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SEISMIC RESPONSE OF HDPE PIPELINE LATERALS

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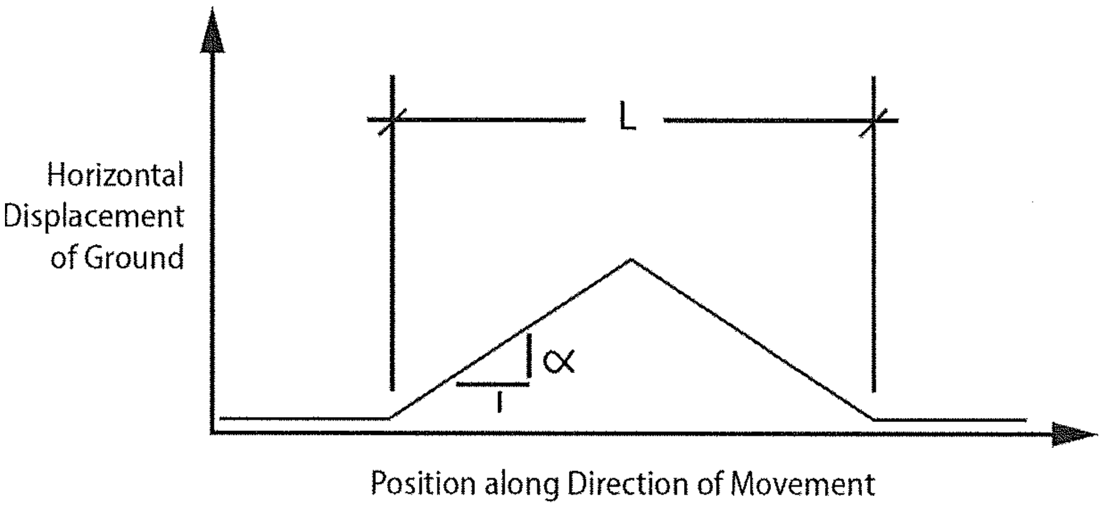
SHORT SUMMARY
It is shown that the longitudinal offset is the most severe seismic hazard. Furthermore, it is shown that for expected amounts of PGD hazard, PE 4710 laterals are at most nominally at the yield strain, that is only a twentieth of the ultimate strain.

KEYWORDS
SERVICE LATERALS, SEISMIC HAZARDS, PERMANENT GROUND DEFORMATION

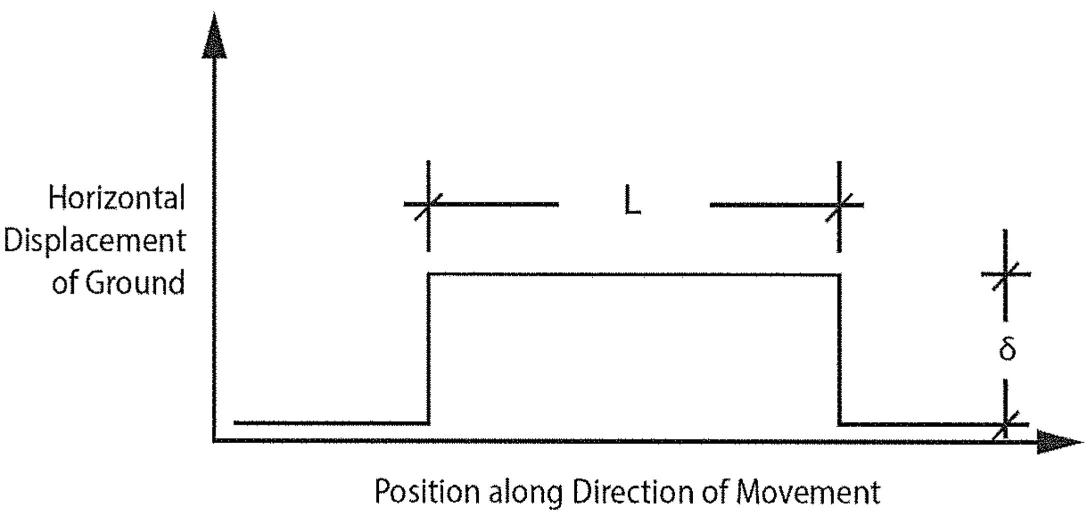
ABSTRACT
The response of HDPE pipe laterals to seismic hazards are investigated. The hazard considered is Permanent Ground Deformation, specifically nominally uniform ground strain, abrupt offset in the longitudinal direction and abrupt offset in the transverse direction.

INTRODUCTION

This paper investigates the response of HDPE (PE 4710) pipe laterals to earthquakes. The two primary seismic hazards to buried pipelines and laterals are wave propagation and permanent ground deformation. Earthquakes cause waves traveling away from the fault. The traveling waves stretch and bend pipeline infrastructure at or near the ground surface and is referred to as the wave propagation (WP) hazard. The WP hazard occurs in all earthquakes and is most commonly quantified by the resulting ground strain which is proportional to the peak ground velocity and inversely proportional to the effective propagation velocity of the traveling seismic waves. The WP hazard is also transitory in that after the shaking ends, the ground returns to its original pre-quake positionHowever, if the earthquake is large, it can result in permanent offsets or movements of the ground which are referred to as permanent ground deformation (PGD). PGD can take many forms. For lateral spreading resulting in a Ridge Pattern (see Chapter 6 of the O'Rourke and Liu monograph), the PGD is characterized by a ground strain α and the length of the PGD zone L. Another common pattern is a Block Pattern in which a block of soil at length L moves uniformly downslope by an amount δ. This form of PGD is often referred to as a lateral spread when away from a free face or a landslide when at or near a free face. Figure 1 presents a sketch of both of these two lateral spread related patterns of PGD. Finally, there is PGD resulting from faulting, where there is an abrupt offset at the ground surface of one side of the fault with respect to the other side.



(a) Ridge Pattern



(b) Block Pattern

Figure 1 Ridge and Block Patterns of Permanent Ground Deformation

There are some earthquakes such as the 1985 Michoacan event where all the pipeline damage in Mexico City was attributed to the WP hazard. There are other events such as the 1994 Northridge earthquake where the pipeline damage was due to both the WP and PGD hazards. In general, the WP hazard affects the whole pipeline network while the PGD hazard affects only limited parts of the network. However, in terms of the intensity of damage as measured by the repair rate (repairs per kilometer of pipe) the PGD hazard is much more intense than the WP hazard. This is due to the fact that the PGD ground strains are generally much larger than ground strains due to WP. In a sense, WP "stretches" the soil while PGD "breaks" the soil. For example, O'Rourke et. al. (2015) investigated the inter-relationship between segmented pipe repair rates and seismic ground strain. For the 14 WP data points, the observed ground strains ranged from roughly 0.005% to 0.1% while for the 13 PGD data points, the ground strains ranged from roughly 0.05% to 5%. As one might expect, there were corresponding differences in the repair rates. For segmented pipe (primarily cast iron, ductile iron and PVC materials), the WP repair rates ranged from roughly 0.01 to 1.0 repairs per kilometer while the PGD repair rates ranged from roughly 2.0 to 35 repairs per kilometer. That is, one expects that if a main pipeline or a pipeline lateral can handle the PGD hazard, it should also be able to handle the WP hazard. As such, herein the PGD hazard is the only seismic hazard considered.

UNIFORM GROUND STRAIN PGD

For a pipe lateral subject to uniform ground strain such as a Ridge Pattern in Figure 1a, the orientation of the component nominally parallel to the ground strain direction (i.e., pipe lateral in N-S direction for ground strain in the N-S direction) produces the largest strains in the component. The axial strain in the pipe lateral is a function of the length of the PGD zone and the restraint to axial movement of the pipe lateral provided by the soil (deep burial in stiff soil provides large soil restraint). For the Ridge Pattern in Figure 2 with downslope movement to the right, there is uniform tensile ground strain α between Points A and D, and uniform compressive ground strain α between Points D and E. For large axial resistance at the soil pipe interface (dashed line), the peak pipe tensile strain matches the ground strain between Points B and C. For small axial soil resistance (dash-dot-dash line) the peak tensile pipe strain (slope of the pipe deformation line) is less than the ground strain value. That is, an upper bound for the axial strain in a pipe lateral is the ground strain value itself.

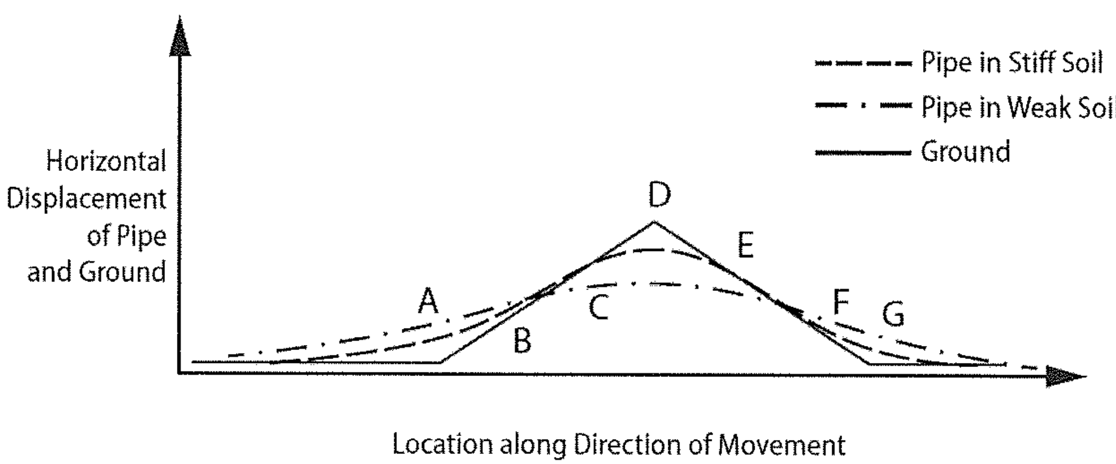


Figure 2 Pipe Response to a Ridge Pattern of PGD

Various authors provide different estimates of ground strain. As noted above, O'Rourke et. al. (2015) presented 13 PGD ground strain data points ranging from 0.05% to 5%, while Davis et. al. (2019) present apparent ground strains of 1.2% to 2.3%. Similarly, Morimoto and Miyajima (2019) used 2.5% as the maximum value of ground strain in reclaimed ground at Port Island in the 1995 Kobe event. Appendix B of the AWWA M55 manual of Water Supply Practice provides a list of four studies with measured ground strains ranging from 0.1% to 4.5%. Omuro and Himono (2018) assert that in the Japan Water Work Association Design Code the design tensile ground strain is set at 1.2% to 2%.

Note that a lateral composed of HDPE (PE 4710) material has an elastic strain limit of about 2%, a yield strain of about 11% and an ultimate strain of about 200% as per the EPRI (2008) report. Hence a PE 4710 lateral can accommodate expected uniform ground strains of nominally 2.5%, the JWWA design value, with a mild excursion into the inelastic range well below the ultimate strain for the material.

ABRUPT MOVEMENT PGD

The Block Pattern of PGD in Figure 1b corresponds to an abrupt uniform movement of soil downslope. Some characterize this movement as "equivalent" soil strain ϵ_{eq}

$$\epsilon_{eq} = \Delta / L \qquad (1)$$

Unfortunately, this equivalent soil strain is neither a lower bound nor an upper bound for the axial strain in a lateral induced by the Block Pattern.

Figure 3, shows the pipe lateral response to a Block Pattern for two different soil restraints (weak soil resistance as a dash-dot, stiff soil resistance as dash-dash). For soil movement to the right, pipeline components, either a main pipeline or a pipeline lateral, have peak tensile strains at Point A, and peak compressive strain at Point B. However, the peak weak soil component strain (slope of line at Points A and B) is less than ϵ_{eq} while the peak "stiff soil" component strain is greater than ϵ_{eq}. That is for a Block Pattern, the soil strain is actually zero to the left of Point A, zero to the right of Point B, zero between Points A and B, and infinite at Points A and B. The pipe or lateral strain is less than infinity but it can be either larger or smaller than the "equivalent" soil strain given in Equation 1.

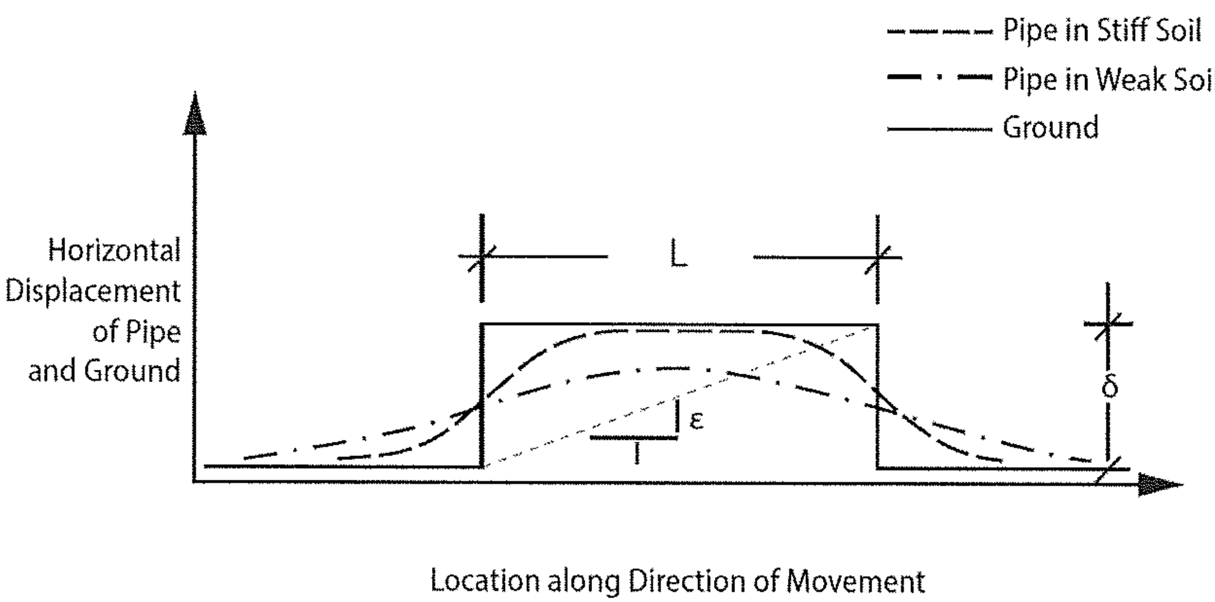


Figure 3 Pipe Response to a Block Pattern of PGD

For such abrupt soil movements determination of pipeline or lateral strain requires explicate consideration of the actual abrupt nature of the soil PGD. In some cases the soil PGD involves an abrupt offset along the longitudinal axis of a pipeline or lateral. In other cases the abrupt offset is transverse to the component axis. Both are discussed below.

Abrupt Longitudinal Offset

Consider the case of a fault offset Δ_f nominally at 90° to the main pipeline axis, sketched for a right lateral offset (as viewed from either side, the other side appears to have moved to the right) in Figure 4. The West side of the fault has moved $^{\Delta_f}/_2$ to the North, while the East side has moved $^{\Delta_f}/_2$ to the South. The main pipeline flexural deformation occurs over a distance l_{mp} on each side of the fault. That is, to the West of Point A, the main pipeline as moved $^{\Delta_f}/_2$ to the North while Point B has moved δ_{pl} to the North, somewhat less that $^{\Delta_f}/_2$. Point C has not moved either North or South. The pipeline lateral at Point B connects the customer, initially at l_c to the North, to the main pipeline. After the earthquake the customer has moved $^{\Delta_f}/_2$ to the North. Hence the original (pre-earthquake) separation between main pipeline and customers is l_c while the post-earthquake separation in l_c + $^{\Delta_f}/_2 - \delta_{pl}$. As such a lower bound estimate of the axial strain in the lateral is

$$\epsilon = \frac{\Delta}{L} = \frac{^{\Delta_f}/_2 - \delta_{pl}}{l_c} \qquad (2)$$

Note that if the customer is located to the West of Point A (further than l_{mp} from the fault) there would be no axial strain in the lateral since the customer and main pipeline experience the same relative movement. Also the larger the original distance from main pipeline to customer, l_c the smaller the induced axial strain in the lateral.

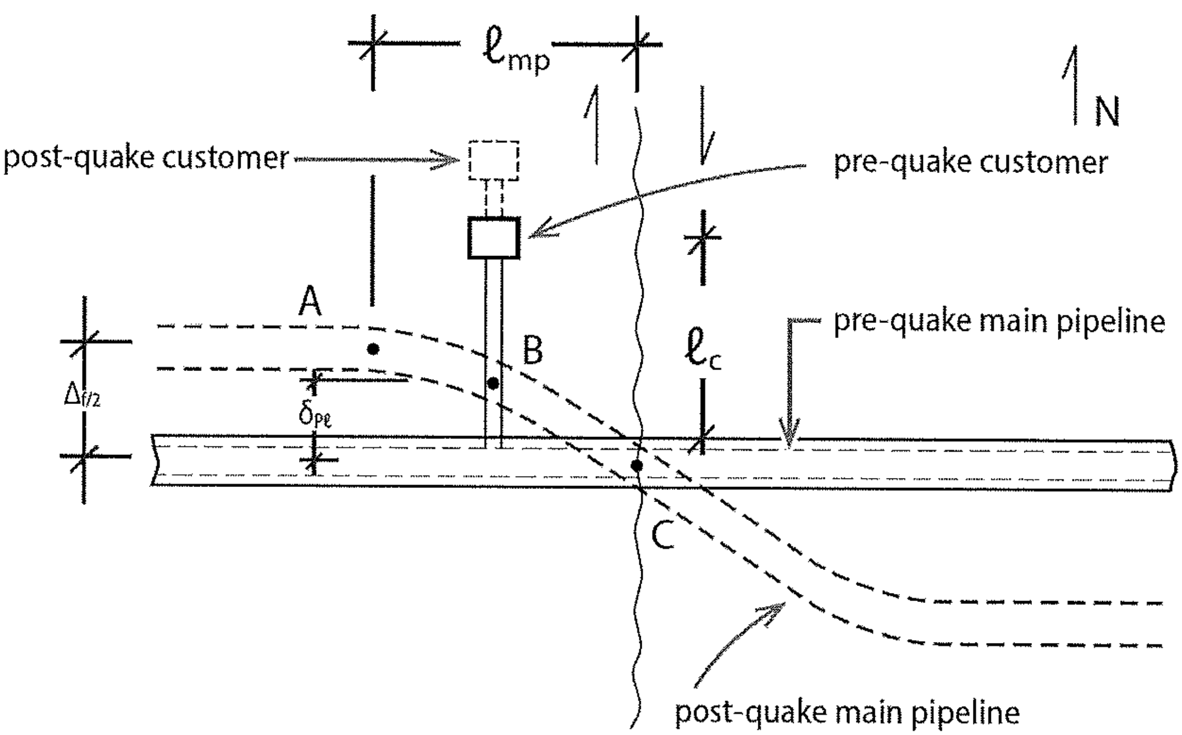


Figure 4 Lateral subject to Abrupt Longitudinal PGD

As noted previously, equation 2 provides a lower bound estimate for the axial strain in a lateral subject to an abrupt longitudinal PGD. The actual strain is somewhat larger due to the soil restraint as characterized by t_u the constant soil friction force per unit length. It is generally accepted (see Section 5.1 and Equation 5.1 in the O'Rourke and Liu monograph) that for sandy soil backfill

$$t_u = \pi D\bar{\gamma}H \left(\frac{1+k_o}{2}\right) \tan k \varphi \quad (3)$$

where D is the diameter of the lateral, $\bar{\gamma}$ is the soil effective unit weight, H is the burial depth of the lateral, K_o is the coefficient of lateral soil pressure, k is a friction coefficient (about 0.6 for epoxy coated Polyethylene) and φ is the angle of shearing resistance for the soil.

Axial equilibrium of the lateral is sketched in Figure 5 where P_c is the axial force in the lateral at the customer, while P_p is the axial force in the lateral at the main pipeline. The soil friction t_u acts towards the customer. Hence

$$P_p = P_c + t_u\, l_l \quad (4)$$

where l_l is the post-quake distance from the pipe to the customer.

$$l_l = l_c + \frac{\Delta_f}{2} - \delta_{pl} \quad (5)$$

and the stretch in the lateral Δ_l from its pre-quake condition to its post-quake condition is

$$\Delta_l = \frac{\Delta_f}{2} - \delta_{pl} \quad (6)$$

The change in length can be determined by integration of the axial strain

$$\Delta_l = \int_o^{l_l} \frac{P(x)\, dx}{AE} \quad (7)$$

It can be shown that

$$P_p = \frac{AE}{l_l}\left[\Delta_l + \frac{t_u l_l^2}{2AE}\right] \quad (8)$$

and the maximum axial strain in the lateral occurs at its connection to the main pipeline.

$$\epsilon_{max} = \frac{\Delta_l}{l_l} + \frac{t_u l_l}{2AE} \quad (9)$$

Note that the first term in equation 9 is close to the lower bound strain in equation 2. For ease of calculations to follow, l_l in equation 9 is conservatively replaced by l_c.

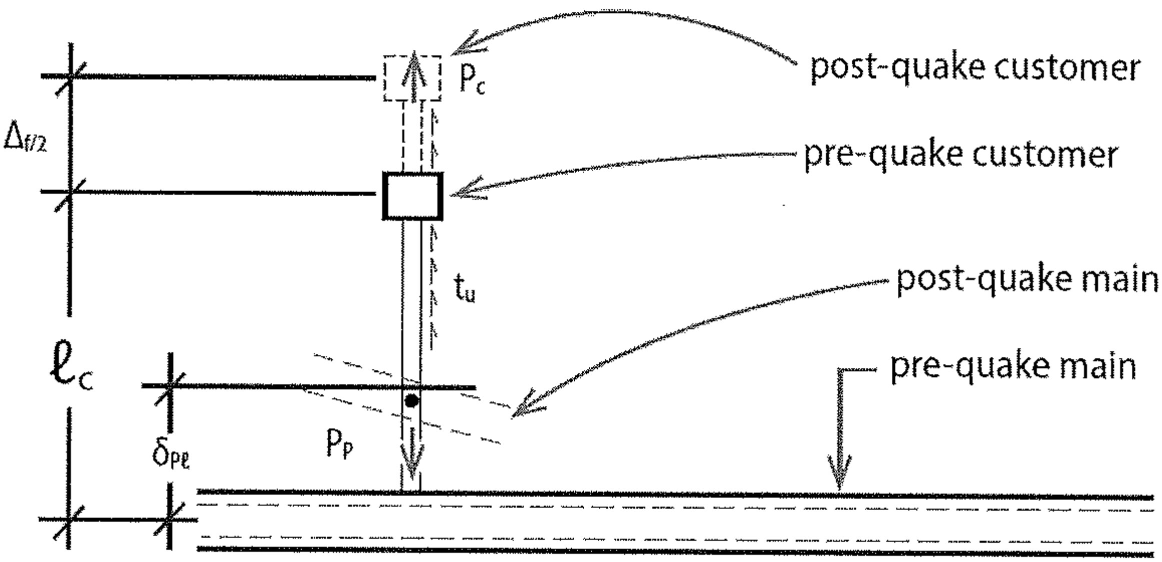


Figure 5 Axial Forces on lateral Subject to Abrupt Longitudinal PGD

The appropriate design fault offset $\Delta_f$is a function of the activity of the fault in question as well as the acceptable level of risk for the pipeline. The American Lifeline Alliance (2005) Guideline establishes four seismic function classes ranging from I with very low risks to human life in the event of failure, to IV for components essential for post-earthquake response. Since a lateral by its nature typically services either a single household (customer a single family residence) or a small number of households (customer an apartment building) it would likely be in class II the ordinary or normal risk group. As such, the ALA guideline recommends a 475- year return period (10% probability of exceedance in 50 years) event. Note that the offset varies along the length of the fault, and that the ALA guideline recommends using the average displacement for class II. To get a sense of scale, the well-studied Thames Water pipeline experienced about 3 meters (9.75 feet) of offset at the Kullar fault during the 1999 Kocaeli earthquake.

Table 1 present the axial strains for a CTS HDPE tube lateral. For the assumed HDPE (PE 4710) material, the modulus of elasticity is 150 ksi as per the 2008 EPRI report. Sandy soil backfill with a $\bar{\gamma}$ = 115 pound/ft.^{3} and φ = 35˚ is assumed. The soil friction t_u from Equation 3 is based upon K_o = 1.0 and k = 0.6. The distance from the pipeline to the customer (pipeline to edge of road or utility corridor right of way, then ROW to customer) prior to the earthquake is taken somewhat conservatively as l_c = 50 feet.
Various values for the burial depth H, diameter D and wall thickness t for the pipe lateral, pipe movement parameter δ_{pl} and fault offset Δ_f are considered.

Pipe Lateral	Burial Depth H (ft)	Fault Offset Δ_f (ft)	Pipe Movement δ_{pl} (ft)	Lower Bound Strain Δ_l/l_c	Soil Term $\frac{t_u l_c}{2AE}$	Total Strain

Avg. Outside Diameter D (in)	Min. Wall Thick. t (in)						
2.125	0.236	4.0	10.0	2.0	6.0%	1.2%	7.2%
1.125	0.125	4.0	10.0	2.0	6.0%	2.2%	8.2%
2.125	0.236	6.0	10.0	2.0	6.0%	1.78%	7.8%
2.125	0.236	2.0	10.0	2.0	6.0%	0.56%	6.6%
2.125	0.236	4.0	15.0	2.0	11.0%	1.2%	12.2%
2.125	0.236	4.0	7.5	2.0	3.5%	1.2%	4.7%
2.125	0.236	4.0	10.0	0.0	10.0%	1.2%	11.2%
2.125	0.236	4.0	10.0	4.0	2.0%	1.2%	3.2%

Table 1 Total Axial Strain in PE Lateral due to Abrupt Longitudinal PGD

As shown in Table 1, for the worst set of parameters (either large Δ_f or small δ_p) the total axial strain is nominally at the yield strain, about one twentieth of the ultimate strain for the HDPE material.

ABRUPT TRANSVERSE OFFSET

Other types of abrupt PGD can result in transverse movement of a lateral. A typical example is the displacement of a lateral when the main pipeline is subject to a block pattern of PGD. As noted above, the abrupt longitudinal offset corresponds, for example, to a N-S lateral subject to a N-S offset, resulting in axial strain in the lateral. A abrupt transverse offset corresponds, to a N-S lateral subject to a E-W offset. The abrupt transverse offsets result in a combination of axial and flexural strains in the lateral. If the initial or pre-seismic length of the lateral is L, and the abrupt transverse offset is Δ, then the post-seismic lateral length would be $\sqrt{L^2 + \Delta^2}$ and the axial strain would be

$$\varepsilon = \left(\sqrt{L^2 + \Delta^2} - L\right)/L = \sqrt{1 + \left(\Delta/L\right)^2} - 1 \qquad (10)$$

As such for an abrupt longitudinal axial strain of Δ/L = 1%, 10% and 50% the corresponding abrupt transverse axial strains would be 0.005%, 0.5% and 11.8% respectively.

There are additional strains due to bending for the case of abrupt transverse offset PGD. However, it can be shown that they are small in comparison to the axial strain, typically less than a tenth of the axial strain value in Equation 10.

CONCLUSIONS

Seismic response of HDPE pipe laterals is investigated by considering three forms of PGD, the most severe seismic hazard. The specific PGD hazards are a ridge pattern of lateral spreading, an abrupt longitudinal offset and finally an abrupt transverse offset. It is shown that abrupt longitudinal offsets generally lead to the largest strains in the laterals. For realistic values of the governing parameters, the total strain induced in the lateral ranged from roughly 3% to 12%. For a pipe lateral composed of PE 4710 material, the elastic strain limit is about 2%, the yield strain is about 11% and the ultimate strain is about 200%. As such, the largest of the calculated pipe strains is nominally at the yield stain, and only a twentieth of the ultimate strain from the HDPE material.

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