container side, particularly from the container floor, as seen in Figure 12. As noted previously, it is speculated that bridging created by the plug's structural membrane in that particular region allowed water to leak. Sealing gaskets consisting of neoprene pads were added to the base of the container to improve the sealing effectiveness of the plug in that particular region. However, this solution did not reduce the amount of leakage and suggested that a different approach would have to be implemented for further tests. Despite the leakage seen in that particular region, the overall blocking capacity of the inflatable plug was acceptable considering that it was holding approximately 12,000 gallons (45,425 liters) of water pressurized at 11.6 psig (79.98 kPa) with a manageable amount of leakage. This leakage rate was compensated with the flooding simulation pump running at a relatively low speed in order to maintain the tunnel pressure constant. Note that a typical single high-capacity diesel pump can drain a flooded area with pumping rates ranging from 2,900 to 5,000 gpm (~11,000 to ~19,000 liters/min). These results demonstrated the ability of the inflatable system to contain tunnel flooding.

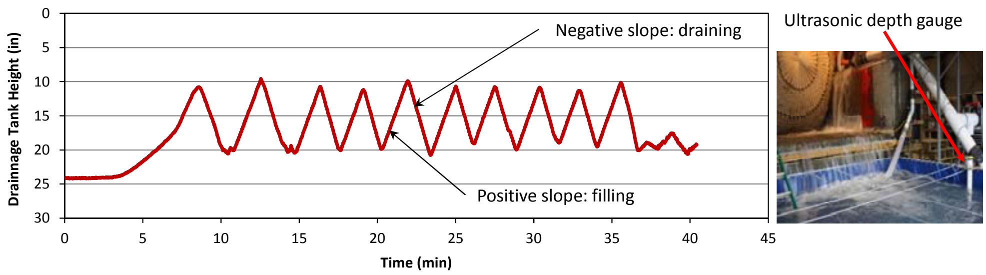


Figure 11: Variation of water depth collected in the dump tank used for estimation of leakage rate.

Table 1: Summary of leakage rates.

Test #	Avg. leakage rate	
	[gallons/min]	[liters/min]
1	450	1,703
2	526	1,991
3	729	2,759
Average	568	2,150

Figure 12: Flooding simulations: Test #1 (left); Test #2 (center); and Test #3 (right).

6 CONCLUSIONS

The preparation work, consisting of folding and packing procedures, allowed the installation of the folded plug well within the available volume of a storage container located against the tunnel sidewall. The restraining mesh, along with the folding procedure, reduced the packing volume so the plug can be accommodated in the interior of a container that can fit in a typical tunnel section.

Plug deployment and initial inflation at a low pressure can be achieved in approximately 3 minutes and pressurization with water can be achieved in approximately 35 minutes with the system configuration used in the testing.

The inflatable plug was able to withstand the selected testing inflation pressure, as well as the external tunnel pressure, originated by the flooding simulation, without slipping. That is, the plug was able to seal effectively a tunnel section in the event of flooding.

The amount of leakage measured during the tests is not negligible but manageable with standard diesel pumps. Improvement of local contact is necessary at the transitions zones of the container in order to reduce the amount of leakage coming from that particular zone.

ACKNOWLEDGMENTS

This work was funded by the U.S. Department of Homeland Security Science and Technology Directorate. Their support is gratefully acknowledged. The inflatable plug was manufactured by ILC Dover.

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