SECTION 6
RAMP/STEP PGD

The axial strain induced in a continuous buried steel pipeline due to a Ramp/Step pattern of longitudinal PGD is determined in this section. As with the other idealized PGD patterns, the burial depth of the pipeline is assumed to be constant in and around the PGD zone and any vertical component of PGD (i.e. subsidence and heaving) is neglected. As shown in Table 3–I the value of D_s, the relative displacement for slippage at the soil pipeline interface, is quite small and as a result the simplified interface model yields accurate results for the idealized PGD patterns investigated in Sections 4 and 5. In this section the simplified model for the soil pipeline interface, that is the rigid spring–slider model shown in Figure 3–3, is used.

As mentioned previously, the idealized Ramp/Step pattern shown in Figure 2–13 could result from a lateral spread near a free face such as a river bank. It would be an appropriate model for the postulated soil displacement pattern shown in Figure 2–10(c) and might be appropriate for the observed PGD patterns shown on the right hand side of Figure 2–6(c), as well as in Figures 2–7(c) and 2–7(o).

As shown in Figure 2–13, a coordinate system is established at the head of the lateral spread zone which has a length L. The soil strains on either side of the zone are zero. Since the Ramp/Step pattern is most likely to occur at a free face, the soil movement would probably be towards the free face resulting in tensile soil strain within the lateral spread zone. Herein, the tensile soil strain is assumed to have constant value of α.

6.1. Possible Configurations

There are two possible configurations for pipeline response to Ramp/Step PGD using the simplified rigid spring–slider model. The first configuration is shown in Figure 6–1 and corresponds to the case where the maximum tensile strain in the pipe is less than the ground strain α. The second configuration is shown in Figure 6–2 where the tensile strain in the pipe is equal to the ground strain, α, over a length L_2. Both configurations are considered herein.

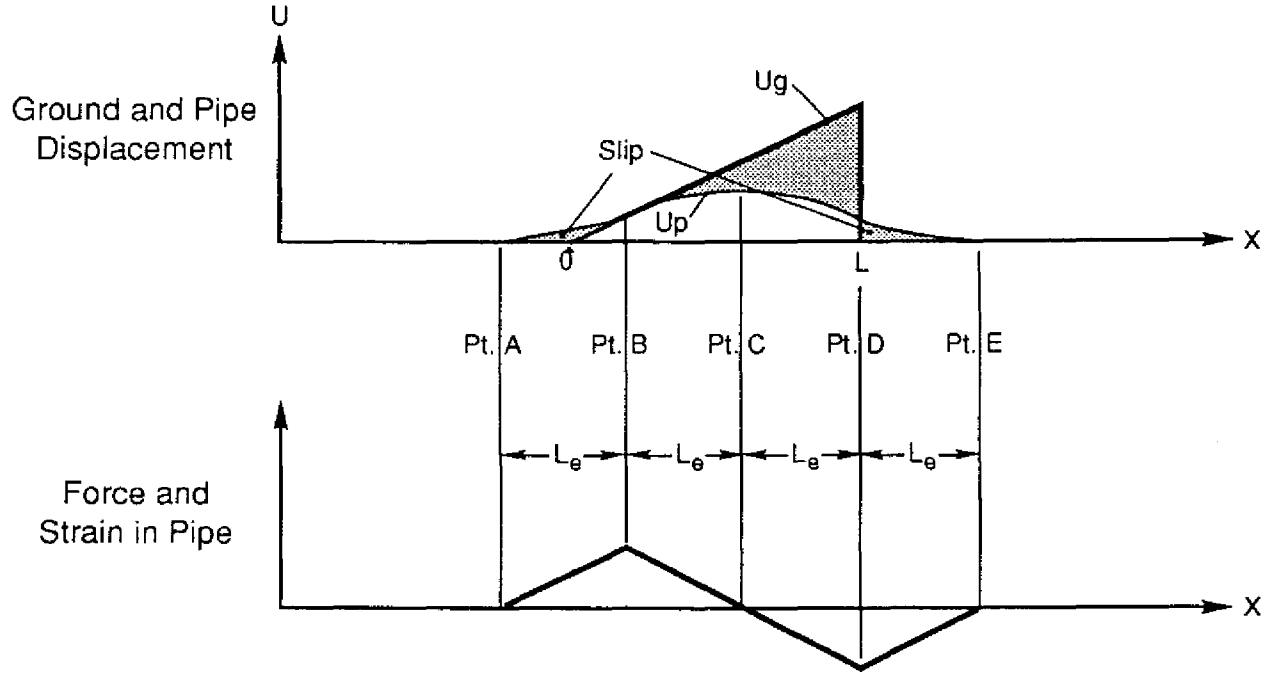

FIGURE 6-1 Simplified Model for Ramp/Step PGD with pipe strain less than ground strain.

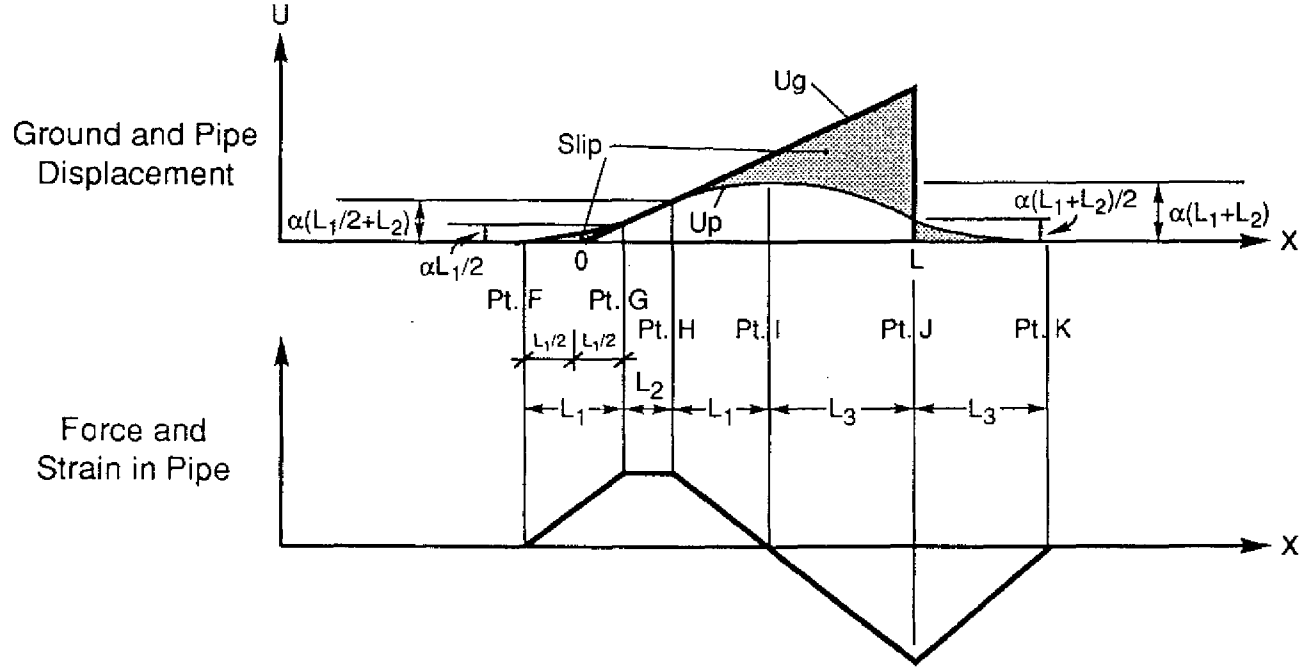

FIGURE 6-2 Simplified Model for Ramp/Step PGD with tensile pipe strain equal to ground strain.

6.2. Tensile Pipe Strain Less Than α

Figure 6.1 shows the case where the pipe strain is less than α. The pipe strain is zero at points A, C and E. The maximum tensile force in the pipe occurs at point B where the pipe displacement matches the ground displacement. The maximum axial displacement of the pipe occurs at point C. The pipe forces to the right of point C, are symmetric about point D. The maximum compressive force in the pipe equal in magnitude to the maximum tensile force, occurs at Point D (i.e., at the free face step). Since the slippage force per unit length is a constant, the separation distances between points A through E is also a constant, L_e. The length L_e can be determined by recalling that the pipe displacement equals the ground displacement at point B. That is

$$U_p(B) = U_g(B) = \alpha(L-2L_e) \tag{6.1}$$

This pipe displacement at point B is due to a force per unit length f_m acting over a length L_e, that is

$$U_p(B) = \int_0^{L_e} \frac{f_m s}{EA}\, ds = \frac{f_m L_e^2}{2EA} \tag{6.2}$$

Equations 6.1 and 6.2 can be solved for the length L_e

$$L_e = \frac{\sqrt{4\alpha^2 + 2f_m \alpha L/EA} - 2\alpha}{f_m/EA} \tag{6.3}$$

which, of course, is always a positive quantity. The maximum pipe strain, tension at point B and compression at point D is then

$$\epsilon = f_m L_e/AE = \sqrt{4\alpha^2 + 2f_m \alpha L/EA} - 2\alpha \tag{6.4}$$

The configuration in Figure 6–1 holds if the maximum pipe strain is less than the ground strain α. Setting $\epsilon < \alpha$ in equation 6.4 yields $L < 5\alpha EA/2f_m$. Hence the configuration in Figure 6–1 is applicable if $L < 5\alpha EA/2f_m$.

6.3 Tensile Pipe Strain Equals α

For an idealized Ramp/Step pattern of longitudinal PGD, the configuration in Figure 6.2 holds if $L > 5\alpha EA/2f_m$. The pipe strain is zero at points F, I and K. The tensile pipe strain equals α over a length L_2 between points G and H, when the pipe displacement matches exactly the assumed ground displacement. The maximum compressive strain in the pipe occurs at point J.

As mentioned above, the force in the pipe at point F is zero. Since the slippage force per unit length between points F and G is a constant, the force in the pipe is a linear function of distance and the pipe axial displacement is a parabolic function of distance between points F and G. Since the pipe strain matches the ground strain at point G, the point of zero ground strain bisects the line segment between F and G as shown in Figure 6.3.

The force in the pipe is zero at point I, and the force per unit length between H and I (decreasing) equals that between F and G (increasing). Hence the distance between H and I must equal L_1. Similarly, the distance between points I and J matches the distance between points J and K. This distance is denoted herein as L_3.

The axial displacement of the pipe equals $\alpha L_1/2$ at point G and $\alpha(L_1/2 + L_2)$ at point H. Since the pipe displacement is zero at point F and the force in the pipe between F and I is symmetric about the midpoint of segment FI, the pipe displacement at point I is $\alpha(L_1 + L_2)$. Similarly, the axial displacement of the pipe at point J equals $\alpha(L_1 + L_2)/2$.

For the configuration in Figure 6–2, the maximum tensile pipe strain is α. The maximum compressive pipe strain is determined herein by enforcing continuity. Recall that the pipe displacement at point G equals the assumed ground displacement at that point

$$U_p(G) = U_g(G) = \frac{\alpha L_1}{2} \tag{6.5}$$

The pipe displacement at this point is due to a force per unit length f_m acting over a distance of L_1, hence

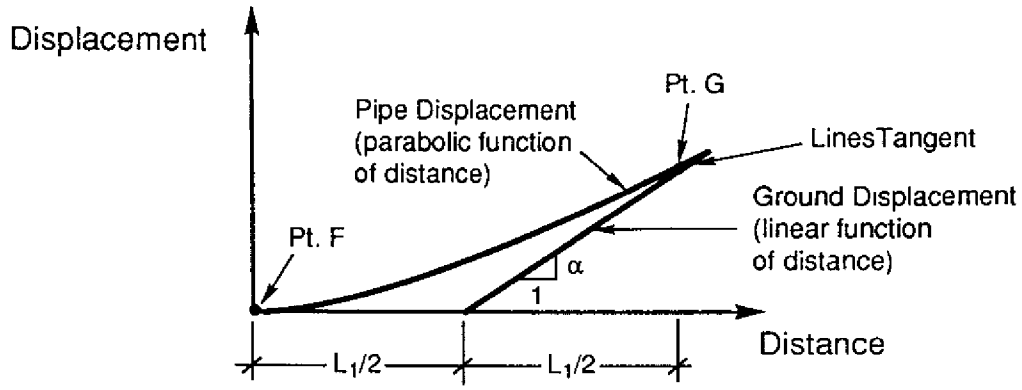

FIGURE 6-3 Diagram showing point of zero ground strain bisecting line segment between F and G.

$$U_p(G) = \int_0^{L_1} \frac{f_m s}{EA} ds = \frac{f_m L_1^2}{2EA} \tag{6.6}$$

Hence, from equations 6.5 and 6.6, we have

$$L_1 = \frac{\alpha EA}{f_m} \tag{6.7}$$

The pipe displacement at point J must equal the pipe displacement at point H plus the stretching and/or compression over the distance from H to J.

$$U_p(H) + \int_H^J \frac{f(s)}{EA} ds = U_p(J) \tag{6.8}$$

or

$$\alpha\left(\frac{L_1}{2} + L_2\right) + \int_0^{L_1+L_3} \left[\frac{L_1 f_m}{EA} - \frac{f_m s}{EA}\right] ds = \frac{\alpha}{2}(L_1 + L_2) \tag{6.9}$$

which reduces to

$$L_2 = \frac{f_m}{\alpha EA}[L_3^2 - L_1^2] \tag{6.10}$$

Finally, note that the total length of the lateral spread zone L is

$$L = \frac{3L_1}{2} + L_2 + L_3 \tag{6.11}$$

Combining equations (6.7), (6.10) and (6.11) results in the following expression for the length L_3

$$L_3 = \frac{\sqrt{\frac{4 f_m L}{\alpha EA} - 1} - 1}{\frac{2 f_m}{\alpha EA}} \tag{6.12}$$

The maximum compressive strain in the pipe, which occurs at point J, is simply

$$\epsilon = f_m L_3/EA = \frac{\alpha}{2}\left[\sqrt{\frac{4 f_m L}{\alpha EA} - 1} - 1\right] \tag{6.13}$$

For $L > 5\alpha EA/2f_m$ which applies to the situation in Figure 6–2, the maximum compressive strain in the pipe, by equation (6.13), is larger than the tensile ground strain α.

6.4 Maximum Pipe Strain

Tables 6–I through 6–XXVII present the maximum compressive pipe strain for an idealized Ramp/Step pattern of longitudinal PGD. Results are calculated using equation (6.4) for $L < 5\alpha EA/2f_m$, and using equation (6.13) for $L > 5\alpha EA/2f_m$.

As with the tables in Sections 4 and 5, the unit weight of the soil, γ, is taken as 100 pcf and the coefficient of friction of the soil pipeline interface, μ, is taken as 0.75. Results are presented for pipe diameters, ϕ, of 12, 30 and 48 inches, pipe wall thicknesses, t, of 1/4, 1/2 and 3/4 inches and for 3, 6 and 9 feet of soil cover, C, over the the top of the pipe.

The range of values for the ground strain, α, and the length of the lateral spread zone L are the same as those used for the Ramp pattern in Section 4. That is, α and L are based upon the work of Suzuki and Masuda [8].

For a fixed value of the ground strain, α, pipe strain is an increasing function of the length of the lateral spread zone L. For a fixed value of L, the pipe strain is an increasing function of α. For fixed α and L, pipe strain is an increasing function of the burial depth H, or C, and a decreasing function of the wall thickness t. For a fixed burial depth to the pipe centerline H, the pipe strain is not a function of the pipe diameter ϕ. This results from the fact that both the slippage force, f_m, and the pipe cross–sectional area, A, are proportional to the pipe diameter, ϕ

α	L(m) 25	50	100	150	200
0.0025	0.0001190	0.0002353	0.0004604	0.0006766	0.0008849
0.0033	0.0001193	0.0002366	0.0004654	0.0006870	0.0009022
0.0050	0.0001197	0.0002380	0.0004705	0.0006980	0.0009208
0.0100	0.0001200	0.0002394	0.0004759	0.0007098	0.0009411
0.0200	0.0001202	0.0002401	0.0004787	0.0007160	0.0009519

TABLE 6–I Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001441	0.0002843	0.0005541	0.0008114	0.0010577
0.0033	0.0001446	0.0002863	0.0005612	0.0008260	0.0010818
0.0050	0.0001451	0.0002882	0.0005686	0.0008418	0.0011082
0.0100	0.0001457	0.0002903	0.0005765	0.0008588	0.0011373
0.0200	0.0001459	0.0002913	0.0005806	0.0008678	0.0011530

TABLE 6–II Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76 2 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001691	0.0003329	0.0006462	0.0009431	0.0012258
0.0033	0.0001698	0.0003356	0.0006557	0.0009625	0.0012574
0.0050	0.0001705	0.0003383	0.0006658	0.0009836	0.0012925
0.0100	0.0001713	0.0003411	0.0006766	0.0010067	0.0013317
0.0200	0.0001716	0.0003425	0.0006822	0.0010190	0.0013531

TABLE 6–III Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002188	0.0004288	0.0008261	0.0011981	0.0015489
0.0033	0.0002200	0.0004331	0.0008413	0.0012284	0.0015974
0.0050	0.0002212	0.0004376	0.0008576	0.0012620	0.0016523
0.0100	0.0002224	0.0004423	0.0008752	0.0012994	0.0017152
0.0200	0.0002230	0.0004447	0.0008846	0.0013198	0.0017505

TABLE 6–IV Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002435	0.0004761	0.0009140	0.0013217	0.0017046
0.0033	0.0002449	0.0004814	0.0009324	0.0013581	0.0017623
0.0050	0.0002464	0.0004869	0.0009523	0.0013986	0.0018281
0.0100	0.0002479	0.0004927	0.0009739	0.0014443	0.0019045
0.0200	0.0002486	0.0004957	0.0009855	0.0014694	0.0019478

TABLE 6–V Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002680	0.0005230	0.0010007	0.0014430	0.0018568
0.0033	0.0002697	0.0005294	0.0010224	0.0014857	0.0019240
0.0050	0.0002715	0.0005360	0.0010461	0.0015336	0.0020013
0.0100	0.0002733	0.0005430	0.0010721	0.0015881	0.0020922
0.0200	0.0002743	0.0005467	0.0010861	0.0016185	0.0021441

TABLE 6–VI Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0 25 in (6.4 mm), C = 6 ft (1.83 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0003168	0.0006157	0.0011702	0.0016789	0.0021515
0.0033	0.0003192	0.0006244	0.0011993	0.0017350	0.0022386
0.0050	0.0003216	0.0006335	0.0012314	0.0017990	0.0023405
0.0100	0.0003242	0.0006433	0.0012671	0.0018731	0.0024628
0.0200	0.0003255	0.0006483	0.0012865	0.0019150	0.0025341

TABLE 6–VII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0003410	0.0006614	0.0012533	0.0017938	0.0022944
0.0033	0.0003437	0.0006714	0.0012863	0.0018570	0.0023918
0.0050	0.0003466	0.0006819	0.0013229	0.0019295	0.0025066
0.0100	0.0003495	0.0006932	0.0013639	0.0020142	0.0026458
0.0200	0.0003511	0.0006991	0.0013864	0.0020624	0.0027278

TABLE 6–VIII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0003651	0.0007068	0.0013353	0.0019068	0.0024345
0.0033	0.0003682	0.0007181	0.0013723	0.0019772	0 0025424
0.0050	0.0003715	0.0007301	0.0014137	0.0020585	0.0026706
0.0100	0.0003749	0.0007430	0.0014603	0.0021544	0.0028273
0.0200	0.0003766	0.0007498	0.0014860	0.0022094	0.0029206

TABLE 6–IX Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000598	0.0001190	0.0002353	0.0003490	0.0004604
0.0033	0.0000599	0.0001193	0.0002366	0.0003519	0.0004654
0.0050	0.0000600	0.0001197	0.0002380	0.0003549	0.0004705
0.0100	0.0000601	0.0001200	0.0002394	0.0003580	0.0004759
0.0200	0.0000602	0.0001202	0.0002401	0.0003596	0.0004787

TABLE 6–X Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000726	0.0001441	0.0002843	0.0004209	0.0005541
0.0033	0.0000727	0.0001446	0.0002863	0.0004250	0.0005612
0.0050	0.0000728	0.0001451	0.0002882	0.0004294	0.0005686
0.0100	0.0000730	0.0001457	0.0002903	0.0004339	0.0005765
0.0200	0.0000730	0.0001459	0.0002913	0.0004362	0.0005806

TABLE 6–XI Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.50 in (12 7 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000853	0.0001691	0.0003329	0.0004918	0.0006462
0.0033	0.0000855	0.0001698	0.0003356	0.0004974	0.0006557
0.0050	0.0000856	0.0001705	0.0003383	0.0005033	0.0006658
0.0100	0.0000858	0.0001713	0.0003411	0.0005095	0.0006766
0.0200	0.0000859	0.0001716	0.0003425	0.0005127	0.0006822

TABLE 6–XII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.50 in (12 7 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001106	0.0002188	0.0004288	0.0006310	0.0008261
0.0033	0.0001109	0.0002200	0.0004331	0.0006401	0.0008413
0.0050	0.0001112	0.0002212	0.0004376	0.0006497	0.0008576
0.0100	0.0001115	0.0002224	0.0004423	0.0006599	0.0008752
0.0200	0.0001116	0.0002230	0.0004447	0.0006653	0.0008846

TABLE 6–XIII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001232	0.0002435	0.0004761	0.0006993	0.0009140
0.0033	0.0001236	0.0002449	0.0004814	0.0007104	0.0009324
0.0050	0.0001239	0.0002464	0.0004869	0.0007221	0.0009523
0.0100	0.0001243	0.0002479	0.0004927	0.0007347	0.0009739
0.0200	0.0001245	0.0002486	0.0004957	0.0007413	0.0009855

TABLE 6–XIV Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001358	0.0002680	0.0005230	0.0007668	0.0010007
0.0033	0.0001362	0.0002697	0.0005294	0.0007800	0.0010224
0.0050	0.0001367	0.0002715	0.0005360	0.0007941	0.0010461
0.0100	0.0001371	0.0002733	0.0005430	0.0008092	0.0010721
0.0200	0.0001374	0.0002743	0.0005467	0.0008172	0.0010861

TABLE 6–XV Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001608	0.0003168	0.0006157	0.0008995	0.0011702
0.0033	0.0001614	0.0003192	0.0006244	0.0009173	0.0011993
0.0050	0.0001621	0.0003216	0.0006335	0.0009365	0.0012314
0.0100	0.0001627	0.0003242	0.0006433	0.0009575	0.0012671
0.0200	0.0001631	0.0003255	0.0006483	0.0009687	0.0012865

TABLE 6–XVI Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001733	0.0003410	0.0006614	0.0009647	0.0012533
0.0033	0.0001740	0.0003437	0.0006714	0.0009850	0.0012863
0.0050	0.0001748	0.0003466	0.0006819	0.0010071	0.0013229
0.0100	0.0001755	0.0003495	0.0006932	0.0010312	0.0013639
0.0200	0.0001759	0.0003511	0.0006991	0.0010442	0.0013864

TABLE 6–XVII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001857	0.0003651	0.0007068	0.0010293	0.0013353
0.0033	0.0001866	0.0003682	0.0007181	0.0010522	0.0013723
0.0050	0.0001874	0.0003715	0.0007301	0.0010772	0.0014137
0.0100	0.0001883	0.0003749	0.0007430	0.0011047	0.0014603
0.0200	0.0001888	0.0003766	0.0007498	0.0011195	0.0014860

TABLE 6–XVIII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000400	0.0000796	0.0001580	0.0002353	0.0003114
0.0033	0.0000400	0.0000798	0.0001586	0.0002366	0.0003137
0.0050	0.0000401	0.0000799	0.0001593	0.0002380	0.0003161
0.0100	0.0000401	0.0000801	0.0001599	0.0002394	0.0003185
0.0200	0.0000401	0.0000802	0.0001602	0.0002401	0.0003198

TABLE 6–XIX Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000485	0.0000965	0.0001913	0.0002843	0.0003757
0.0033	0.0000486	0.0000968	0.0001922	0.0002863	0.0003791
0.0050	0.0000486	0.0000970	0.0001931	0.0002882	0.0003825
0.0100	0.0000487	0.0000972	0.0001940	0.0002903	0.0003861
0.0200	0.0000487	0.0000973	0.0001945	0.0002913	0.0003880

TABLE 6–XX Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000570	0.0001134	0.0002243	0.0003329	0.0004394
0.0033	0.0000571	0.0001137	0.0002255	0.0003356	0.0004439
0.0050	0.0000572	0.0001140	0.0002268	0.0003383	0.0004486
0.0100	0.0000573	0.0001143	0.0002280	0.0003411	0.0004535
0.0200	0.0000573	0.0001145	0.0002287	0.0003425	0.0004561

TABLE 6–XXI Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000740	0.0001469	0.0002897	0.0004288	0.0005644
0.0033	0.0000741	0.0001474	0.0002917	0.0004331	0.0005717
0.0050	0.0000743	0.0001480	0.0002938	0.0004376	0.0005795
0.0100	0.0000744	0.0001485	0.0002959	0.0004423	0.0005876
0.0200	0.0000745	0.0001488	0.0002970	0.0004447	0.0005919

TABLE 6–XXII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000825	0.0001636	0.0003222	0.0004761	0.0006259
0.0033	0.0000826	0.0001642	0.0003246	0.0004814	0.0006348
0.0050	0.0000828	0.0001649	0.0003272	0.0004869	0.0006443
0.0100	0.0000830	0.0001656	0.0003298	0.0004927	0.0006544
0.0200	0.0000830	0.0001659	0.0003312	0.0004957	0.0006596

TABLE 6–XXIII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000909	0.0001802	0.0003544	0.0005230	0.0006867
0 0033	0.0000911	0.0001810	0.0003574	0.0005294	0.0006974
0.0050	0.0000913	0.0001818	0.0003604	0.0005360	0.0007087
0.0100	0.0000915	0.0001826	0.0003636	0.0005430	0.0007209
0.0200	0.0000916	0.0001830	0.0003653	0.0005467	0.0007273

TABLE 6–XXIV Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001078	0.0002133	0.0004182	0.0006157	0.0008064
0.0033	0.0001081	0.0002144	0.0004224	0.0006244	0.0008209
0.0050	0.0001083	0.0002155	0.0004266	0.0006335	0.0008365
0.0100	0.0001086	0.0002167	0.0004311	0.0006433	0.0008533
0.0200	0.0001088	0.0002173	0.0004334	0.0006483	0.0008622

TABLE 6–XXV Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001162	0.0002298	0.0004499	0.0006614	0.0008654
0.0033	0.0001165	0.0002311	0.0004546	0.0006714	0.0008819
0.0050	0.0001169	0.0002324	0.0004596	0.0006819	0.0008998
0.0100	0.0001172	0.0002337	0.0004647	0.0006932	0.0009191
0.0200	0.0001174	0.0002344	0.0004674	0.0006991	0.0009295

TABLE 6–XXVI Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001246	0.0002462	0.0004814	0.0007068	0.0009237
0.0033	0.0001250	0 0002477	0.0004868	0.0007181	0.0009424
0.0050	0 0001253	0.0002492	0.0004924	0.0007301	0.0009627
0.0100	0.0001257	0.0002507	0.0004983	0.0007430	0.0009848
0.0200	0.0001259	0.0002515	0.0005014	0.0007498	0.0009966

TABLE 6–XXVII Maximum Compressive Pipe Strain for a Ramp/Step Pattern of Longitudinal PGD using the Simplified Soil–Pipeline Interface Model. ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

SECTION 7
RIDGE PGD

The axial strain induced in a continuous steel pipeline due to a Ridge pattern of longitudinal PGD is determined in this section. As with the other idealized PGD patterns, the burial depth of the pipeline is assumed to be constant in and around the PGD zone and any vertical component of PGD (i.e. subsidence and heaving) is neglected. As shown in Table 3.1 the value of D_s, the relative displacement for slippage at the soil pipeline interface, is quite small and as a result the simplified interface model yields accurate results for the idealized PGD patterns investigated in Sections 4 and 5. As in Section 6, the simplified model for the soil pipeline interface, that is the rigid spring–slider model shown in Figure 3–3, is used herein to evaluate pipe strains.

As mentioned previously, the idealized Ridge pattern shown in Figure 2–14 may be an appropriate model for the observed PGD patterns to the left of the Bandai Bridge in Figure 2–6(c), in Figures 2–7(b) and on the south side of the Yoshino Creek in Figure 2–8.

As shown in Figure 2–14, a coordinate system is established at the head of the lateral spread zone which has a length L. The soil strains on either side of the zone are zero. Within the lateral spread zone, there is uniform tensile ground strain, α, to the left of the ridge and uniform compressive ground strain, α, to the right of the ridge.

7.1. Possible Configurations

There are two possible configurations for pipeline response to Ridge PGD using the simplified rigid spring–slider model. The first configuration is shown in Figure 7–1 and corresponds to the case where the maximum strain in the pipe is less than the ground strain α. The second configuration is shown in Figure 7–2 where the strain in the pipe is equal to the ground strain α over a limited distance on each side of the ridge. Both configurations are considered herein.

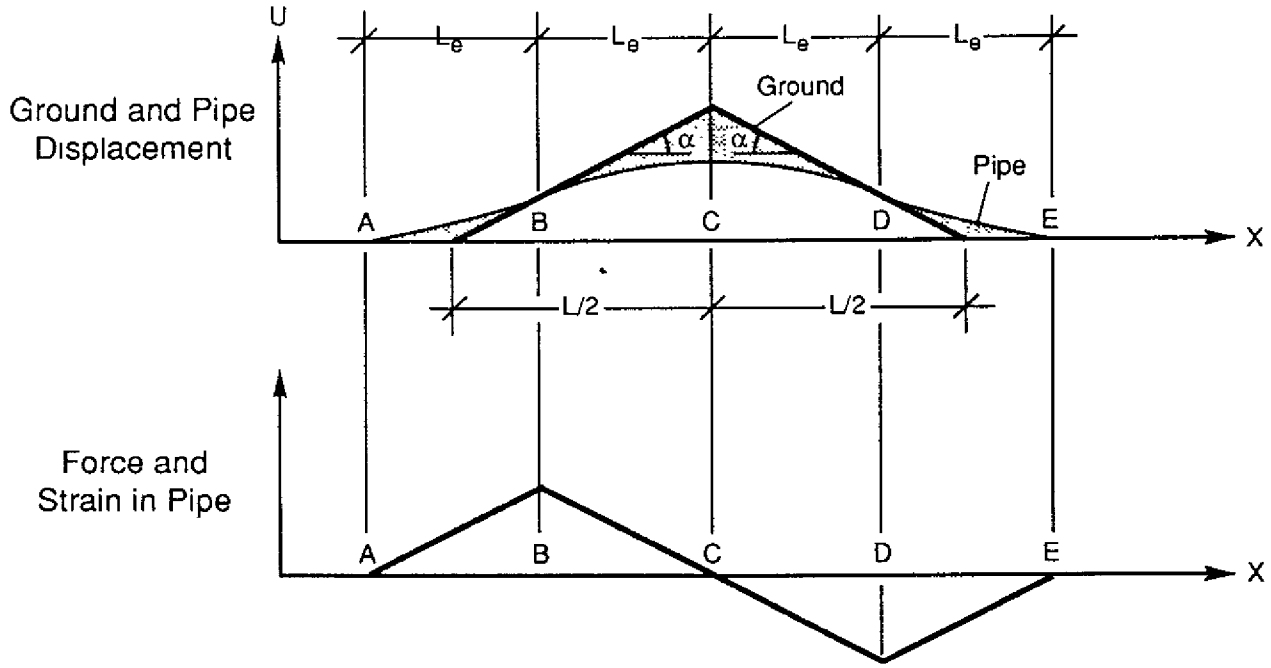

FIGURE 7-1 Simplified Model for Ridge PGD with pipe strain less than ground strain.

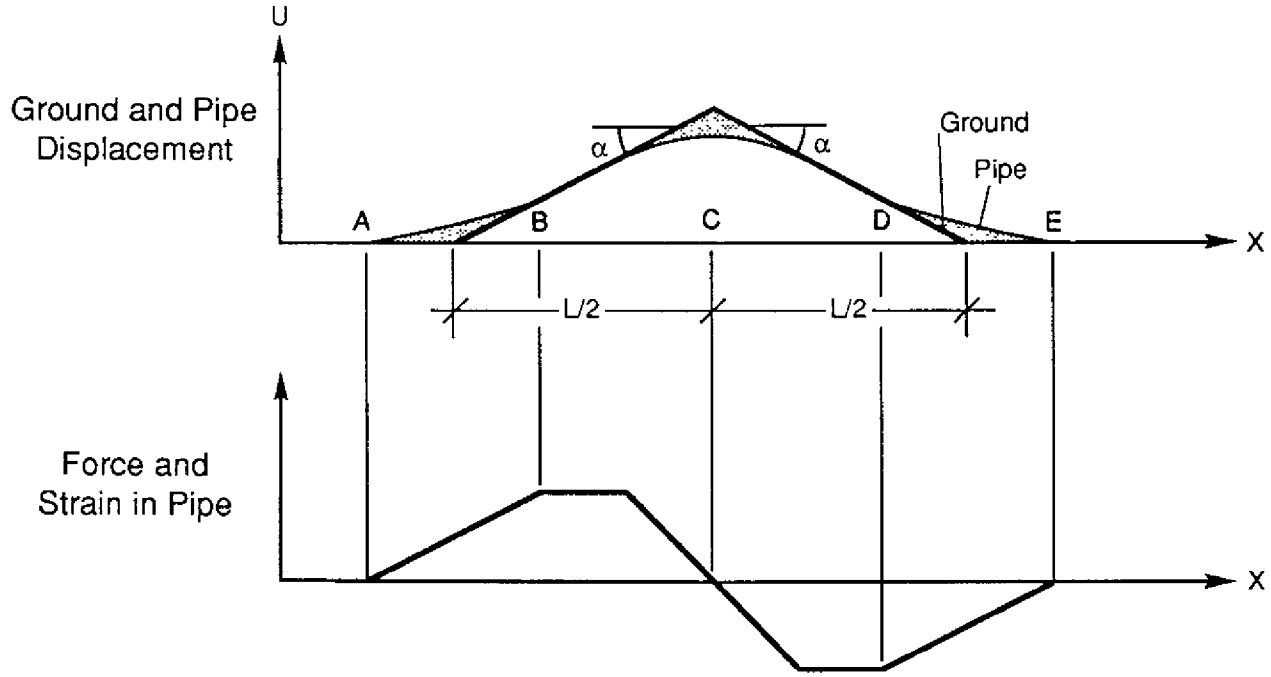

FIGURE 7-2 Simplified Model for Ridge PGD with maximum pipe strain equal to ground strain.

7.2. Tensile Pipe Strain Less Than α

Figure 7.1 shows the case where the pipe strain is less than α. The pipe strain is zero at points A, C and E. The maximum tensile and compressive strains in the pipe occur at points B and D respectively. The pipe displacement matches the ground displacement at these points. The maximum axial displacement of the pipe occurs directly under the ridge, at point C. To the left and right of point C, the pipe force is symmetric about points B and D respectively. Since the slippage force per unit length is a constant, the separation distances between points A through E is also a constant L_e. The length L_e can be determined by recalling that the pipe displacement equals the ground displacement at point B.

$$U_p(B) = U_g(B) = \alpha(\frac{L}{2} - L_e) \tag{7.1}$$

This pipe displacement at point B is due to a force per unit length f_m acting over a length L_e,

$$U_p(B) = \int_0^{L_e} \frac{f_m s}{EA} ds = \frac{f_m L_e^2}{2EA} \tag{7.2}$$

Equations 7.1 and 7.2 can be solved for the length L_e

$$L_e = \frac{\sqrt{\alpha^2 + f_m L \alpha/EA} - \alpha}{f_m/EA} \tag{7.3}$$

which, of course, is always a positive quantity. The maximum pipe strain, tension at point B and compression at point D is then

$$\epsilon = f_m L_e/AE = \sqrt{\alpha^2 + f_m L \alpha/EA} - \alpha \tag{7.4}$$

The configuration in Figure 7–1 holds if the maximum pipe strain is less than the ground strain α. Setting $\epsilon < \alpha$ in equation 7.4 yields $L < 3\alpha EA/f_m$. That is, the configuration in Figure 7–1 is applicable if $L < 3\alpha EA/f_m$.

7.3 Tensile Pipe Strain Equals α

For an idealized Ridge pattern of longitudinal PGD, the configuration in Figure 7–2 holds if $L > 3\alpha EA/f_m$. For this case, the maximum tensile pipe strain equals the ground strain α over a limited distance somewhere to the left of point C while the maximum compressive pipe strain equals the ground strain, α, over a limited distance somewhere to the right of point C.

7.4 Maximum Pipe Strain

Tables 7–I through 7–XXVII present the maximum pipe strain for an idealized Ridge pattern of longitudinal PGD. Results are calculated using equation (7.4) for $L < 3\alpha EA/f_m$. For $L > 3\alpha EA/f_m$ the maximum pipe strain equals the ground strain α.

As with the tables in Sections 4 through 6, the unit weight of the soil, γ, is taken as 100 pcf and the coefficient of friction at the soil pipeline interface, μ, is taken as 0.75. Results are presented for pipe diameters, ϕ, of 12, 30 and 48 inches, pipe wall thicknesses, t, of 1/4, 1/2 and 3/4 inches and for 3, 6 and 9 feet of soil cover, C, over the the top of the pipe.

The range of values for the ground strain, α, and the length of the lateral spread zone, L, are the same as those used for the Ramp pattern in Section 4 and the Ramp/Step pattern in Section 6.

For a fixed value of the ground strain α, pipe strain is an increasing function of the length of the lateral spread zone for $L \leq 3\alpha EA/f_m$. For lengths beyond that value the pipe strain is a constant. For a fixed value of L, the pipe strain is an increasing function of the burial depth, H or C, and a decreasing function of the pipe wall thickness t. For a fixed burial depth to the pipe centerline, H, the pipe strain is not a function of the pipe diameter ϕ. This results from both f_m and A being proportional to the pipe diameter ϕ.

α	L(m) 25	50	100	150	200
0.0025	0.0001176	0.0002302	0.0004424	0.0006404	0.0008266
0.0033	0.0001183	0.0002327	0.0004511	0.0006575	0.0008538
0.0050	0 0001190	0.0002353	0.0004604	0.0006766	0.0008849
0.0100	0.0001197	0.0002380	0.0004705	0.0006980	0.0009208
0.0200	0.0001200	0.0002394	0.0004759	0.0007098	0.0009411

TABLE 7–I Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30 5 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001422	0.0002770	0.0005289	0.0007613	0.0009782
0.0033	0.0001431	0.0002806	0.0005409	0.0007848	0.0010150
0.0050	0.0001441	0.0002843	0.0005541	0.0008114	0.0010577
0.0100	0.0001451	0.0002882	0.0005686	0.0008418	0.0011082
0.0200	0.0001457	0.0002903	0.0005765	0.0008588	0.0011373

TABLE 7–II Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001665	0.0003231	0.0006129	0.0008779	0.0011235
0.0033	0.0001678	0.0003279	0.0006287	0.0009083	0.0011705
0.0050	0.0001691	0.0003329	0.0006462	0.0009431	0.0012258
0.0100	0.0001705	0.0003383	0.0006658	0.0009836	0.0012925
0.0200	0.0001713	0.0003411	0.0006766	0.0010067	0.0013317

TABLE 7–III Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002144	0.0004131	0.0007744	0.0010997	0.0013979
0.0033	0.0002166	0.0004207	0.0007987	0.0011450	0.0014663
0.0050	0.0002188	0.0004288	0.0008261	0.0011981	0.0015489
0.0100	0.0002212	0.0004376	0.0008576	0.0012620	0.0016523
0.0200	0.0002224	0.0004423	0.0008752	0.0012994	0.0017152

TABLE 7–IV Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002381	0.0004570	0.0008523	0.0012057	0.0015281
0.0033	0.0002407	0.0004662	0.0008811	0.0012587	0.0016076
0.0050	0.0002435	0.0004761	0.0009140	0.0013217	0.0017046
0.0100	0.0002464	0.0004869	0.0009523	0.0013986	0.0018281
0.0200	0 0002479	0.0004927	0.0009739	0.0014443	0.0019045

TABLE 7–V Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0002615	0.0005003	0.0009284	0.0013087	0.0016543
0.0033	0.0002647	0.0005112	0.0009620	0.0013698	0.0017449
0.0050	0.0002680	0.0005230	0 0010007	0.0014430	0.0018568
0.0100	0.0002715	0.0005360	0.0010461	0.0015336	0.0020013
0.0200	0.0002733	0.0005430	0.0010721	0.0015881	0.0020922

TABLE 7–VI Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0003078	0.0005851	0.0010757	0.0015067	0.0018957
0.0033	0.0003122	0.0005997	0.0011193	0.0015843	0.0020090
0.0050	0.0003168	0.0006157	0.0011702	0.0016789	0.0021515
0.0100	0.0003216	0.0006335	0.0012314	0.0017990	0.0023405
0.0200	0.0003242	0.0006433	0.0012671	0.0018731	0.0024628

TABLE 7–VII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0003307	0.0006267	0.0011472	0.0016022	0.0020115
0.0033	0.0003357	0.0006432	0.0011959	0.0016881	0.0021363
0.0050	0.0003410	0.0006614	0.0012533	0.0017938	0.0022944
0.0100	0.0003466	0.0006819	0.0013229	0.0019295	0.0025066
0.0200	0.0003495	0.0006932	0.0013639	0.0020142	0.0026458

TABLE 7–VIII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0003534	0.0006676	0.0012173	0.0016955	0.0021245
0.0033	0.0003591	0.0006862	0.0012712	0.0017899	0.0022606
0.0050	0.0003651	0.0007068	0.0013353	0.0019068	0.0024345
0.0100	0.0003715	0.0007301	0.0014137	0.0020585	0.0026706
0.0200	0.0003749	0.0007430	0.0014603	0.0021544	0.0028273

TABLE 7–IX Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000595	0.0001176	0.0002302	0.0003383	0 0004424
0.0033	0.0000597	0.0001183	0.0002327	0.0003435	0.0004511
0.0050	0.0000598	0.0001190	0.0002353	0.0003490	0.0004604
0.0100	0.0000600	0.0001197	0.0002380	0.0003549	0.0004705
0.0200	0.0000601	0.0001200	0.0002394	0.0003580	0.0004759

TABLE 7–X Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000721	0.0001422	0.0002770	0.0004057	0.0005289
0.0033	0.0000723	0.0001431	0.0002806	0.0004130	0.0005409
0.0050	0.0000726	0.0001441	0.0002843	0.0004209	0.0005541
0.0100	0.0000728	0.0001451	0.0002882	0.0004294	0.0005686
0.0200	0.0000730	0.0001457	0.0002903	0.0004339	0.0005765

TABLE 7–XI Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000846	0.0001665	0.0003231	0.0004715	0.0006129
0.0033	0.0000849	0.0001678	0.0003279	0.0004813	0.0006287
0.0050	0.0000853	0.0001691	0.0003329	0.0004918	0.0006462
0.0100	0.0000856	0.0001705	0.0003383	0.0005033	0.0006658
0.0200	0.0000858	0.0001713	0.0003411	0.0005095	0.0006766

TABLE 7–XII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.50 in (12.7 mm), C = 3 ft (0.91 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0001094	0.0002144	0.0004131	0.0005990	0.0007744
0.0033	0.0001100	0.0002166	0.0004207	0.0006142	0.0007987
0.0050	0.0001106	0.0002188	0.0004288	0.0006310	0.0008261
0.0100	0.0001112	0.0002212	0.0004376	0.0006497	0.0008576
0.0200	0.0001115	0.0002224	0.0004423	0.0006599	0.0008752

TABLE 7–XIII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0001217	0.0002381	0.0004570	0.0006609	0.0008523
0.0033	0.0001225	0.0002407	0.0004662	0.0006790	0.0008811
0 0050	0.0001232	0.0002435	0.0004761	0.0006993	0.0009140
0.0100	0.0001239	0.0002464	0.0004869	0.0007221	0.0009523
0.0200	0.0001243	0.0002479	0.0004927	0.0007347	0.0009739

TABLE 7–XIV Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0001340	0.0002615	0.0005003	0.0007215	0.0009284
0.0033	0.0001349	0 0002647	0.0005112	0.0007428	0.0009620
0.0050	0.0001358	0.0002680	0.0005230	0.0007668	0.0010007
0.0100	0.0001367	0.0002715	0.0005360	0.0007941	0.0010461
0.0200	0.0001371	0.0002733	0.0005430	0.0008092	0.0010721

TABLE 7–XV Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.50 in (12.7 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001584	0.0003078	0.0005851	0.0008395	0.0010757
0.0033	0 0001596	0.0003122	0.0005997	0.0008675	0.0011193
0.0050	0.0001608	0.0003168	0.0006157	0.0008995	0.0011702
0.0100	0.0001621	0.0003216	0.0006335	0.0009365	0.0012314
0 0200	0.0001627	0.0003242	0.0006433	0.0009575	0.0012671

TABLE 7–XVI Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001705	0.0003307	0.0006267	0.0008969	0.0011472
0.0033	0.0001719	0.0003357	0.0006432	0.0009285	0.0011959
0 0050	0.0001733	0.0003410	0.0006614	0.0009647	0.0012533
0.0100	0.0001748	0.0003466	0.0006819	0.0010071	0.0013229
0.0200	0.0001755	0.0003495	0.0006932	0.0010312	0.0013639

TABLE 7–XVII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001825	0.0003534	0.0006676	0.0009534	0 0012173
0.0033	0.0001841	0.0003591	0.0006862	0.0009886	0.0012712
0.0050	0.0001857	0.0003651	0.0007068	0.0010293	0.0013353
0.0100	0.0001874	0.0003715	0.0007301	0.0010772	0.0014137
0.0200	0.0001883	0.0003749	0.0007430	0.0011047	0.0014603

TABLE 7–XVIII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000398	0.0000790	0.0001557	0.0002302	0.0003027
0.0033	0.0000399	0.0000793	0.0001568	0.0002327	0.0003069
0.0050	0.0000400	0.0000796	0.0001580	0.0002353	0.0003114
0.0100	0.0000401	0.0000799	0.0001593	0.0002380	0.0003161
0 0200	0.0000401	0.0000801	0.0001599	0.0002394	0.0003185

TABLE 7–XIX Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000483	0.0000956	0.0001879	0.0002770	0.0003634
0.0033	0.0000484	0.0000961	0.0001895	0.0002806	0.0003694
0.0050	0.0000485	0.0000965	0.0001913	0.0002843	0.0003757
0.0100	0.0000486	0.0000970	0.0001931	0.0002882	0.0003825
0.0200	0.0000487	0.0000972	0.0001940	0.0002903	0.0003861

TABLE 7–XX Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000567	0.0001122	0.0002197	0.0003231	0.0004229
0.0033	0.0000568	0.0001128	0.0002219	0.0003279	0.0004308
0.0050	0.0000570	0.0001134	0.0002243	0.0003329	0.0004394
0.0100	0.0000572	0.0001140	0.0002268	0.0003383	0.0004486
0.0200	0.0000573	0.0001143	0.0002280	0.0003411	0.0004535

TABLE 7–XXI Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 3 ft (0.91 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000735	0.0001449	0.0002822	0.0004131	0.0005383
0.0033	0.0000737	0.0001459	0.0002859	0.0004207	0.0005508
0.0050	0.0000740	0.0001469	0.0002897	0.0004288	0.0005644
0.0100	0.0000743	0.0001480	0.0002938	0.0004376	0.0005795
0.0200	0.0000744	0.0001485	0.0002959	0.0004423	0.0005876

TABLE 7–XXII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000818	0 0001611	0.0003129	0.0004570	0.0005944
0.0033	0.0000821	0.0001623	0.0003174	0.0004662	0.0006094
0.0050	0.0000825	0.0001636	0.0003222	0.0004761	0.0006259
0.0100	0.0000828	0.0001649	0.0003272	0.0004869	0.0006443
0.0200	0.0000830	0.0001656	0.0003298	0.0004927	0.0006544

TABLE 7–XXIII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0000901	0.0001772	0.0003434	0.0005003	0.0006495
0.0033	0.0000905	0.0001787	0.0003487	0.0005112	0.0006671
0.0050	0.0000909	0.0001802	0 0003544	0.0005230	0.0006867
0.0100	0.0000913	0.0001818	0.0003604	0.0005360	0.0007087
0.0200	0.0000915	0.0001826	0.0003636	0.0005430	0.0007209

TABLE 7–XXIV Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 6 ft (1.83 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001067	0.0002091	0.0004032	0.0005851	0.0007569
0.0033	0.0001072	0.0002112	0.0004105	0.0005997	0.0007802
0.0050	0.0001078	0.0002133	0.0004182	0.0006157	0.0008064
0.0100	0.0001083	0.0002155	0.0004266	0.0006335	0 0008365
0.0200	0.0001086	0.0002167	0.0004311	0.0006433	0.0008533

TABLE 7–XXV Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001149	0.0002249	0.0004327	0.0006267	0.0008093
0.0033	0.0001155	0.0002273	0.0004410	0.0006432	0.0008355
0.0050	0.0001162	0.0002298	0.0004499	0.0006614	0.0008654
0.0100	0.0001169	0.0002324	0.0004596	0.0006819	0.0008998
0.0200	0.0001172	0.0002337	0.0004647	0.0006932	0.0009191

TABLE 7–XXVI Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

α	L(m) 25	50	100	150	200
0.0025	0.0001231	0.0002407	0.0004619	0.0006676	0.0008609
0.0033	0.0001238	0.0002434	0.0004712	0.0006862	0.0008902
0.0050	0.0001246	0.0002462	0.0004814	0.0007068	0.0009237
0.0100	0.0001253	0.0002492	0.0004924	0.0007301	0.0009627
0.0200	0.0001257	0.0002507	0.0004983	0.0007430	0.0009848

TABLE 7–XXVII Maximum Pipe Strain for a Ridge Pattern of Longitudinal PGD Using the Simplified Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)