Verification of Design Method of Pipeline Crossing Fault with Earthquake Resistant Ductile Iron Pipe using Large-scale Split-box Test

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ABSTRACT

This paper describes a safety verification result of the design method of a pipeline crossing fault using Earthquake Resistant Ductile Iron Pipe (ERDIP). In order to confirm the performance limit of the joint and pipeline behavior, we performed ultimate four-point bending tests and a fault rupture test using the test equipment at Cornell University in the U.S.

Consequently, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint. Thus, the result showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage. The following are the details of the test results.

(a) Four-point bending test: A joint bending test was performed on the ERDIP joint (DN150, GX-type) under water pressure of 0.55 MPa. No leakage was found until the joint deflection of 12.2°. Subsequently, first leakage was confirmed over 12.2°. Consequently, the test result shows that there was no leakage until the joint deflection of 1.5 times larger than the maximum joint deflection angle (i.e., 8°).

(b) Large-scale fault rupture test: ERDIP (DN150, GX-type) under water pressure of 0.55 MPa was installed in a test sand box divided into two sections. The fault displacement was simulated by moving one side of the divided test box. Six joints were placed in the sand box. Both ends of the pipeline were fixed to the box. Normally, an actual chain structure pipeline is installed under less severe conditions than those under which this test was performed. Consequently, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint by the fault rupture.

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INTRODUCTION

It has been reported that there are approximately 2,000 faults in Japan. The 2016 Kumamoto Earthquake was caused by the movement of the Futagawa-Hinagu fault zone [1]. A surface earthquake fault whose maximum displacement was approximately 2 m caused significant damage to houses and infrastructure[2].

We previously reported the verification of the design method of a pipeline that crosses a fault using pipeline behavior analyses and large-scale split-box test with Earthquake Resistant Ductile Iron Pipes (ERDIPs) [3]. An ERDIP pipeline is capable of absorbing the large ground displacements that occur during severe earthquakes owing to the movement of its joint (extension, contraction, and deflection) and the use of the joint locking system. The pipeline is thus referred to as a “chain structure pipeline.” The existing ERDIP pipelines have been exposed to several severe earthquakes such as the 1995 Kobe Earthquake, the 2011 Great East Japan Earthquake, and the 2016 Kumamoto Earthquake and there has been no documentation of their failure in the last 40 years.

ERDIP has been used for measures against earthquakes on the western coast of North America, which is an earthquake-prone zone. In recent years, pipeline design for measures against fault displacement has become necessary, because there are many active faults in the area. The design displacement of a fault is determined by the past fault activities in general; however, we have to know whether the pipeline behavior during a fault movement becomes more excessive than assumed in order to be prepared in case the actual fault displacement is greater than the design displacement. Therefore, we conducted a four-point bending test and a large-scale split-box test under severe conditions wherein a bending moment or displacement exceeds the joint performance. We report the result of these examinations.

STRUCTURE OF ERDIP AND ITS BEHAVIOR

Figure 1 shows a cut-away view of a GX-type joint, which is a type of ERDIP joint investigated in the present study. The bell of an ERDIP is equipped with a locking ring and rubber gasket to prevent water leakage. The spigot is inserted into the bell past the rubber gasket and the locking ring. The spigot end has a special feature called spigot projection, which bears against the locking ring to resist pullout of the spigot from the bell.

Figure 2 shows the behavior of a GX-type joint. Table I presents the performance parameters of the joint. The joint is capable of extending/contracting by 1% of its standard pipe length (e.g., 5 m in the case of DN150). When the joint is fully extended, the spigot projection and locking ring lock tightly together to prevent leakage resulting from the pullout of the joint. The pipeline is thus referred to as a “chain structure pipeline” (Figure 3).

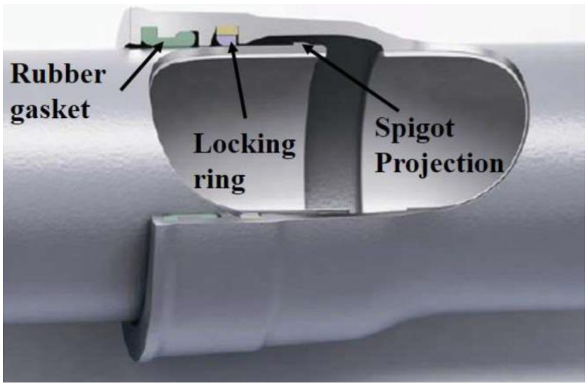

Figure 1. Cut-away view of a GX-type joint

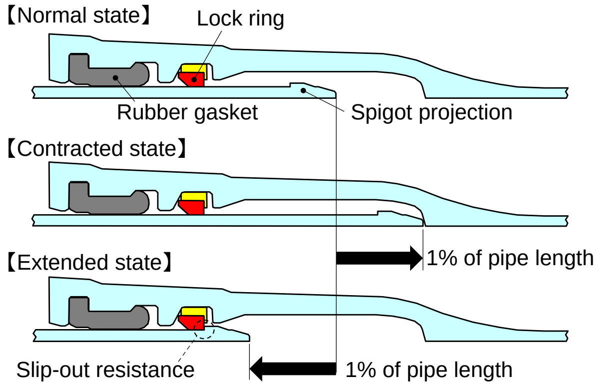

Figure 2. Behavior of a GX-type joint

TABLE I. PERFORMANCE OF GX-TYPE JOINT

Property	Performance
Pullout resistance	3D kN (D : nominal diameter [mm])
Amount of extension/ contraction	± 1% of pipe length
Deflection angle	8°

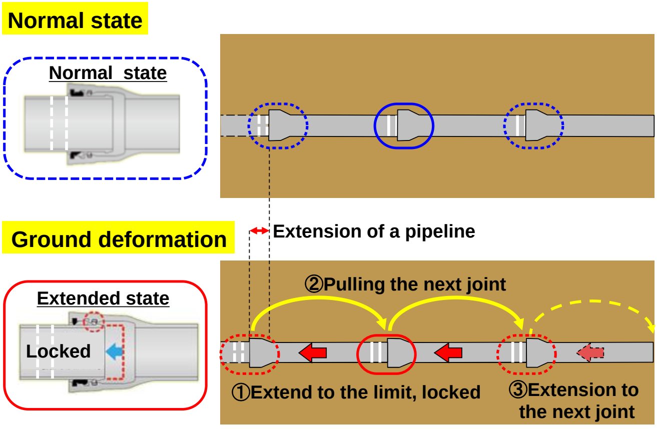

Figure 3. Behavior of a chain structure pipeline

FOUR-POINT BENDING TEST

We conducted a four-point bending test to confirm the ERDIP joint behavior in case the bending moment applied to the joint is larger than the limit performance of the ERDIP joint. The experiment was performed at the Cornell Large-scale Lifelines Testing Facility, which is part of the Bovay Laboratory Complex at Cornell University.

Materials and Methods

The four-point load test set-up for the 150 mm (6 in) GX-type ERDIP is shown in Figure 4. Figure 5 is a photograph of the bending specimen before the test. A bending moment load is applied to the pipe under pressurized conditions with water up to approximately 550 kPa (80 psi).

The specimen was initially set up at a fully inserted position. It was subsequently pressurized with water to approximately 550 kPa (80 psi) while allowing the joint to extend fully in response to the axial forces on the end caps. The internal pressure was adjusted continuously to maintain a nearly constant pressure for the rest of the test.

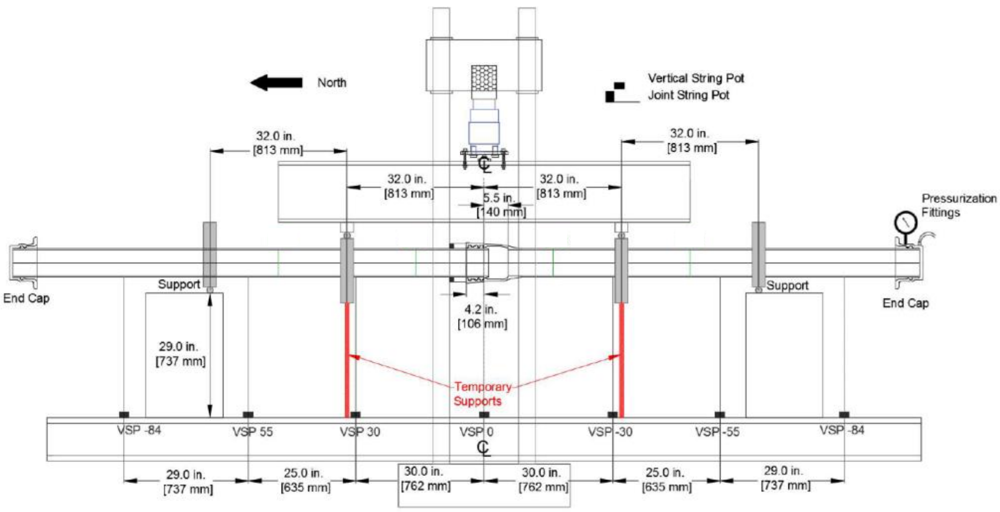

Figure 4. Four-point load test set-ups for the 6-in GX-type ERDIP

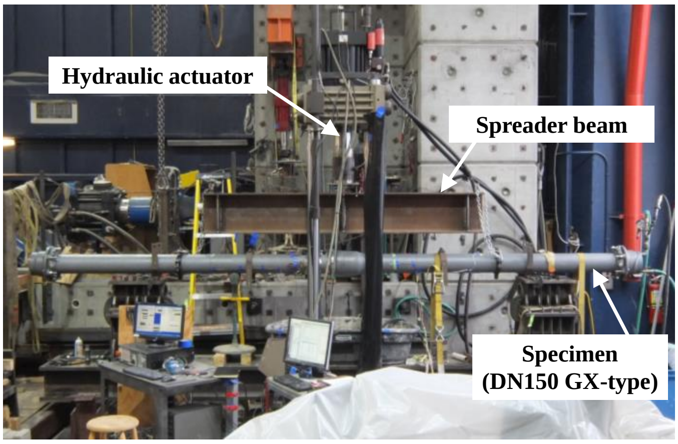

Figure 5. Bending specimen before the test

Results

The bending moment versus joint deflection relationship is shown in Figure 6. The bending moments owing to the pipe, water, and spreader beam weights are included in the bending moment versus the deflection calculations. Figure 7 shows the pipe specimen during and after the test. The results are as follows.

(1) No leakage occurred at 8°, which is the performance limit of GX-type joint.
(2) No leakage occurred at 12°, which is 1.5 times the performance limit of GX-type joint.
(3) The first leakage of approximately 0.4 l/min (0.1 gal/min) was observed at the deflection of 12.2°, corresponding to a small fluctuation in the pressure as shown in Figure 6.
(4) At the deflection of 14.3°, the pressure reduced to 410 kPa (60 psi), and the pipe leaked at a significant leakage rate of approximately 26.5 l/min (7 gal/min).
(5) The leakage stopped at the deflection of 16.6°, after which the pressure stabilized with very small pressure fluctuations.
(6) The test was stopped when the joint reached the joint deflection of 32°, as shown in the figure. The pipe was unloaded, thereby reducing the deflection to 29.2° after which the pipe was depressurized.

From the aforementioned results, no leakage immediately occurred even though the test pipes exceeded the design performance limit of the joint. Thus, the result showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage.

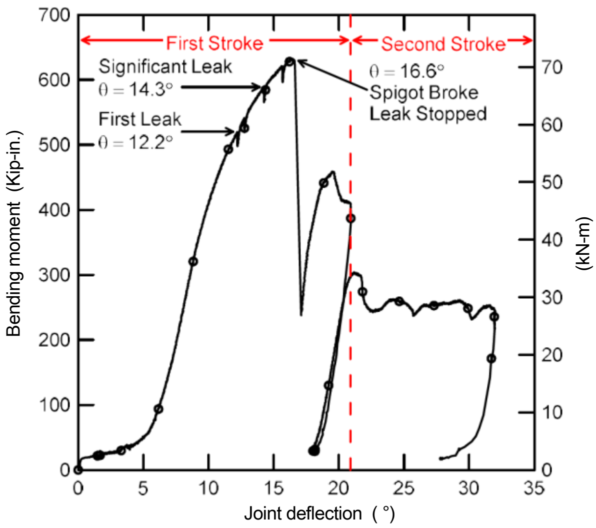

Figure 6. Bending moment versus joint deflection

[12.2°] [32°]

Figure 7. Bending specimen during and after the test

LARGE-SCALE SPLIT-BOX TEST

We conducted several large-scale split-box tests and confirmed that an ERDIP pipeline could absorb the fault displacement by the behavior of the chain structure pipeline [3].

In this study, we conducted a large-scale split-box test with an ERDIP joint under severe conditions wherein the ends of pipes were fixed to the split-box for the same purpose as the aforementioned four-point bending test. All the testing was performed in the large-scale test basin at the Cornell University Large-scale Lifelines Testing Facility.

Materials and Methods

Figure 8 shows the plan view of a large-scale split-box test for the 150 mm (6-in) GX-type ERDIP and Figure 9 shows the test equipment before the test. The dimensions of box were 12.1 m in length, 3.2 m in width, and 2.3 m in height. The pipe was placed on a bed of compacted sand, aligned, the instruments checked, and subsequently backfilled with compacted sand to a depth of cover of 30 in (762 mm) above the pipe crown. Table II shows the backfill sand conditions. The crossing angle between the fault and pipeline was 50°, and the box was moved to pull the pipe.

The number of joints in the boxes was six (S18, S15, S5, N5, N15, N18) and the specimen was initially set up at a fully inserted position as the amount of extension was 120 mm.

First, one of the two boxes was moved by 1.0 m using an actuator to simulate a fault displacement. At this time, all the joints in the boxes were fully extended. Second, one of the two boxes was moved by 1.1 m and we observed the pipeline behavior.

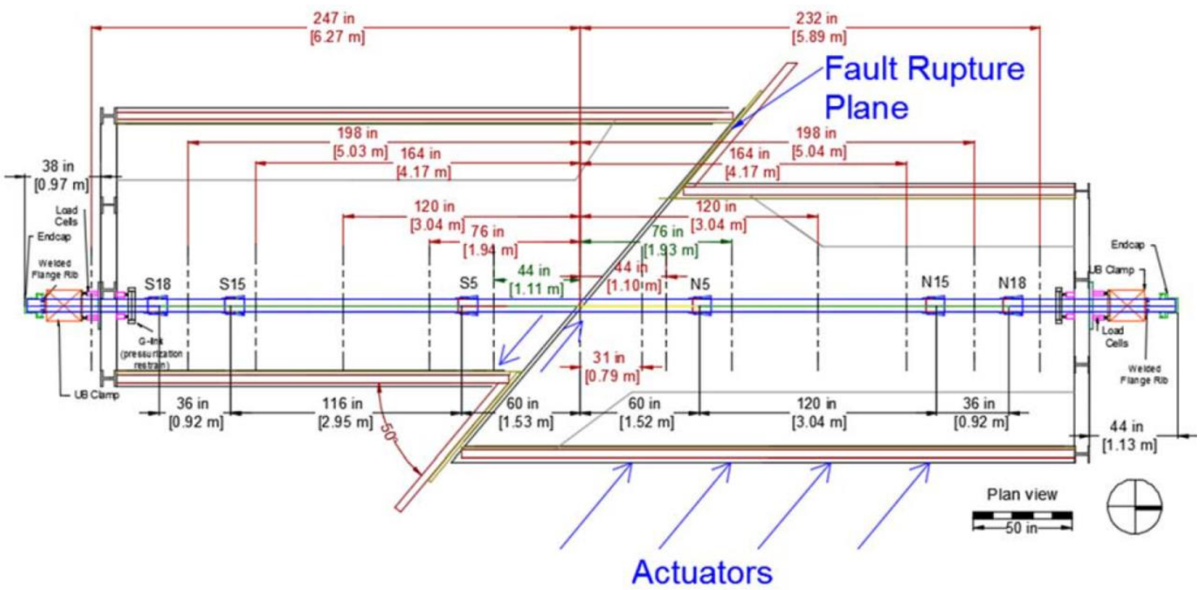

Figure 8. Large-scale split-box test set-ups for the 6-in GX-type ERDIP

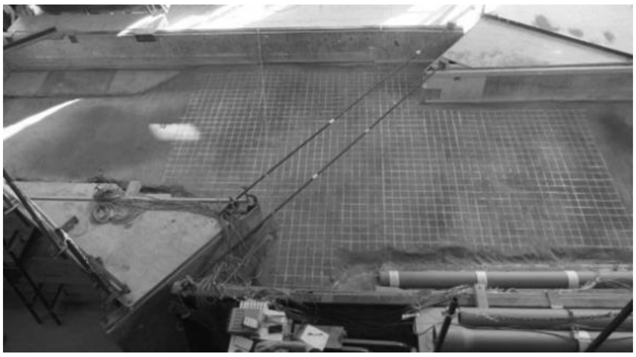

Figure 9. Large-scale split-box test set-ups for the 6-in GX-type ERDIP

TABLE II. BACKFILL SAND CONDITIONS

Items	Conditions
Type	Glacio-fluvial sand (produced by RMS Gravel Consisting)
Global average dry unit weight	16.6 kN/m^3 (105.6 lb/ft^3) with a standard deviation of 0.24 kN/m^3
Global average moisture content	3.7% with a standard deviation of 0.5%
50% particle diameter	0.59 mm
Coefficient of uniformity	3.35
Coefficient of curvature	0.83
Friction angle	42°

Results

Figures 10 and 11 show the test equipment and specimen, respectively, after the test. The behavior of the chain structure pipeline was observed such that the joints were extended and bent following the fault displacement.

Figure 12 shows the amount of joint extension versus fault displacement. Figure 13 shows the joint deflection versus fault displacement. The results are as follows.

(1) After the joints S5 and N5 located near the fault began to extend to their limits, the joints S15, N15, S18, and N18 on both sides of S5 and N5 began to extend to absorb the ground displacement. The behavior of the chain structure pipeline was observed.

(2) When the fault displacement was 0.96 m, all the joints in the boxes were fully extended. No leakage occurred in this step.

(3) When even larger displacement that exceeded the performance limit of the ERDIP was applied to the fully extended pipeline, joint S5 began to pull out. However, no leakage occurred immediately.

(4) When the fault displacement was 1.13 m, the amount of extension of joint S5 reached 210 mm. At this time, the end of the spigot passed the rubber gasket and leakage occurred.

According to the aforementioned results, we confirmed that the ERDIP pipeline could absorb large fault displacement well and no leakage occurred when the joint deflection and extended to a large extent. When both ends of the pipeline were fixed to the box and the fault displacement exceeded the performance limit of the joint, one of the joints began to pull out; however, no leakage occurred immediately. The water tightness performance of the ERDIP joint had a safety margin against pulling out.

Discussion

The pipeline used in the large-scale split-basin test could accommodate 28.5 in (725 mm) of axial extension, corresponding to an average tensile strain of 5.9% along the pipeline. Such extension is sufficiently large to accommodate the majority (more than 99%) of the liquefaction-induced lateral ground strains measured using high-resolution light detection and ranging (LiDAR) after each of the four major earthquakes during the recent Canterbury Earthquake Sequence (CES) in Christchurch, NZ [4]. These high-resolution LiDAR measurements provide a comprehensive basis for quantifying the ground strains caused by liquefaction on a regional basis for the first time. In order to place the CES ground strains in perspective, the levels of liquefaction-induced ground deformation measured in Christchurch exceeded those documented in San Francisco during the 1989 Loma Prieta earthquake and in the San Fernando Valley during the 1994 Northridge earthquake. They are comparable to the levels of most severe liquefaction-induced ground deformation documented during the 1906 San Francisco earthquake, which caused extensive damage to the San Francisco water distribution system. The tests confirm that the ERDIP joints can sustain large levels of ground deformation without leakage, the magnitude of which will vary depending on the ground deformation patterns and spacing of the joints.

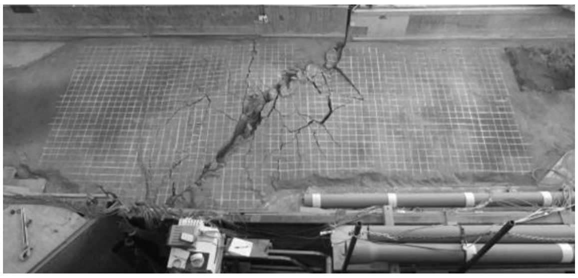

Figure 10. Test equipment after the test

Figure 11. Test specimen after the test

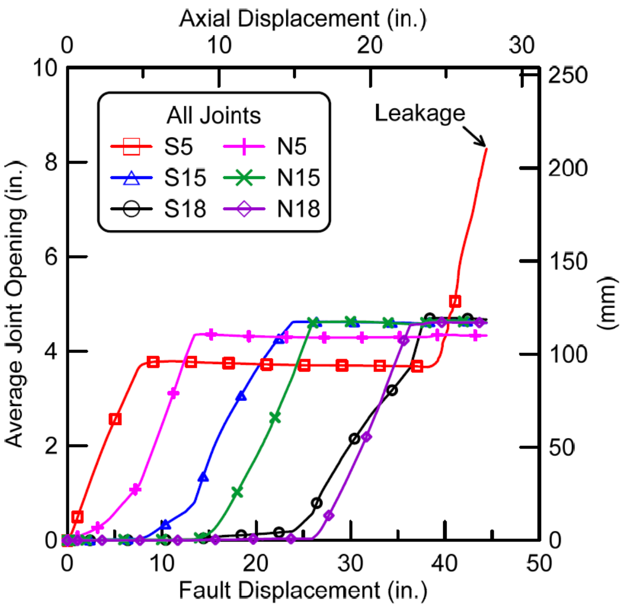

Figure 12. Amount of joint extension

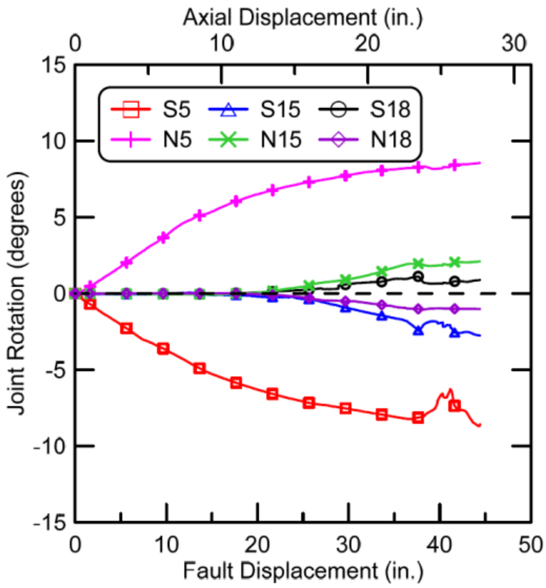

Figure 13. Joint deflection angle

CONCLUSION

In this study, we performed a four-point bending test and a large-scale split-box test using ERDIPs in order to observe the behavior of ERDIPs under severe conditions that exceed the performance limit of the joint. The following is a summary of the findings of this study.

(1) According to the result of the four-point bending test, it was not until the joint deflection reached 12.2° (which is approximately 1.5 times larger than the maximum joint deflection i.e., 8°) that no leakage was visually observed.

(2) According to the result of the large-scale split-box test, we confirmed that the ERDIP pipeline could absorb large fault displacement well and no leakage occurred when the joint deflected and extended to a large extent.

(3) According to the result of the large-scale split-box test, when both ends of the pipeline were fixed to the box and the fault displacement exceeded the performance limit of the joint, one of the joints began to pull out; however, no leakage occurred immediately. The precise performance of the ERDIP joint had a safety margin against pulling out.

(4) The aforementioned points (1) to (3) showed that a pipeline design method based on the performance limit of the ERDIP joint can result in a satisfactory advantage.

REFERENCES

[1] Ohashi K. and Tamura. T. 2016. "An outcrop of the active Futagawa Fault, which ruptured during the 2016 Kumamoto earthquake" *Journal Geol. Soc. Japan,* Vol. 122 (2016) No. 12

[2] Watanabe, M., Suzuki, Y., Kumahara, Y., Goto, H.,and Nakata T. 2016. "Evaluation of active faults and concentration of earthquake disaster related to 2016 Kumamoto Earthquake," *Proceedings of the General Meeting of the Association of Japanese Geographers*, 2016a(0), 100053, 2016

[3] Oda K., Miyajima M., Ishihara T., 2015 "Pipeline design method against large fault displacement", *Proceedings of the ASME 2015 Pressure Vessels & Piping Conference*, PVP2015-45709, 2015

[4] O'Rourke, T.D., Jeon, S-S., Toprak, S., Cubrinovski, M., Hughes, M., van Ballegooy, S., and Bouziou, D. 2014 "Earthquake Response of Underground Pipeline Networks in Christchurch, NZ", *Earthquake Spectra*, EERI, Vol. 30, No.1, pp. 183-204.