Behavior of full-scale concrete segmented pipelines under permanent ground displacements

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ABSTRACT

Concrete pipelines are one of the most popular underground lifelines used for the transportation of water resources. Unfortunately, this critical infrastructure system remains vulnerable to ground displacements during seismic and landslide events. Ground displacements may induce significant bending, shear, and axial forces to concrete pipelines and eventually lead to joint failures. In order to understand and model the typical failure mechanisms of concrete segmented pipelines, large-scale experimentation is necessary to explore structural and soil-structure behavior during ground faulting. This paper reports on the experimentation of a reinforced concrete segmented concrete pipeline using the unique capabilities of the NEES Lifeline Experimental and Testing Facilities at Cornell University. Five segments of a full-scale commercial concrete pressure pipe (244 cm long and 37.5 cm diameter) are constructed as a segmented pipeline under a compacted granular soil in the facility test basin (13.4 m long and 3.6 m wide). Ground displacements are simulated through translation of half of the test basin. A dense array of sensors including LVDT's, strain gages, and load cells are installed along the length of the pipeline to measure the pipeline response while the ground is incrementally displaced. Accurate measures of pipeline displacements and strains are captured up to the compressive and flexural failure of the pipeline joints.

Keywords: pipelines, concrete segmented pipe, permanent ground displacement, full-scale test, earthquake engineering

1. INTRODUCTION

In the United States, buried pipelines are a vital infrastructure system that is used for the transportation of water (*e.g.,* drinking water, sewage) and energy (*e.g.*, oil, gas) resources. Pipelines are buried below grade for both aesthetic and safety reasons. Specifically, their underground location ensures pipelines can operate with little risk of interruption. However, major ground displacement induced by seismic events and landslides can result is disturbance of the pipeline and possible failure. For example, during recent earthquakes in the United States, extensive damage to buried pipelines of varying construction types (*e.g.,* concrete, metallic) has been reported [1]. Unfortunately, the subterranean location of the pipelines renders inspection and investigation of their health challenging after an earthquake. Rapid detection of damage along a pipeline can help to minimize any interruption in service the pipeline provides. Unlike other infrastructure systems that are readily accessible to inspectors, buried pipelines are not easy to inspect visually. Furthermore, recent advanced sensing technologies that can infer subterranean conditions from the surface (*e.g.*, infra-red thermography [2], ground penetrating radar [3]) have proven unreliable for accurate characterization of pipeline damage.

The analysis of underground pipelines during earthquakes has been extensively studied over the years [4-9]. During an earthquake, the propagation of transient seismic waves can cause damage [1]. However, damage introduced in the

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vicinity of the fault where permanent ground deformation (PGD) is experienced is often more severe to the pipeline [1, 4]. The damage introduced into a buried pipeline by ground deformation is also common in other non-seismic events such as landslides [6]. The behavior of pipelines under PGD shares strong similarity to the classical geotechnical engineering problem on the behavior of laterally loaded piles or vertical pile foundation [6]. Soil-structure interaction models have been developed for buried pipelines in the literature. For example, Audibert and Nyman [8] comprehensively studied the problem using small scale pipe models. Their work focused on soil failure mechanisms rather than on the pipe itself when developing load-displacement (P-y) curves of displaced pipelines. More detailed study of the small-scale pipeline behavior has also been investigated by other researchers [4, 9]. However, the establishment of the Network for Earthquake Engineering and Simulation (NEES) Lifeline Experimental and Testing Facility at Cornell University has provided the research community with the capability to test large-scale pipelines exposed to PGD. To date, a wide variety of different pipeline systems have been tested using this unique testing facility including metallic and high-density polyethylene pipelines with ranging diameters (25 to 40 cm) and differing geotechnical conditions (*e.g.*, burial depth, fault orientation)[9].

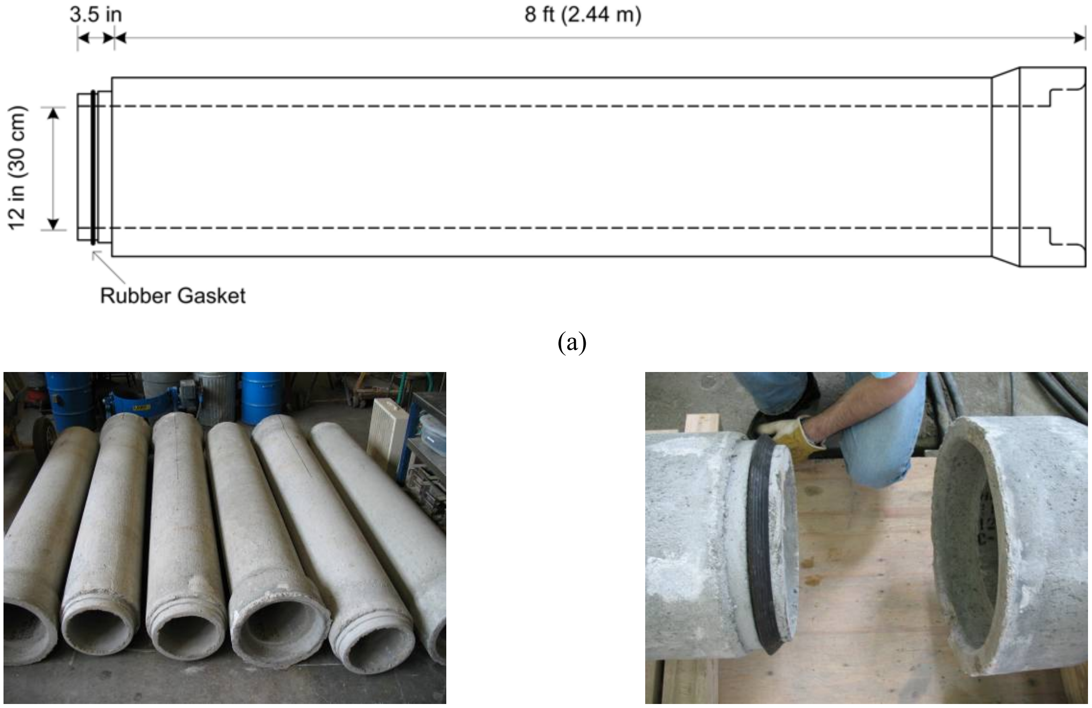
In this study, an experimental program focused on the behavior of buried segmented concrete pipelines is pursued. Concrete segmented pipe is one the most widely used pipe constructions. For example, concrete segmented pipe is widely used in the construction of sanitary sewer systems due to their low cost, high strength, and resistance to deterioration under exposure to sewage. However, the bell-spigot joint of segmented concrete pipes are known to be a weak structural component that is vulnerable to failure under PGD [10]. PGD imposes flexural bending and shear on the pipeline accompanied by axial compression or tension, depending on the geometric orientation of the pipeline crossing an active fault. Under axial compression, the crushing of the joint bell is common while under axial tension, joint pull-out is possible [4]. Due to the nonlinearity and uncertainty inherent to the joint, the behavior of non-continuous segmented pipes, especially segmented concrete pipes, is considered to be a challenging engineering problem. Despite their importance, comparatively less experimental work has been focused on segmented concrete pipelines in the literature to date.

To explore the behavior of a segmented concrete pipeline during PGD, experimental testing of a commercial concrete segmented pipeline section is performed at the NEES Lifeline Experimental and Testing Facilities at Cornell University. A dense array of sensors is installed along the length of the pipeline to measure its response to PGD introduced during fault displacement. The sensing strategy is optimized to: 1) provide real-time pipeline displacement information to researchers actively involved with the testing, and 2) capture the failure mechanisms of the segmented pipeline during larger displacements. In this paper, the experimental setup (including the instrumentation plan) used to test the segmented concrete pipeline is described in detail. The pipeline is exposed to PGD created by a 50 degree fault plane exposed during displacement-controlled movement of the facility test basin. The results obtained from the dense array of displacement transducers and strain gages during faulting are presented. The paper then concludes with a summary of the key project findings including an assessment of the pipeline performance and likely failure mechanisms.

2. SEGMENTED CONCRETE PIPE SPECIMEN

A full-scale, 12 inch (30.48 cm) diameter commercial reinforced concrete pipe (Class 3/4) was selected as the pipeline specimen for this study (Fig. 1). The pipe was manufactured by Hanson, Inc. (Rhode Island) according to ASTM C 76 [11] and C 655 [12] specifications. The full-scale pipe was 8 ft (2.44 m) long and approximately 900 lb (408 kg) in weight. The pipe cross-section consisted of a 12 inch (30.48 cm) inside wall diameter with a 2.38 in (6.3 cm) wall thickness. The pipe walls were reinforced with steel bars using a reinforcement ratio of 0.07 (in^2/linear ft). The compressive strength of the concrete material was tested to be 4000 psi (27.58 MPa).

The pipe joints are the classical bell-spigot joint type. A rubber gasket was placed near the spigot end to ensure a snug bell-spigot connection and to seal the joint during assembly of the pipeline. In total, six pipe segments were shipped to the NEES Lifeline Experimental and Testing Facility at Cornell University where they were assembled into a complete segmented pipeline consisting of 5 full segments and one partial segment (that was cut to size). Assembly consisted of fitting the spigot end of one pipe into the bell end of another. A wet grout containing 30% fine aggregate, a 0.5 water-to-cement ratio, and 0.5% high-range water reducer, was mixed and poured into the annular spaces of each bell-spigot connection accommodated by a thin plastic mold designed to hold the grout in the connection while setting.



(a)

(b)

(c)

Fig. 1. Reinforced concrete segmented pipe: (a) pipe segment geometry; (b) pipe segments upon delivery at the NEES-Cornell facility; (b) close-up view of an open bell-spigot connection with a rubber seal evident on the spigot end of the left-most pipe.

3. EXPERIMENTAL PLAN

3.1 Soil Test Basin

The Lifeline Experimental and Testing Facility at Cornell University contains a large test basin in which pipelines can be constructed and tested under PGD. The basin itself is a 3.4 m wide, 13.4 m long, and 2 m high box. The basin was designed to simulate a transverse fault oriented 50 degree relative to the longitudinal length of the basin as seen in Fig. 2. The north end of the test basin was attached to four hydraulic actuators for controlled displacement while the south end of the basin was held fixed. The test basin was filled with one initial layer of soil, approximately 20 cm deep, to create a bed for the pipeline to be installed on. After being instrumented with various sensors, the pipe segments were lifted by crane into the test basin and installed, beginning at the south end (Fig. 3a). Each time a pipe segment was laid into the basin, wiring for the sensors was fed through the inside of the pipe or arranged along the outside of the pipe, depending on the location of the sensor. The final segmented concrete pipeline consisted of five full pipe segments in addition to a sliced pipe segment installed at the north-end of the basin (Fig. 2). The pipeline was fixed at both ends of the test basin using steel plates. The center pipe segment (designated as pipe segment #3 in Fig. 2) crossed the 50 degree transverse fault. This fault geometry would place the pipe in a state of compression during PGD.

After all pipe segments were laid, the joints of the pipeline were wrapped with a plastic mold and grouted. Granular soil was backfilled into the test basin to bury the pipeline roughly 140 cm beneath the soil surface. Backfilling of the test basin was conducted one layer at a time with each layer 20 cm deep. Once a layer of soil was placed in the basin, it was compacted according to field construction practice. During the backfilling stage, a nuclear density gage was used to repeatedly measure the density and water content of the soil; a relatively constant density (1.7 Mg/m^3) and water content (5%) was observed throughout the soil column. After backfilling (Fig. 3b), a grid was laid on the surface of the soil to aid in visually observing disturbances to the soil surface during PGD.

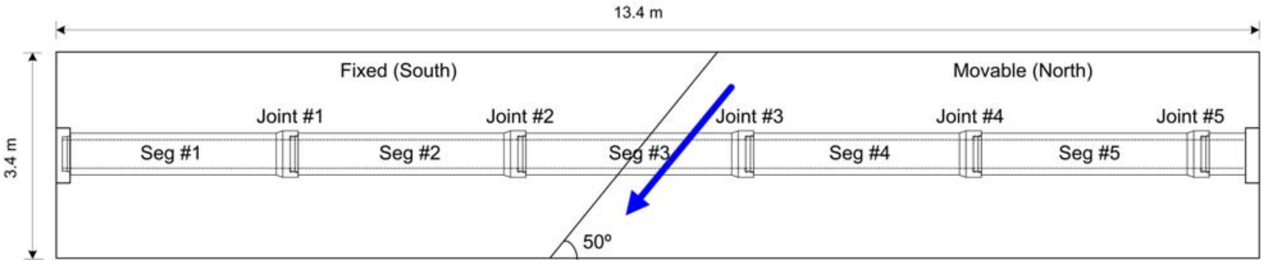


Fig. 2. Layout of the segmented concrete pipeline in the Cornell Lifeline Experimental and Testing Facility's test basin.


(a)

(b)

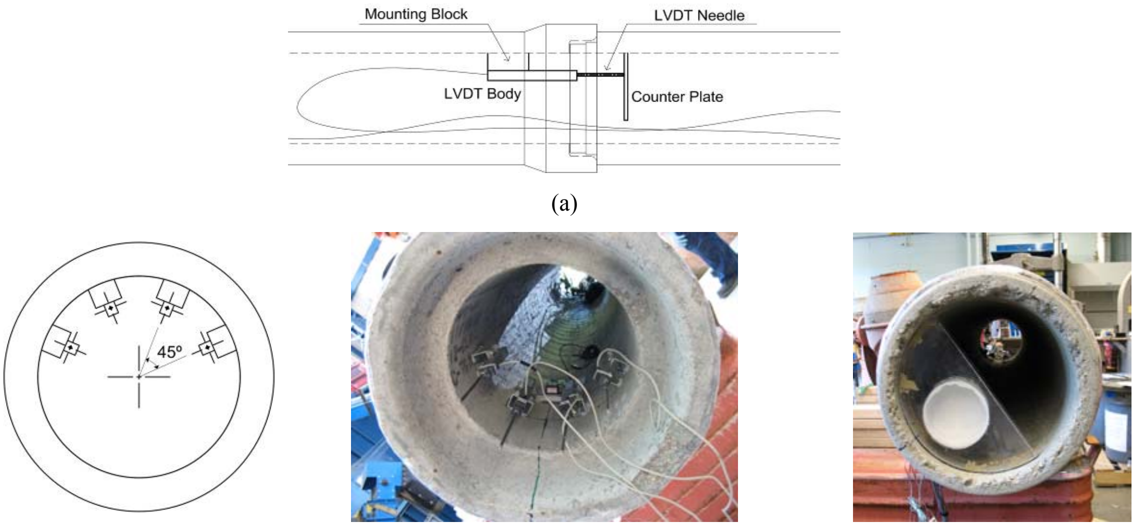
Fig. 3. (a) Installation of the instrumented pipe segments in the test basin; (b) test basin fully backfilled with compacted granular soil (prior to testing).

3.2 Instrumentation Plan

Displacement and Rotation Sensing

A dense array of sensors was installed throughout the buried segmented concrete pipeline in an effort to monitor deformation and failure modes during PGD. An elaborate instrumentation plan was followed to measure translational and rotational movement of the segmented pipeline joints. Four sets of four linear variable differential transducers (Novotechnik TR100 LVDT) were installed at joints #1 through #4, totaling 16 LVDTs for the complete pipeline. As shown in Figs. 4a and 4b, four LVDTs were installed along the upper, inner surface of the pipe. The LVDTs were installed on C-channel blocks, roughly 3 cm tall, in order to allow more spacing between the LVDT needles and the pipe wall. The C-channel mounting blocks were epoxy set to the concrete roughly 45 degrees apart from one another. LVDT needles protruding from the bell end of one pipe joint are designed to make contact with a Lucite plate (Fig. 4d) epoxy mounted inside of the spigot end of the adjacent segmented pipe. Shielded coaxial wiring from the LVDTs are strung through the interior of the pipeline. The LVDT wires are brought outside of the basin through an opening in the basin wall near the location where the pipeline is mounted.

The LVDTs installed in each joint are designed to directly measure joint translation and rotation along the length of the pipeline. A specific plane is geometrically determined in three-dimensional space using the coordinates of 3 points located on the plane. Thus, three LVDTs can be used to determine the orientation of the Lucite plate (plane); one of the four LVDTs is designed to be redundant and can be used if one LVDT is found to not be operating properly during the test. Using the coordinate system established in Fig. 5 (where the z-axis is oriented in the direction of the LVDT



(a)

(b) (c) (d)

Fig. 4. (a) Schematic of a LVDT installation at a typical joint; (b) A set of four LVDTs at upper part of pipe cross section; (c) Four LVDTs mounted on C-channel blocks on the interior of the pipe near the bell; (d) A dichotomy-shaped Lucite plate mounted in the spigot.

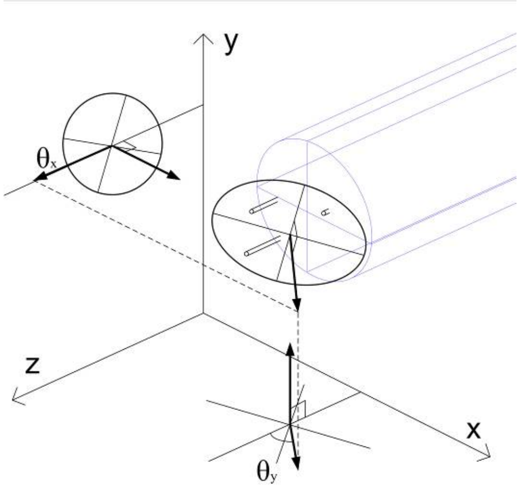


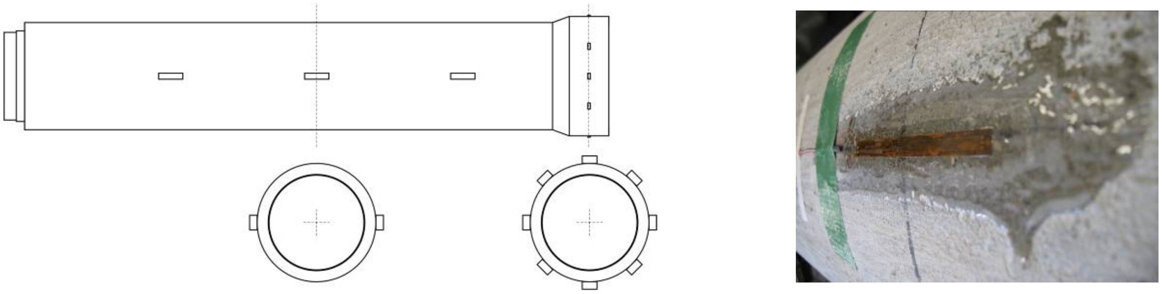
Fig. 5. Geometric interpretation of joint rotations from three LVDT measurements. The center ellipse stands for the plane determined by three LVDTs; The normal vector for the plane is projected on x-z and y-z plane.

Fig. 6. Four instrumented load cells at the ends of the pipeline.

needles), two rotational angles along the x- and y-axes (representing the vertical and horizontal rotations of the pipe segment) are calculated by projection of the plane vector onto the x-z and y-z planes. Movement along the z-axis, which represents the axial translation at the joint, can be also calculated by averaging the change in length of three LVDTs.

Axial Loading

At each of the two ends of the pipeline, four load cells were installed to measure the axial force imparted by the test basin during compression deformation of the pipeline. Each load cell consists of a steel annulus instrumented by a rosette strain gage array which are interfaced with a half-bridge circuit in a National Instrument SCXI-1520 data acquisition system. Precise calibration tests for determining axial force from measured strain were conducted before the test.



(a) (b)

Fig. 7. (a) Installation of strain gages on the pipe segments. Axial strain measured on six strain gages mounted at the center of pipe segments. An additional 8 strain gages installed at the bell end of pipe segment #2 and #3 to measure hoop strain. (b) Strain gage mounted to the pre-coated layer on the surface of the concrete.

Strain Response

In addition to measuring joint movement, deformation along the pipe was also monitored using strain gages. Strain gages (Vishay N2A-06-40CBY 350Ω metal foil gages) designed for measuring concrete strain on the surface of a concrete structure were mounted longitudinally along the length of the pipeline. The long gage length (101.6 mm) allows strain integration along non-homogeneous specimens. Strain gages were placed equidistant along the pipe length and on each side of the pipe segment as seen in Fig. 7a. These six strain gages allow for the measurement of both axial and bending strain at three sections of each pipe segment. Axial strain at a section is calculated by taking the mean of the two strain measurements. Similarly, flexural response of the pipe at a given section is calculated using the difference between the two strain gages. An additional 8 strain gages (Vishay L2A-06-250LW 350Ω metal foil gages) were mounted circumferentially on the bells of pipe segments near the fault line, namely joints #2 and #3. These eight gages were installed to measure hoop strain at the pipeline connections. During installation of the strain gages, the rough concrete pipe surface was ground smooth and then a very thin and smooth surface epoxy layer was applied as seen in Fig. 7b. The epoxy layer was delicately cleaned by fine sand papers followed by additional cleaning using acid and base solution. Strain gages were firmly mounted above the smoothed epoxy surface using strain gage bonding adhesive.

4. EXPERIMENTAL RESULTS DURING PGD

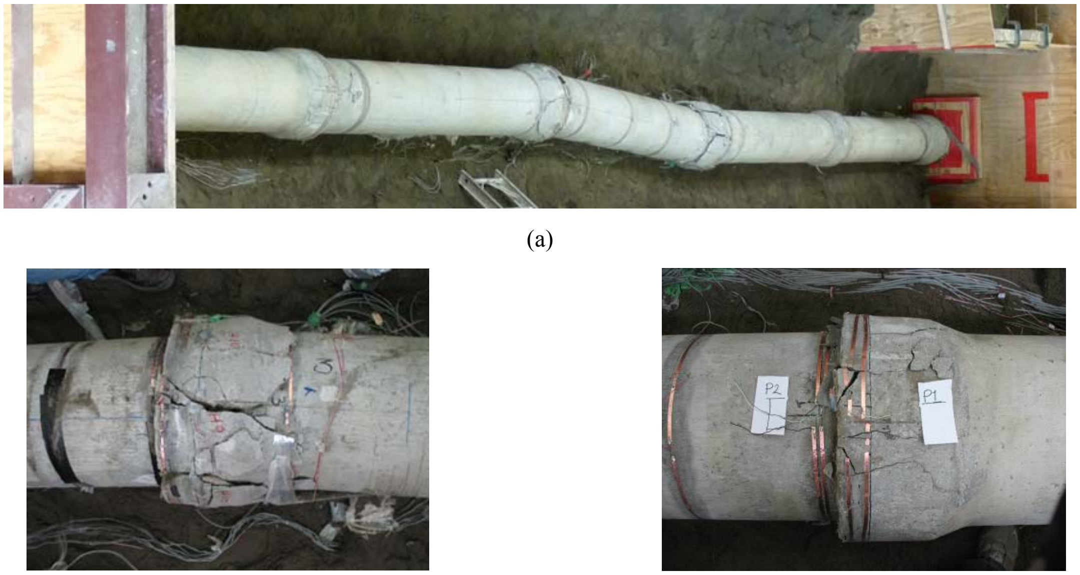
4.1 Testing Protocol

Ground faulting was simulated by displacement of the northern portion of the test basin using four hydraulic actuators mounted to the lab's reaction wall. The actuators were operated under displacement-control with a 0.5 cm/s displacement rate. The actuators for this test were set to displace 2.5 cm along the fault line during each displacement increment. Following each displacement increment, the test was paused so as to allow for the investigation of possible relaxation of the soil-pipe system and to permit the team to check that all monitoring system components were in a perfect working state.

Two monitoring systems were used during testing. First, a National Instrument data acquisition system (Fig. 8a) was setup near both ends of the test basin to record data from the 16 LVDTs, 46 strain gages, 8 load cells, and 4 actuators (which output actuator displacement and force measurements). Considering the slow movement of the northern portion of the test basin, a modest sample rate of 10 Hz was utilized by the National Instrument data acquisition system. A second monitoring system was used during testing. The output of the 16 LVDTs was split so that it could be interfaced to wireless sensor nodes (termed *Narada*) under development for structural health monitoring at the University of Michigan [14]. The additional wireless monitoring system for the LVDTs was designed to provide real-time measurement of the pipe joint movements during testing. The LVDT data was sent by the wireless sensors to a wirelessly-enabled data sever which was setup to process and convert displacement measurements at each joint into pipe movement for online, real-time display as shown in Fig. 8b. This allowed the team to monitor the behavior of the buried

(a) (b)

Fig. 8. Experimental setup: (a) data acquisition systems near the north test basin; (b) real-time pipeline movement after the 11th actuation step.



(a)

(b) (c)

Fig. 9. (a) Excavated pipeline after the test. Two main failure modes were found: (b) Combined failure by rotation and contraction at two joints (#2 and #3) near the ground fault, and (c) compressive telescoping failures at the other joints (#1, #4, and #5).

pipeline as testing was conducted. Based on this real-time measurement of pipeline deformation, the team could more accurately assess when significant failure of the pipeline occurred, thereby effectively ending the test.

The test ended after 12 actuation steps with the final PGD measured at 30.5 cm along the fault line. During the 12th actuation step, significant movement was observed at the joints near the fault line. After the end of testing, the backfilled soil was carefully removed and visual forensic analysis of the damaged pipeline was conducted. Video cameras were also installed above the test basin to record the ground faulting during the test and the pipeline after excavation.

4.2 Visual Inspection after Permanent Ground Displacement

After testing was complete, the soil above the pipeline was carefully excavated so as not to disturb the pipeline's deformed condition. As shown in Fig. 9a, the center pipe segment (segment #3) rotated to accommodate the applied PGD. Thus, considerable damage was immediately witnessed in both segment joints (joint #2 and #3). Besides rotations,

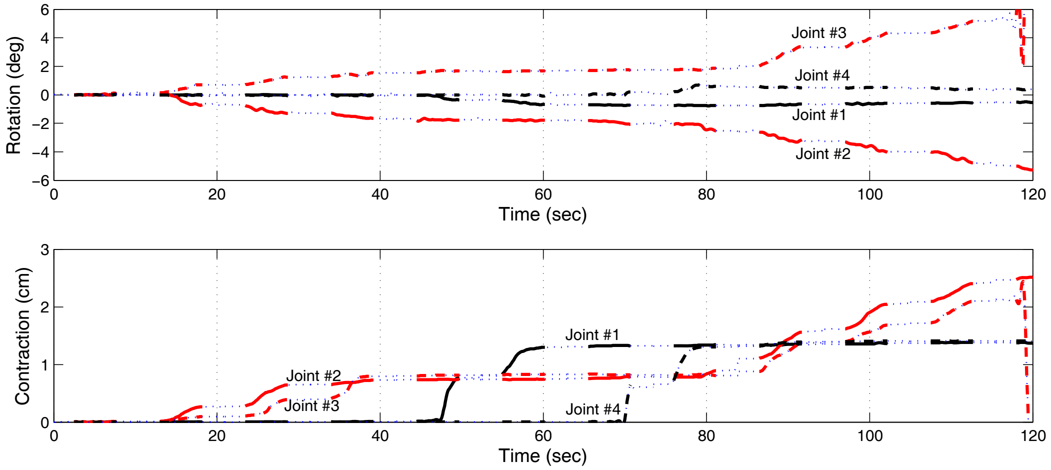


Fig. 10. Joint rotation (top) and contraction (bottom) at joints #1 through #4.

approximately 1 inch-long spigot telescoping was witnessed with the spigot of segments compressed into the bells of the adjacent pipe. Large portions of the concrete cover were spalled from the bell as seen in Fig. 9b. It can be speculated that these damage modes are due to a combination of failure mechanisms due to rotation and contraction. Other joints also experienced some telescopic damage (Fig. 9c), but not as severe as that of the two center joints (joint #2 and #3). The minor telescopic damage observed in joints #1, 4, and 5, and the severe damage encountered in joints #2 and #3 suggest strong soil-pipe interaction along the entire pipeline, which can be explained by the relatively high flexural rigidity and axial stiffness of the pipeline compared to the stiffness of the surrounding soil. No damage was found within the pipe bodies throughout the entire pipeline.

4.3 Analysis of the Pipeline Measured Response

The behavior of full-scale concrete segmented pipelines under PGD was thoroughly investigated by analysis of the data collected from the test. First, investigation of joint rotations and contractions, which were processed from the LVDT's, revealed generic failure behavior of the concrete segmented pipeline. Fig. 10 plots the measured joint movement at joint #1, 2, 3 and 4 over the duration of the test. Strong axisymmetric behavior was observed with respect to the pipeline center. As actuation steps proceeded, significant rotations (5.7^{o}) occurred at joints (joint #2 and #3) close to the fault plane compared to small rotations (0.6^{o}) at joints #1 and #4 which are close to the pipeline ends. However, significant joint contractions (ranging from 1.3 to 2.5 cm) happened at every joint due to fairly uniform axial compression along the pipeline length. The results obtained can explain the aforementioned joint failure modes, *i.e.*, combined rotation and contraction failures at the center of the pipeline but compressive telescoping failures away from the fault plane.

A detailed stepwise interpretation of the results explains the possible failure sequence of the pipeline joints. During the first 2.5 cm of displacement (termed actuation step A#1), no significant movement was found at any joint, which implies that the pipeline structure behaved linearly under PGD. However, joint failures occured in the actuation sequences that followed. Rotation and contraction were monitored at the two joints near the fault line (*i.e.*, joint #2 and #3) from A#2 through A#4. Following that, joint #1 was damaged from A#5 and A#6 while joint #4 was damaged from A#7 to A#8. During these stages, no more significant movement was found at joint #2 and #3. From actuation step A#9 until the final actuation step (A#12), joint #2 and #3 experienced severe contraction and rotation, resulting in the crushing of the grout and spalling of the concrete cover. As the grout crushes, adjacent pipe segments come into direct contact effectively increasing the flexural rigidity and axial stiffness of the pipeline. This is different from a situation where the pipeline is fully broken into articulated segments.

Investigation of the axial compressive forces (Fig. 11) measured at both ends of the pipeline also support the aforementioned interpretation of the pipeline behavior. During the test, the pipeline underwent strong axial force due to the geometry of the fault line. Similar compressive forces were monitored at both ends of the pipe through 12 actuation

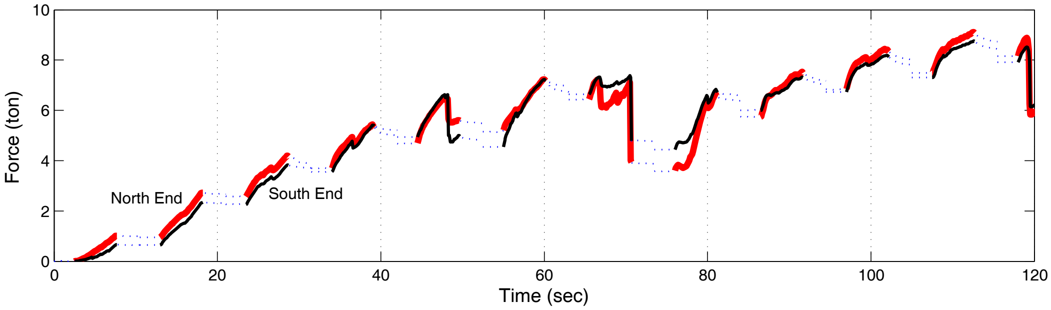


Fig. 11. Axial forces at the end of the pipelines measured by load cells.

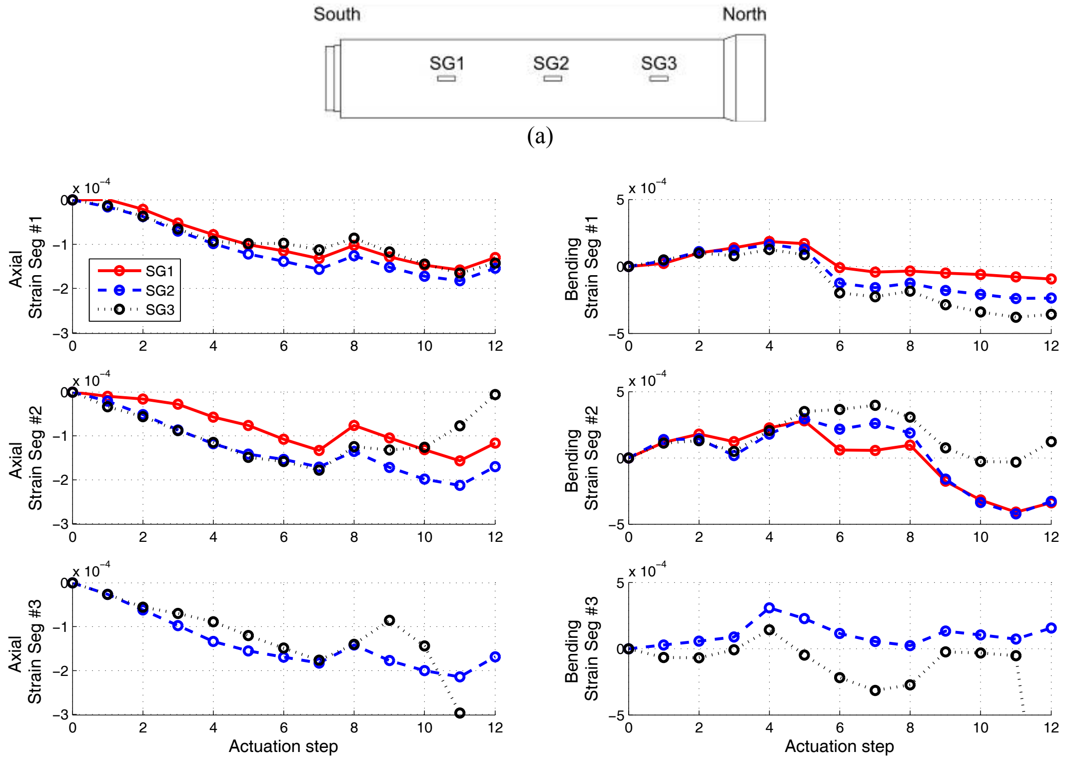
steps as seen in Fig. 11. As the ground displacement proceeded, the pipeline end forces also increased. However, three sudden drops of end force were found at both ends during actuation steps A#5, A#7, and A#12. During step A#5 and A#7, joint #1 and #4 started to undergo damage (likely telescopic-type damage) thereby releasing axial force along the pipeline. A sudden drop of end force at A#12 reflected the sudden introduction of severe damage along the pipeline. It should be noted that no significant end force drop was monitored at A#2 and A#3 when joint #2 and #3 were damaged. This can be explained by soil friction around the pipeline; at the early stage of the test, soil disturbance was not severe and the two joints were more than 5 meter apart from each end.

The strain gage data provided additional information on the behavior of the pipeline (Fig. 12). The axial and bending strain at three equidistant points along pipe segments #1, #2, and #3 (Fig. 2) are depicted in Fig. 12. For the case of segment #3 (*i.e.*, the center pipe), the first strain gage pair did not work during the test. Generally, the increase in axial strain observed in each pipe segment was found to be proportional to each actuation step. However, depending on the stage of the test, the bending direction changed at each pipe segment.

5. CONCLUSIONS

A primary objective of this study was to observe the sequential failure of concrete segmented pipelines under permanent ground displacements. A 13 meter pipeline assembled from 5 full pipe segments was constructed within a large test basin at Cornell University's Lifeline Experimental and Testing Facilities. A 30.5 cm ground fault displacement was simulated along a 50° angle which imposed compression, shear, and bending along the pipeline length. A dense array of sensors was installed to measure pipe deformation and joint movement. A real-time monitoring system was strategically utilized to observe the displacement of the pipe segments during the execution of ground faulting. Using this instrumentation strategy, the behavior of a full-scale buried concrete segmented pipeline exposed to permanent ground displacement was successfully observed.

Two evident failure modes of the pipeline joints were found by post-event visual inspection: combined rotation and contraction failure as well as compressive telescoping failure. Based on the analysis of the sensor data, a gradual failure sequence of the buried concrete segmented pipeline was also identified. Specifically, as the ground gradually moved, grout crushing occurred in the pipeline joints thereby allowing each concrete pipe segment to come into direct contact with the adjacent pipe. Grout crushing began at the joints adjacent to the fault line and propagated out toward the end joints consecutively. Once the grout was destroyed, the overall pipeline axial stiffness and flexural rigidity had reached its maximum. Finally, severe failure occurred during the last actuation step at the joints nearest the fault plane.



(a)

(b)

Fig. 12. (a) Strain gage locations; (b) axial and bending strain for three pipe segments (segments #1,#2, and #3).

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