Testing of Full-Scale Inflatable Plug for Flood Mitigation in Tunnels

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The protection of high-risk underwater and underground assets, such as rail and road tunnels, is a high priority. Disasters and extraordinary events can significantly disrupt the functionality of such critical civil infrastructure. Events such as the 2012 flooding of New York City, when Hurricane Sandy caused seven subway tunnels and three vehicular tunnels to flood and remain inoperable for several days, have demonstrated the need for methods to mitigate vulnerabilities to or, at least, minimize the consequences of those events. Conventional emergency sealing systems are not always installed or operational during extraordinary events; this situation has prompted the investigation of alternative solutions, such as inflatable plugs capable of sealing off and protecting an underground system by stopping hazards. The development and testing of confined inflatable structures was performed at West Virginia University to verify the viability of flood containment with an inflatable plug in a tunnel section. The work was performed under the Resilient Tunnel project, which has progressed from the production of a proof of concept, air-inflated prototype to reduced and full-scale prototypes pressurized with water and subjected to back pressure for flooding simulations. This work summarizes the results of tests performed at full scale for the evaluation of the conformity of an inflatable plug to a typical tunnel section as well as the plug's ability to withstand simulated flooding and maintain axial stability. The tests comprised deployment, inflation, pressurization, and flooding simulation. The test results demonstrated that an inflatable plug could be installed and deployed and could seal a tunnel section by holding test pressures, while maintaining axial stability, with manageable levels of water leakage.

According to FHWA, by 2003 there were at least 337 highway tunnels and 211 rail transit tunnels in the United States (*1*). Approximately 11 million passengers in 35 metropolitan areas and 22 states use some form of rail transit for a daily commute (*2*). The mobility of many users can be significantly affected during natural disasters or other extraordinary events that disrupt the normal functioning of critical infrastructure, such as bridges and tunnels. Tunnel safety is a subject of special concern, not only because tunnels have difficult and limited accessibility but also because of potential threats, such as fires, flooding, or noxious substances. These threats not only compromise the integrity of the section in which the event takes place but also the entire connecting system.

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The protection of high-risk underwater and underground assets is a high federal priority. The National Tunnel Security Initiative has identified 29 critical underwater rail transit tunnels that are susceptible to disruption as a result of flooding (*2*). Examples of such incidents include the 1992 Chicago, Illinois, freight tunnel flood, which forced the shutdown of the subway system, caused damage to numerous businesses, and required the evacuation of about 250,000 people from the area (*3*). In the 2003 flooding of the Midtown Tunnel, Virginia, caused by Hurricane Isabel, about 44 million gallons (167 million liters) of water from the Elizabeth River flooded the tunnel system in just 40 min. The flooding left the tunnel damaged and closed for nearly 1 month (*4*). Most recently, in New York City, seven subway tunnels under the East River and three road tunnels flooded during Hurricane Sandy and remained inoperable for several days (*5*).

These incidents and others summarized in NCHRP Report 525–TCRP Report 86 have demonstrated a need for research on ways to mitigate vulnerabilities to or, at least, minimize the consequences of catastrophic events (*6*). Although it is impossible to prevent all situations that could lead to flooding, damage can be substantially minimized by reducing the area affected by the event. To minimize the effects of any threat, a possible approach is to compartmentalize the tunnel system. However, it can be difficult, if not impossible, to install in an existing tunnel the elements required for compartmentalization. Usually, there is no space available for the installation of protective devices, such as floodgates, and the elevated costs of interrupting the tunnel operations or making major infrastructure modifications have discouraged attempts to improve tunnel resilience by these means.

Since 2007, West Virginia University has been conducting research in the area of high-pressure confined inflatable plugs that can be rapidly deployed and pressurized to stop a tunnel from flooding. Under the Resilient Tunnel project, West Virginia University developed a solution that consisted of one or more inflatable plugs that could be placed at different locations along a tunnel. The Resilient Tunnel project has progressed from the production of a proof of concept, air-inflated prototype to reduced and full-scale prototypes pressurized with water and subjected to back pressure for flooding simulations (*7–11*). The Resilient Tunnel project system is designed to be remotely activated when a threatening event is detected; the activation triggers the deployment and inflation of one or more of the inflatables to isolate and seal the tunnel sections of concern. The inflatable plugs have the ability to conform to the tunnel geometry and provide a seal tight enough to contain water, smoke, fumes, or debris. This work summarizes the results of tests performed at full scale for the evaluation of the conformity of a prototype inflatable plug to a typical tunnel section, as well as the plug's ability to withstand simulated flooding.

In recent years, the availability of high-strength fabrics and the progress in the development of large-scale inflatable technology have made possible the creation of temporary and quickly deployable structures. Inflatable structures offer the benefits of being relatively lightweight and portable and of maintaining the necessary rigidity while in operation. These benefits have prompted the use of inflatables in confined spaces, such as pipes and tunnels, to act as barriers with minimal infrastructure modification. Examples include (*a*) the large-scale inflatable tunnel plugs tested and installed in the London subway system to block the smoke spread and limit the oxygen supply to tunnel fires and (*b*) a 23-ft (7.0-m) diameter plug that was filled with water and used in a uranium mine to successfully stop flooding (*12, 13*).

Inflatable plugs for the protection of tunnels are, to a certain extent, similar to inflatable dams used for diversion structures, check structures for flood control, overflow weirs, flashboard and gate replacement, sluice gates, and barriers for erosion (*14*). Inflatable dams were invented in the 1960s and since then have been used extensively across the world and in the United States (*15, 16*). Recently, inflatable rubber dams were installed in large sewer lines to control stormwater and wastewater and reduce pollution during heavy rain events in areas such as the New York Harbor (*17*). Inflatable dams are typically manufactured from multilayer fabrics, which may be rubberized on one or both sides; have cylindrical shapes, normally attached to a rigid, horizontal base; and can be inflated either with air or water. However, the main characteristic of inflatable structures for tunnel protection that differentiates them from inflatable dams is the confinement produced by the tunnel inner perimeter in contact with the external surface of the inflatable, which modifies its structural behavior. A confined inflatable plug is subjected to a combination of membrane stresses and frictional forces that make the design process more complex (*18*). The advances in recent years in fabric technology to increase strength and long-term performance through the incorporation of new synthetic fibrous materials, such as aramids or liquid crystal polymers, allow higher inflation pressures to be reached and increase resilience in harsh environments (*19*). These advances also provide greater flexibility for folding into a more compact shape for storage, as well as durability when the inflatable plug is not operational.

INFLATABLE PLUG AND TEST PREPARATION

The full-scale inflatable plug used for testing consists of a cylinder with two hemispherical end caps. The cylinder has a diameter of 194.5 in. (4.940 m) and a length of 182.7 in. (4.641 m). The radius of each hemispherical end cap is 97.2 in. (2.469 m), and the total plug length is 377.2 in. (9.581 m). The two most important geometric characteristics of the inflatable plug are (*a*) the length of the cylindrical portion, which has been determined on the basis of friction tests run at the coupon level on samples of membrane materials, as well as on small-scale prototypes subjected to induced slippage over concrete surfaces typically found in tunnel sections, and (*b*) the perimeter of the cylindrical portion, which has been designed to cover elements that typically exist in a tunnel segment, such as duct banks, pipes, cables, and rails. The length of the cylindrical portion of the plug provides sufficient contact length for the development of frictional forces to maintain the axial stability; the extra material in the perimeter ensures local conformity of the plug to the tunnel surface.

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 fabric restraint acts as a middle layer and protects the bladder. The outermost layer is a macrofabric comprised of woven webbings designed to undertake the membrane stresses generated by the pressurization. Structurally, the outer layer is the most important; the two inner layers provide watertightness and contribute to the mass and volume of the plug. The macrofabric of the outer layer consists of a plain weave pattern of 2-in. (0.05-m) wide webbings manufactured with Vectran fibers (*19*). Two fittings are also integrated into the membrane. One functions as either an air or water filling port, the other as an air release port. The total weight of the plug is approximately 2,000 lb (908 kg).

The plug required preparation work before the execution of a test. A sequence of preparation steps was developed to pack the deflated plug inside a portable container that was later placed inside a mock-up tunnel section specially built for the tests. These steps were developed to systematize the preparation process so that it could be repeated multiple times. The preparation steps included (*a*) unconstrained inflation for repositioning and surface inspection, followed by a controlled deflation (Figure 1*a*); (*b*) the attachment of the deflated plug to the container (Figure 1*b*); (*c*) the implementation of a folding sequence (Figure 1*c*); (*d*) the packing of the folded plug into the container (Figure 1*d*); and (*e*) the transportation and securing of the container into the tunnel mock-up (Figure 1, *e* and *f*). The final position of the container on the sidewall of the tunnel mock-up at the end of the preparation activities is illustrated in Figure 2.

FULL-SCALE TEST SETUP

The inflation system for the full-scale tests was designed to operate with air during the initial inflation and then with water for the full pressurization of the inflatable. The test setup was also designed to provide 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 3 shows a schematic of the major components of the inflation system. The test system consisted of a 50-ft (15.2-m) long by 16.2-ft (4.94-m) diameter steel structure and a concrete-lined tunnel mock-up, specially built to replicate a typical rail tunnel section. The initial inflation and positioning of the plug required a high-capacity air blower that was connected to the inflation port of the plug. An 85,000-gal (321,760-L) tank provided water for plug pressurization and flooding simulation. Two high-capacity diesel pumps were used for different functions. The water inflation diesel pump was used initially to pump water from the tank to the inflated plug and replace the air used for deployment and initial inflation; once the air from the plug had been purged and the desired plug water pressure had been achieved, the same pump was used through a series of valves for the flooding simulation by filling and pressurizing the cavity left between the plug and the tunnel end cap. The water recirculation diesel pump was used to pump the leaking water collected in the dump tank and return that water to the main water tank. A smaller electrical pump and a pressure regulator were used to control the plug pressure; the tunnel pressure was regulated by changing the pumping speed of the flood simulation diesel pump.

TEST PROCEDURE

The testing procedure consisted of the following seven major steps:

Step 1. Deployment of the inflatable plug. As the release system was activated, the container cover opened, and the plug was initially deployed by gravity by rolling out of the container.

Step 2. Inflation with air. The initial deployment was immediately followed by the activation of the air blower running at 1,500 standard

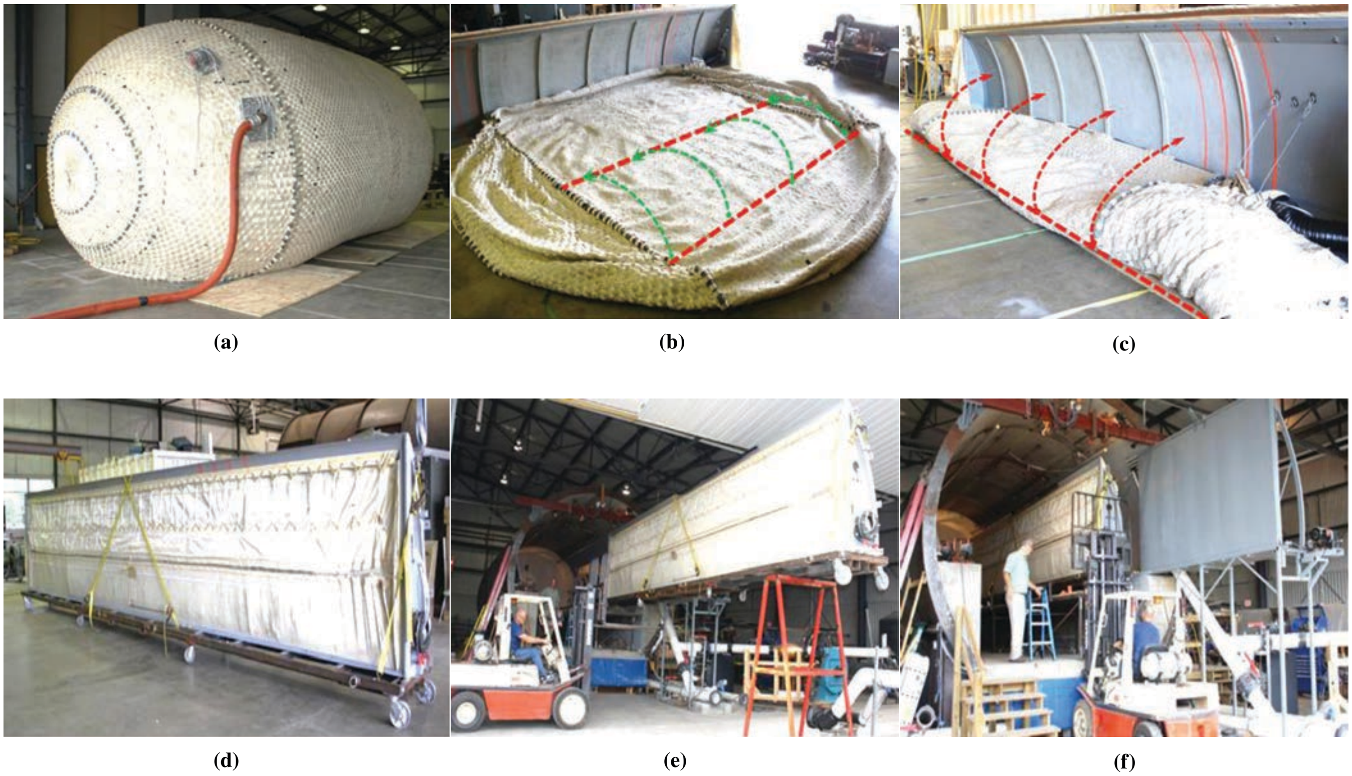

FIGURE 1 Sequence of plug preparation.

cubic feet per minute (scfm) (42 m^3/min). The inflation continued until the plug completed its positioning in the tunnel section. When the plug was fully inflated, a constant pressure of 0.25 pounds per square inch gauge (psig) (1.72 kPa) was maintained by the control software.

Step 3. Evaluation of local and global conformity. The level of conformity of the plug to the tunnel section was evaluated by two metrics on the basis of a visual inspection and the information provided by the contact sensors, as described in the evaluation metrics section.

FIGURE 2 Tunnel section and folded plug placed in tunnel sidewall before beginning of test.

Step 4. Filling of the plug with water and the subsequent pressurization. Once the evaluation of conformity indicated proper inflation, the blower was turned off and isolated from the rest of the piping system. The main water tank valve was opened, which allowed water to fill the piping system. Then, the water inflation pump was turned on, and the plug filling commenced. During the filling process, air in the plug was allowed to escape, and the pressure was maintained at approximately 3 psig (21 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 the air. When all the air had been removed, the water inflation diesel pump was turned off and replaced by an electric pump that provided flow to the pressure regulator, which was set to reach and maintain a continuous maximum plug pressure [internal plug pressure (P_i)] of 17 psig (120 kPa) to ensure proper system operation. The plug pressure followed a hydrostatic distribution, and the maximum pressure was measured at the tunnel floor level.

Step 5. Tunnel flooding simulation. When the valves in the piping system were adjusted to redirect the water flow, the flood simulation diesel pump (the same pump used for water inflation in Figure 3) was turned on to fill the cavity between the plug end cap and the tunnel end cap. The tunnel flood pressure was maintained through the diesel throttle adjustment of the pump to reach and maintain a nominal pressure [external pressure (P_e)] of 11.6 psig (79.9 kPa), measured at the tunnel floor level.

Step 6. Stabilization of pressures to evaluate the leakage rate. During the tunnel filling and pressurization, the plug pressure was maintained at a constant through the continuous adjustment of the

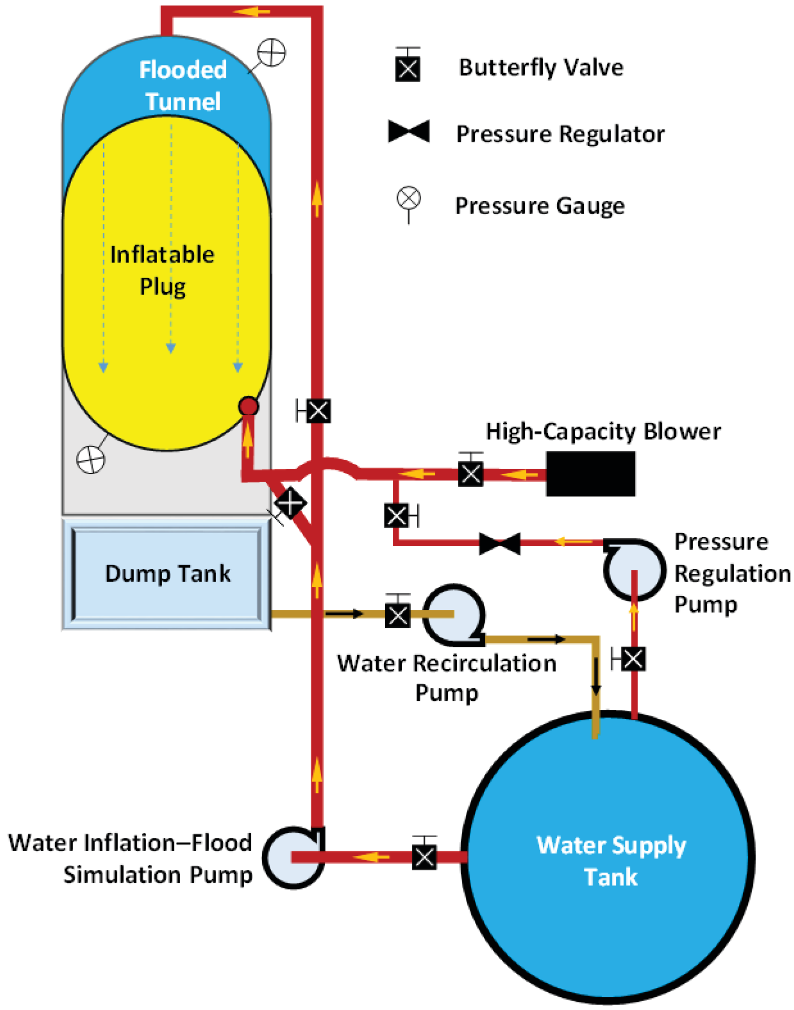

FIGURE 3 Flooding simulation system used for full-scale tests.

pressure regulator. The water leakage from the tunnel was collected in the dump tank; the water recirculation diesel pump was cycled as needed to remove the water that had accumulated within the dump tank. The cycles of dump tank filling and draining allowed the leakage rates to be measured while the plug and tunnel pressures were maintained at a constant for at least 75 min.

Step 7. Depressurization and plug removal. After the measurements had been completed, the plug pressure was maintained at a constant while the tunnel was depressurized and the water allowed to drain. After the tunnel was empty, the plug was depressurized and drained. After the plug was completely deflated, it was removed from the tunnel and prepared for another test.

Six tests were executed. Four of them consisted of only deployment followed by air inflation at 0.25 psig (1.72 kPa) (Steps 1 to 3) and were labeled 1-A to 4-A. The remaining two tests comprised deployment, air inflation, plug pressurization, and flooding simulation, as described in Steps 1 to 7. These two tests were labeled 5-AW and 6-AW and were limited to the evaluation of the performance of the system during the normal operation of the plug with a constant pressure ratio of P_e/P_i = 17/11.6 = 0.68, which was below the critical ratio for slippage (~0.8) that had been found in tests at a reduced scale.

METRICS FOR EVALUATION OF CONFORMITY

The evaluation of local and global conformity performed in Step 3 was carried out with two metrics that were created to quantify the plug's level of conformity to the tunnel section. The main features of each metric follow:

Metric 1. This metric was based on a visual inspection of specific locations on the perimeter of the plug accessible from the open end of the tunnel and was created with the objective of quantifying the quality of the deployment by assigning numerical grades to specific zones considered critical for the success of a test. Nine locations were identified as critical zones and were deemed potential leakage areas (see Figure 4*a*). Each location was qualified by a weighted grade on the basis of the level of conformity of the membrane to the tunnel surface, as observed during visual inspections, and the importance of having a good seal. In general terms, a good level of conformity would lead to a higher grade, and low levels of conformity or no contact at all would lead to the lowest grade assigned to the particular zone. Under this metric, the maximum score that a deployment could get was 10 (perfect sealing) and the minimum was zero (plug misaligned with multiple gaps). A limitation of this metric was that the evaluations

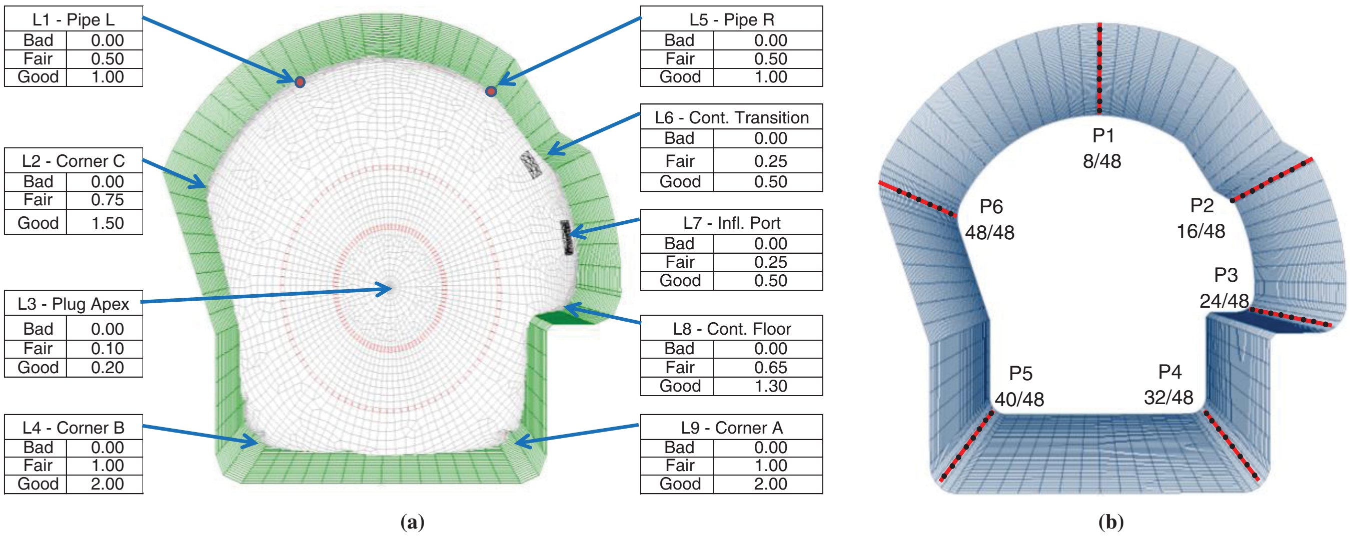

FIGURE 4 Evaluation of local conformity: (*a*) inspection points with partial grades used for Metric 1 and (*b*) position of longitudinal strips with electronic contact sensors used for Metric 2 (l = location; cont. = container; infl. = inflation; p = position).

were based only on the inspection of the visible side of the plug. The metric implicitly assumed that the other side had the same level of local conformity; that assumption may not have been true for all the tests that were evaluated by this metric. However, it served as a tool to quantify the quality of each deployment and eventually led to a better understanding of the dynamic of the system sealing.

Metric 2. This metric was based on the detection of the contact developed between the plug and the tunnel perimeter along the cylindrical portion of the plug. The contact was detected by electronic contact sensors, placed in six sets of eight, bonded to thin metallic strips, and installed at locations considered critical for successful sealing. The objective of installing multiple units was to detect the contact of the cylindrical portion of the plug at corners, transitions, and changes of geometry in the tunnel perimeter, as illustrated in Figure 4*b*. The quality of the conformity was measured by the number of sensors activated during the test with respect to the total number of available sensors. The level of conformity was expressed as a percentage of contact.

RESULTS AND DISCUSSION

Deployment and Air Inflation

The deployment started with the automatic activation of the opening mechanism on the container cover; this activation immediately released the different portions of the cover and allowed the folded plug to unroll by its own weight as the air inflation began. The air inflation process consisted of two stages: (*a*) the initial inflation at 1,500 scfm (42 m^3/min) until the plug pressure reached 0.25 psig (1.72 kPa) and (*b*) the reduction of the air flow, once this level of pressure had been achieved, to maintain the constant 0.25-psig pressure. With this test configuration, the total time from deployment to full inflation averaged 2.9 min. A key aspect for the successful positioning of the plug was the sequential release of the membrane material. This release was achieved by the installation of passive restrainers during the folding process that gradually broke and released material during the inflation and assured relatively uniform coverage of the tunnel perimeter. Figure 5 shows an example of the sequence of deployment and air inflation.

Evaluation of Conformity

The conformity of the plug to the tunnel section was evaluated at the end of the air inflation. Metric 1, which was based on visual inspection and the grading of critical locations (see Figure 4), was implemented for all the tests. The 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. Each point of inspection was assigned a partial grade that added up

FIGURE 5 Sequence of deployment and initial air inflation for Test 6-AW.

to a global grade indicative of the quality of the deployment. The preliminary trials showed that a minimum score of seven out of 10 was necessary to proceed with the flooding simulations. For the tests reported in this work, the scores ranged from 7.5 to 9.3, with an average of 8.4. These results are indicative of a relatively good level of conformity of the plug to the tunnel section. The contact along the cylindrical portion of the plug was evaluated by Metric 2. At the end of the air inflation, the contact detected by the sensors ranged from 60% to 94%, with an average of 78%. In this metric, higher percentages were also indicative of good levels of local conformity in places that were not accessible for visual inspection.

Metric 2 was also useful in monitoring the evolution of the contact detected by the electronic contact sensors as the tests progressed from air inflation at low pressure to the flooding simulation at the target pressures. Examples of contact sensor outputs obtained during the tests are illustrated in Figure 6 for Tests 5-AW and 6-AW. For Test 5-AW, the presence of bridging at Position P4 was evidenced by the lack of signal sent by the contact sensors located at that position. Despite this singularity, the test demonstrated that a significant amount of water leakage could result as a consequence of the fabric bridging. Increasing the plug pressure from 3 psig (21 kPa) to 17 psig (120 kPa) did not improve the contact at Position P4. It was only during the flooding simulation that sensors at Position P4 started to detect contact. However, this contact was attributed to the pressure generated by the water leaking under the fabric bridge that originated during the deployment. For Test 6-AW, except at Position P5, the contact was relatively uniform at all positions and remained approximately constant as the test progressed from air inflation to flooding simulation, as illustrated in Figure 6.

These results demonstrate not only the importance of achieving good levels of local conformity during the deployment and inflation process but also the difficulty of improving the quality of local conformity by increasing the plug pressure; this difficulty results from the inextensibility of the plug outer layer and the friction of the tunnel concrete surface. From previous tests (*13*), as well as from test results reported in this work, it was found that the presence of gaps or bridging material was influenced by two main factors: (*a*) the degree to which the hoop perimeter of the plug was oversized in comparison to the tunnel perimeter and (*b*) the shape of the transitions at the corners and angles. For the first factor, the hoop perimeter needed to be oversized by at least 5% to achieve acceptable local conformity. Higher percentages could be beneficial in reducing the formation of

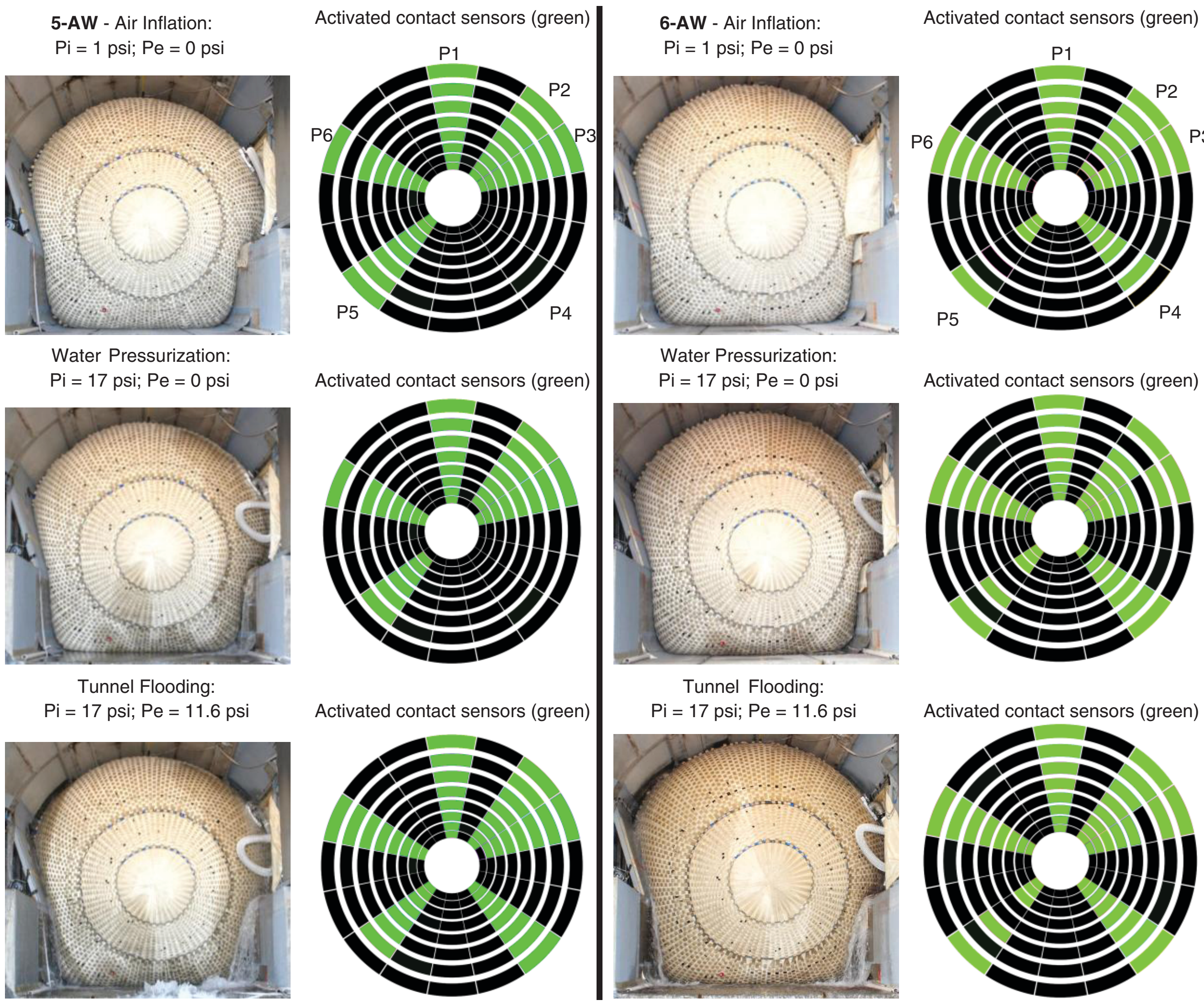

FIGURE 6 Local contact detected by contact sensors for Tests 5-AW (*left*) and 6-AW (*right*) (Pi = internal plug pressure; Pe = external pressure).

gaps during the deployment, but the hoop perimeter being oversized by more than 5% may be counterproductive as large wrinkles may appear and lead to the formation of gaps or distortions with subsequent increased leakage. Additional tests are needed to determine the upper limit by which the hoop perimeter should be oversized. For the second factor, rounded transitions can perform well when the deployment is nearly flawless; however, repeated testing demonstrated the variability in the quality of local conformity. One way to reduce the possibility of local bridging would be the implementation of low curvature or flat transitions at changes of direction or acute angles; these transitions would minimize the creation of the gaps that can lead to increased leakage.

Pressurization and Monitoring of Axial Stability

Once the evaluation of conformity had been completed, the test continued with the water pressurization of the plug. The process of filling the plug consisted of replacing air with water at a rate of 1,100 gal/min (4,200 L/min). Air was released through a snorkel pipe located inside the plug. This process took approximately 35 min until all the air inside the plug had been replaced with nearly 35,000 gal (~132,000 L) of water. Once the plug was completely full, the water inflation pump was replaced with the electric pump for the fine adjustment and stabilization of the plug pressure at 17 psig (120 kPa).

Once the plug pressure was stabilized, the valves of the pipe system were adjusted to redirect the water flow from the water tank to the tunnel. The flood simulation pump was turned on to initiate the tunnel-filling process for flooding simulation. The volume of the cavity between the plug and the tunnel end cap was estimated to be nearly 12,000 gal (~45,000 L), and the filling of this cavity took approximately 8 min at a rate of approximately 1,500 gal/min (~5,700 L/min). Once the cavity was full, the same pump was used to stabilize and maintain the tunnel pressure at 11.6 psig (79.9 kPa). At the end of the tunnel pressurization, an overshoot of the target tunnel pressure induced fluctuations in the plug pressure. This overshoot was attributed to a delayed response in the diesel pump in reducing the water flow when the cavity behind the plug was completely full. The overshoot produced a perturbation in the plug pressure that required readjustment until it was stabilized again. When both the plug and tunnel pressures reached the test values, those pressures were maintained approximately constant for approximately 75 min to evaluate the leakage rate and the axial displacement. An example of the pressure progression is illustrated in Figure 7 for Test 6-AW.

The stability of the plug was verified through the continuous monitoring of the plug's axial movement during the tunnel pressurization. The relative axial movement was measured by a laser range meter that pointed horizontally to the visible tip of the plug for the duration of the pressurization sequence. An example of the displacement measurements is illustrated in Figure 7. The results show that, after the initial oscillation produced by the fluctuation in the pressures, there was minor plug movement once the selected test pressures had been stabilized. From the beginning of the tunnel pressurization until the tunnel depressurization, the axial displacement ranged by ±0.05 in. (±1.2 mm). The oscillations seen in the axial displacement signal are partially attributable to the water that leaked over the surface of the plug interfering with the laser beam used during the measurements. Similar results were obtained for Test 5-AW. These results confirmed the axial stability of the system.

Evaluation of Leakage Rate

The water leakage originated from nonuniform local contact between the external surface of the plug and the inner surface of the tunnel concrete liner. Leaking water was collected in a dump tank placed in front of the tunnel mock-up. The tank was allowed to fill while an ultrasonic depth gauge measured the change in 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, and the tank was able to fill again. This process of filling and draining the dump tank was repeated at least 15 times to enable multiple readings for the computation of the leakage rate. An example of the recorded data for the evaluation of leakage is shown in Figure 7.

The average leakage rate for Test 5-AW was 661 gal/min (2,502 L/min); for Test 6-AW, the leakage rate reduced to 393 gal/min (1,488 L/min), with an average value of 527 gal/min (1,995 L/min). The significant difference between the results of the two tests is attributed to the following causes: (*a*) the bridging of the fabric material at Position P4 detected by the electronic contact sensors during the initial deployment in Test 5-AW; this bridging led to an opening from which a significant amount of water leakage was observed during the test; (*b*) another source of leakage observed during Test 5-AW at the container side, similar to that observed during the trial tests reported in Stocking (*13*); (*c*) the installation, in the preparation for Test 6-AW, of foam gaskets inside the container to reduce the bridging between the plug and the inner ribs of the container; these gaskets were placed on the curved surface of the container wall and extended to the container's floor and therefore created barriers that restricted the leakage flow; and (*d*) the good level of local conformity achieved during the initial deployment of Test 6-AW that contributed to the improved sealing capacity of the plug. An illustration of the differences between Tests 5-AW and 6-AW is shown in Figure 8; the zones with higher leakages are emphasized to highlight the differences between the two flooding tests.

These results show that the overall blocking capacity of the inflatable plug was satisfactory as it was holding pressurized water at 11.6 psig (79.9 kPa) at an average leakage rate of 527 gal/min (1,995 L/min); the leaked water was quickly recirculated by the draining pump. This leakage rate was compensated by the flooding simulation pump running at a relatively low speed to maintain the constant tunnel pressure.

A typical single, portable, high-capacity diesel-powered pump with intakes in the range of 6 to 12 in. (0.15 to 0.30 m) in diameter can drain a flooded area with pumping rates ranging from 2,900 to 5,000 gal/min (~11,000 to ~19,000 L/min). Moreover, during Hurricane Sandy, seven subway tunnels flooded with more than 400 million gallons (~1,500 million liters) of water; several high-capacity diesel-powered pumps ran continuously for nearly 2 weeks to completely drain the tunnels (*20, 21*). Therefore, the results obtained in this set of experiments demonstrate the ability of the inflatable plug to contain tunnel flooding.

CONCLUSIONS

The plug test preparation procedures—folding, packing into a removable storage container, and installing in the interior of the tunnel mock-up—demonstrated the feasibility of installing a compact and deployable system well within the volume typically available in a tunnel sidewall.

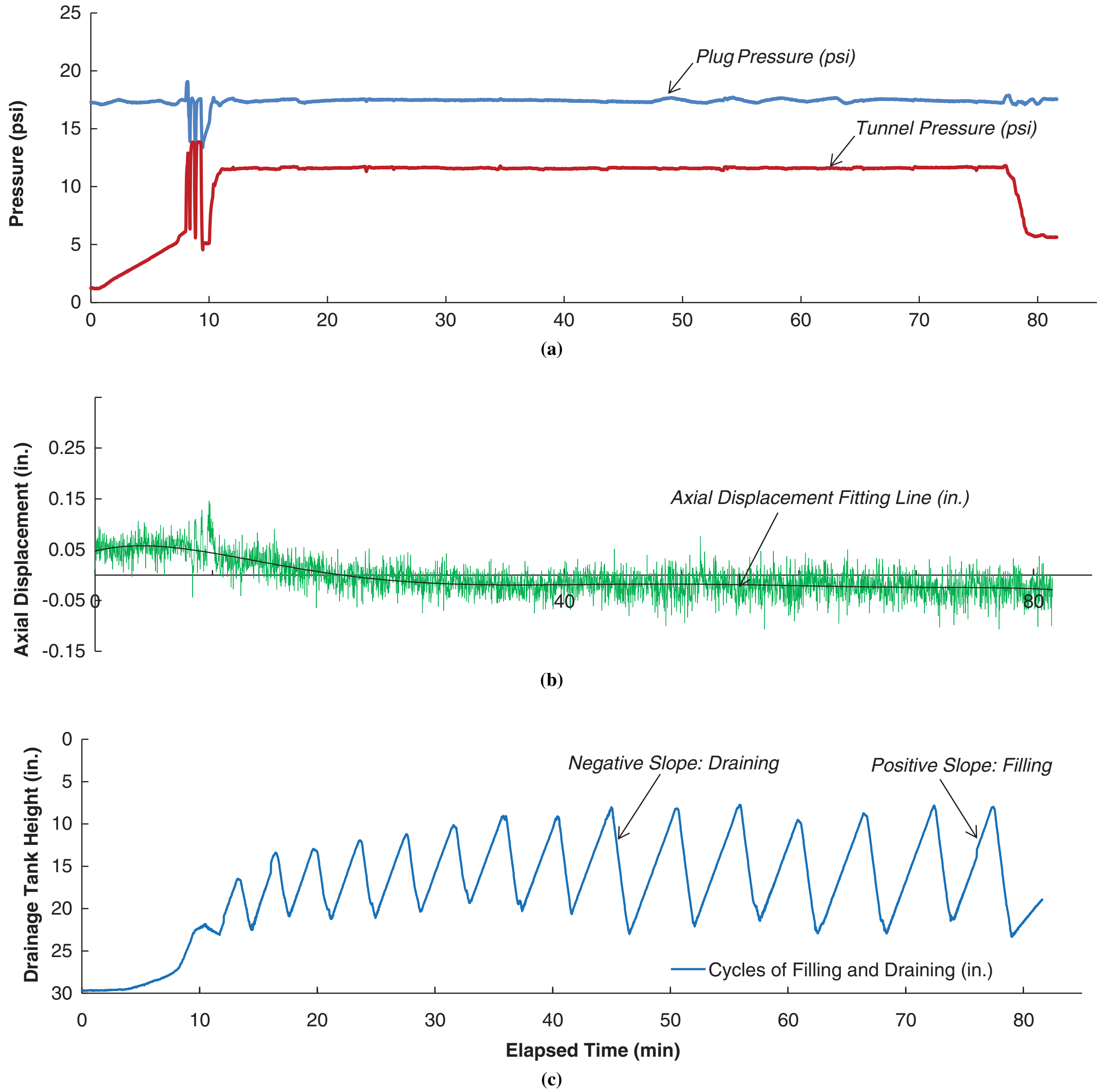

FIGURE 7 Test pressures, axial displacement, and leakage measurements for Test 6-AW.

The deployment of the plug and the initial inflation with air at a low pressure could be achieved in approximately 3 min; pressurization with water could be achieved in approximately 35 min with the system configuration used during this test program.

Once fully positioned and pressurized, the inflatable plug was able to withstand, without slipping, the external tunnel pressure originated by the flooding simulation. That is, the plug was able to effectively seal a tunnel section in the event of flooding. The flooding simulations produced nonnegligible but manageable water leakage rates. The amount of leakage measured during the tests would be manageable with the pumping equipment available in existing tunnel infrastructure.

The achievement of acceptable local conformity at the beginning of the process of deployment and inflation with air at low pressure was demonstrated to be critical in reducing the water leakage rates. Further improvements in the local conformity could be achieved through a combination of an adequate amount of membrane material in contact with the tunnel perimeter, a controlled release of that material during the deployment, and modifications in the transition zones of the tunnel perimeter to further reduce the leakage coming from those particular zones.

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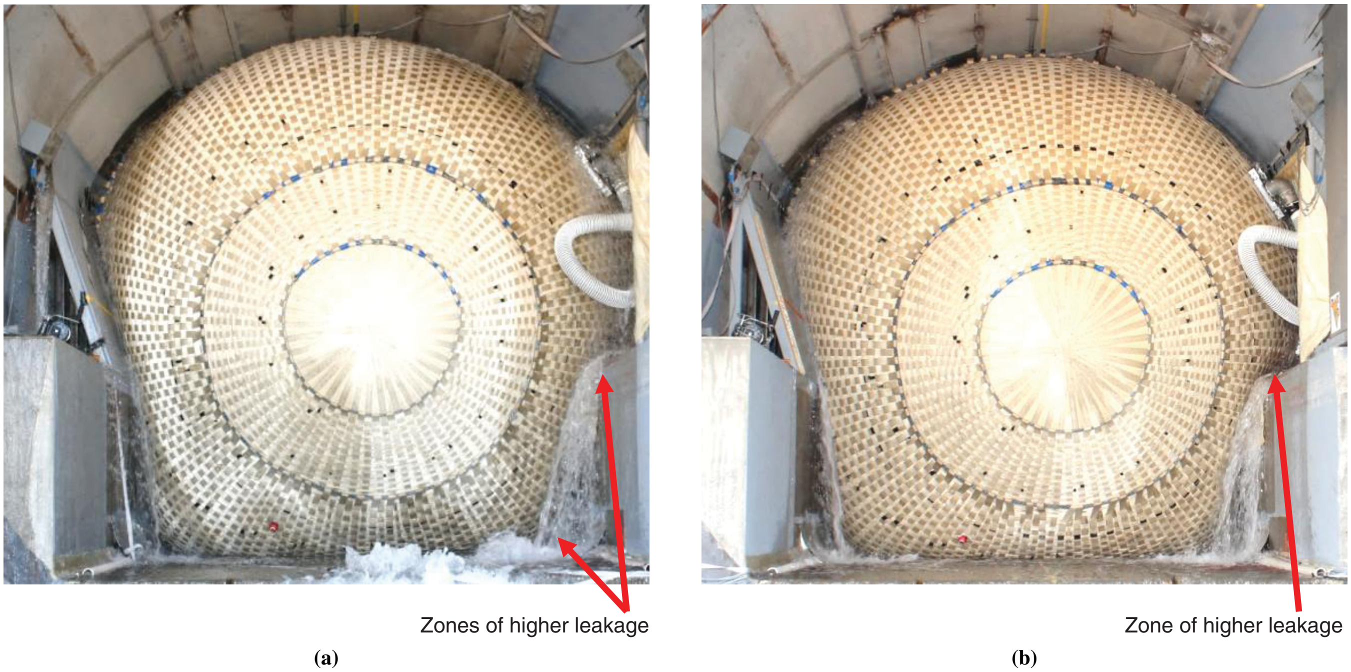

FIGURE 8 Flooding simulations: (*a*) Test 5-AW and (*b*) Test 6-AW.

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