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Behavior of buried pipelines subject to permanent ground deformation

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ABSTRACT: Closed–form analytical relationships for the response of buried pipelines to spatially distributed permanent ground deformation (PGD) are presented. Both segmented and continuous pipe subjected to either longitudinal or transverse PGD are considered. A case history of PGD damage to a 500 mm (20 inch) concrete pipe occasioned by the April 1991 earthquake in Costa Rica is used to benchmark the available analytical relations.

1 INTRODUCTION

Permanent ground deformation refers to nonrecoverable soil movement due to landslides, surface faulting, settlement, or liquefaction induced lateral spreading. Herein we restrict our attention to spatially distributed PGD. The response of a buried pipeline to this type of PGD is a function of the pipeline orientation with respect to the direction of ground movement. In general, a pipeline would be exposed to some combination of transverse PGD and longitudinal PGD. For transverse PGD the soil movement is perpendicular to the pipeline axis, while for longitudinal PGD the soil movement is parallel to the pipeline axis. This type of movement can result in pipeline failure. For example O'Rourke and Tawfik (1983) describe damage to five steel pipelines near the Upper Van Norman Reservoir due to transverse PGD resulting from the 1971 San Fernando earthquake.

For continuous steel pipe, damage is likely due to tearing of the pipe wall caused by local compressional buckling (wrinkling). For segmented lines, damage particularly in larger diameter pipe often occurs at the bell and spigot joints. For a given pipe, the probability of damage is a function of the type (longitudinal or traverse), amount, and spatial extent of the PGD zone.

Herein we present a review of observed PGD geometries as well as available closed form analytical relations for pipelines response. Finally, a case history of segmented pipe damage due to the recent Costa Rica earthquake is used as a benchmark.

2 PERMANENT GROUND DEFORMATION GEOMETRY

As noted previously, buried pipeline behavior is a function of the PGD magnitude, the spatial extent of the PGD zone and the pattern of ground

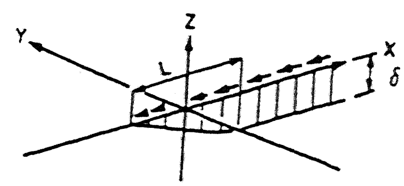

Figure 1 Ramp pattern of longitudinal PGD

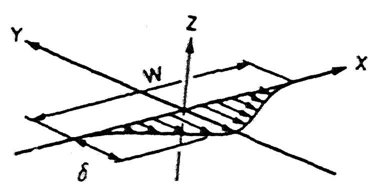

Figure 2 Transverse PGD

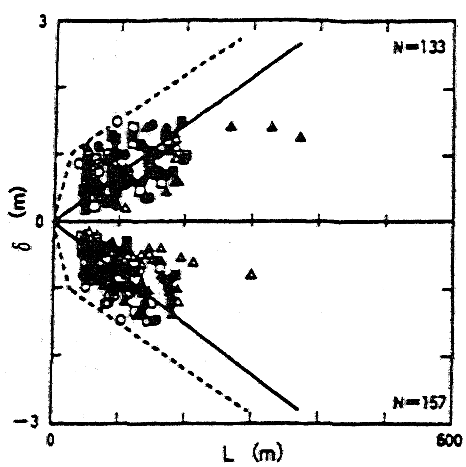

Figure 3 Magnitude δ and length L for longitudinal PGD (after Suzuki and Masada 1991)

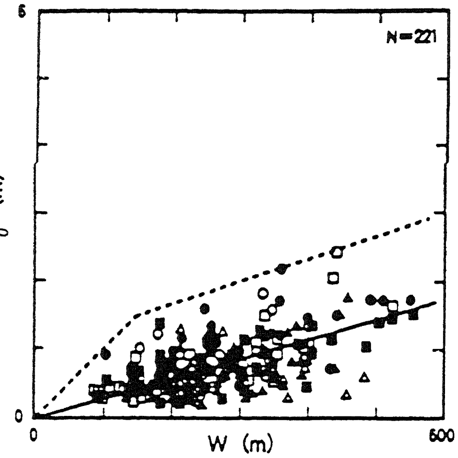

Figure 4 Magnitude δ and width W for transverse PGD (after Suzuki and Masada 1991)

movement along the pipeline route. Using data from the 1964 Niigata Earthquake and the 1983 Nihonkai Chubu Earthquake, Suzuki and Masuda (1991) identify a number of PGD patterns. Figure 1 shows a typical pattern of longitudinal PGD which induces axial compression in a buried pipeline while Figure 2 shows a typical pattern of transverse PGD which induces bending in a buried pipeline. Figure 3 is a plot of observed values for the magnitude δ and length L for longitudinal PGD. There are a total of 290 data points in this figure. The 133 data points with positive values of δ correspond to tensile ground strain. The remaining 157 data points below the $\delta = 0$ line are compressive deformation corresponding to Figure 1. Note in Figure 3 that $L \leq 400$ m and $\delta < 1.5$ m. The average ground strain, $\alpha = \delta/L$, for both tensile and compressive deformations generally falls in the range $0.002 \leq \alpha \leq 0.03$ with typical values being 0.007 or 0.008.

Figure 4 is a plot of observed values for the magnitude δ and the width W for transverse PGD. Note that the minimum observed width was roughly 80 m and the ratio δ/W generally fall in the range $1/1000 \leq \delta/W \leq 1/100$ with an average value of $\delta/W \simeq 1/350$.

Hamada et al. (1986) present detailed patterns of PGD observed in Japan. Figure 5 shows longitudinal PGD observed near the Showa Bridge in Niigata City after the 1964 Earthquake. In the figure, a vertical line with an open circle indicates permanent movement to the right while a solid circle indicates movement to the left. In general, at the bank of a river the PGD is towards the river as shown in Figure 5.

3 CONTINUOUS PIPELINES AND TRANSVERSE PGD

As a first approximation for transverse PGD we model the lateral ground displacement in Figure 2 as a sinusoidal

$$y(x) = \frac{\delta}{2}\left[1 - \cos \frac{2\pi x}{W} \right] \qquad (1)$$

Assuming conservatively that the lateral displacement of a buried pipeline exactly matches the ground displacement pattern given in Equation (1), the bending strain in the pipeline becomes

$$\epsilon_b = \pi^2 \frac{\delta \phi}{W^2} \qquad (2)$$

where ϕ is the pipe diameter . O'Rourke and Nordberg (1991) have shown that equation (2) matches well the results of finite element analysis by O'Rourke (1988), Suzuki et al. (1988) and Kobayashi et al. (1989) for the range of observed transverse PGD patterns given in Figure 4.

To determine the level of pipe strain which one might expect, consider a 600 mm (24 in) diameter welded steel pipe subject to transverse PGD with $\delta = 0.70$ m and W = 245 m. For this PGD geometry, which represents "typical" conditions from Figure 4, the bending strain in the pipe is 6.9×10^{-5}.

4 CONTINUOUS PIPELINES AND LONGITUDINAL PGD

For a continuous pipeline subject to longitudinal PGD, movement and stress in the buried pipeline is due to forces at the soil–pipeline interface. Herein, we conservatively model the interface as a slider. For the case where the trench is backfilled with cohesiveless soil, the friction force per unit length at the soil–pipeline interface f_m is simply the coefficient of friction times the product of the pipe circumference and the average of the vertical and the horizontal pressure on the pipeline, that is:

$$f_m = \mu \cdot \gamma H \cdot \frac{(1+K_0)}{2} \cdot \pi\phi \qquad (3)$$

where μ is the coefficient of friction at or near the soil/pipeline interface, γ is the unit weight of the soil, H is the depth to the pipe center line, and K_0 is the coefficient of lateral earth pressure.

Elhmadi and O'Rourke (1989) suggest $\mu = 0.9 \tan\phi_s$ for most pipe where ϕ_s is the angle of shearing resistance of the soil. Because of the backfilling and compaction of the soil around the pipeline, $K_0 = 1.0$ is recommended as a conservative estimate under most conditions of pipeline burial.

For a ramp pattern of longitudinal PGD shown in Figure 1, Nordberg (1991) has shown that the

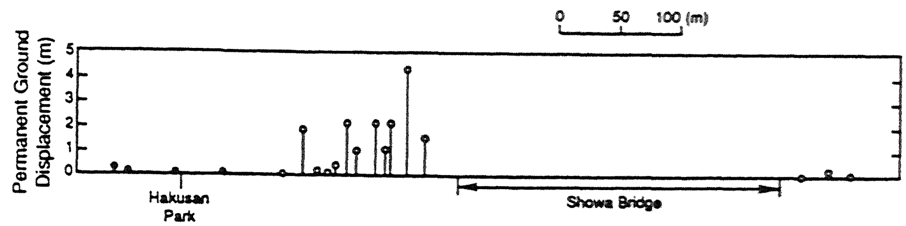

Figure 5 Longitudinal PGD near the Showa Bridge, 1964 Niigata earthquake (after Hamada et al. 1986).

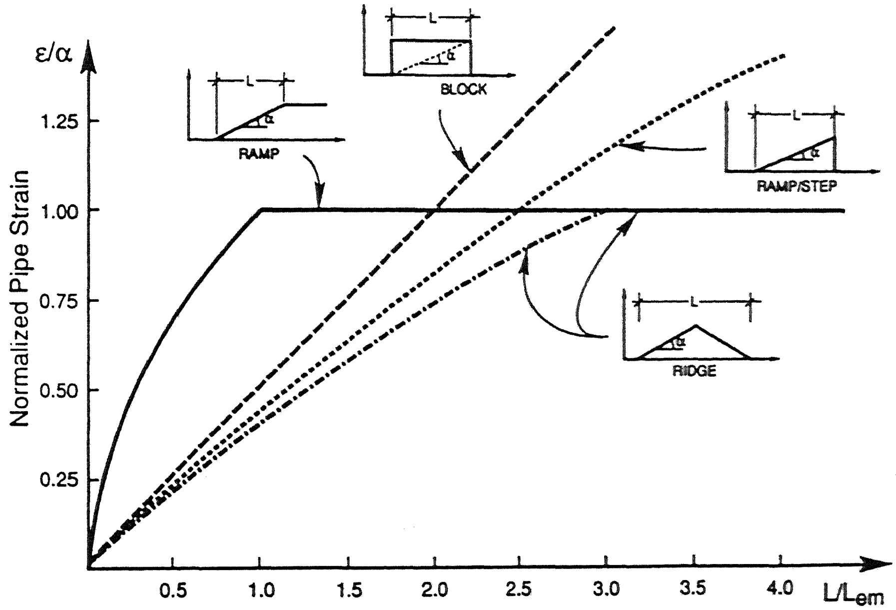

Figure 6 Normalized pipe strain for various patterns of longitudinal PGD (after Nordberg, 1991).

axial strain induced in the buried pipeline ϵ_a is given by

$$\epsilon_a = \begin{cases} \alpha\sqrt{L/L_{em}} & L < L_{em} \\ \alpha & L > L_{em} \end{cases} \quad (4)$$

when α is the ground strain, L is the length of the PGD zone and L_{em} is the embedment distance over which the constant slippage force f_m must act to induce a pipe strain equal to the ground strain.

$$L_{em} = \alpha EA/f_m \quad (5)$$

where E is the pipe modulus of elasticity and A is the pipe cross–sectional area.

For $L < L_{em}$, the pipe strain is derived by noting that the pipe displacement, by symetry, matches the ground displacement of the center of the PGD zone. For $L > L_{em}$, the pipe strain at and near the center of the PGD zone matches the ground strain.

Nordberg (1991) also considered other idealized patterns of longitudinal PGD which might be appropriate models for observations such as shown in Figure 5. Figure 6 is a plot of normalized pipe strain as a function of the normalized length of the PGD zone for four idealized longitudinal PGD patterns.

To determine the level of pipe strain which one might expect, consider a steel pipe subject to a ramp pattern of longitudinal PGD with $\delta = 0.875$ m and L = 125 m. This corresponds to an average ground strain of $\delta/L = 0.007$ and represents "typical" conditions in Figure 3. For a pipe with wall thickness of 6.4 mm (1/4 in), buried depth to the pipe center line H = 0.91 m (3 ft) in soil with a coefficient of friction $\mu = 0.60$ (soil angle of shearing resistance $\phi_s = 34°$), the embedment distance for a ground strain of 0.007 is 1030 m. From Equation (4) or Figure 6, the induced pipe strain is 2.44 x 10^{-3}. Hence the axial strain in a continuous buried pipeline subject to "typical" longitudinal PGD from Figures 1 and 3 is more than an order of magnitude larger than the bending strain due to "typical" transverse PGD from Figures 2 and 4.

5 SEGMENTED PIPEPLINES AND TRANSVERSE PGD

For segmented pipelines, transverse PGD such as shown in Figure 2 induces bending in the pipe segments, and relative rotation at the pipeline joints due to the induced ground curvature. In addition, the increase in the total arc length induces axial tension in the pipe segments and relative axial displacement at the pipeline joints.

As a first approximation, one can look at a segmented pipeline as a series of relatively short rigid links connected by relatively flexible joints. Under this assumption, the transverse PGD is accommodated by relative axial displacement and rotations at the joints.

O'Rourke and Nordberg (1991) consider a sinusoidal variation of lateral soil displacement given by Equation (1). To evaluate the relative joint displacement due to arc length effects, they assume that the lateral displacement of the midpoint of the rigid pipe segment exactly matches the lateral ground displacement at that point. To evaluate the relative joint rotation due to ground curvature effects, they assume that the slope of the rigid pipe segment in the horizontal plane exactly matches the lateral ground rotation at the pipe segments midpoint. Combining these effects and assuming that the pipe segment length is small compared to the width W of the PGD zone, the maximum joint opening becomes

$$\Delta x = \frac{\pi^2 \ell \delta^2}{W^2}[\frac{2\phi}{\delta}] \tag{6}$$

for $0.268 \leq \phi/\delta \leq 3.72$. For $\phi/\delta \leq 0.268$ or $\phi/\delta \geq 3.73$

$$\Delta x = \frac{\pi^2 \ell \delta^2}{2W^2}[1+(\frac{\phi}{\delta})^2] \tag{7}$$

To determine the level of joint opening one might expect, consider a 600 mm (24 inch) diameter segmented line with individual pipe segment length of ℓ=6 m (20 ft), subject to transverse PGD with $\delta = 0.70$ m and W = 245 m (ie typical condictions from Figure 4). For $\phi/\delta = 0.6/0.7 = 0.86$, Equation 6 gives a maximum joint opening of 0.083 cm.

6 SEGMENTED PIPELINES AND LONGITUDINAL PGD

For segmented pipelines, longitudinal PGD induces axial stress (tension or compression) in the pipe segments and relative extension or contraction at the pipeline joints. If the pipe segments are rigid, as assumed herein, all of the longitudinal PGD is accommodated by extension or contraction of the joint. The authors are unaware of analytical relations for compressive ground strain shown in Figure 1. However O'Rourke and Nordberg (1991) developed a relation for a ramp pattern of longitudinal PGD which results in tensile ground strain, that is, corresponding to the data points in the upper half of Figure 3. They assume that the ground strain $\alpha = \delta/L$ is constant over the length L of the PGD zone. ElHmadi and O'Rourke (1989) have considered the response of segmented buried pipe to uniform tensile ground strain. Using realistic variations of joint stiffness, the resulting joint displacements for uniform ground strain varied from joint to joint. The mean joint displacement, Δx_m, is simply the ground strain times the pipe segment length ℓ

$$\Delta x_m = \alpha \cdot \ell \tag{8}$$

However, the coefficient of variation for joint displacement is an increasing function of the relative stiffness of the joint. For Cast Iron (CI) pipe with lead caulked joints the variation is significant while for Ductile Iron (DI) pipe with rubber gasket joints the variation of relative joint displacement is small and can be neglected. The largest joint displacement within a PGD zone is a function of the number of joints in the PGD zone as well as the mean and coefficient of variation of the joint displacements. Figure 7 is a plot of the largest joint displacement for CI and DI pipe as a function of ground strain α for two value of the length L of the longitudinal PGD zone.

To determine the level of joint opening one might expect, consider a segmented pipeline subject to a ramp pattern of longitudinal PGD with $\delta = 0.875$ m and L = 125 m. Again, this corresponds to an average ground strain $\alpha = \delta/L$ of 0.007 and represents "typical" conditions in Figure 3. For DI pipe, Figure 7 predicts a maximum joint opening of about 4.2 cm and about 5.5 cm for CI pipe. Hence the largest joint opening in a segmented pipeline subject to "typical" longitudinal PGD from Figures 1 and 3 is more than an order of magnitude larger that that due to "typical" transverse PGD from Figures 2 and 4.

7 COSTA RICA CASE HISTORY

The first author inspected damage to water transmission and distribution pipelines in Limón occasioned by the April 1991 earthquake in Costa Rica. One area of particular interest is a 750 m section of the main road out of Limón. There were 20 repairs to the 500 mm (20 inch) Reinforced Concrete Cylinder Pipe (RCCP) which parallels the road at this location. The nominal segment length, ℓ for the RCCP pipe was 7.4 m (24 ft). Figure 8 is a plan view showing about 0.4 m (16 inch) of lateral offset over a 12.8 m (42 ft) length of sever road damage near a railroad underpass. The vertical offset , if any, near the railroad underpass could not be determined. About 500 meters to the East of the railroad underpass, there was an area of vertical PGD near a drainage culvert. There was a total vertical offset of about 0.2 m (8 inches) over a

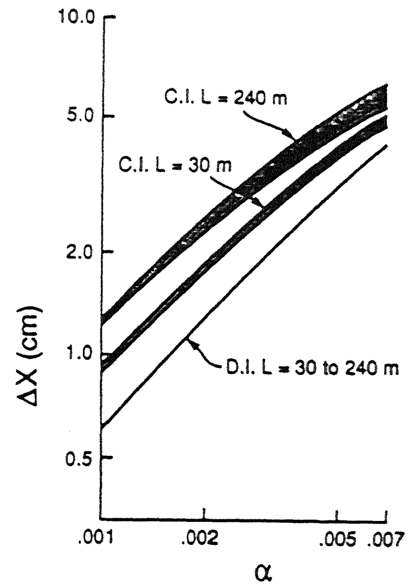

Figure 7 Largest joint opening for segmented pipe subject to longitudinal PGD (after O'Rourke and Nordberg 1991)

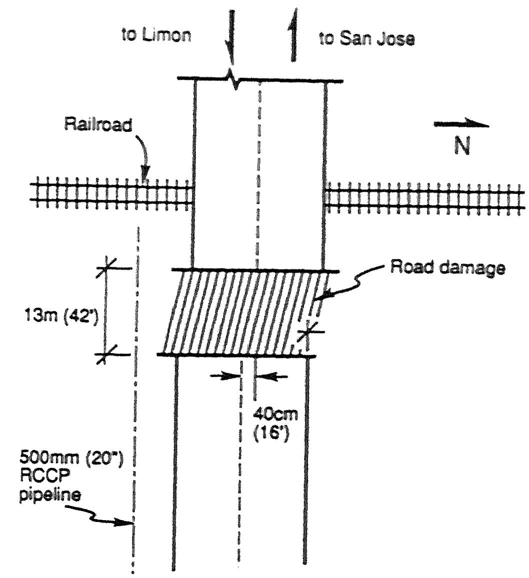

Figure 8 Lateral offset of road near railroad underpass, Limón, Costa Rica, 1991

distance of roughly 15.8 m (52 feet). The individual vertical offsets were 2.5, 7.6, 7.6 and 2.5 cm (1, 3, 3 and 1 inch) separated by distances of 4.3, 6.4 and 5.2 m (14,21 and 17 feet) respectively as shown in Figure 9.

The RCCP joints at both these locations required repair. The observed PGD in Figures 8 and 9 are used herein to benchmark the analytical relation for segmented pipe subject to transverse PGD. The PGD in Figure 8 is modeled as a sinusoidal variation of lateral ground movement with $\delta = 0.4$ m and $W = 25.6$ m in Equation 1 (that is the width of the sinusoidal variation is taken as twice the observed shear variation). For $\phi/\delta = 0.50/0.40 = 1.25$, Equation 6 gives a maximum joint opening of 4.46 cm.

The PGD in Figure 9 is similarly modeled as a sinusoidal variation of transverse PGD with $\delta = 0.2$ m and $W = 31.6$ m. For $\phi/\delta = 0.5/0.2 = 2.5$, Equation 6 gives a maximum joint opening of 1.46 cm. The failure criterion for the case history considered herein would be a joint opening which exceeds a leakage threshold. The authors are not aware of published leakage data for RCCP pipe. However, manufactures literature contain the maximum recommended joint deflection angle for laying purposes. These maximum recommended angles vary somewhat from manufacture to manufacture. For RCCP pipe, the values are about 1.4° for a 61 cm (24 inch) diameter pipe and about 1.05° for a 122 cm (48 inch) diameter pipe. We assume herein that the leakage threshold for RCCP is 1.5 times the joint opening corresponding to the manufacture's maximum recommended joint angle. Based upon joint geometry, this would correspond to roughly 2.2 cm of joint opening. Hence the analytical relationship in Equation 6 predicts leakage for the PGD pattern in Figure 8, but it does not predict leakage for the pattern in Figure 9. Recall that joints at both locations required repair. It should be mentioned that the analytical relations in Equations 6 and 7 assume that the pipe segment length ℓ is small compared to the width of the transverse PGD zone. Since the pipe segment length is 7.4 m this assumption is violated for the PGD patterns in Figure 8 and 9. This suggest the need for analytical relations for transverse PGD where the individual pipe segment length is the same order of magnitude as the width of the PGD zone.

8 SUMMARY AND CONCLUSIONS

The response of buried pipelines to PGD in which there is no abrupt relative displacement at the margins of the PGD zone was studied. Observed geometries of PGD were reviewed and analytical relationships for the amount of joint opening in segmented pipe and the longitudinal strain in continuous pipe were presented. Separate relationships for longitudinal PGD (ground movement parallel to pipe axis) and transverse PGD (ground movement perpendicular to the pipe axis) were considered. However, it appears that there are no currently available relations for segmented pipe subject to longitudinal PGD which induce compression at pipeline joints. For the typical geometries considered, longitudinal PGD was found to be more likely to result in failure than

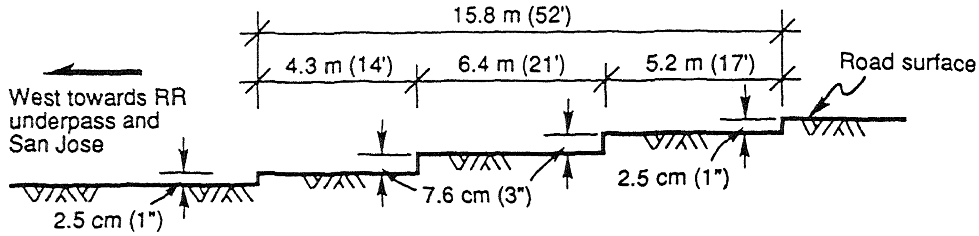

Figure 9 Verticle offset of road, Limón, Costa Rica, 1991

transverse PGD for both segmented and continuous pipe.

Two case histories of Reinforced Concrete Cylinder Pipe failure due to transverse PGD occasioned by the April 1991 Costa Rica earthquake are presented. In one case history, failure was predicted by the available analytical relations while in the second case history no failure would have been predicted. This highlights the need for analytical relations for situations where the width of the transverse PGD zone is the same order of magnitude as the pipe segment length.

9 ACKNOWLEDGEMENTS

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REFERENCES

Elhmadi, K., & O'Rourke, M. 1989. Seismic wave propagation effects on straight joined buried pipeline. Tech. Rept. NCEER–89–0022, Natl. Center for Earthquake Engineering Research, Buffalo, NY

Hamada, M., Yasuda, S., Isoyama, R., & Emoto, K. 1986. Study of liquefaction induced permanent ground displacements. Assoc. for the development of earthquake prediction, Japan: 87.

Kobayashi, T., Nakane, H., Suzuki, N., Ishikawa, M. 1989. Parametric study on flexibility of buried pipeline subject to large ground displacement. Tech. Rept. NCEER–89–0032 Proc. Second US–Japan Workshop on liquefaction, large ground deformation and their effects on lifelines, Buffalo, NY September 1989: 348–362.

Nordberg, C. 1991. Analysis procedures for buried pipelines subject to longitudinal permanent ground deformation. M.S. Thesis, Rensselaer Polytechnic Institute, Troy, NY USA.

O'Rourke, M. & Nordberg, C. 1991. Analysis procedures for buried pipelines subject to longitudinal and transverse permanent ground deformation. Tech. Rept. NCEER–91–0001, Proc. 3rd Japan–US Workshop on Earthquake resistant design of lifeline facilities and countermeasures for soil liquefaction, San Francisco, CA, 439–453.

O'Rourke, T. 1988. Critical aspects of soil–pipeline interaction for large ground deformation. Proc. First Japan–US Workshop on liquefaction, large ground deformation and their effects on lifeline facilities, Tokyo, November 1988:118–126.

O'Rourke, T., & Tawfik, M. 1983. Effects of lateral spreading on buried pipelines during the 1971 San Fernando Earthquake, Earthquake behavior and safety of oil and gas storage facilities, buried pipelines and equipment, PVP–Vol. 77, ASME, New York, NY: 124–132.

Suzuki, N., & Masuda, N. 1991. Idealization of permanent ground movement and strain estimation of buried pipes. Technical Report NCEER–91–0001. Proc. 3rd Japan–US Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures for Soil liquefaction, San Francisco, CA: 455–469.

Suzuki, N., Arata, O., & Suzuki, I. 1988. Parametric study of deformation analysis of welded pipeline subject to liquefaction–induced permanent ground deformation. Proc. First Japan–US Workshop on Liquefaction, large ground deformation and their effects on lifeline facilities, Tokyo, Japan, November 1988: 155–162.