SECTION 4
RAMP PGD

The axial strain induced in a continuous steel pipeline due to a Ramp pattern of longitudinal PGD is determined in this section. As mentioned previously, pipe response to the horizontal component of PGD parallel to the pipe axis will be determined and any vertical component (i.e. subsidence and heaving) is neglected. Initially the soil–pipeline interface is modeled by the elastic spring–slider model shown in Figure 3–2. In addition, the pipeline strain is also determined using a simplified rigid spring–slider model for the soil–pipeline interface as shown in Figure 3–3. For the Ramp pattern considered in this section as well as the other longitudinal PGD patterns investigated in Sections 5, 6 and 7, the burial depth to the pipeline centerline, H, is assumed to be constant in and around the PGD zone.

As noted previously the idealized Ramp pattern shown in Figure 2–11 approximates the PGD patterns quantified by Suzuki and Masuda [8] and shown in Figure 2–4. It may also be appropriate for the observed PGD patterns shown in Figure 2–6(d), 2–6(e) and 2–7(q). Results are presented herein for Ramp PGD with tensile ground strain α. However the results are also applicable with a change in sign, to situations with a compressive ground strain of magnitude α.

As shown in Figure 4–1, a coordinate system is established with $x = 0$ at the head of the transition zone, and the assumed ground movement is given as a function of the axial coordinate x by Equation 2.4. The length of the transition zone is L. Since the distribution of pipe strain is symmetric about the center of the transition zone, only the area $x \leq L/2$ is considered.

4.1 Elastic Spring/Slider Model

The solution using the elastic spring/slider model is obtained by dividing the pipeline into three regions (Region I, II and III) as shown in Figure 4–1. Differential equations governing the pipe response in each region are derived. The solution for the pipeline as a whole is then obtained by enforcing equilibrium and continuity at the boundaries between regions.

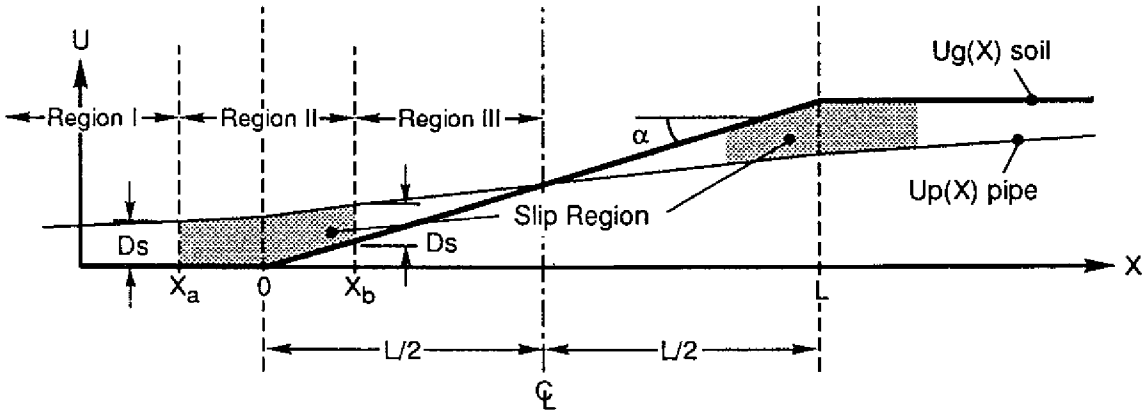

FIGURE 4-1 Model of Pipeline Subjected to a Ramp pattern of Longitudinal PGD.

In Region I ($x \leq x_a$) the displacement of the soil is zero and the relative displacement between the pipe and soil is small enough so that the soil–pipeline interface behaves as a linear spring. That is, the interface force is less than f_m given by Equation 3.1. Region II ($x_a \leq x \leq x_b$) is a slip region where the relative displacements between the pipe and soil are large and the soil–pipeline interface force is a constant equal to f_m. In Region III ($x_b \leq x \leq L/2$) the soil displacement is a linear function of the coordinate x, but the relative displacements between the pipe and soil are small and hence the soil–pipeline interface is again modeled as a linear spring. The values for x_a and x_b are not known a priori, but are calculated as part of the solution.

4.1.1 Region I ($x \leq x_a$)

Figure 4–2(a) shows the forces acting on a differential length of pipe in Region I. Since the ground displacement, u_g, equals zero, the soil–pipeline interface force is simply the pipe displacement, $u_p(x)$, times the spring constant, k given in equation 3.3. Summing forces we obtain:

$$A(\sigma + d\sigma) = k u_p(x)\, dx + A\sigma \tag{4.1}$$

where A is the cross sectional area of the pipeline and σ is the induced stress in the pipeline. Assuming a linear elastic pipe material ($\sigma = E\epsilon$) and noting $\epsilon = du_p/dx$, we obtain:

$$\frac{d^2u_p(x)}{dx^2} - \frac{k}{EA} u_p(x) = 0 \tag{4.2}$$

where E is Young's modulus for the pipe. Thus the differential equation governing the displacement of the pipe in Region I becomes:

$$\frac{d^2u_p(x)}{dx^2} - \beta^2 u_p(x) = 0 \tag{4.3}$$

where $\beta^2 = k/EA$.

At $x = -\infty$ the displacement of the pipeline is zero. We define F_a as the force in the pipe at x_a. Thus, the boundary conditions for Region I are

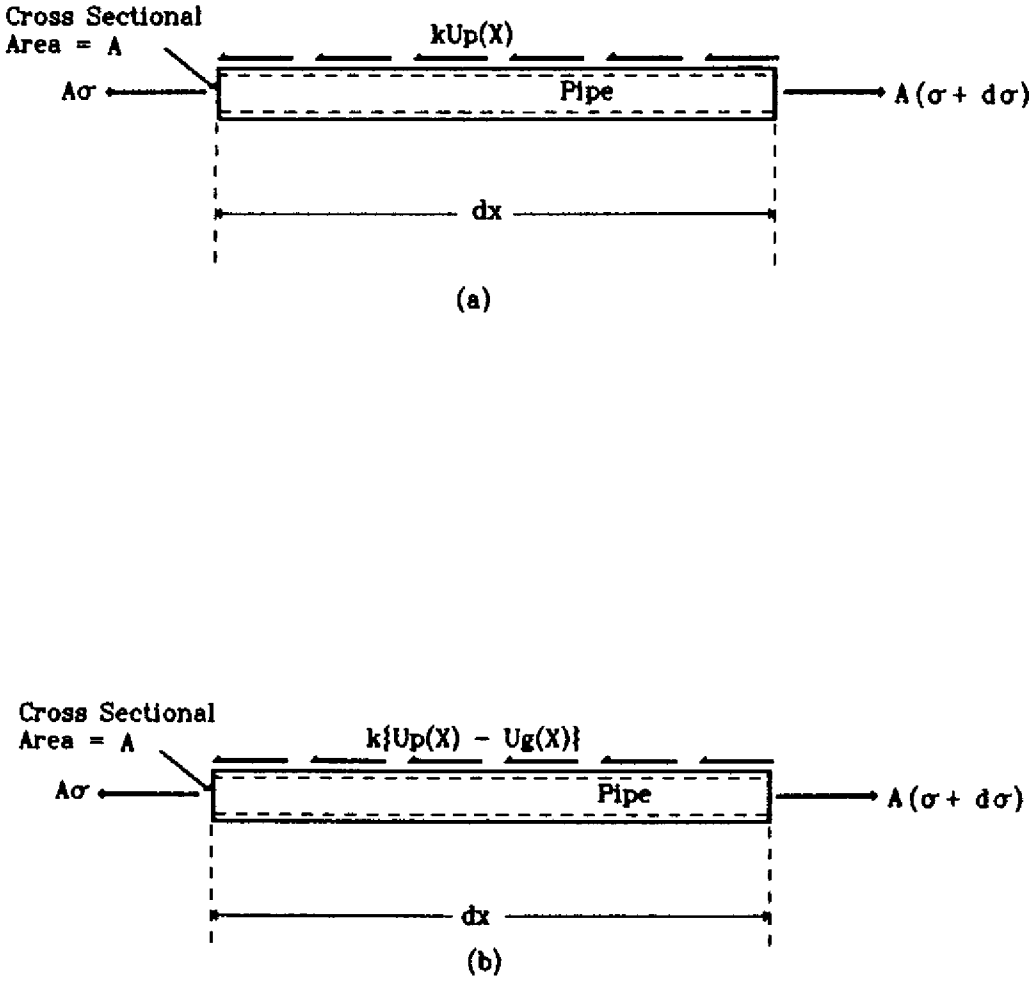

FIGURE 4-2 Forces Acting on a Differential Length of Pipe in Region I (a) and Region III (b) for a Ramp pattern of Longitudinal PGD.

$$u_p(-\infty) = 0 \tag{4.4}$$

$$\frac{du_p(x_a)}{dx} = \frac{F_a}{EA} \tag{4.5}$$

The solution of the differential equation given by equation (4.3) subject to the boundary conditions in equations (4.4) and (4.5) is:

$$u_p(x) = \frac{F_a}{EA\beta} e^{\beta(x-x_a)} \tag{4.6}$$

Since $x = x_a$ is the boundary between the linear spring (Region I) and the "plastic" slider (Region II), the relative displacement between the pipe and the soil equals D_s at x_a (i.e. $u_g(x_a) - u_p(x_a) = D_s$ which is a property of the soil–pipeline interface as discussed in Section 3). However, since the soil displacement in Region I is zero:

$$u_p(x_a) = \frac{F_a}{EA\beta} = D_s \tag{4.7}$$

and

$$u_p(x) = D_s e^{\beta(x-x_a)} \qquad -\infty \le x \le x_a \tag{4.8}$$

Note that, based on Equation 4.7, the soil–pipe system in Region I can be treated as an equivalent linear spring with spring constant $K_a = EA\beta$. That is, as shown in Figure 4–3, the displacement of this equivalent spring is taken as the relative displacement between the pipeline and soil at $x = x_a$ (i.e. D_s) and the force in this equivalent spring is taken as the force in the pipe at $x = x_a$ (i.e. F_a).

4.1.2 Region II ($x_a \le x \le x_b$)

The displacement of the pipeline in Region II can be determined from the known displacement at $x = x_a$ and the distribution of forces on the pipe as shown in Figure 4–4. Note that the displacement of the pipe at $x = x_a$ is equal to D_s. The force in the pipe in Region II is the sum of the force at $x = x_a$ (i.e. K_aD_s) and a contribution due to the

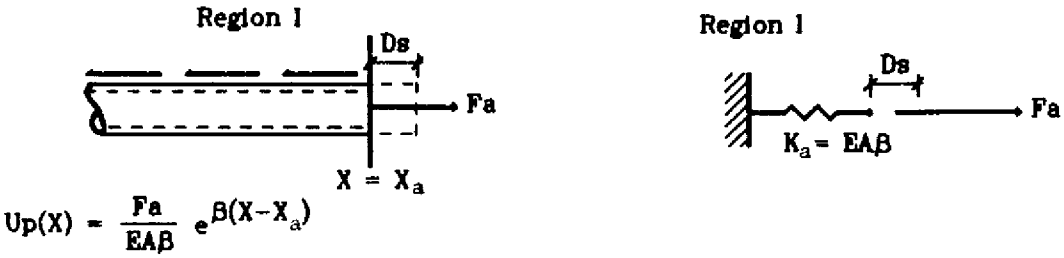

FIGURE 4-3 Equivalent Spring for the Soil-Pipe System in Region I.

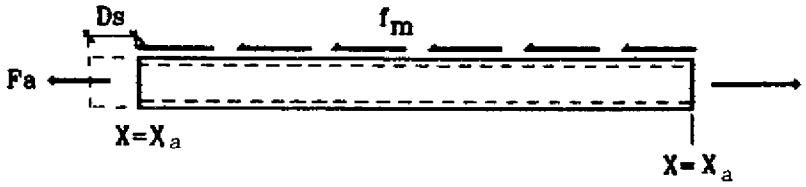

FIGURE 4-4 Forces Acting on Pipe in Region II.

soil–pipeline interaction force f_m:

$$f(x) = K_a D_s + f_m(x - x_a) \tag{4.9}$$

The displacement of the pipe in Region II then becomes:

$$u_p(x) = D_s + \int_{x_a}^{x} \frac{f(x)}{EA}\,dx \tag{4.10}$$

or

$$u_p(x) = D_s + \frac{K_a D_s\,(x - x_a)}{EA} + \frac{f_m(x - x_a)^2}{2EA} \qquad x_a \le x \le x_b \tag{4.11}$$

4.1.3 Region III ($x_b \le x \le L/2$)

Figure 4–2(b) shows the forces acting on a differential length of pipe in Region III. Equating these forces we obtain:

$$A\sigma + d\sigma) = k(u_p(x) - u_g(x))dx + A\sigma \tag{4.12}$$

Again for a linear elastic pipe material and noting $\epsilon = du_p/dx$, the differential equation governing the pipe displacement, u_p, in Region III becomes:

$$\frac{d^2u_p(x)}{dx^2} - \beta^2 u_p(x) = -\beta^2 u_g(x) \tag{4.13}$$

At the boundary between Region II and III (i.e. $x = x_b$) the displacement of the pipeline is equal to the ground displacement plus the relative displacement at which the soil spring becomes plastic (i.e. relative displacement = D_s).

$$u_p(x_b) = D_s + u_g(x_b) \tag{4.14}$$

Noting that $u_g(x) = \alpha x$ in Region III this boundary condition becomes:

$$u_p(x_b) = D_s + \alpha x_b \tag{4.15}$$

At the center of the transition zone, the displacement of the pipe by symmetry, equals the displacement of the soil; as shown in Figure 4–1:

$$u_p(L/2) = u_g(L/2) = \alpha L/2 \tag{4.16}$$

The solution to the differential equation given in equation (4.13) subject to the boundary conditions given in equations (4.15) and (4.16) is:

$$u_p(x) = -\frac{D_s e^{\beta(x-x_b)}}{e^{\beta(L-2x_b)} - 1} + \frac{D_s e^{-\beta(x+x_b)}}{e^{-2\beta x_b} - e^{-\beta L}} + \alpha x \qquad x_b \le x \le L/2 \tag{4.17}$$

which is the pipe displacement in Region III.

4.1.4 Continuity

Continuity of the pipe requires that the pipe displacement immediately to the left of $x = x_b$ (i.e. equation (4.11) evaluated at $x = x_b$) must match the displacement immediately to the right (i.e. equation (4.17) evaluated at $x = x_b$). That is:

$$D_s + \frac{K_a D_s (x_b - x_a)}{EA} + \frac{f_m (x_b - x_a)^2}{2EA} = D_s + \alpha x_b \tag{4.18}$$

Rearranging the terms yields the following:

$$\frac{f_m (x_b - x_a)^2}{2EA} + \frac{K_a D_s}{EA}(x_b - x_a) - \alpha x_b = 0 \tag{4.19}$$

This can be viewed as a quadratic equation in terms of the quantity $x_b - x_a$. Since we are interested in the solution with $x_b > x_a$, the quadratic equation results in the following transcendental equation:

$$x_b - x_a = \frac{-K_a D_s/EA + \sqrt{(K_a D_s/EA)^2 + 2f_m \alpha x_b/EA}}{f_m/EA} \tag{4.20}$$

4.1.5 Equilibrium

A second relation for the quantity $x_b - x_a$ can be derived by enforcing equilibrium. The force in the pipe immediately to the left of $x = x_b$ must equal the force in the pipe immediately to the right of $x = x_b$. The force in the pipe immediately to the left is given by Equation 4.9 evaluated for $x = x_b$. The force immediately to the right is simply the pipe axial rigidity EA times the pipe strain in Region III evaluated for $x = x_b$. Thus:

$$K_a D_s + f_m(x_b - x_a) = EA \frac{du_p}{dx}(x_b) \tag{4.21}$$

where $u_p(x_b)$ is given by equation 4.17. Hence

$$\frac{K_a D_s}{EA} + \frac{f_m(x_b - x_a)}{EA} = -\beta D_s \left[\frac{e^{-\beta L} + e^{-2\beta x_b}}{e^{-2\beta x_b} - e^{-\beta L}} \right] + \alpha \tag{4.22}$$

Equation (4.22) can be simplified and rearranged to yield a second expression for $x_a - x_b$:

$$x_a - x_b = -\frac{K_a D_s}{f_m} \left[\frac{e^{-\beta L} + e^{-2\beta x_b}}{e^{-2\beta x_b} - e^{-\beta L}} + 1 \right] + EA\alpha/f_m \tag{4.23}$$

The right hand side of equations 4.20 and 4.23 can be set equal to each other. This results in an equation which is solely a function the unknown x_b. Herein, the Newton–Raphson Method is applied to the resulting equation to determine x_b.

4.1.6 Maximum Pipe Strain

The maximum strain, ϵ, in the pipe occurs at $x = L/2$. Knowing the value of x_b, ϵ can be determined by evaluating the derivative of equation (4.17) for $x = L/2$:

$$\frac{du_p(L/2)}{dx} = \epsilon = \alpha - \frac{2\beta D_s e^{-\beta(L/2+x_b)}}{e^{-\beta 2x_b} - e^{-\beta L}} \tag{4.24}$$

Tables 4–Ia through 4–XXVIIa present the maximum pipe strain, ϵ, for a Ramp pattern of longitudinal PGD evaluated using equation 4.24. In these tables the unit weight of soil, γ, is taken as 100 pcf and the coefficient of friction of the soil pipe interface, μ, is taken as 0.75. Results are presented for pipe diameters, ϕ, of 12, 30 and 48 inches, pipe wall thickness, t, of 1/4, 1/2, and 3/4 inch, and soil cover C over the top of the pipe of 3, 6, and 9 feet. The range of values for the ground strain, α, and the length of the PGD zone, L, are based on the work by Suzuki and Masuda [8].

For fixed ground strain, α, the maximum stress in the pipe increases with the length of the transition zone, L. For fixed L, the maximum pipe strain increases with increasing soil strain, α. For fixed α and L the pipe strain is an increasing function of the cover over top of pipe $C = H - \phi/2$, and a decreasing function of the wall thickness, t. It also appears to be an increasing function of pipe diameter, ϕ.

4.2 Rigid Spring/Slider Model

The results presented in table 4–Ia through 4–XXVIIa cover what is felt to be a reasonable range for the parameters of interest. However, for situations not covered by these tables, or for hand calculation, a simplified approach is useful. This simplified approach uses the rigid spring/slider model for the soil pipe interface shown in Figure 3–3. Figure 4–5 shows the two possible configurations of such a simplified model. It is assumed that slip occurs between the soil and pipeline over a length L_e on either side of the center of the transition zone, $x = L/2$. Beyond L_e the relative displacement between the soil and pipe is assumed to be zero.

In Figure 4–5(a) the slip region extends all the way to the center of the transition zone and the resulting pipe strain is less than the ground strain α. In Figure 4–5(b), the slip region exists over a limited length near the ends of the transition zone, and the pipe strain towards the center of the zone is equal to the ground strain α. That is the maximum pipe strain for the Ramp pattern is always less than or equal to α. For the configuration in Figure 4.5(a), the maximum pipe strain ($\epsilon < \alpha$) can be determined by noting that the displacement of the pipeline at the center of the transition zone is equal to the displacement of the soil (i.e. $u_p(L/2) = u_g(L/2)$). Hence, the stretching of the pipe along

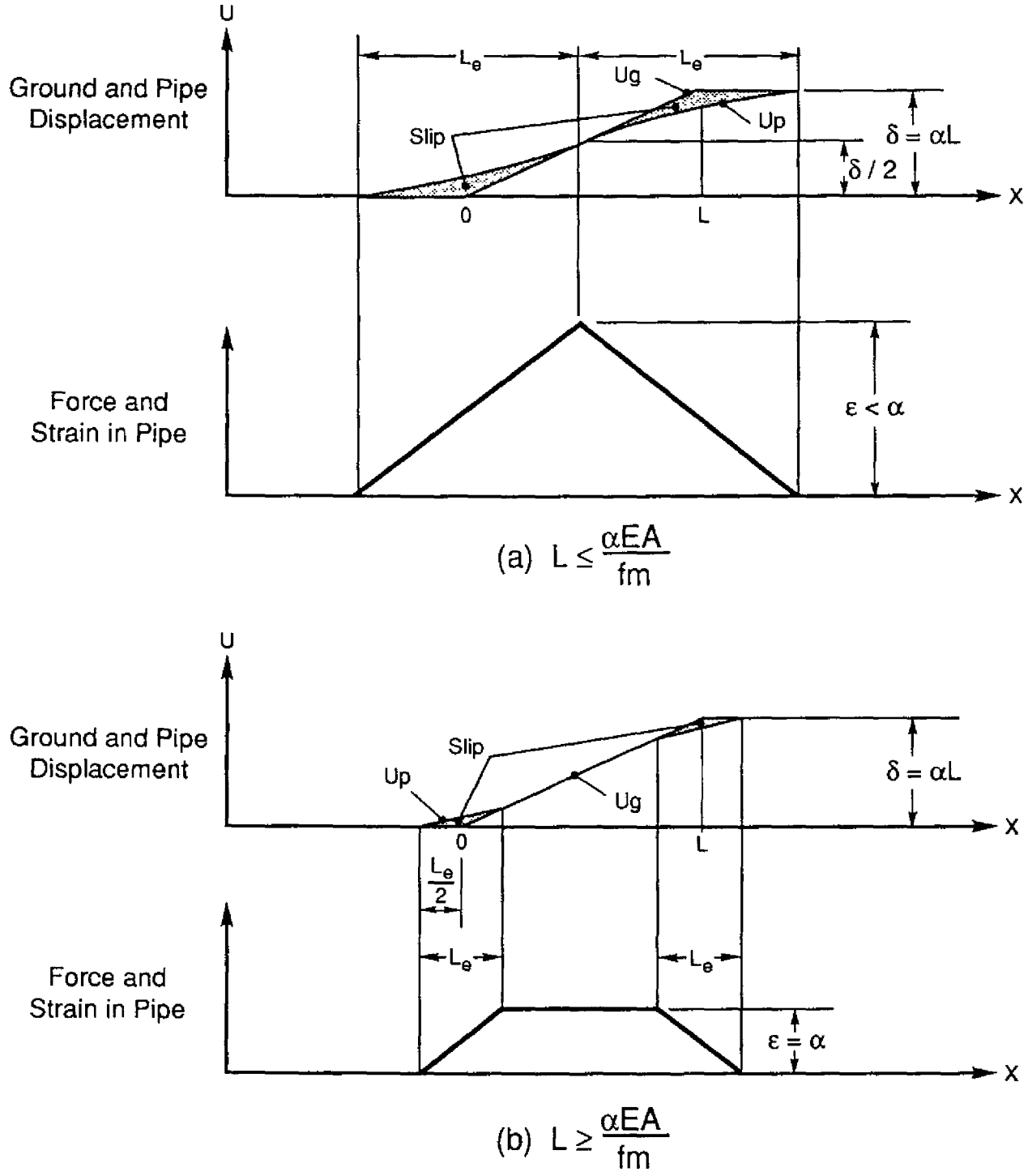

FIGURE 4-5 Simplified Model of Buried Pipe Subjected to a Ramp pattern of Longitudinal PGD.

the length L_e is due to the constant force per unit length, f_m, at the soil pipe interface and results in a pipe displacement of $\alpha L/2$ at $x = L/2$. The displacement can be calculated by integration of the pipe strain over the slip length L_e.

$$u_p(L/2) = \alpha L/2 = \int_0^{L_e} \frac{f_m s}{EA}\, ds = \frac{f_m L_e^2}{2EA} \tag{4.25}$$

Equation (4.25) can be solved for L_e. The maximum force in the pipe is equal to f_m time L_e since it is assumed that the pipe is not stressed beyond L_e. The maximum pipe strain, ϵ_a, is then $f_m L_e/EA$.

$$\epsilon = \sqrt{\frac{\alpha L f_m}{EA}} \leq \alpha \tag{4.26}$$

Note for $L \leq \alpha EA/f_m$, which corresponds to Figure 4–5(a), the maximum pipe strain is a function of the length of the transient spread zone, but is less than the ground strain, α. For $L \geq \alpha EA/f_m$, which corresponds to Figure 4–5(b) the maximum pipe strain is independent of the length, L, and is equal to the ground strain, α. That is if the length of the transient zone is large enough the maximum pipe strain and the ground strain are identical.

Tables 4–Ib through 4–XXVIIb present results from equation 4.26 for the maximum pipe strain using the simplified model. Results are given for the same range of parameters used with the elastic spring/slider model which were presented in Tables 4–Ia through 4–XXVIIa. Note that equation (4.26) explains the influence of various parameters on the maximum pipe strain which were observed previously in relation to the complete interface model. That is the pipe strain is always an increasing function of the ground strain α. For situations where $L \leq \alpha EA/f_m$, ϵ is an increasing function of the length L, and cover over the top of the pipe, C, or the burial depth, H. It is a decreasing function of the wall thickness, t. Since f_m and A are proportional to the pipe diameter, ϕ, the maximum pipe strain using the simplified soil pipe interface model is not directly a function of the pipe diameter. However, since table 4–I through 4–XXVII are presented in terms of cover over top of pipe C, a larger pipe diameter results in a larger burial depth, $H = C + \phi/2$, and pipe strain is a function of burial depth.

4.3 Comparison of Models

Tables 4–Ic through 4–XXVIIc list the percent difference in the maximum pipe strain due to Ramp PGD evaluated using the complete elastic spring/slider model and the simplified rigid spring/slider model. Note that both models give very similar results, and the simplified model is always conservative predicting maximum pipe strain slightly higher than the complete model. In the cases examined, which represent what is felt to be typical pipeline conditions, the error between the models does not exceed 4 percent.

α	L(m) 25	50	100	150	200
0.0025	0.0007745	0.0010961	0.0015505	0.0018989	0.0021919
0.0033	0.0008948	0.0012661	0.0017910	0.0021936	0.0025328
0.0050	0.0010964	0.0015511	0.0021939	0.0026872	0.0031029
0.0100	0.0015512	0.0021940	0.0031028	0.0037996	0.0043864
0.0200	0.0021942	0.0031032	0.0043542	0.0053236	0.0061355

TABLE 4–Ia Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD using the Complete 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	0.0007759	0.0010973	0.0015518	0.0019005	0.0021945
0.0033	0.0008959	0.0012670	0.0017918	0.0021945	0.0025340
0.0050	0.0010973	0.0015518	0.0021945	0.0026877	0.0031035
0.0100	0.0015518	0.0021945	0.0031035	0.0038010	0.0043891
0.0200	0.0021945	0.0031035	0.0043891	0.0053755	0.0062071

TABLE 4–Ib Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD using the Simplified 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	0.174	0.107	0.079	0.083	0.122
0.0033	0.124	0.073	0.049	0.044	0.047
0.0050	0.077	0.043	0.027	0.022	0.022
0.0100	0.039	0.025	0.025	0.037	0.061
0.0200	0.017	0.010	0.800	0.974	1.167

TABLE 4–Ic Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0008503	0.0012049	0.0017051	0.0020866	0.0023932
0.0033	0.0009834	0.0013929	0.0019712	0.0024143	0.0027866
0.0050	0.0012062	0.0017076	0.0024161	0.0029595	0.0034175
0.0100	0.0017081	0.0024168	0.0034187	0.0041872	0.0048348
0.0200	0.0024170	0.0034190	0.0048358	0.0059228	0.0068392

TABLE 4–IIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0008550	0.0012091	0.0017100	0.0020943	0.0024183
0.0033	0.0009873	0.0013962	0.0019745	0.0024183	0.0027924
0.0050	0.0012091	0.0017100	0.0024183	0.0029618	0.0034199
0.0100	0.0017100	0.0024183	0.0034199	0.0041886	0.0048365
0.0200	0.0024183	0.0034199	0.0048365	0.0059235	0.0068399

TABLE 4–IIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.556	0.353	0.287	0.368	1.045
0.0033	0.390	0.235	0.167	0.165	0.208
0.0050	0.241	0.138	0.088	0.074	0.072
0.0100	0.110	0.061	0.036	0.031	0.035
0.0200	0.052	0.028	0.015	0.012	0.010

TABLE 4–IIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0009173	0.0013021	0.0018426	0.0022462	0.0024753
0.0033	0.0010627	0.0015073	0.0021340	0.0026126	0.0030089
0.0050	0.0013054	0.0018497	0.0026183	0.0032073	0.0037033
0.0100	0.0018508	0.0026199	0.0037069	0.0045407	0.0052436
0.0200	0.0026204	0.0037075	0.0052444	0.0064236	0.0074175

TABLE 4–IIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

a	L(m) 25	50	100	150	200
0.0025	0.0009274	0.0013115	0.0018547	0.0022716	0.0025000
0.0033	0.0010708	0.0015144	0.0021416	0.0026230	0.0030287
0.0050	0.0013115	0.0018547	0.0026230	0.0032125	0.0037094
0.0100	0.0018547	0.0026230	0.0037094	0.0045431	0.0052459
0.0200	0.0026230	0.0037094	0.0052459	0.0064249	0.0074189

TABLE 4–IIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.100	0.722	0.656	1.128	0.999
0.0033	0.763	0.472	0.359	0.398	0.660
0.0050	0.467	0.273	0.180	0.160	0.165
0.0100	0.211	0.117	0.070	0.052	0.045
0.0200	0.099	0.053	0.029	0.022	0.018

TABLE 4–IIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0010533	0.0014912	0.0021072	0.0024860	0.0025000
0.0033	0.0012177	0.0017237	0.0024381	0.0029827	0.0033242
0.0050	0.0014929	0.0021127	0.0029886	0.0036602	0.0042256
0.0100	0.0021131	0.0029892	0.0042284	0.0051790	0.0059802
0.0200	0.0029896	0.0042286	0.0059804	0.0073241	0.0084563

TABLE 4–IVa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete Soil–Pipeline Interface Model.
ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.82 m)

α	L(m) 25	50	100	150	200
0.0025	0.0010574	0.0014953	0.0021147	0.0025000	0.0025000
0.0033	0.0012209	0.0017267	0.0024419	0.0029906	0.0033333
0.0050	0.0014953	0.0021147	0.0029906	0.0036628	0.0042294
0.0100	0.0021147	0.0029906	0.0042294	0.0051800	0.0059813
0.0200	0.0029906	0.0042294	0.0059813	0.0073256	0.0084588

TABLE 4–IVb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified Model.
ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.82 m)

α	L(m) 25	50	100	150	200
0.0025	0.387	0.277	0.355	0.565	0.001
0.0033	0.264	0.173	0.156	0.265	0.276
0.0050	0.159	0.097	0 070	0.069	0.090
0.0100	0.074	0.048	0.024	0.019	0.018
0.0200	0.034	0.020	0.015	0.019	0.030

TABLE 4–IVc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.82 m)

α	L(m) 25	50	100	150	200
0.0025	0.0011042	0.0015661	0.0022043	0.0024874	0.0024998
0.0033	0.0012797	0.0018142	0.0025658	0.0031208	0.0033268
0.0050	0.0015721	0.0022271	0.0031518	0.0038596	0.0044510
0.0100	0.0022289	0.0031549	0.0044636	0.0054675	0.0063136
0.0200	0.0031556	0.0044645	0.0063152	0.0077350	0.0089318

TABLE 4–Va Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0011167	0.0015792	0.0022334	0.0025000	0.0025000
0.0033	0.0012894	0.0018235	0.0025789	0.0031585	0.0033333
0.0050	0.0015792	0.0022334	0.0031585	0.0038683	0.0044668
0.0100	0.0022334	0.0031585	0.0044668	0.0054706	0.0063170
0.0200	0.0031585	0.0044668	0.0063170	0.0077367	0.0089335

TABLE 4–Vb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.130	0.840	1.320	0.507	0.009
0.0033	0.764	0.515	0.508	1.207	0.196
0.0050	0.456	0.281	0.211	0.227	0.354
0.0100	0.200	0.114	0.070	0.057	0.053
0.0200	0.092	0.050	0.029	0.022	0.019

TABLE 4–Vc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0011490	0.0016326	0.0022763	0.0024873	0.0024995
0.0033	0.0013358	0.0018972	0.0026806	0.0032081	0.0033275
0.0050	0.0016453	0.0023340	0.0033044	0.0040441	0.0046472
0.0100	0.0023377	0.0033110	0.0046861	0.0057405	0.0066289
0.0200	0.0033124	0.0046879	0.0066322	0.0081238	0.0093812

TABLE 4–VIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0011730	0.0016589	0.0023461	0.0025000	0.0025000
0.0033	0.0013545	0.0019155	0.0027090	0.0033178	0.0033333
0.0050	0.0016589	0.0023461	0.0033178	0.0040635	0.0046921
0.0100	0.0023461	0.0033178	0.0046921	0.0057466	0.0066357
0.0200	0.0033178	0.0046921	0.0066357	0.0081270	0.0093842

TABLE 4–VIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	2.090	1.613	3.066	0.510	0.021
0.0033	1.400	0.967	1.060	3.421	0.177
0.0050	0.827	0.518	0.406	0.480	0.967
0.0100	0.360	0.206	0.129	0.107	0.102
0.0200	0.165	0.090	0.051	0.039	0.033

TABLE 4–VIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0012698	0.0017973	0.0024580	0.0024999	0.0025000
0.0033	0.0014696	0.0020806	0.0029370	0.0033290	0.0033333
0.0050	0.0018032	0.0025523	0.0036102	0.0044178	0.0049753
0.0100	0.0025538	0.0036132	0.0051110	0.0062600	0.0072283
0.0200	0.0036137	0.0051117	0.0072299	0.0088549	0.0102246

TABLE 4–VIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0012783	0.0018078	0.0025000	0.0025000	0.0025000
0.0033	0.0014760	0.0020874	0.0029521	0.0033333	0.0033333
0.0050	0.0018078	0.0025566	0.0036155	0.0044281	0.0050000
0.0100	0.0025566	0.0036155	0.0051131	0.0062623	0.0072310
0.0200	0.0036155	0.0051131	0.0072310	0.0088562	0.0102262

TABLE 4–VIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.668	0.583	1.708	0.003	0.000
0.0033	0.439	0.326	0.514	0.132	0.000
0.0050	0.255	0.167	0.147	0.233	0.496
0.0100	0.110	0.064	0.042	0.036	0.038
0.0200	0.050	0.027	0.016	0.014	0.016

TABLE 4–VIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0013032	0.0018462	0.0024489	0.0024991	0.0025000
0.0033	0.0015146	0.0021481	0.0030144	0.0033232	0.0033332
0.0050	0.0018646	0.0026432	0.0037392	0.0045615	0.0049792
0.0100	0.0026476	0.0037489	0.0053049	0.0064980	0.0075028
0.0200	0.0037504	0.0053071	0.0075077	0.0091960	0.0106191

TABLE 4–VIIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0013278	0.0018778	0.0025000	0.0025000	0.0025000
0.0033	0.0015332	0.0021683	0.0030664	0.0033333	0.0033333
0.0050	0.0018778	0.0026556	0.0037555	0.0045996	0.0050000
0.0100	0.0026556	0.0037555	0.0053111	0.0065048	0.0075110
0.0200	0.0037555	0.0053111	0.0075110	0.0091991	0.0106222

TABLE 4–VIIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.883	1.711	2.087	0.038	0.001
0.0033	1.228	0.937	1.724	0.303	0.006
0.0050	0.707	0.469	0.437	0.834	0.418
0.0100	0.300	0.176	0.117	0 105	0.110
0.0200	0.135	0.075	0.044	0.034	0.029

TABLE 4–VIIIc Percent Difference in Maximum Pipe Strain for Uniform Strain PGD Between the Complete and Simplified Models.
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	0.0013306	0.0018854	0.0024424	0.0024975	0.0024999
0.0033	0.0015543	0.0022084	0.0030681	0.0033193	0.0033327
0.0050	0.0019213	0.0027281	0.0038584	0.0046754	0.0049807
0.0100	0.0027367	0.0038785	0.0054905	0.0067256	0.0077646
0.0200	0.0038814	0.0054948	0.0077750	0.0095240	0.0109982

TABLE 4–IXa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0013755	0.0019452	0.0025000	0.0025000	0.0025000
0.0033	0.0015883	0.0022462	0.0031766	0.0033333	0.0033333
0.0050	0.0019452	0.0027510	0.0038905	0.0047649	0.0050000
0.0100	0.0027510	0.0038905	0.0055020	0.0067385	0.0077810
0.0200	0.0038905	0.0055020	0.0077810	0.0095297	0.0110040

TABLE 4–IXb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	3.375	3.174	2.358	0.098	0.004
0.0033	2.185	1.712	3.535	0.422	0.018
0.0050	1.246	0.839	0.833	1.913	0.387
0.0100	0.523	0.309	0.210	0.192	0.211
0.0200	0.235	0.130	0.077	0.060	0.052

TABLE 4–IXc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0005478	0.0007752	0.0010967	0.0013433	0.0015512
0.0033	0.0006328	0.0008954	0.0012665	0.0015512	0.0017914
0.0050	0.0007753	0.0010967	0.0015511	0.0018995	0.0021942
0.0100	0.0010969	0.0015514	0.0021942	0.0026873	0.0031029
0.0200	0.0015515	0.0021810	0.0030834	0.0037739	0.0043543

TABLE 4–Xa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0005486	0.0007759	0.0010973	0.0013439	0.0015518
0.0033	0.0006335	0.0008959	0.0012670	0.0015518	0.0017918
0.0050	0.0007759	0.0010973	0.0015518	0.0019005	0.0021945
0.0100	0.0010973	0.0015518	0.0021945	0.0026877	0.0031035
0.0200	0.0015518	0.0021945	0.0031035	0.0038010	0.0043891

TABLE 4–Xb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.154	0.087	0.053	0.044	0.040
0.0033	0.111	0.062	0.039	0.037	0.024
0.0050	0.077	0.047	0.042	0.055	0.013
0.0100	0.036	0.021	0.015	0.016	0.019
0.0200	0.017	0.621	0.655	0.721	0.798

TABLE 4–Xc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0006017	0.0008526	0.0012070	0.0014787	0.0017075
0.0033	0.0006957	0.0009853	0.0013945	0.0017084	0.0019729
0.0050	0.0008531	0.0012077	0.0017088	0.0020932	0.0024172
0.0100	0.0012079	0.0017090	0.0024175	0.0029611	0.0034193
0.0200	0.0017091	0.0024176	0.0034795	0.0041881	0.0048202

TABLE 4–XIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0006046	0.0008550	0.0012091	0.0014809	0.0017100
0.0033	0.0006981	0.0009873	0.0013962	0.0017100	0.0019745
0.0050	0.0008550	0.0012091	0.0017100	0.0020943	0.0024183
0.0100	0.0012091	0.0017100	0.0024183	0.0029618	0.0034199
0.0200	0.0017100	0.0024183	0.0034199	0.0041886	0.0048365

TABLE 4–XIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.483	0.277	0.176	0.149	0.144
0.0033	0.347	0.194	0.118	0.093	0.084
0.0050	0.220	0.121	0.071	0.052	0.044
0.0100	0.104	0.055	0.031	0.023	0.019
0.0200	0.050	0.026	0.014	0.010	0.339

TABLE 4–XIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0006496	0.0009223	0.0013068	0.0016011	0.0018486
0.0033	0.0007521	0.0010668	0.0015108	0.0018511	0.0021378
0.0050	0.0009235	0.0013084	0.0018522	0.0022692	0.0026206
0.0100	0.0013089	0.0018528	0.0026214	0.0032111	0.0037081
0.0200	0.0018530	0.0026217	0.0037085	0.0045423	0.0052452

TABLE 4–XIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0006557	0.0009274	0.0013115	0.0016062	0.0018541
0.0033	0.0007572	0.0010708	0.0015114	0.0018547	0.0021416
0.0050	0.0009274	0.0013115	0.0018547	0.0022716	0.0026230
0.0100	0.0013115	0.0018547	0.0026230	0.0032125	0.0037094
0.0200	0.0018547	0.0026230	0.0037094	0.0045431	0.0052459

TABLE 4–XIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.939	0.547	0.361	0.319	0.330
0.0033	0.670	0.380	0.236	0.193	0.180
0.0050	0.423	0.233	0.136	0.105	0.090
0.0100	0.198	0.105	0.058	0.043	0.036
0.0200	0.095	0.049	0.026	0.019	0.015

TABLE 4–XIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0007453	0.0010553	0.0014933	0.0018289	0.0021109
0.0033	0.0008614	0.0012193	0.0017252	0.0021131	0.0024400
0 0050	0.0010559	0.0014941	0.0021137	0.0025890	0.0029896
0.0100	0.0014943	0.0021139	0.0029898	0.0036616	0.0042276
0.0200	0.0021140	0.0029901	0.0042290	0.0051795	0.0059807

TABLE 4–XIIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0007477	0.0010574	0.0014953	0.0018314	0.0021147
0.0033	0.0008633	0.0012209	0.0017267	0.0021147	0.0024419
0.0050	0.0010574	0.0014953	0.0021147	0.0025900	0.0029906
0.0100	0.0014953	0.0021147	0.0029906	0.0036628	0.0042294
0.0200	0.0021147	0.0029906	0.0042294	0.0051800	0.0059813

TABLE 4–XIIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.319	0.193	0.139	0.138	0.179
0.0033	0.226	0.132	0.087	0.076	0.078
0.0050	0.141	0.079	0.048	0.039	0.035
0.0100	0.068	0.039	0.028	0.032	0.044
0.0200	0.032	0.017	0.011	0.010	0.010

TABLE 4–XIIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0007825	0.0011104	0.0015726	0.0019255	0.0022181
0.0033	0.0009059	0.0012845	0.0018189	0.0022281	0.0025723
0.0050	0.0011122	0.0015757	0.0022302	0.0027322	0.0031552
0.0100	0.0015763	0.0022311	0.0031567	0.0038667	0.0044651
0.0200	0.0022314	0.0031570	0.0044656	0.0054697	0.0063160

TABLE 4–XIVa Maximum Pipe Strain for a Ramp pattern of PGD using the Complete 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	0.0007896	0.0011167	0.0015792	0.0019342	0.0022334
0.0033	0.0009118	0.0012894	0.0018235	0.0022334	0.0025789
0.0050	0.0011167	0.0015792	0.0022334	0.0027353	0.0031585
0.0100	0.0015792	0.0022334	0.0031585	0.0038683	0.0044668
0.0200	0.0022334	0.0031585	0.0044668	0.0054706	0.0063170

TABLE 4–XIVb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD using the Simplified 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	0.916	0.563	0.421	0.453	0.690
0.0033	0.646	0.381	0.257	0.235	0.256
0.0050	0.402	0.228	0.140	0.114	0.105
0.0100	0.185	0.100	0.057	0.043	0.037
0.0200	0.087	0.046	0.025	0.018	0.014

TABLE 4–XIVc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0008159	0.0011610	0.0016456	0.0020127	0.0023056
0.0033	0.0009467	0.0013451	0.0019063	0.0023353	0.0026945
0.0050	0.0011646	0.0016521	0.0023400	0.0028672	0.0033111
0.0100	0.0016535	0.0023419	0.0033144	0.0040604	0.0046891
0.0200	0.0023424	0.0033151	0.0046900	0.0057448	0.0066339

TABLE 4–XVa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0008295	0.0011730	0.0016589	0.0020317	0.0023461
0.0033	0.0009578	0.0013545	0.0019155	0.0023461	0.0027090
0.0050	0.0011730	0.0016589	0.0023461	0.0028733	0.0033178
0.0100	0.0016589	0.0023461	0.0033178	0.0040635	0.0046921
0.0200	0.0023461	0.0033178	0.0046921	0.0057466	0.0066357

TABLE 4–XVb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.667	1.039	0.810	0.946	1.755
0.0033	1.168	0.696	0.483	0.460	0.539
0.0050	0.722	0.412	0.259	0.215	0.203
0.0100	0.330	0.179	0.103	0.077	0.065
0.0200	0.156	0.082	0.045	0.032	0.026

TABLE 4–XVc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0008993	0.0012740	0.0018025	0.0022039	0.0024761
0.0033	0.0010400	0.0014728	0.0020840	0.0025521	0 0029444
0.0050	0.0012755	0.0018055	0.0025544	0.0031289	0.0036129
0.0100	0.0018060	0.0025552	0.0036143	0.0044269	0.0051117
0.0200	0.0025554	0.0036146	0.0051124	0.0062616	0.0072304

TABLE 4–XVIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0009039	0.0012783	0.0018078	0.0022140	0.0025000
0.0033	0.0010437	0.0014760	0.0020874	0.0025566	0.0029521
0.0050	0.0012783	0.0018078	0.0025566	0.0031311	0.0036155
0.0100	0.0018078	0.0025566	0.0036155	0.0044281	0.0051131
0.0200	0.0025566	0.0036155	0.0051131	0.0062623	0.0072310

TABLE 4–XVIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.512	0.333	0.293	0.459	0.965
0.0033	0.357	0.219	0.163	0.174	0.262
0.0050	0.219	0.128	0.083	0.073	0.073
0.0100	0.099	0.055	0.032	0.027	0.028
0.0200	0.047	0.025	0.014	0.010	0.008

TABLE 4–XVIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
ϕ = 12 in (30.5 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0009257	0.0013154	0.0018616	0.0022645	0.0024750
0.0033	0.0010735	0.0015239	0.0021581	0.0026415	0.0030381
0.0050	0.0013198	0.0018712	0.0026494	0.0032456	0.0037473
0.0100	0.0018727	0.0026516	0.0037522	0.0045964	0.0053080
0.0200	0.0026521	0.0037529	0.0053088	0.0065022	0.0075079

TABLE 4–XVIIa Maximum Pipe Strain for a Ramp pattern of PGD using the Complete Soil–Pipeline Interface Model.
ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0009389	0.0013278	0.0018778	0.0022998	0.0025000
0.0033	0.0010841	0.0015332	0.0021683	0.0026556	0.0030664
0.0050	0.0013278	0.0018778	0.0026556	0.0032524	0.0037555
0.0100	0.0018778	0.0026556	0.0037555	0.0045996	0.0053111
0.0200	0.0026556	0.0037555	0.0053111	0.0065048	0.0075110

TABLE 4–XVIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD using the Simplified Model.
ϕ = 30 in (76.2 cm), t = 0.50 in (12.7 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	1.423	0.939	0.868	1.556	1.010
0.0033	0.985	0.612	0.470	0.532	0.929
0.0050	0.602	0.353	0.234	0.209	0.220
0.0100	0.271	0.150	0.088	0.068	0.059
0.0200	0.129	0.071	0.044	0.039	0.042

TABLE 4–XVIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0009487	0.0013528	0.0019139	0.0023076	0.0024740
0.0033	0.0011040	0.0015712	0.0022270	0.0027227	0.0031113
0.0050	0.0013612	0.0019333	0.0027395	0.0033564	0.0038742
0.0100	0.0019361	0.0027438	0.0038845	0.0047592	0.0054962
0.0200	0.0027450	0.0038859	0.0054983	0.0067351	0.0077776

TABLE 4–XVIIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0009726	0.0013755	0.0019452	0.0023824	0.0025000
0.0033	0.0011231	0.0015883	0.0022462	0.0027510	0.0031766
0.0050	0.0013755	0.0019452	0.0027510	0.0033693	0.0038905
0.0100	0.0019452	0.0027510	0.0038905	0.0047649	0.0055020
0.0200	0.0027510	0.0038905	0.0055020	0.0067385	0.0077810

TABLE 4–XVIIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	2.519	1.681	1.636	3 243	1 049
0.0033	1.734	1.086	0.861	1.038	2.098
0.0050	1.052	1.620	0.419	0.384	0.420
0.0100	0.471	0.261	0.154	0.120	0.105
0.0200	0.219	0.118	0.066	0.050	0.044

TABLE 4–XVIIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0004473	0.0006330	0.0008955	0.0010969	0.0012666
0.0033	0.0005167	0.0007311	0.0010342	0.0012667	0.0014626
0.0050	0.0006330	0.0008955	0.0012666	0.0015512	0.0017911
0.0100	0.0008956	0.0012668	0.0017916	0.0021943	0.0025337
0.0200	0.0012668	0.0017806	0.0025183	0.0030834	0.0035589

TABLE 4–XIXa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0004480	0.0006335	0.0008959	0.0010973	0.0012670
0.0033	0.0005173	0.0007315	0.0010345	0.0012670	0.0014630
0.0050	0.0006335	0.0008959	0.0012670	0.0015518	0.0017918
0.0100	0.0008959	0.0012670	0.0017918	0.0021945	0.0025340
0.0200	0.0012670	0.0017918	0.0025340	0.0031035	0.0035837

TABLE 4–XIXb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.146	0.080	0.047	0.036	0.031
0.0033	0.107	0.058	0.034	0.027	0.026
0.0050	0 073	0 043	0.032	0.035	0.043
0.0100	0.035	0.020	0.013	0.012	0.013
0.0200	0.016	0.633	0.623	0.653	0.696

TABLE 4–XIXc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0004914	0.0006963	0.0009858	0.0012077	0.0013947
0.0033	0.0005681	0.0008046	0.0011388	0.0013951	0.0016111
0.0050	0.0006966	0.0009861	0.0013953	0.0017091	0.0019737
0.0100	0.0009863	0.0013954	0.0019739	0.0024178	0.0027919
0.0200	0.0013955	0.0019740	0.0027920	0.0034108	0.0039377

TABLE 4–XXa Maximum Pipe Strain for a Ramp pattern of PGD using the Complete 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	0.0004936	0.0006981	0.0009873	0.0012091	0.0013962
0.0033	0.0005700	0.0008061	0.0011400	0.0013962	0.0016122
0.0050	0.0006981	0.0009873	0.0013962	0.0017100	0.0019745
0.0100	0.0009873	0.0013962	0.0019745	0 0024183	0.0027924
0.0200	0.0013962	0.0019745	0.0027924	0.0034199	0.0039490

TABLE 4–XXb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.456	0.253	0.151	0.118	0.103
0.0033	0.331	0.180	0.104	0.079	0.067
0.0050	0.212	0.114	0.064	0.048	0.042
0.0100	0.101	0.053	0.029	0.021	0.017
0.0200	0.049	0.025	0.013	0.268	0.288

TABLE 4–XXc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0005307	0.0007535	0.0010676	0.0013083	0.0015111
0.0033	0.0006143	0.0008713	0.0012340	0.0015120	0.0017463
0.0050	0.0007541	0.0010685	0.0015125	0.0018530	0.0021400
0.0100	0.0010688	0.0015128	0.0021405	0.0026219	0.0030278
0.0200	0.0015130	0.0021406	0.0030280	0.0037088	0.0042827

TABLE 4–XXIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0005354	0.0007572	0.0010708	0.0013115	0.0015144
0.0033	0.0006182	0.0008743	0.0012365	0.0015144	0.0017486
0.0050	0.0007572	0.0010708	0.0015144	0.0018547	0.0021416
0.0100	0.0010708	0.0015144	0.0021416	0.0026230	0.0030287
0.0200	0.0015144	0.0021416	0.0030287	0.0037094	0.0042833

TABLE 4–XXIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.881	0.494	0.300	0.240	0.217
0.0033	0.636	0.350	0.205	0.157	0.135
0.0050	0.406	0.219	0.124	0.091	0.075
0.0100	0.192	0.101	0.055	0.039	0.031
0.0200	0.093	0.048	0.025	0.018	0.014

TABLE 4–XXIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0006087	0.0008619	0.0012196	0.0014939	0.0017251
0.0033	0.0007034	0.0009957	0.0014088	0.0017257	0.0019927
0.0050	0.0008622	0.0012200	0.0017259	0.0021140	0.0024412
0.0100	0.0012201	0.0017260	0.0024413	0.0029900	0.0034525
0.0200	0.0017261	0.0024414	0.0034530	0.0042291	0.0048372

TABLE 4–XXIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0006105	0.0008633	0.0012209	0.0014953	0.0017267
0.0033	0.0007049	0.0009969	0.0014098	0.0017267	0.0019938
0.0050	0.0008633	0.0012209	0.0017267	0.0021147	0.0024419
0.0100	0.0012209	0.0017267	0.0024419	0.0029906	0.0034533
0.0200	0.0017267	0.0024419	0.0034533	0.0042294	0.0048837

TABLE 4–XXIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.296	0.170	0.109	0.092	0.090
0.0033	0.212	0.120	0.072	0.058	0.052
0.0050	0.135	0.074	0.043	0 032	0.027
0.0100	0.065	0.036	0.023	0.022	0.024
0.0200	0.031	0.017	0.010	0.008	0.961

TABLE 4–XXIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0006393	0.0009073	0.0012853	0.0015748	0.0018184
0.0033	0.0007400	0.0010492	0.0014858	0.0018204	0.0021023
0.0050	0.0009083	0.0012867	0.0018213	0.0022313	0.0025768
0.0100	0.0012871	0.0018218	0.0025775	0.0031573	0.0036460
0.0200	0.0018220	0.0025777	0.0036462	0.0044660	0.0051571

TABLE 4–XXIIIa Maximum Pipe Strain for a Ramp pattern of PGD using the Complete 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	0.0006447	0.0009118	0.0012894	0.0015792	0.0018235
0.0033	0.0007445	0.0010528	0.0014889	0.0018235	0.0021057
0.0050	0.0009118	0.0012894	0.0018235	0.0022334	0.0025789
0.0100	0.0012894	0.0018235	0.0025789	0.0031585	0.0036471
0.0200	0.0018235	0.0025789	0.0036471	0.0044668	0.0051578

TABLE 4–XXIIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.845	0.491	0.321	0.281	0.286
0.0033	0.604	0.342	0.211	0.171	0.158
0.0050	0.382	0.210	0.123	0.094	0.080
0.0100	0.179	0.095	0.052	0.038	0.031
0.0200	0 086	0.045	0.024	0.017	0.013

TABLE 4–XXIIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0006670	0.0009493	0.0013464	0.0016500	0.0019045
0.0033	0.0007736	0.0010991	0.0015580	0.0019094	0.0022052
0.0050	0.0009513	0.0013494	0.0019113	0.0023420	0.0027049
0.0100	0.0013502	0.0019123	0.0027064	0.0033156	0.0038290
0.0200	0.0019126	0.0027068	0.0038295	0.0046907	0.0054167

TABLE 4–XXIVa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0006772	0.0009578	0.0013545	0.0016589	0.0019155
0.0033	0.0007820	0.0011059	0.0015640	0.0019155	0.0022119
0.0050	0.0009578	0.0013545	0.0019155	0.0023461	0.0027090
0.0100	0.0013545	0.0019155	0.0027090	0.0033178	0.0038311
0.0200	0.0019155	0.0027090	0.0038311	0.0046921	0.0054180

TABLE 4–XXIVb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.529	0.895	0.599	0.541	0.579
0.0033	1.088	0.619	0.388	0.322	0.305
0.0050	0.684	0.378	0.223	0.172	0.150
0.0100	0.318	0.170	0.094	0.068	0.056
0.0200	0.152	0.079	0.042	0.030	0.024

TABLE 4–XXIVc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
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	0.0007346	0.0010408	0.0014731	0.0018042	0.0020823
0.0033	0.0008494	0.0012029	0.0017022	0.0020852	0.0024077
0.0050	0.0010416	0.0014743	0.0020859	0.0025551	0.0029506
0.0100	0.0014746	0.0020863	0.0029512	0.0036147	0.0041740
0.0200	0.0020865	0.0029514	0.0041694	0.0051050	0.0058926

TABLE 4–XXVa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete 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	0.0007380	0.0010437	0.0014760	0.0018078	0.0020874
0.0033	0.0008522	0.0012052	0.0017044	0.0020874	0.0024103
0.0050	0.0010437	0.0014760	0.0020874	0.0025566	0.0029521
0.0100	0.0014760	0.0020874	0.0029521	0.0036155	0.0041748
0.0200	0.0020874	0.0029521	0.0041748	0.0051131	0.0059041

TABLE 4–XXVb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	0.464	0.280	0.199	0.195	0.244
0.0033	0.329	0.192	0.125	0.109	0.110
0.0050	0.206	0.116	0.072	0.056	0.050
0.0100	0.096	0.052	0.029	0.022	0.019
0.0200	0 045	0.024	0.130	0.159	0.196

TABLE 4–XXVc Percent Difference in Maximum Pipe Strain for Between the Complete and Simplified Models.
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	0.0007569	0.0010757	0.0015245	0.0018669	0.0021512
0.0033	0.0008772	0.0012452	0.0017642	0.0021615	0.0024955
0.0050	0.0010780	0.0015283	0.0021641	0.0026514	0.0030620
0.0100	0.0015292	0.0021652	0.0030639	0.0037533	0.0043344
0.0200	0.0021655	0.0030643	0.0043348	0.0053094	0.0061309

TABLE 4–XXVIa Maximum Pipe Strain for a Ramp pattern of PGD using the Complete 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	0.0007666	0.0010841	0.0015332	0.0018778	0.0021683
0.0033	0.0008852	0.0012518	0.0017704	0.0021683	0.0025037
0.0050	0.0010841	0.0015332	0.0021683	0.0026556	0.0030664
0.0100	0.0015332	0.0021683	0.0030664	0.0037555	0.0043365
0.0200	0.0021683	0.0030664	0.0043365	0.0053111	0.0061327

TABLE 4–XXVIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified 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	1.283	0.779	0.567	0.582	0.791
0.0033	0.906	0.530	0.351	0.313	0.329
0.0050	0.564	0.318	0.194	0.156	0.142
0.0100	0.260	0.140	0.079	0.059	0.048
0.0200	0.125	0.067	0.039	0.031	0.029

TABLE 4–XXVIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
ϕ = 30 in (76.2 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0007766	0.0011078	0.0015721	0.0019240	0.0022100
0.0033	0.0009027	0.0012849	0.0018225	0.0022333	0.0025775
0.0050	0.0011122	0.0015795	0.0022385	0.0027433	0.0031684
0.0100	0.0015812	0.0022407	0.0031722	0.0038865	0.0044885
0.0200	0.0022414	0.0031730	0.0044896	0.0054995	0.0063508

TABLE 4–XXVIIa Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Complete Soil–Pipeline Interface Model.
ϕ = 48 in (122 cm), t = 0 75 in (19.1 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	0.0007941	0.0011231	0.0015883	0.0019452	0.0022462
0.0033	0.0009170	0.0012968	0.0018340	0.0022462	0.0025937
0.0050	0.0011231	0.0015883	0.0022462	0.0027510	0.0031766
0.0100	0.0015883	0.0022462	0.0031766	0.0038905	0.0044924
0.0200	0.0022462	0.0031766	0.0044924	0.0055020	0.0063532

TABLE 4–XXVIIb Maximum Pipe Strain for a Ramp pattern of Longitudinal PGD Using the Simplified Model.
ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)

	L(m)				
α	25	50	100	150	200
0.0025	2.260	1.380	1.029	1.103	1.635
0.0033	1.587	0.932	0.629	0.575	0.627
0.0050	0.984	0.555	0.343	0.279	0.258
0.0100	0.451	0.244	0.138	0.103	0.086
0.0200	0.213	0.113	0.062	0.045	0.037

TABLE 4–XXVIIc Percent Difference in Maximum Pipe Strain Between the Complete and Simplified Models.
ϕ = 48 in (122 cm), t = 0.75 in (19.1 mm), C = 9 ft (2.74 m)