Proceedings of the 21st Plastic Pipes Conference, PPXXI
September 25-27, 2023, Lake Buene Vista, FL, USA

DESIGN OF HDPE WATER MAINS FOR THE LATERAL SPREAD SEISMIC HAZARD

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SHORT SUMMARY

Simple relations are developed for the required wall thickness for a HDPE water main subject to the lateral spread seismic hazard.

KEYWORDS

seismic hazard, HDPE water mains, PGD, lateral spread.

ABSTRACT

The required wall thickness for a fully fused HDPE water main subject to an earthquake induced lateral spread is addressed in this paper. The water main is assumed to be buried via cut and cover (i.e., open cut with typical burial depths in the 2 to 15 feet range) procedures and any laterals have small diameters. For the lateral spread hazard, the required wall thickness is a function of site information (burial depth and unit weight of the soil), the acceptable pipe axial strain, and geometric characteristics of the hazard (amount of ground movement and length of the lateral spread zone).

INTRODUCTION

The two primary seismic hazards to buried pipelines are wave propagation and permanent ground deformation. Earthquakes are caused by relative movement at a fault. This movement results in 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. The WP hazard is also transitory in that after the shaking ends, the ground returns to its original pre-quake position. If the earthquake is large, it can also result in permanent offsets at the surface or movements of the ground (lateral spread hazard) both referred to as permanent ground deformation (PGD). As noted above, the lateral spread hazard is addressed herein. As will be shown later, the strains due to PGD are larger and hence more important than those due to WP.

NOMENCLATURE

A Pipe Cross Sectional Area (in^2)

D Pipe Diameter (in.)

E' Effective Elastic Modulus for a specific peak axial strain (specimen subject to linearly increasing axial stress) (psi)

H Pipe Burial Depth (ground surface to pipe spring line) (ft.)

k_o Earth Pressure Coefficient

L Horizontal Extent of Lateral Spread Zone (plan dimension) in direction of ground movements (ft.)

L_{min} Minimum value of L for which response is Case II

M, M_w Earthquake Magnitude

PGD Abbreviation for Permanent Ground Deformation

R, R_{eg} Horizontal Distance from Seismic Energy Zone (km)

t Pipe Wall Thickness (in.)

t_u Axial Friction Force per unit length at Soil/Pipe Interface

γ Unit Weight of Soil (pcf)

ε_{eq}, ε Equivalent Ground Strain

δ Peak Horizontal Ground Displacement within Lateral Spread Zone (ft.)

δ_{min} Minimum Value of δ for which response is Case I

Δ Horizontal Displacement of Pipe at head and Toe of the Lateral Spread Zone (ft.)

σ_{max} Peak Pipe Axial Stress (psi)

μ Friction Coefficient between Pipe and Soil

Lateral spreads can take many forms. A 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.

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 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. 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%. One expects that if a pipeline can handle the PGD hazard, it should also be able to handle the WP hazard.

ABRUPT MOVEMENT PGD

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

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

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

Seismic design of fully fused HDPE pipe for the lateral spread hazard involves determination of the required wall thickness. The following section provides the governing engineering relationships.

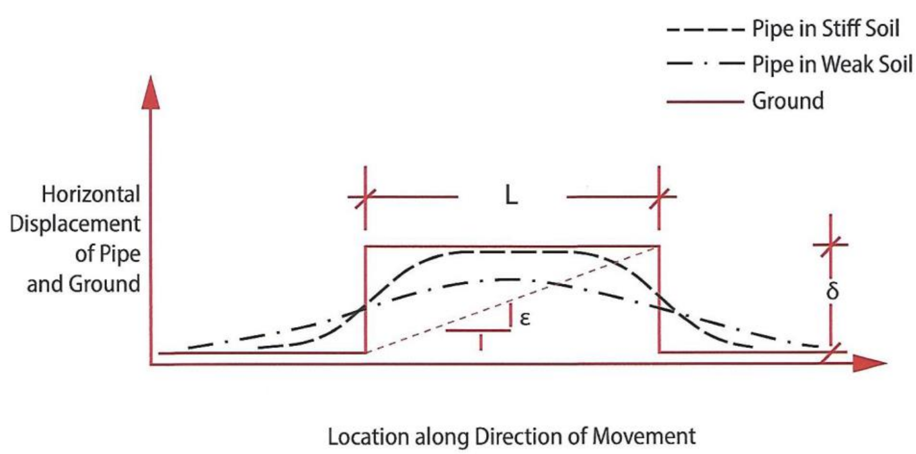

Figure 1 - -Pipe Response to a Block Pattern of PGD

REQUIRED WALL THICKNESS

O'Rourke and Nordberg (1992) have shown that for given values of δ and L, the axial strain in a fully fused or continuous buried pipeline is largest for the Block Pattern of lateral spreading. Herein we will assume the worst case (Block) pattern of lateral spreading. As noted above, a Block Pattern corresponds to a block of soil of length L moving downslope by an amount of δ. This results in "infinite" ground strain at two points, and zero ground strain elsewhere. The pipeline strains are largest for a buried pipeline nominally parallel to the direction of ground movement. This results in axial tension at the head (Point B) of the lateral spread and axial compression at the toe (Point D) as shown for Case I in Figure 2. At both the head and toe, the pipe axial strain is a maximum, less than the "infinite" ground strain but either larger or smaller than the Equivalent" ground strain in Equation 1.

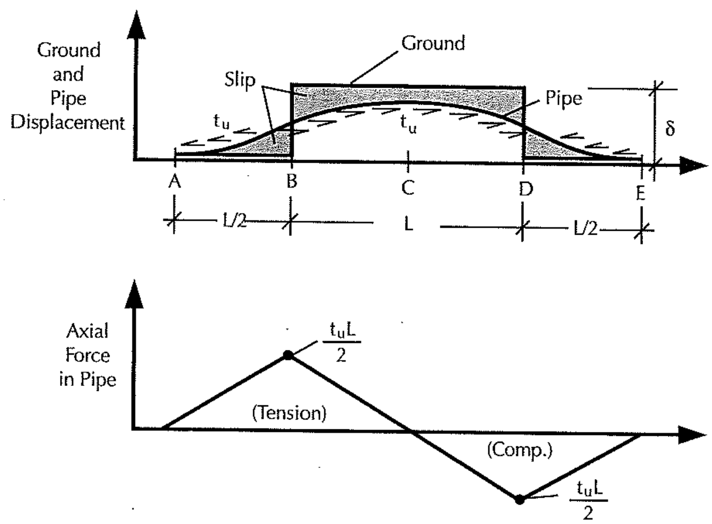

Figure 2 Ground and Pipe Displacement (upper figure), Axial Force in Pipe, (lower figure) Case I

Case I

If the length of the lateral spread is small, Case I applies as shown in Figure 2 wherein the peak pipe displacement is less than the ground displacement. The peak axial stress σ_{max} (tension at Point B, compression at Point D) is the soil friction force t_u times half the block length L, divided by the pipe cross-sectional area A

$$\sigma_{max} = \frac{t_u\, L}{2A} \qquad (2)$$

where the soil friction force (lbs/ft) is given by

$$t_u = \pi\, D\, \gamma\, H \left(\frac{1+k_o}{2}\right) \mu \qquad (3)$$

where D is the pipe diameter, γ is the soil unit weight taken herein to be 115 lbs/ft^3, H is the burial depth to the pipe centerline, generally in the 3 to 5 feet range, k_o is the lateral earth pressure coefficient taken herein to be 1.0, and μ is the coefficient of friction at the soil-pipe interface taken herein to be 0.25 based upon tests by Gemperline and Rinehart (2018).

Note in Figure 2 that the axial force and hence the axial stress is linear in both the head and toe regions of the lateral spread. As such the total axial displacement of the pipe is twice the displacement at the head (i.e., Point B in Figure 2). Integrating the axial strain (axial stress divided by the effective modulus of elasticity E').

$$\text{Peak Pipe Displacement} = 2\,\Delta$$

$$\Delta = \int_{o}^{L/2} \frac{t_u\,x}{AE'}\,dx = \frac{1}{8}\,\frac{t_u (L)^2}{AE'} \qquad (4)$$

where the effective modulus of elasticity E' for HDPE pipe is a function of the allowable axial strain.

As noted above, there are two equations of interest. From Equation 2 noting that the pipe cross-sectional area
$A = \pi\,D\,t$

$$\sigma_{max} = \frac{t_u\,L}{2\pi\,D\,t} = \frac{t_u}{2\,\pi\,D}\,\frac{L}{t} \qquad (5)$$

where t is the pipe wall thickness. It can be shown that

$$L = \text{Peak Pipe Displacement}\left(2\,E'/\sigma_{max}\right) \qquad (6)$$

However, the ratio E'/σ_{max} is a dimensionless constant which for PE 4710 material is a function of the peak strain.

For Case 1 the peak pipe displacement at Point C is less than the ground movement δ and hence from Equation 6

$$\text{Peak Pipe Displacement} = \frac{\sigma_{max}\,L}{2\,E'} \qquad (7)$$

and

$$\delta > \text{Peak Pipe Displacement} = \frac{\sigma_{max}\,L}{2\,E'}$$

or

$$L \leq 2\,\delta\,E'/\sigma_{max} \qquad (8)$$

and from Equation 5

$$t = \frac{t_u\left(L/2\right)}{\pi\,D\,\sigma_{max}} \qquad (9)$$

Given the relation for t_u in Equation 3, the required wall thickness for $k_o = 1.0$ and $\mu = 0.25$ becomes

$$t = \frac{\gamma\,H\,L}{8\,\sigma_{max}} \qquad (10)$$

Case II

If the length of the lateral spread zone is large, we have Case II as sketched in Figure 3 wherein the peak pipe displacement equals the ground displacement. As with Case I, the peak pipeline axial force, axial stress and axial strain still occur at the head (Point B in Figure 3) and toe (Point E in Figure 4) of the lateral spread. However, unlike Case I, the peak pipe displacement matches that for the ground between Points C and D in Figure 3. In addition, the regions of slip between the pipeline and soil are within L_e of both the head and toe of the lateral spread (between Points A and C at the head and between Points D and F at the toe).

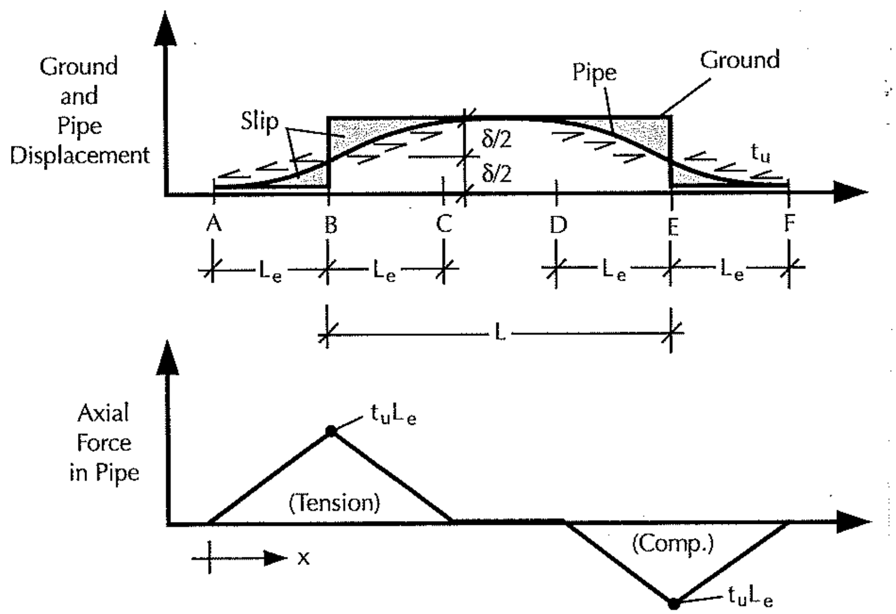

Figure 3 Ground and Pipe Displacement (upper figure), Axial Force in Pipe (lower figure) Case II

It can be shown that

$$t = \frac{L_e t_u}{\pi\, D\, \sigma_{max}} \tag{11}$$

where $L_e = {E'\,\delta}/{\sigma_{max}}$

Notice the similarity between Equations 9 and 11. The required pipe wall thickness is proportional to a length $L/2$ in Equation 9 and the length L_e in Equation 11. Both these lengths correspond to the same thing, the distance between the start of the slip between ground and pipe (Point A in both Figures 2 and 3) and the head of the lateral spread (Point B in both Figures 2 and 3). Given the relation for t_u in Equation 3, the required wall thickness, again for k_o = 1.0 and μ = 0.25, becomes

$$t = \frac{\gamma\, H\, L_e}{4\, \sigma_{max}} \tag{12}$$

Note that the required wall thickness is not a function of the pipe diameter. This results from the fact that both the lateral spread demand and the pipe capacity are both linearly proportional to the pipe diameter.

For Case I, the length of the lateral spread zone L is small, specifically less than $2\delta E'/\sigma_{max}$ from Equation 8, and the wall thickness is given by Equation 10. For Case II, the wall thickness is given by Equation 12.

Besides the pipe burial parameters (γ and H), users need to input information about the seismic hazard (δ and L) as well as information about the pipeline axial strain capacity. Unfortunately, local or state building codes do not specify the acceptable peak pipeline axial strain for earthquake induced lateral spreads. Hence it is the pipeline system owners/operator's, decision as to what is the acceptable peak pipeline strain. For PE 4710 material the elastic strain limit is about 2%, the yield strain is about 11% and the ultimate strain is about 200%.

For Polyethylene PE 4710 pipe materials peak pipeline strains in the 6% to 10% range can be tolerated without fracture. It is recommended that the acceptable peak pipe strain for comparatively less important small diameter lines (diameters generally in the 4-to-12 inch range) be 8 to 10%. For more important lines (diameters generally more than 12 inches), peak pipe strains of 6 to 8% are suggested.

In relation to the seismic hazard, the two parameters used herein to characterize a lateral spread are δ, the amount of PGD movement and L, the length of the lateral spread zone. There is much more information on δ than there is on L.

GROUND DISPLACEMENT δ

Herein a simple but limited method to estimate δ will be used for typical site conditions. Figure 4 adapted from the corresponding figure in Youd et. al. (2002) presents the predicted displacement for various values of the earthquake magnitude, M, and the horizontal site-to-source distance R. They were based upon a combination of observed data points from the U.S. and Japan. Youd cautions that δ values of 6.0 m or more are questionable and that R or R_{eq} should be no smaller than 0.5 km. For sites in the U.S. and southern Canada, the United States Geological Survey web site https://earthquake.usgs.gov/hazards/interactive provides earthquake magnitude M_w and closest distance information.

LENGTH OF LATERAL SPREAD ZONE L

Available information on the length of the lateral spread zone is more limited than that for the amount of movement δ. Honegger (1994) presents a cumulative distributed function of the length of the lateral spread zone shown in Figure 5. The Honegger curve is based upon over 150 measured lateral spread lengths from two Japanese events. Note that for the Honegger data, the median value is about 90 m (295 ft.), the 75% below value is about 150 m (492 ft.) while the 95% below value is about 280 m (918 ft.).

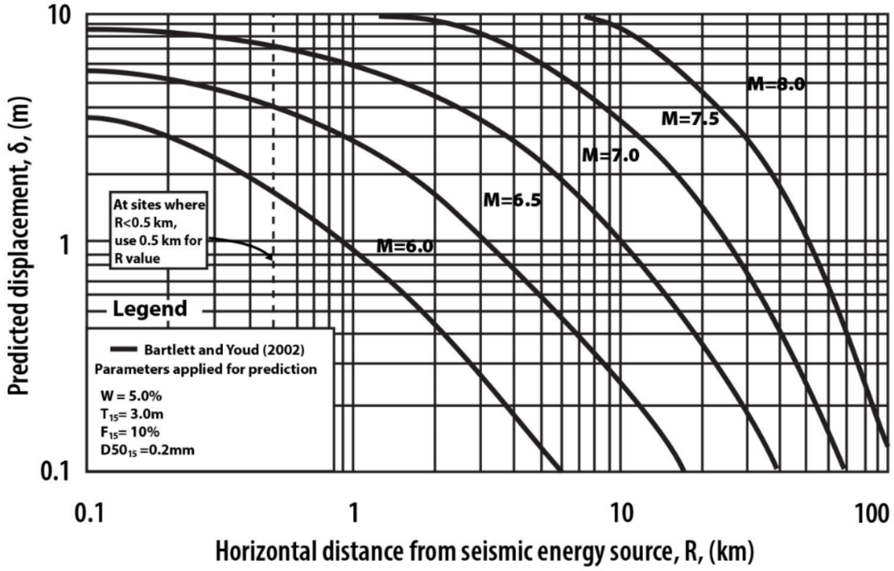

Figure 4 Youd et. al. Predicted Displacement δ as a Function of Earthquake Magnitude M and Horizontal Distance from Seismic Energy Source R

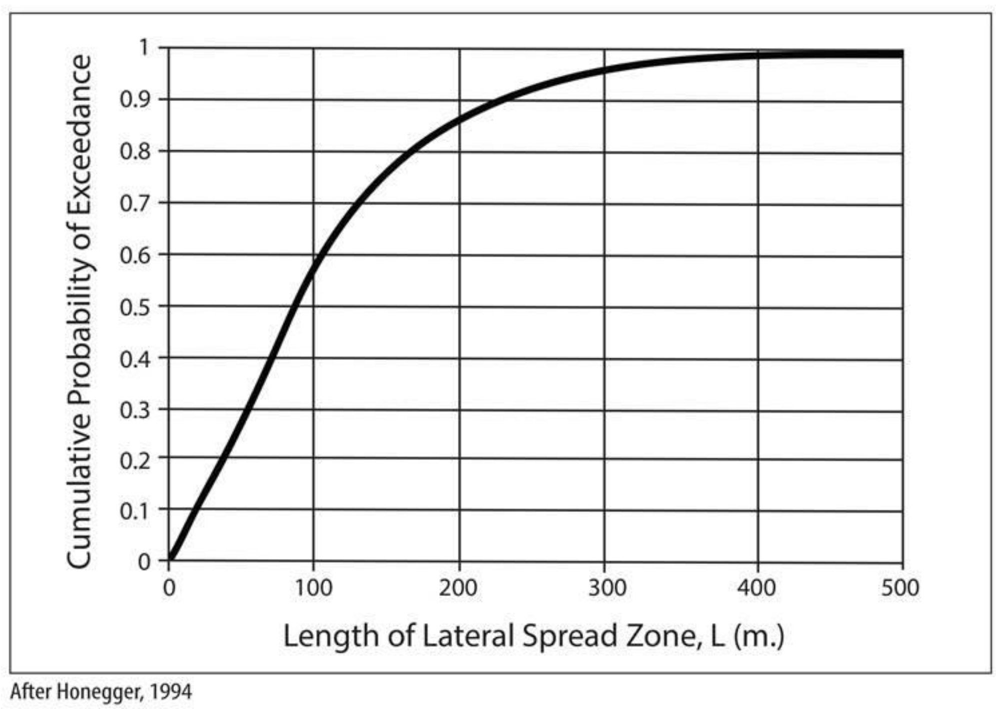

Figure 5 Cumulative Distribution Function

A project specific estimate for the length of the potential lateral spread could be determined through a geotechnical engineering study of the plan area of liquefiable soil.

The two pipe properties needed to determine the required wall thickness are the effective modulus E´ and the peak axial stress, both of which are functions of the maximus allowable axial strain. Both parameters are summarized in Table 1. Note that the yield strain is about 8% and hence the peak stress for 8 and 10% strain are nominally the same.

Table 1 Peak Stress and Effective Modulus for Various Peak Strain Values

Peak Strain	Peak Stress (psi)	Effective Modulus (psi)	Ratio E'/σ_{max}
6%	4040	145,650	36.1
8%	4250	134,860	31.7
10%	4250	127,460	30.0

WALL THICKNESS EVALUATION

Tables 2, 3, and 4 present the required wall thickness t for peak pipe strains of 6%, 8%, and 10% and various values for the burial parameters γ and H, and for three values of the ground displacement δ. Tables 2 through 4 are for Case II, where the wall thickness is controlled by the ground displacement δ, the most common case. For convenience, the corresponding minimum length of the lateral spread zone L_{min} (i.e., $L_{min} = 2\,\delta\,E'/\sigma_{max}$) is also listed. As one would expect the required wall thickness for Case II is an increasing function of the soil unit weight γ, the burial depth H, and the ground displacement δ, and a decreasing function of the peak pipe strain.

Table 2 Required Wall Thickness t (in inches) for Case II and Peak Pipe Strain of 6%

δ	L_{min}	γ = 100 lb/ft^3			γ = 115 lb/ft^3		
(ft)	(ft)	H = 2 ft	H = 4 ft	H = 6 ft	H = 2 ft	H = 4 ft	H = 6 ft
3.28	237	0.12	0.24	0.37	0.14	0.28	0.42
6.56	473	0.24	0.49	0.73	0.28	0.56	0.84
9.85	710	0.37	0.73	1.10	0.42	0.84	1.26

Table 3 Required Wall Thickness t (in inches) for Case II and Peak Pipe Strain of 8%

δ	L_{min}	γ = 100 lb/ft^3			γ = 115 lb/ft^3		
(ft)	(ft)	H = 2 ft	H = 4 ft	H = 6 ft	H = 2 ft	H = 4 ft	H = 6 ft
3.28	208	0.10	0.20	0.31	0.12	0.23	0.35
6.56	416	0.20	0.41	0.61	0.23	0.47	0.70
9.85	625	0.31	0.61	0.92	0.35	0.70	1.06

Table 4 Required Wall Thickness t (in inches) for Case II and Peak Pipe Strain of 10%

δ	L_{min}	γ = 100 lb/ft^3			γ = 115 lb/ft^3		
(ft)	(ft)	H = 2 ft	H = 4 ft	H = 6 ft	H = 2 ft	H = 4 ft	H = 6 ft
3.28	197	0.10	0.19	0.29	0.11	0.22	0.33
6.56	393	0.19	0.39	0.58	0.22	0.44	0.67

9.85	591	0.29	0.58	0.87	0.33	0.67	1.00

CONCLUSIONS

A procedure for calculating the required wall thickness for an HDPE water main subject to the lateral spread hazard is presented. Separate acceptable peak pipe strains are recommended for “important” water mains (diameters greater than 12 inches) and for “less important” mains (diameters less than 12 inches). The required wall thicknesses are shown to be an increasing function of the burial depth and unit weight of backfill. Somewhat surprisingly, the required wall thickness is shown to be independent of the pipe diameter. Examples show that even for large amounts of ground movement and poor burial conditions (heavy backfill and deep burial depth) the required wall thickness is met by currently available pipe DR. This is consistent with the excellent seismic performance of HDPE pipe in past earthquakes.

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