Prediction and Simulation Methods for Geohazard Mitigation – Oka, Murakami & Kimoto (eds)

Damage detection and health monitoring of buried concrete pipelines

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ABSTRACT: Rapid assessment of damage to buried pipelines from earthquake ground faulting is a crucial component to quickly plan repair efforts. This paper briefly reviews sensor technologies currently used for monitoring the health (i.e. assessing damage) of buried concrete pipelines. This paper also reports on the first of a four-year study aimed at developing rapid, reliable, and cost-effective sensing systems for health monitoring of buried concrete pipelines. The study includes testing of buried concrete pipelines in a large-scale facility that is capable of simulating earthquake ground faulting. Two modes of failure were identified in the first pipeline test, which were compression and bending at the pipeline joints closest to the fault line. As a result future research aimed at advancing sensing technology will likely focus on the behavior of the joints.

1 INTRODUCTION

Assessment of damage to lifelines after natural disasters, such as earthquakes, is crucial for management of an effective emergency response. Of particular importance is the water supply system because water is an important survival resource; even minor damage to water pipelines may result in contamination and epidemic outbreaks. Water pipelines are considered one of the most vulnerable systems to damage from earthquakes (Eidinger 1996). In particular, pipelines in the vicinity of permanent ground displacements are most vulnerable to damage.

The assessment of the condition or health of pipeline systems is very difficult given that they are typically buried and therefore not readily accessible for visual inspection. In urban settings the water system is just one of a number of underground utilities, making access for inspection or repair even more difficult. Furthermore, the need for earthwork and heavy equipment to expose buried pipelines makes a rapid emergency response unfeasible. Hence, there is a clear need for systems which can rapidly assess the health of a pipeline after an earthquake. For this reason the Authors are currently participating in a four-year study aimed at developing sensing technologies for health monitoring (i.e. assessing damage) of buried concrete water pipelines. Though damage to buried pipelines can be caused by seismic waves (Barenberg 1988, O'Rourke & Ayala 1993), this study focuses on damage attributed to permanent ground displacement, which is often more severe (O'Rourke 2005).

This paper reviews some of the current technologies used for damage detection of concrete pipelines. This paper also reports on the first of four large-scale tests that was performed on a buried segmental concrete pipeline at the Large Displacement Facility at Cornell University (part of the Network for Earthquake Engineering Simulation). The test facility is capable of simulating permanent ground displacements that can occur in regions subjected to earthquakes.

2 SENSING TECHNOLOGIES FOR PIPELINES

The three basic types of sensing technologies for concrete pipelines include: (1) internal sensing, (2) fiber-optic sensing, and (3) remote sensing. Internal sensing involves inspecting the pipeline walls using technology deployed inside the pipe. These include remote video cameras or ultrasonic transducers. Ultrasonic transducers are used to map the thickness of the pipe walls by transmitting an acoustic wave and recording the travel time of the waves that are reflected at the interior and exterior surface of the pipe.

Fiber optic sensors, such as the Fiber Bragg Gratings (FBG), have been used for structural sensing since the 1970s. The FBG strain sensor consists of a traditional silicon glass fiber, upon which a Bragg grating is etched (Tennyson 2003). The sensor works by measuring the optical wavelength, which changes linearly with strain. Recently in Italy, a 500 meter stretch of pipeline was instrumented with FBG strain sensors to monitor its strain response to landslides (Inaudi & Glisic 2005). The application of fiber-optic sensing technology for pipelines is typically cost prohibitive, with a typical system ranging from \$20k to \$100k (Bergmeister 2000).

Remote sensing technologies include Infrared Thermography Systems (ITS) and Ground Penetrating Radar (GPR). Infrared technology indirectly detects damage by detecting leaks in the pipeline, which show up as temperature anomalies. ITS has been successfully used to detect pipeline leaks and poor backfill conditions (Inagaki & Okamoto 1997). GPR uses electromagnetic wave energy to map the conditions below the ground surface by measuring the reflections that occur at discontinuities between soil strata and soil pipe interfaces. However, the image quality is usually poor and requires a fair amount of user judgment to interpret (Hayakawa & Kawanaka 1998).

There is currently a need for reliable and cost-effective sensing systems that can rapidly assess the health of buried pipelines. Development of new technologies requires a test facility that can simulate the conditions that a pipe might experience during ground faulting. Given the difficulty in scaling experiments, it is desired to test as close as possible to full-scale. To this end, this study utilized the large-scale testing facility at Cornell University, which can simulate permanent ground displacements associated with earthquake ground faulting.

3 LARGE-SCALE PIPELINE TESTING

Pipeline testing for the four-year study is being performed in the large-scale pipeline test facility at Cornell University. The facility is one of the Network for Earthquake Engineering Simulation (NEES) equipment sites which are located throughout the United States. Previous tests at this facility included pipelines made of materials other than concrete (e.g. high-density polyethylene) (O'Rourke et al. 2008). The study described herein is the first such study performed on segmental concrete pipes. This section describes some preliminary results of the first pipeline test performed in June 2008. The objective of this first test was to observe the modes of failure in order to direct future research.

3.1 *Test facility*

The pipeline test basin, shown in Figure 1, consists of a 11.7-meter long by 3.4-meter wide by 1.9-meter deep box, having a transverse fault oriented at an angle of 65 degrees relative to the longitudinal axis of the basin. The basin is able to accommodate a pipeline that is fixed to the ends of the test basin and buried with granular backfill. To simulate earthquake induced permanent ground displacement, one half of the basin is moved laterally parallel to the fault line using two large hydraulic actuators placed between the basin and a reaction wall, while the other half of the basin remains stationary. The box can be displaced in either direction, causing the pipeline to be put in axial compression or tension.

Figure 1. Pipeline test basin at Cornell University.

Figure 2. Typical bell-and-spigot connection between two pipe segments. The three potentiometers shown inside the pipe were used to measure displacement and rotation at the joint.

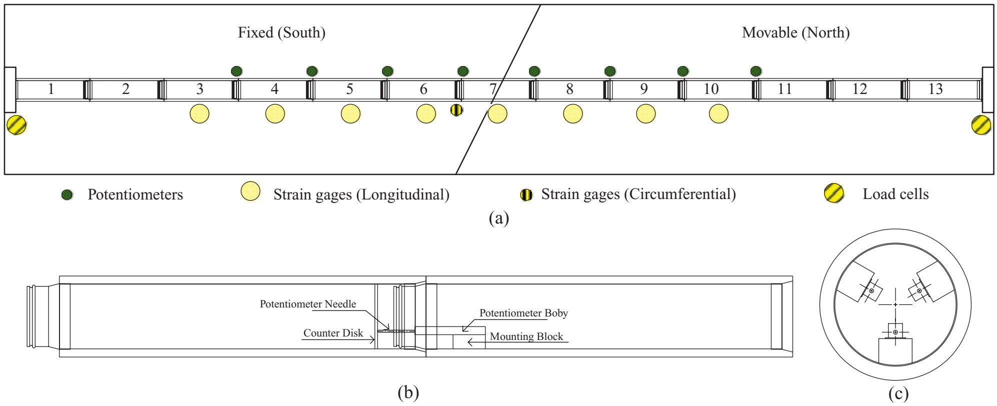

Figure 3. Instrumented sensors: (a) three types of sensors (potentiometers, strain gages and load cells) and their instrumentation location; (b) schematic of a potentiometer installation at a typical joint; (c) cross-sectional view of a potentiometer set at a joint.

3.2 *Test preparation*

Pipe segments used for the experimental program were manufactured according to AWWA C300 (AWWA 2004). This standard specifies requirements for concrete pressure pipes with internal diameter of 76 to 365 cm. Since there was some concern in the first test of exceeding the load capacity of the test basin, pipe segments were linearly scaled down to 15.24 cm inner diameter resulting in 19.2 cm outer diameter.

Fifteen 90-centimeter long pipe segments were fabricated at the Materials Engineering Lab at Purdue University. The pipe segments consist of a thin-walled (0.8 mm) steel tube covered by a concrete shell with steel rebar. Thirteen pipe segments were required to span the entire length of the test basin. The segments were connected by bell-and-spigot connections, shown in Figure 2. The segments were placed such that the center segment bisected the fault plane.

The pipeline was instrumented with three different types of sensors whose locations are shown in Figure 3. Sixteen surface-mounted strain gages were attached to the exterior of the pipeline at various locations. Four sets of three potentiometers were mounted on the interior of pipe to measure rotation at the four joints closest to the fault plane. Six load cells were used to measure axial forces at the ends of the pipeline.

The pipeline was assembled inside the test basin working from one side of the basin to the other. Once the entire pipeline was assembled (Figure 4), the gaps between segments were grouted using mortar with 50% aggregate and a water-cement ratio of 0.5 produced using ASTM Type I/II Portland cement. Given the narrow joints, a 0.5% high range water reducer (by weight of cement) was used as needed to improve the flowability of the grout. Plastic sheets or "diapers" wrapped around the joints kept the grout in place during pouring and also served to prevent moisture loss during curing.

Figure 4. Assembled pipeline segments prior to joint grouting. Grout was poured in the annular space shown at each joint location.

The pipeline was buried beneath about 115 cm of granular soil, compacted in roughly 20-cm thick lifts. The density and water content of each lift was measured with a nuclear density gauge. The backfill soil was classified as poorly-graded sand (SP), per ASTM D 2487 (ASTM 2002). The optimum water content was about 9% and the maximum dry density was 2.1 Mg/m^3, as determined by a modified Proctor test, ASTM D 1557 (ASTM 2002). Direct simple shear tests (see O'Rourke et al. 2008) indicate that the effective friction angle of the backfill soil is between 39° and 40° when prepared to dry densities within the range of 1.58 Mg/m^3 to 1.61 Mg/m^3.

The in situ dry density and water content are shown in the depth profile in Figure 5. Each data point in the figure represents the average value for the lift. The data indicate relatively consistent properties within the soil placed above the bottom of the pipeline, which was located at a depth of about 115 cm. The average dry density in this zone was about 1.67 Mg/m^3, and the average water content was about 5%. These values indicated an average relative compaction of about 80%, relative to the modified Proctor test. The soil located below the pipeline had a higher density due to foot traffic while the pipeline was being assembled.

3.3 *Preliminary results*

Earthquake induced permanent ground displacement was simulated by displacing one half of the test basin parallel to the strike of the fault plane. The box was configured to put the pipeline in compression as half of the basin was slowly displaced. The box was displaced at a constant rate of 0.5 cm/s to a maximum displacement of 1.22 m. The test was paused at 15-cm intervals for a period of 60 seconds. This was done to allow more controlled observation of the test and to investigate possible stress relaxation phenomena. The ground deformation at the completion of the test is shown in Figure 6.

After the test was completed, the pipeline was carefully excavated so as not to disturb its deformed condition. Observations of the deformed pipe indicated that most of the pipeline damage was concentrated in the two joints on both sides of the fault plane, with cracks propagating away from the damaged joints.

Two modes of joint failure were observed: compression and bending. During the initial phases of the test, large compressive loads caused the spigot to telescope into the bell as shown in Figure 7. However, these axial forces were not detected in the load cells at the ends of the pipeline. Therefore, it is hypothesized that the compressive loads generated in the mid-section of the pipeline were reacted by the shear forces induced at the pipe-soil interface. The telescoping-type failures occurred between the second and third pipe segments, on either side of the fault plane.

In the bending mode of failure, the un-reinforced grouted joints underwent initial micro-cracking which ultimately lead to coalesces of micro-cracks and macro-cracking and spalling/crushing of grout. The large deformations and rotation observed at the joints adjacent to the fault, shown in Figure 8, relieved any axial compressive loads that were initially developed within the pipeline.

The two failure modes are also confirmed by the data obtained from the sensors instrumented on the pipeline. Figure 9 represents the calculation of joint displacement and rotation using data obtained from

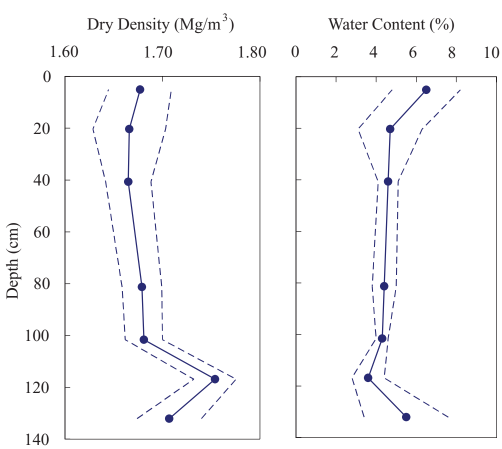

Figure 5. Profile of dry density and water content of the backfill soil averaged within each lift. The dashed lines indicate ± one standard deviation.

Figure 6. Ground faulting observed at the end of the test. The gridlines shown are spaced at approximately 10 cm.

Figure 7. Compressive telescoping observed in one of the bell-and-spigot joints adjacent to the fault plane.

Figure 8. Pipeline deformation observed near the fault. Note that the fault plane ran through the middle of the pipe segment shown in the center of the figure.

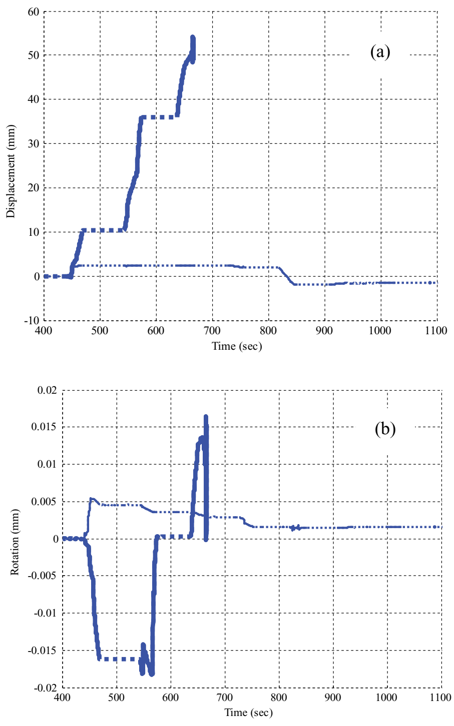

Figure 9. (a) Joint displacements and (b) rotations obtained from the potentiometers at the intersection of pipe segments. The continuous line corresponds to the response during displacement while the dotted line is with the actuator off. The thick line corresponds to the joint between pipe segments 6 and 7 (see Figure 3) while the thin line corresponds to the joint between segments 3 and 4.

the three potentiometers installed at two of the instrumented joints. Specifically, the thick line corresponds to joint behavior between segments 6 and 7 (see Figure 3) while the thin line corresponds to the joint between segments 3 and 4. The joint between segments 6 and 7 experienced large displacements and rotations during the test, suggesting plastic behavior at the joint. In fact, at the end of the third actuated displacement (650 seconds into the record of Figure 9) the joint movement exceeded the maximum sensing range of the potentiometers. This is consistent with extreme rigid body motion of pipe segment 7; during post-testing excavation, this segment was later found to be totally separated from segments 6 and 8 (Figure 8).

It is also interesting to consider the response of the joint between segments 3 and 4. Under the initial fault displacement, the joint is seen to compress, consistent with telescopic compression due to the faulting. However, once segment 7 rotated free of segments 6 and 8, relaxation of the joint between segments 3 and 4 is evident in the displacement record (Figure 9a).

4 SENSOR DEVELOPMENT

The first pipeline test provided significant information on the nature and the most prominent types of damage due to faulting of segmented concrete pipelines. In the pipeline segments closest to the fault, the joints and the areas immediately adjacent to joints were damaged (see Figure 8). This leads to the conclusion that sensing in the joint areas will be most effective. Hence, sensors will be designed to monitor damage in joints and in areas adjacent to joints. Currently two groups of sensing techniques are being developed: (1) electrical sensing, and (2) Acoustic Emission (AE) sensing.

Electrical sensing techniques utilize highly conductive materials typically in the form of a graphite-filled epoxy which is applied to the joint area, or an electrically conductive grout used in the joint. Damage is detected by measuring changes in the electrical resistance of these materials over predefined time intervals. This technique has been utilized in the detection of shrinkage cracking in cement-based composites (Pour-Ghaz & Weiss, in prep.).

Acoustic emission techniques evaluate damage through analysis of acoustic waves using either active or passive methods. Continued development will focus on passive methods where acoustic waves that are generated from damage are captured and the energy, amplitude and duration of the captured waves are evaluated and related to the type of damage (Kim & Weiss 2003).

5 CONCLUSIONS

There is a need for rapid assessment of damage and health monitoring of buried concrete pipelines after earthquakes. Currently available sensing systems are either slow, unreliable, or cost prohibitive. For this reason, development of rapid, reliable and cost-effective systems is needed. In order to focus future sensor system development, a test was performed on a segmental concrete pipeline to investigate possible failure modes. The large-scale test represented the conditions that a buried pipeline will likely experience during earthquake-induced permanent ground displacement. Two modes of failure were observed, which were telescoping of the bell-and-spigot connections and plastic bending at the joints. Most of the damage was confined to the four joints closest to the fault plane. Accordingly, future efforts in this study will include methods that focus on behavior of these joints.

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