XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

SEISMIC EFFECTS ON PIPELINES DUE TO GROUND DEFORMATIONS

EFFECTS SEISMIQUES SUR LES TUYAUTERIES DUS AUX DEFORMATIONS DU TERRAIN

R. Flores-Berrones[1] **M. O'Rourke**[2]

[1]Technical Consultant, Mexican Institute of Water Technology (IMTA)
Mexico City, Mexico
[2]Civil and Environmental Engineering Department, Rensselaer Polytechnic Institute
Troy, New York, U.S.A.

SYNOPSIS: The behavior of buried, welded steel pipelines subjected to longitudinal permanent deformations (PGD) is considered. Longitudinal PGD refers to soil movements which are parallel to the pipelines axis. The induced axial strain in the pipe is shown to theoretically be a function of the length of the PGD zone, the spatial distribution of the ground movement and the pipes emebedment length. The embedment length for the pipe is similar to a development length for a reinforcing bar in concrete design.

Analytical expressions and graphs are developed for evaluating strain in elastic pipe due to five idealized patterns of longitudinal PGD. These expressions are then used to determine axial strain in three hypothetical pipeline due to 27 PGD patterns observed by Japanese investigators.

INTRODUCTION

Seismic damage to buried welded steel pipelines is usually attributed to either seismic wave propagation or permanent ground deformation effects (O'Rourke et al, 1985). In this paper particular attention is given to the seismic effect created by permanent ground deformation (PGD).

PGD damage to pipelines has been reported by several researchers. For example O'Rourke and Tawfik (1983) describe damage to welded steel pipelines occasioned by the 1971 San Fernando Earthquake, while Hamada et al. (1986) describe damage to a buried gas pipeline occasioned by the 1983 Nihonkai-Chubu earthquake. These soil deformations might be caused by lateral ground displacements, liquefaction or cycle compaction of sandy soils. For the general case, a buried pipeline would be subject to some combination of transverse (ground movement perpendicular to the pipeline axis) and longitudinal (ground movement parallel to the pipelines axis) PGD. However, O'Rourke & Nordberg (1991), have demonstrated that the strains in straight buried pipelines due to longitudinal PGD is typically more than an order of magnitude larger than that due to transverse PGD.

In this paper the effect of longitudinal PGD on straight (ie no bends or elbows) elastic steel pipe with constant burial depth is considered. Five idealized longitudinal PGD patterns based on observed patterns from previous earthquakes are used and analytical relations for the axial strain in the pipe are developed.

LATERAL SPREAD GEOMETRY

Although there are different kinds of permanent soil deformation (active geological faults, consolidation or densification of compressible soils, landslides, etc.), the only ones that are considered in this analysis are those caused by soil liquefaction and subsequent lateral spreading. Estimation of the magnitude of such deformations has been addressed by several authors. For example, Hamada et al (1986) suggests the following empirical formula to predict the magnitude of horizontal PGD δ, in meters.:

$$\delta = 0.75\sqrt{h}\cdot\sqrt[3]{\phi_g} \qquad (1)$$

where h is the thickness of the liquefied layer (m), and ϕ_g is the slope, in percent, of the lower boundary of the liquefied layer or the ground surface, whichever is larger. The above formula was deducted after quantitatively analyzing data from the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes in Japan, and the 1971 San Fernando earthquake in the US. In these earthquakes, horizontal PGD in the order of 1 to 5 meters were observed. Youd and Perkins (1987) developed an empirical relation for their measure of PGD magnitude, the Liquefaction Severity Index (LSI). Using data from Western US earthqakes, LSI is given as a function of earthquake magnitude and site-source distance. More recently Baziar (1991) and Towhata et al (1991) have developed analytical relations for the amount of horizontal PGD.

PGD often also results in a vertical component of ground movement. However, the vertical component is typically smaller than the horizontal component, and the vertical component of PGD is disregarded herein.

SOIL-PIPE INTERACTION

Strain in a continuous buried pipeline subject to longitudinal PGD is due to friction-like forces at the soil pipe interface. The elasto-plastic model shown in Fig. 1 is often adopted (ASCE, 1984). This model is fully defined by two parameters; the maximum force per unit per length at the soil pipe interface f_m and D_s, the relative displacement at which slippage between pipe and soil occurs. The axial stiffness of the soil spring is f_m/D_s.

The maximum axial force per unit of length f_m depends on the type of soil surrounding the pipe and the method of pipe installation (i.e. the compaction control of the backfill). For cohesionless soils f_m depends on the effective normal stress at the soil-pipe interface, the coefficient of friction between the soil and the pipe material, and the pipe diameter ϕ. Considering that we are in a plain strain problem, and that the coefficient of lateral pressure k_g for compacted soils is approximately equal to unity, the effective normal stress will be simply equal to the product of the effective unit weight of soil γ, and the depth H to the pipe center line. We assume herein that H is constant in and around the PGD zone.

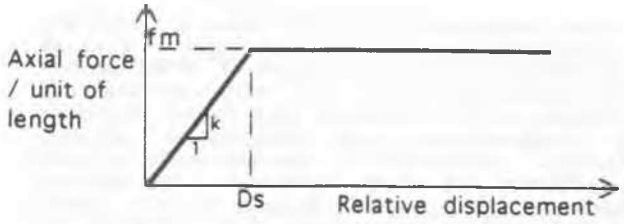

Fig. 1. Elasto-plastic Model of Soil Pipeline Interface

For the case of a steel pipeline, the coefficient of friction of the soil pipeline interface, based upon experimental results, is $\mu = 0.9 \tan \phi_s$ where ϕ_s is the angle of shearing resistance of the soil. Hence for cohesionless backfill, the friction force per unit length becomes

$$f_m = \mu . \gamma H . \pi\phi \tag{2}$$

For cohesive soils, f_m depends on the undrain shear strength S_u of the soil. For normally consolidated clays, S_u gives a good estimation of the adhesion to the pipe. For overconsolidated soils, the observed adhesion is generally less than the undrain strength. For overconsolidated soils Lambe & Whitman (1969) recommended to use as adhesion the undrain shear strength of an equivalent normally consolidated soil. So for cohesive soils, $f_m = S_u . \pi\phi$. For the most general soil condition, when the soil surroundings the pipe has both friction and cohesive characteristics, f_m will be given by:

$$f_m = (c + \mu . \gamma H)\pi\phi \tag{3}$$

where c is the shear strength of the soil corresponding to zero effective vertical stress on the shear strength curve.

The relative axial displacement for slippage D_s in cohesionless soils is an increasing function of pipe diameter, the coefficient of friction μ, and the pipe burial depth. Note that the relative axial displacement for slippage at the soil pipeline interface is quite small being less than 0.15 cm (0.06 inches) for H = 1.52 m (5 ft), $\mu = 0.75$ and pipe diameters 1.22 m (48 inches) or less. O'Rourke and Nordberg, (1991) have shown that a simplified model of the soil pipe interface in which D_s is taken as zero, yields maximum pipe strain within 4% of those using the model in Figure 1. Hence the simplified model (ie $D_s = 0$) will be used herein to evaluate response to longitudinal PGD.

SIMPLIFIED PGD PATTERNS

O'Rourke and Nordberg (1991) determined the response of straight continuous welded steel pipelines with constant buried depth to three idealized patterns of longitudinal PGD. The three patterns considered were Block, Ramp, and Ridge patterns. The Block pattern, for example, corresponds to a mass of soil having a length L moving horizontally as a rigid block. A ground crack or gap occurs at the head of the slide and a compression mound at the toe. This pattern is an approximation to horizontal PGD observed by Hamada et al (1986) and shown in Figure 2. In Figure 2, the height of the vertical line corresponds to the amount of observed horizontal PGD. The Block pattern approximation, shown as a dashed line, is 1.8 m of uniform horizontal movement δ over a length L of 150 m.

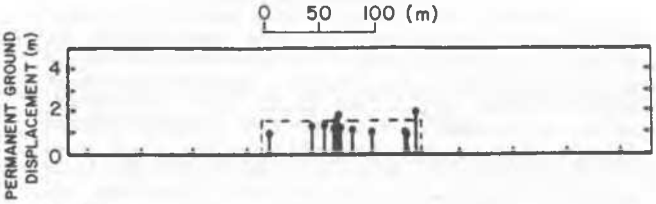

Fig. 2. Horizontal PGD observed at Section S-10 in Noshiro City after the 1983 Nohonkai-Chubu Earthquake.

Using a simplified model of the soil pipeline interface with D_s taken as zero, and defining an equivalent ground strain for the Block pattern as $\alpha = \delta/L$, O'Rourke and Nordberg (1991) show that the axial strain induced in a continuous buried pipeline due to a Block pattern of longitudinal PGD is

$$\varepsilon = \begin{cases} \dfrac{\alpha L}{2L_{em}} & L < 4L_{em} \\ \alpha\sqrt{L/L_{em}} & L > 4L_{em} \end{cases} \tag{4}$$

where L_{em} is an embedment length defined as the length over which the constant slippage force f_m must act to induce a pipe strain ϵ equal to the ground strain α

$$L_{em} = \frac{\alpha EA}{f_m} \tag{5}$$

Table 1 presents the embedment length L_{em} for a steel pipe in cohesionless soil, with unit weight 100 pcf (1600 kg/m^3) for five values of ground strain α. Values are presented for three combinations of the buried depth H, pipe wall thickness t, and the coefficient of friction at the soil pipe interface μ.

Table 1. Embedment length L_{em} for Steel Pipe in cohesionless soil with γm = 1600 kg/m^3 (100 pcf)

Soil strain α	H=3'(0.91m) t=¾"(1.9cm) μ=0.45	H=6'(1.83m) t=½"(1.27cm) μ=0.60	H=9'(2.74m) t=¼"(0.64cm μ=0.75
0.002	1 178	294	78
0.005	2 944	736	196
0.010	5 889	1 472	393
0.020	11 778	2 944	785
0.030	17 667	4 417	1 178

For a Ramp pattern of longitudinal PGD, the pipe strain is given by

$$\varepsilon = \begin{cases} \alpha\left[\sqrt{4 + 2L/L_{em}} - 2\right] & L < 2.5L_{em} \\ \alpha/2\left[\sqrt{4L/L_{em}} - 1\right] & L > 2.5L_{em} \end{cases} \tag{6}$$

while for a Ridge pattern

$$\varepsilon = \begin{cases} \alpha\left[\sqrt{1 + L/L_{em}} - 1\right] & L > 3L_{em} \\ \alpha & L > 3L_{em} \end{cases} \tag{7}$$

The axial strain ϵ in the pipe, normalized by the ground strain α is plotted in figure 3 as a function of the normalized length of the PGD zone, for the Block, Ramp, and Ridge patterns considered by O'Rourke and Nordberg (1991).

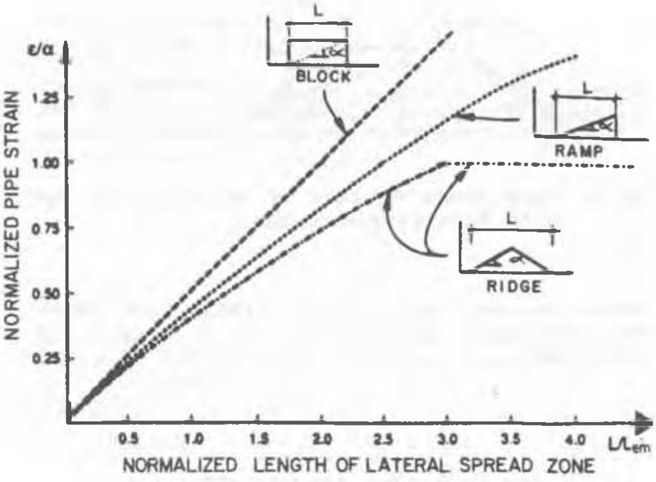

Fig. 3. Normalized Pipe Strain as Function of Normalized Length of PGD Zone for Three Simplified Patterns

COMPLEX PGD PATTERNS

The three simplified longitudinal PGD patterns shown in Figure 3 are realistic approximation to a number of PGD patterns observed by Hamada et al (1986). However, there are other observed PGD patterns, such as shown in Figure 4, which are more complex than the three given in Figure 5. Recently Flores-Berrones and O'Rourke (1992) have determined the strain in a straight continuous steel pipeline with constant burial depth, subject to a Ramp Block and an Asymmetrical Ridge pattern of longitudinal PGD.

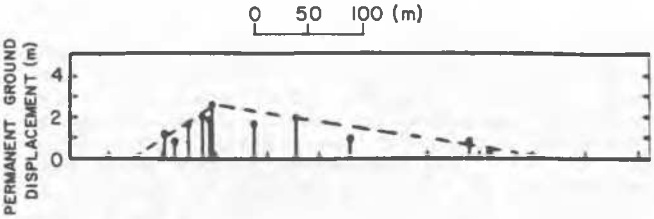

Fig. 4. Horizontal PGD Observed at Section S-19 and Asymmetric Ridge Approximation.

Ramp/Block Pattern

The idealized Ramp/Block pattern is shown in Figure 5.

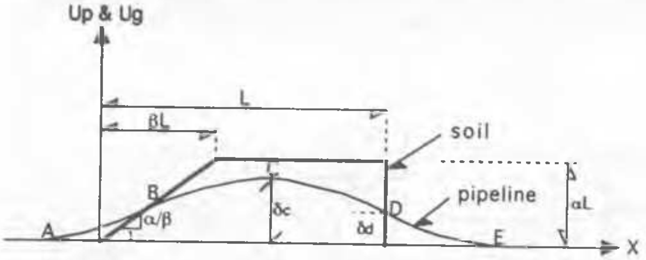

Fig. 5. Ramp-Block Pattern of Longitudinal PGD with Pipe Displacement.

Flores-Berrones and O'Rourke (1992) have shown that the peak pipe stream to a Ramp/Block pattern is

$$\varepsilon = \frac{\alpha}{\beta}\left\{\sqrt{4 + 2\beta\frac{L}{L_{em}}} - 2\right\} \qquad (8)$$

Equation 8 applies as long as the pipe strain is less than the ground strain α/β, and the maximum pipe displacement is less than the maximum ground displacement αL. It can be shown that those conditions apply for

$$\frac{L}{L_{em}} \le \frac{16}{4 - 4\beta + \beta^2} \qquad \text{for } 0 \le \beta \le 0.4$$

and

$$\frac{L}{L_{em}} \le \frac{5}{2\beta} \qquad \text{for } 0 \le \beta \le 0.1$$

However, as it will be shown later, the length of the PGD zone is typically less than twice the pipes embedment length, hence equation 8 is considered adequate for most situations of a Ramp/Block pattern of longitudinal PGD. Note that for $\beta = 1$, the Ramp/Block pattern yield the same results as the Ramp pattern in Equation 6 and Figure 3, while the Block results for $\beta = 0$, as expected.

Asymmetrical Ridge Pattern

The idealized asymmetric Ridge pattern of longitudinal PGD is shown in Figure 6. It approximates an actual PGD pattern shown in Figure 4.

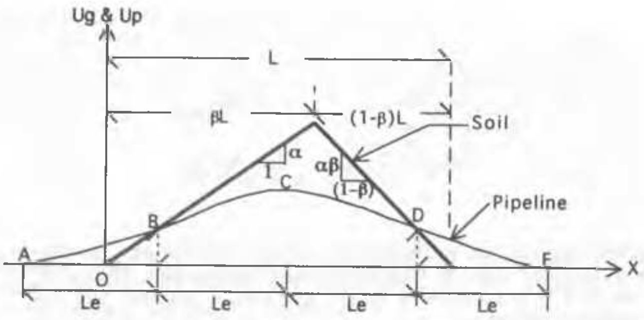

Fig. 6. Unsymmetric Ridge pattern of Longitudinal PGD Showing Soil and Pipe Displacement.

Flores-Berrones and O'Rourke (1992) have shown for the unsymmetric Ridge pattern that the maximum pipe strain, tension at point B and compression at point D, becomes

$$\varepsilon = \frac{f_m L_e}{AE} = \alpha\beta\left(\sqrt{4 + \frac{2L}{\beta L_{em}}} - 2\right) \qquad (9)$$

Equation 9 applies for $\epsilon < \alpha$. It can be shown that this condition is satisfied for

$$L \le L_{em}\left(2 + \frac{1}{2\beta}\right)$$

However, as mentioned previously, the length of the PGD zone is typically less than twice L_{em}. Hence equation 9 is considered adequate for most situation of an Asymmetric Ridge pattern of longitudinal PGD. Note that for $\beta = 0.5$ we get the same results as the Ridge pattern in Equation 7 while for $\beta = 1.0$ we get the Ramp results in Equation 6, as expected.

PIPE STRAIN

Hamada et al (1986) present 27 observed patterns of horizontal PGD in Noshiro City, which resulted from the 1983 Nohonkai Chubu Earthquake. Idealized longitudinal PGD patterns, Block, Ramp, Ridge, Ramp/Block or Assymmetrical Ridge which best approximate the observed patterns, were determined. For example, the observed PGD at Section S-19 which is shown in Figure 4 is approximated by an idealized Asymmetrical Ridge pattern with L = 390 m, δ = 2.5 m, α = 0.0081 and β = 0.79.

The axial strains in three hypothetical pipelines were determined for each of the 27 PGD pattern. Each pipeline is assured to be buried in cohesionless soil with unit weight of 100 pcf (1600 kg/m^3). The water table is assumed to be located below the pipeline hence the pipeline is contained in a non-liquefied layer which overrides a liquefied layer below. The wall thickness t, burial depth H, and coefficient of friction for the three hypothetical pipeline are presented in Table 2. The pipes were chosen to represent what is felt to be a reasonable range of actual pipe burial conditions. Pipe # 3 is the most vulnerable to seismic damage due to its small wall thickness, large burial depth and high coefficient of friction corresponding to a soil with an angle of shearing resistance of 40°. On the other hand, Pipe # 1 is the least vulnerable with low μ corresponding to an angle of shearing resistance of 27°. Axial strain induced in each of the three hypothetical pipes due to the 27 patterns of longitudinal PGD are presented in Table 3, along with the PGD pattern geometry. As expected, the axial strains are smallest in the first hypothetical pipe (Pipe #1). Since the pipeline is assumed to be linear elastic, the computed pipe strain is correct if it is below the pipe yield strain ϵ_y. If $\epsilon > \epsilon_y$ the actual strain in the hypothetical pipeline is unknown, but it is at least equal to the yield strain. Except for section S-12 and S-15 (L = 35m and 140 m respectively) the axial stress in pipe # 3 is always larger than the yield stress for X-52 grade steel. The axial strain in pipe # 2 is always less than the yield stress for X-52 grade steel, except for section S-7, N-3, N-4 and N-6 (L = 615 m, 590 m, 720 m and 740 m respectively). Note that the pipe strain is poorly correlated with δ. Figure 7 plots strain in pipes #1 and #2 versus the length of the PGD zone L. This figure suggests that the length of the PGD zone is the key parameter in determining axial strain in straight continuous pipe with constant burial depth subject to longitudinal PGD. That is, although pipe strain is theoretically a function of the pattern or spatial distribution of the PGD, the lengths of the PGD zone are small enough with respect to the embankment length L_{em} that variations between different patterns is a second order effect.

That is, as a first approximation, at least for the 27 patterns of longitudinal PGD considered herein, the pipe strain corresponds to a Block pattern where $L < 4L_{em}$ and

$$\epsilon \approx \frac{f_m L}{2AE} \qquad (10)$$

Table 2. Parameteres for three hypothetical steel pipeline

Pipe No.	t (in)	H (ft)	μ
1	3/4	3	0.45
2	1/2	6	0.60
3	1/4	9	0.75

Table 3. Pipe strains for different PGD published by Hamada et al (1986)

OBSERVED			IDEALIZATION			AXIAL STRAIN (x10^{-3})		
Section	δ (m)	L (m)	Idealized pattern	α	β	Pipe #1	Pipe #2	Pipe #3
S-1	3.3	340	Unsym. Ridge	0.0124	0.78	0.290	1.12	3.90 *
S-2	4.0	230	"	0.028	0.61	0.193	0.77	2.82 *
S-3	4.0	265	Ramp/Block	0.0151	0.28	0.22	0.90	3.28 *
S-4	3.0	385	"	0.0078	0.73	0.32	1.27	4.4 *
S-5	3.0	455	Unsym. Ridge	0.008	0.824	0.38	1.46	4.87 *
S-6	3.0	520	Ramp	0.0058	--	0.43	1.65	5.25 *
S-7	2.1	615	Ramp/Block	0.0034	0.715	0.51	1.9 *	4.75 *
S-8	2.5	300	Unsym. Ridge	0.0125	0.66	0.25	1.0	3.5 *
S-9	1.4	300	Block	0.0047	--	0.26	1.0	3.9 *
S-10	1.8	150	"	0.012	--	0.13	0.51	1.9 *
S-11	1.4	250	Ramp/Block	0.0056	0.3	0.21	0.84	3.05 *
S-12	1.5	35	Block	0.0429	--	0.03	0.12	0.44 *
S-13	2.6	210	Unsym. Ridge	0.0158	0.786	0.18	0.70	2.5 *
S-14	2.0	190	"	0.0143	0.74	0.16	0.63	2.3 *
S-15	2.50	140	Ramp	0.0179	--	0.119	0.473	1.74 *
S-16	2.0	280	Symetric Ridge	0.0143	--	0.236	0.907	3.2 *
S-17	1.8	380	Ramp-Block	0.0047	0.47	0.32	1.25	4.35 *
S-18	1.8	480	Ramp-Block	0.0037	0.48	0.402	1.55	5.23 *
S-19	2.50	290	Unsym. Ridge	0.0119	0.72	0.245	0.959	3.36 *
N-1	1.20	350	Ramp	0.0034	--	0.29	1.1	3.52 *
N-2	2.20	470	Block	0.0047	--	0.399	1.6	5.97 *
N-3	2.60	590	Ramp-Block	0.0044	0.36	0.495	1.92 *	6.6 *
N-4	2.70	720	Ramp-Block	0.0037	0.61	0.596	2.23 *	7.1 *
N-5	2.20	420	Block	0.0052	--	0.357	1.42	5.35 *
N-6	1.80	740	Ramp-Block	0.0024	0.52	0.592	2.18 *	6.72 *
N-7	2.0	390	Block	0.0051	--	0.331	1.32	4.97 *
N-8	2.30	500	Unsym. Ridge	0.0066	0.7	0.415	1.56	5.01 *

* pipe strain ≥ yield strain for X-52 grade steel

SUMMARY AND CONCLUSIONS

A method for estimating the strain in a straight continuous pipeline subjected to various patterns of longitudinal permanent ground deformations (PGD) is presented in this paper. The method takes into account the shear strength characteristics of the soil surrounding the pipeline. It is based in a simplified force-displacement model for the soil pipe interface, which for practical purposes gives the same results than those obtained using a more elaborate elasto-plastic model. Five patterns of idealized longitudinal PGD, based on observations by Japanese investigators in previous earthquakes, are considered.

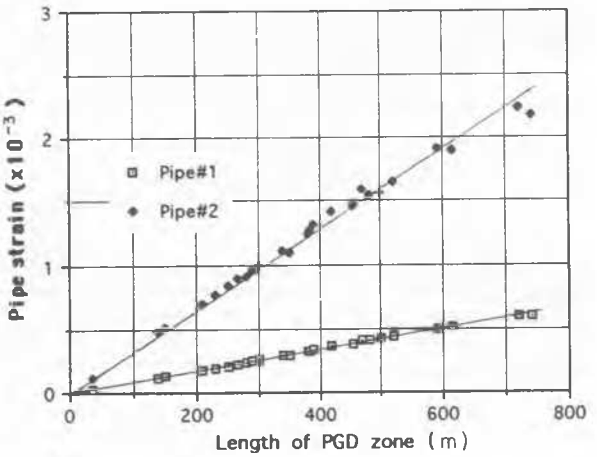

Fig. 7. Pipe Strain Versus Length of PGD Zone.

The pipe strain ϵ is presented in terms of the length L of the PGD zone, a characteristic ground strain α (peak horizontal ground displacement divided by a characteristic length of the PGD zone) and an embedment length L_{em} is defined as the distance over which the soil-pipe friction force per unit length f_m must act to induce a pipe strain equal to the characeteristics ground strain α. L_{em} is similar in concept to the "development length" in reinforced concrete design.

Three hypothetical pipeline, having various wall thickness, burial depths and friction coefficents at the soil pipeline interface were analyzed for 27 patterns of longitudinal PGD observed by Japanese investigators. This analysis indicates the following:

1) The key parameteres influencing the pipeline axial strain is the length L of the PGD zone. The amount of PGD, δ, and the spatial distritubion or pattern of longitudinal PGD are second order effects.

2) Pipeline axial strain due to longitudinal PGD is reduced by increasing the pipe wall thickness, reducing the pipe burial depth, and reducing the angle of shearing resistance of the landfill material. Pipeline axial strain is not influenced by pipe diameter.

The authors believe that the following items should be considered for future research in this area; (a) Analytical or empirical relations for the length or spatial extent of PGD zones should be established; (b) The response of buried pipelines to the vertical component of PGD (neglected herein) should be investigated; (c) The influence of pipeline bends and elbows in both horizontal and vertical planes should be determined. This is particularly important in light of the fact that PGD often occurs near river banks where, by necessity, the pipeline profile contains bends, elbows or other stress raisers.

ACKNOWLEDGEMENTS

The work presented in this paper was sponsored by the National Center for Earthquake Engineering Research under project number NCEER-91-3331. However, the finding and conclusions are the authors alone and do not necessarily reflect the views of NCEER nor the US National Science Foundation. The first author also wants to thank the Mexican Institute of Water Technology (IMTA), for the support provided during his stay at the Rensselaer Polytechnic Institute, Troy, N.Y.

REFERENCES

American Society of Civil Engineers (1984), "Guidelines for the Seismic Design of Oil and Gas Pipeline Systems", Committee on Gas and Liquid Fuel Lifelines, ASCE, New York, N.Y.

Baziar, M., (1991), "Engineering Evaluation of Permanent Ground Deformation Due to Seismically-Induced Liquefaction"dissertation for Ph. D. in Civil Engineering, Rensselaer Polytechnic Institute, August.

Flores-Berrones, R., and O'Rourke, M. (1992) "Seismic Effects on Underground Pipelines due to Permanent Longitudinal Ground Deformation" Proc. 4th US Japan Workshop Earthquake Resistant Design at Lifeline Facilities and Countermeasures against soil liquefaction, Honolulu, Hawaii, May 1992.

Hamada, M., Yasuda, S., Isoyama, R., and Emoto, K., (1986), "Study of Liquefaction Induced Permanent Ground Displacements", Association for the Development of Earthquake Prediction, Japan, November.

Lambe, W., and Whitman, R., (1969), "Soil Mechanics" John Wiley & Sons, pp. 452 & 502.

O'Rourke, M., and Nordberg, C., (1991), "Longitudinal Permanent Ground Deformation Effects on Buried Continuous Pipelines", Technical Report No. NCEER-91-XXXX, National Center for Earthquake Engineering Research, State University of New York at Buffalo, November.

O'Rourke, T., and Tawfic, 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, N.Y.

O'Rourke, T., Grigoriu, M., and Khather, M., (1985) "Seismic Response of Buried Pipelines", Pressure Vessels and Piping Technology, A Decade of Progress, Edited by C. Sundararajan, ASME, N.Y., pp. 281-323.

Towhata, I., Tokida, K., Tamari, y., Matsumoto, H., and Yamada, K., (1991), "Prediction of Permanent Lateral Displacement of Liquefied Ground by Means of Variational Principle," 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, pp. 237-251.

Youd, T., and Perkins, D., (1987) "Mapping of Liquefaction Severity Index", Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 11, pp. 1374-1392, November.