SECTION 5
RIGID BLOCK PGD

The axial strain induced in a continuous steel pipeline due to a Rigid Block pattern of longitudinal PGD is determined in this section. As mentioned previously, pipe response to the horizontal component of PGD is determined and any vertical component of ground deformation (i.e. subsidence and heaving) is neglected. It is assumed that the burial depth of the pipeline is constant in and around the PGD zone. Initially the soil–pipeline interface is modeled by the elastic spring–slide model shown in Figure 3–2. The pipeline strain is also determined using a simplified rigid spring–slider model for the soil–pipeline interface as shown in Figure 3–3.

As mentioned previously, the idealized Rigid Block pattern shown in Figure 2–12 corresponds to a mass of soil having length L, moving down a slight incline. There is little or no relative displacement within the soil block which overrides a liquefied layer. It may be an appropriate model for the observed PGD patterns shown in Figure 2–7(j) and 2–7(u).

As noted previously, a coordinate system is established with $x = 0$ at the head of the slide. The assumed ground movement is given, as a function of the axial coordinate x, in Equation 2.5. The maximum tensile strain in the pipe occurs at $x = 0$ while the maximum compressive strain occurs at $x = L$. The problem is anti–symmetric about the point $x = L/2$ where the pipe strain is zero. Results are presented herein for the region $x \leq L/2$. However because of the aforementioned anti–symmetry they apply to $x > L/2$ with a change of sign.

5.1 Elastic Spring–Slider Model

The solution for the elastic spring–slider model of the soil pipeline interface was obtained by dividing the pipeline into three regions as shown in Figure 5–1. In Region I ($x \leq x_a$) and Region III ($x_b \leq x \leq L/2$) the relative displacement between the pipe and soil are small and the soil–pipeline interaction behaves as a linear spring. Region II ($x_a \leq x \leq x_b$) is the slip region where a constant force per unit length, f_m, acts on the pipe. The values of x_a and x_b are not known a priori but are calculated as part of the solution. Note, however, that the magnitude of x_b is always greater than or equal to the magnitude of x_a. This is due to the fact that Region I is infinite in length while Region III is finite.

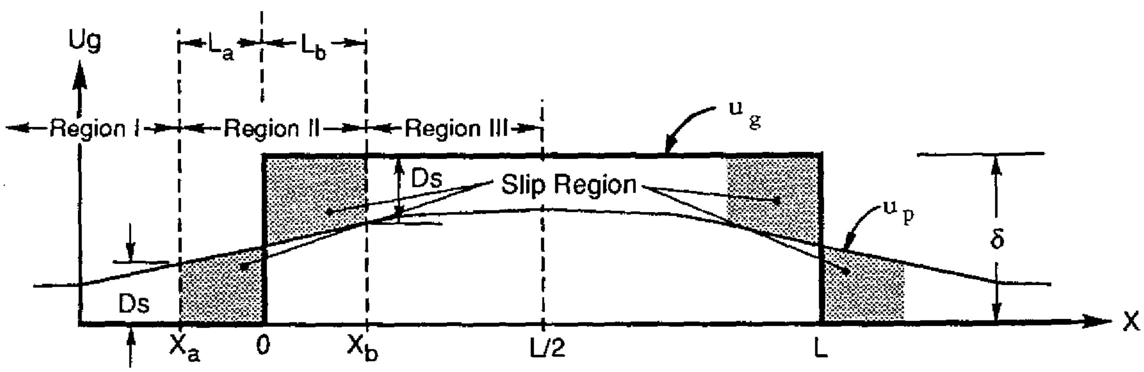

FIGURE 5-1 Model of Pipeline Subjected to Rigid Block PGD.

5.1.1 Region I ($x \le x_a$)

As noted in the previous section, the soil–pipeline system in Region I can be represented by an equivalent linear spring with spring constant K_a as shown in Figure 4–3. The pipe displacement at $x = x_a$ is equal to D_s, and displacement of the pipe in Region I is:

$$u_p(x) = D_s e^{\beta(x-x_a)} \qquad -\infty \le x \le x_a \tag{5.1}$$

as shown in Section 4.1.1.

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

Equating the forces acting on a differential length of pipe in Region III and noting that the ground displacement, u_g, equals a constant, δ, we obtain:

$$A(\sigma + d\sigma) = k(u_p(x) - \delta)dx + A\sigma \tag{5.2}$$

Assuming a linear elastic pipe material the differential equation for Region III becomes:

$$\frac{d^2u_p(x)}{dx^2} - \beta^2 u_p(x) = -\beta^2\delta \tag{5.3}$$

At the boundary between Region II and III (i.e. $x = x_b$) the relative displacement between the soil and pipe equals D_s. The displacement of the pipeline is therefore equal to the ground displacement, δ, minus the relative displacement, D_s:

$$u_p(x_b) = \delta - D_s \tag{5.4}$$

At the center of the PGD zone the strain in the pipe is zero by symmetry:

$$\frac{du_p}{dx}(L/2) = 0 \tag{5.5}$$

The solution to the differential equation (5.3) subjected to the boundary conditions of equations (5.4) and (5.5) is simply:

$$u_p(x) = -D_s \left[\frac{e^{\beta x}}{e^{\beta x_b} + e^{\beta(L-x_b)}} + \frac{e^{-\beta x}}{e^{-\beta x_b} + e^{-\beta(L-x_b)}} \right] + \delta \tag{5.6}$$

5.1.3 Continuity

The pipe displacements at the beginning and end of Region II are known, as well as the forces on the pipe in the region . Continuity requires that the displacement of the pipe at x_b equals the displacement at x_a plus the stretching over the length $L_a + L_b$. A relation for L_b in terms of L_a can be derived from this requirement:

$$D_s + \frac{K_a D_s (L_b + L_a)}{EA} + \frac{f_m}{2EA}(L_a^2 + 2L_aL_b - L_b^2) = \delta - D_s \tag{5.7}$$

Rearranging yields:

$$L_b^2 - (2L_a + \frac{2}{\beta})L_b - \left[\frac{4}{\beta^2} + \frac{2L_a}{\beta} - \frac{2AE\delta}{f_m} + L_a^2 \right] = 0 \tag{5.8}$$

which can be solved for L_b by noting that equation 5.8 is a quadratic equation in terms of the unknown L_b.

$$L_b = \frac{1}{\beta} + L_a \pm \sqrt{\frac{5}{\beta^2} + \frac{4L_a}{\beta} + 2L_a^2 - \frac{2AE\delta}{f_m}} \tag{5.9}$$

5.1.4 Equilibrium

A second relation can be derived by enforcing equilibrium The force in the pipe in Region I plus the net force exerted along the pipe in Region II must equal the force in the pipe at the start of Region III:

$$K_a D_s + f_m(L_a - L_b) = EA \frac{du_p}{dx}(L_b) \tag{5.10}$$

where $u_p(L_b)$ is given by equation (5.6). Hence:

$$\frac{K_a D_s}{EA} + \frac{f_m(L_a - L_b)}{EA} = -\beta D_s \left[\frac{e^{\beta L_b}}{e^{\beta L_b} + e^{\beta(L-L_b)}} - \frac{e^{-\beta L_b}}{e^{-\beta L_b} + e^{-\beta(L-L_b)}} \right] \quad (5.11)$$

Note that $K_a D_s = f_m/\beta$. Rearranging and simplifying yields a relation for L_a in terms of L_b.

$$L_a = -\frac{1}{\beta} - \frac{1}{\beta} \left[\frac{e^{\beta(2L_b-L)} - e^{\beta(L-2L_b)}}{2 + e^{\beta(L-2L_b)} + e^{\beta(2L_b-L)}} \right] + L_b \quad (5.12)$$

The length L_b can now be determined by substitution of equation (5.9) into equation (5.12):

$$L_b = \frac{1}{\beta} + [-\frac{1}{\beta} - \frac{1}{\beta}v + L_b] + \sqrt{\frac{5}{\beta^2} + \frac{4L_a}{\beta} + 2L_a^2 - \frac{2AE\delta}{f_m}} \quad (5.13)$$

which reduces to

$$\frac{3}{\beta^2} + \frac{v^2}{\beta^2} - \frac{4vL_b}{\beta} + 2L_b^2 - \frac{2AE\delta}{f_m} = 0 \quad (5.14)$$

where:

$$v = \frac{e^{\beta(2L_b-L)} - e^{\beta(L-2L_b)}}{2 + e^{\beta(L-2L_b)} + e^{\beta(2L_b-L)}} \quad (5.15)$$

The secant method is applied to equation (5.13) to evaluate L_b.

5.1.5 Maximum Pipe Strain

For a Rigid Block pattern of longitudinal PGD, the maximum tensile pipe strain occurs at the head of the slide (i.e. at x=0). This strain can be evaluated from the force in the pipe at this point. The total force is the force in the pipe at $x = x_a$, which is $K_a D_s$ from Figure 4–3, plus the friction force per unit length acting over the length L_a.

$$\epsilon = (K_a D_s + f_m L_a)/EA \tag{5.16}$$

The length L_a is determined by substituting the value of L_b given by equation 5.13 into equation 5.12.

Tables 5–Ia through 5–XXVIIa present the maximum pipe strain, ϵ, for a Rigid Block pattern of longitudinal PGD evaluated using equation 5.16. In these tables, the soil and pipe properties are the same as for Ramp PGD. That is, unit weight of soil $\gamma = 100$ pcf, coefficient of friction $\mu = 0.75$, pipe diameters, ϕ, of 12, 30 and 48 inches, wall thickness, t, of 1/4, 1/2, and 3/4 inch, and burial depths to the top of the pipe, C, of 3, 6, and 9 feet. In the tables the amount of ground movement δ ranges from 0.1 to 0.7 m, and the length L of the PGD zone ranges from 200 to 800 m. For a fixed amount of ground movement, δ, the maximum pipe strain increases with the block length, L, to a certain value and then is constant for further increases in L. Similarly, for fixed value of the length, L, the pipe strain is an increasing function of the ground displacement, δ, to a certain value and then is constant for further increases in δ. As with Ramp PGD, the pipe strain for Rigid Block PGD is an increasing function of the burial depth and a decreasing function of the pipe wall thickness. It also appears to be an increasing function of the pipe diameter ϕ.

5.2 Rigid Spring/Slider Model

The response of a buried pipeline to Rigid Block PGD is determined herein using the simplified rigid spring/slider model for the soil pipeline interface shown in Figure 3.3. Two possible configurations are shown in Figure 5–2. For both configurations the pipe strain is largest at the head and toe of the PGD zone. At the head, $x = 0$, the strain is tensile. At the toe, $x = L$, the strain is compressive but equal in magnitude to that at the head In addition the pipe strain is zero at the center of the PGD zone, $x = L/2$. For small length, L, of the PGD zone shown in Figure 5–2(a), there is slippage at the soil pipeline interface over the whole length of the PGD zone but the maximum pipe displacement at the center of the zone is less than the ground movement δ. Since the force in the pipe by symmetry is zero at $x = L/2$, a slip zone of length $L/2$ exists before the head of the slide zone and beyond the toe of the slide zone.

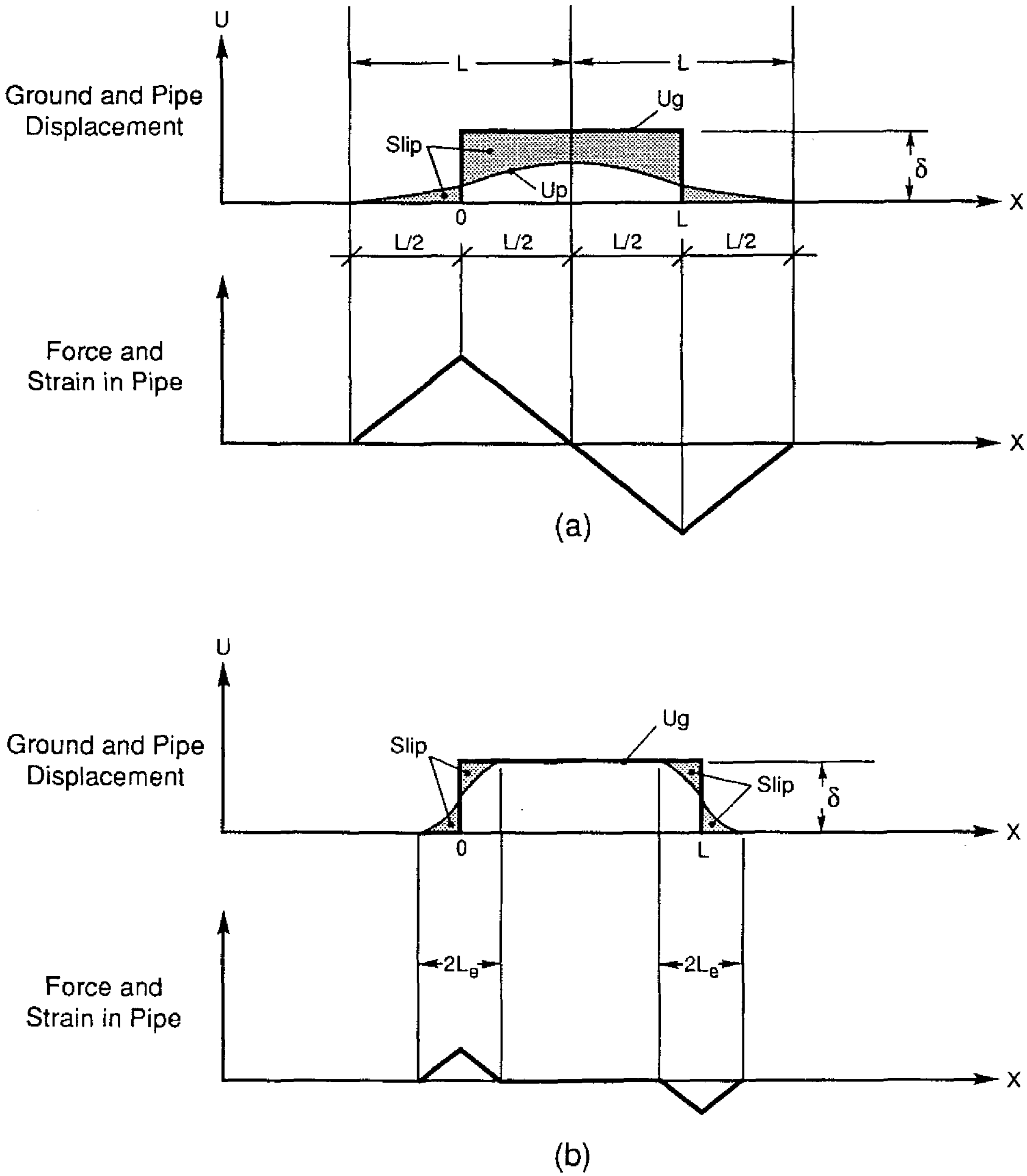

FIGURE 5-2 Simplified Model of Buried Pipe Subjected to Rigid Block PGD.

For large length L of the PGD zone shown in Figure 5–2(b), a slip zone of length L_e exists at either side of both the head and toe. However the pipe displacement matches ground displacement over a region of length $L - 2L_e$ within the PGD zone. Assuming that L is large as shown in Figure 5–2(b), an equation for L_e can be determined by enforcing continuity of the pipe. The displacement due to the stretching of the pipe over the slip region must equal the displacement of the soil, δ, since relative displacement between the soil and pipe are assumed to be zero beyond the slip region. Noting that the length L_e can not exceed L/2, we have

$$\frac{f_m(L_e^2 + L_e^2)}{2EA} = \delta \tag{5.17}$$

and

$$L_e = \sqrt{\frac{AE\delta}{f_m}} \leq L/2 \tag{5.18}$$

The maximum force in the pipe is equal to the force per unit length times L_e. Upon substitution of the constitutive equations, the maximum pipe strain, ϵ, due to Rigid Block PGD is:

$$\epsilon = \sqrt{\frac{f_m \delta}{EA}} \leq \frac{f_m L}{2EA} \tag{5.19}$$

For $L > \sqrt{4\delta EA/f_m}$, the maximum pipe strain is due to friction forces which result in a pipe displacement of δ towards the center of the PGD zone. In this case the pipe strain is a function of δ and Figure 5–2(b) applies.

For $L < \sqrt{4\delta EA/f_m}$, the maximum pipe strain is due to friction forces acting over a distance of L/2 on either side of both the head and toe of the PGD zone. In this case, the pipe strain is a function of L and Figure 5–2(a) applies.

Tables 5–Ib through 5–XXVIIb present results from equation 5.19 for maximum pipe strain using the simplified rigid spring/slider model. Results are given for the same range of parameters used with the complete elastic spring/slider model which were presented in Table 5–Ia through 5–XXVIIa. Note that equation 5.19 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 maximum pipe strain is always an increasing function of the burial depth, H, and a decreasing function of the wall thickness t.

For a fixed value of δ, the maximum pipe strain is an increasing function of the length of the PGD zone for $L \leq \sqrt{4\delta EA}/f_m$ and is a constant value of $(f_m\delta/EA)^{\frac{1}{2}}$ for larger values of L. Similarly for a fixed value of L, the maximum pipe strain is an increasing function of amount of ground movement for $\delta \leq (L/4EA)^{\frac{1}{2}}$ and is a constant value of $f_m L/2AE$ for larger values of δ. As with Ramp PGD, the maximum pipe strain using the simplified soil pipe interface model is not directly a function of the pipe diameter ϕ. However since Tables 5–I through 5–XXVII are presented in terms of the cover over the top of the 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 H.

The simplified model in Figure 5–2(b) for which the maximum pipe strain is $(f_m\delta_g/EA)^{\frac{1}{2}}$, is also applicable to an idealized ground displacement pattern

$$u_g(x) = \begin{cases} 0 & x < 0 \\ \delta & x > 0 \end{cases} \tag{5.20}$$

This corresponds to the situation of zero soil strain on either side of a tensile ground crack of width δ at the head of a very long landslide as shown in Figure 5–3. It is also applicable to the corresponding compression situation of an abrupt relative displacement of δ at the toe of a very long landslide.

5.3 Comparison of Models

Tables 5–Ic through 5–XXVIIc list the percent different in the maximum pipe strain due to Rigid Block 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 strains slightly higher than the complete model. In the cases examined, which correspond to what is felt to be typical conditions, the error between the models does not exceed 1.5 percent.

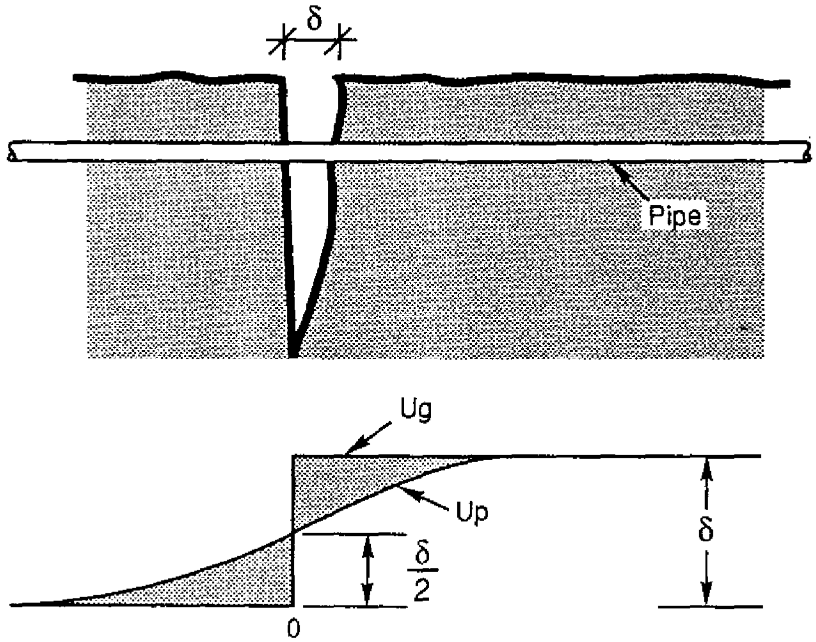

FIGURE 5-3 Simplified Model of a Buried Pipeline at a tensile ground crack of width δ

δ (m)	L(m)			
	200	400	600	800
0.10	0.0009632	0.0009807	0.0009807	0.0009807
0.20	0.0009632	0.0013874	0.0013874	0.0013874
0.30	0.0009632	0.0016995	0.0016995	0.0016995
0.40	0.0009632	0.0019264	0.0019625	0.0019625
0.50	0.0009632	0.0019264	0.0021942	0.0021942
0.60	0.0009632	0.0019264	0.0024037	0.0024037
0.70	0.0009632	0.0019264	0.0025963	0.0025963

TABLE 5–Ia Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m)			
	200	400	600	800
0.10	0.0009632	0.0009814	0.0009814	0.0009814
0.20	0.0009632	0.0013879	0.0013879	0.0013879
0.30	0.0009632	0.0016999	0.0016999	0.0016999
0.40	0.0009632	0.0019264	0.0019629	0.0019629
0.50	0.0009632	0.0019264	0.0021945	0.0021945
0.60	0.0009632	0.0019264	0.0024040	0.0024040
0.70	0.0009632	0.0019264	0.0025966	0.0025966

TABLE 5–Ib Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m)			
	200	400	600	800
0.10	0.0000000	0.0750274	0.0750274	0.0750274
0.20	0.0000000	0.0374928	0.0374928	0.0374928
0.30	0.0000000	0.0249906	0.0249905	0.0249905
0.40	0.0000000	0.0000000	0.0187411	0.0187411
0.50	0.0000000	0.0000000	0.0148633	0.0148633
0.60	0.0000000	0.0000000	0.0123949	0.0123949
0.70	0.0000000	0.0000000	0.0106302	0.0106302

TABLE 5–Ic Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0010790	0.0010790	0.0010790	0.0010790
0.20	0.0011696	0.0015277	0.0015277	0.0015277
0.30	0.0011696	0.0018718	0.0018718	0.0018718
0.40	0.0011696	0.0021617	0.0021617	0.0021617
0.50	0.0011696	0.0023392	0.0024172	0.0024172
0.60	0.0011696	0.0023392	0.0026481	0.0026481
0.70	0.0011696	0.0023392	0.0028604	0.0028604

TABLE 5–IIa Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.0010815	0.0010815	0.0010815	0.0010815
0.20	0.0011696	0.0015294	0.0015294	0.0015294
0.30	0.0011696	0.0018732	0.0018732	0.0018732
0.40	0.0011696	0.0021630	0.0021630	0.0021630
0.50	0.0011696	0.0023392	0.0024183	0.0024183
0.60	0.0011696	0.0023392	0.0026491	0.0026491
0.70	0.0011696	0.0023392	0.0028613	0.0028613

TABLE 5–IIb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.2334565	0.2282779	0.2282779	0.2282779
0.20	0.0000000	0.1139465	0.1139465	0.1139465
0.30	0.0000000	0.0759216	0.0759216	0.0759216
0.40	0.0000000	0.0570809	0.0569251	0.0569251
0.50	0.0000000	0.0000000	0.0455324	0.0455324
0.60	0.0000000	0.0000000	0.0379394	0.0379394
0.70	0.0000000	0.0000000	0.0325168	0.0325168

TABLE 5–IIc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0011680	0.0011680	0.0011680	0.0011680
0.20	0.0013760	0.0016554	0.0016554	0.0016554
0.30	0.0013760	0.0020288	0.0020288	0.0020288
0.40	0.0013760	0.0023435	0.0023435	0.0023435
0.50	0.0013760	0.0026207	0.0026207	0.0026207
0.60	0.0013760	0.0027520	0.0028713	0.0028713
0.70	0.0013760	0.0027520	0.0031016	0.0031016

TABLE 5–IIIa Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.0011730	0.0011730	0.0011730	0.0011730
0.20	0.0013760	0.0016589	0.0016589	0.0016589
0.30	0.0013760	0.0020317	0.0020317	0.0020317
0.40	0.0013760	0.0023461	0.0023461	0.0023461
0.50	0.0013760	0.0026230	0.0026230	0.0026230
0.60	0.0013760	0.0027520	0.0028733	0.0028733
0.70	0.0013760	0.0027520	0.0031035	0.0031035

TABLE 5–IIIb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.4335768	0.4309769	0.4309769	0.4309769
0.20	0.0000000	0.2148071	0.2148071	0.2148071
0.30	0.0000000	0.1430534	0.1430533	0.1430533
0.40	0.0000000	0.1072490	0.1072331	0.1072331
0.50	0.0000000	0.0878803	0.0857592	0.0857592
0.60	0.0000000	0.0000000	0.0714508	0.0714508
0.70	0.0000000	0.0000000	0.0612343	0.0612343

TABLE 5–IIIc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 3 ft (0.91 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0013356	0.0013356	0.0013356	0.0013356
0.20	0.0017888	0.0018901	0.0018901	0.0018901
0.30	0.0017888	0.0023155	0.0023155	0.0023155
0.40	0.0017888	0.0026740	0.0026740	0.0026740
0.50	0.0017888	0.0029898	0.0029898	0.0029898
0.60	0.0017888	0.0032753	0.0032753	0.0032753
0.70	0.0017888	0.0035378	0.0035379	0.0035379

TABLE 5–IVa Maximum Pipe Strain for a Rigid Block 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 (1.83 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0013375	0.0013375	0.0013375	0.0013375
0.20	0.0017888	0.0018915	0.0018915	0.0018915
0.30	0.0017888	0.0023165	0.0023165	0.0023165
0.40	0.0017888	0.0026749	0.0026749	0.0026749
0.50	0.0017888	0.0029906	0.0029906	0.0029906
0.60	0.0017888	0.0032761	0.0032761	0.0032761
0.70	0.0017888	0.0035386	0.0035386	0.0035386

TABLE 5–IVb Maximum Pipe Strain for a Rigid Block Pattern of Longitudinal PGD Using the Simplified Model. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

δ (m)	L(m) 200	400	600	800
0.10	0.1394697	0.1394696	0.1394696	0.1394696
0.20	0.0000000	0.0696627	0.0696627	0.0696627
0.30	0.0000000	0.0464258	0.0464258	0.0464258
0.40	0.0000000	0.0348133	0.0348133	0.0348133
0.50	0.0000000	0.0278478	0.0278478	0.0278478
0.60	0.0000000	0.0232061	0.0232049	0.0232049
0.70	0.0000000	0.0217990	0.0198889	0.0198889

TABLE 5–IVc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0014070	0.0014070	0.0014070	0.0014070
0.20	0.0019952	0.0019937	0.0019937	0.0019937
0.30	0.0019952	0.0024434	0.0024434	0.0024434
0.40	0.0019952	0.0028223	0.0028223	0.0028223
0.50	0.0019952	0.0031560	0.0031560	0.0031560
0.60	0.0019952	0.0034577	0.0034577	0.0034577
0.70	0.0019952	0.0037351	0.0037351	0.0037351

TABLE 5–Va Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.0014125	0.0014125	0.0014125	0.0014125
0.20	0.0019952	0.0019976	0.0019976	0.0019976
0.30	0.0019952	0.0024465	0.0024465	0.0024465
0.40	0.0019952	0.0028250	0.0028250	0.0028250
0.50	0.0019952	0.0031585	0.0031585	0.0031585
0.60	0.0019952	0.0034599	0.0034599	0.0034599
0.70	0.0019952	0.0037372	0.0037372	0.0037372

TABLE 5–Vb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.3903500	0.3903413	0.3903413	0.3903413
0.20	0.0000000	0.1946111	0.1946111	0.1946111
0.30	0.0000000	0.1296163	0.1296163	0.1296163
0.40	0.0000000	0.0971655	0.0971655	0.0971655
0.50	0.0000000	0.0777100	0.0777100	0.0777100
0.60	0.0000000	0.0647493	0.0647459	0.0647459
0.70	0.0000000	0.0557386	0.0554888	0.0554888

TABLE 5–Vc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0014736	0.0014736	0.0014736	0.0014736
0.20	0.0020906	0.0020912	0.0020912	0.0020912
0.30	0.0022016	0.0025641	0.0025641	0.0025641
0.40	0.0022016	0.0029625	0.0029625	0.0029625
0.50	0.0022016	0.0033133	0.0033133	0.0033133
0.60	0.0022016	0.0036303	0.0036303	0.0036303
0.70	0.0022016	0.0039219	0.0039219	0.0039219

TABLE 5–VIa Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.0014838	0.0014838	0.0014838	0.0014838
0.20	0.0020984	0.0020984	0.0020984	0.0020984
0.30	0.0022016	0.0025700	0.0025700	0.0025700
0.40	0.0022016	0.0029676	0.0029676	0.0029676
0.50	0.0022016	0.0033178	0.0033178	0.0033178
0.60	0.0022016	0.0036345	0.0036345	0.0036345
0.70	0.0022016	0.0039257	0.0039257	0.0039257

TABLE 5–VIb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.6922295	0.6921823	0.6921823	0.6921823
0.20	0.3727553	0.3443454	0.3443454	0.3443454
0.30	0.0000000	0.2291761	0.2291761	0.2291761
0.40	0.0000000	0.1717367	0.1717367	0.1717367
0.50	0.0000000	0.1373197	0.1373195	0.1373195
0.60	0.0000000	0.1143984	0.1143941	0.1143941
0.70	0.0000000	0.0981334	0.0980284	0.0980284

TABLE 5–VIc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 48 in (122 cm), t = 0.25 in (6.4 mm), C = 6 ft (1.83 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0016136	0.0016136	0.0016136	0.0016136
0.20	0.0022843	0.0022843	0.0022843	0.0022843
0.30	0.0026144	0.0027987	0.0027987	0.0027987
0.40	0.0026144	0.0032322	0.0032322	0.0032322
0.50	0.0026144	0.0036140	0.0036140	0.0036140
0.60	0.0026144	0.0039593	0.0039593	0.0039593
0.7000	0.0026144	0.0042767	0.0042767	0.0042767

TABLE 5–VIIa Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.1000	0.0016169	0.0016169	0.0016169	0.0016169
0.20	0.0022867	0.0022867	0.0022867	0.0022867
0.30	0.0026144	0.0028006	0.0028006	0.0028006
0.40	0.0026144	0.0032338	0.0032338	0.0032338
0.50	0.0026144	0.0036155	0.0036155	0.0036155
0.60	0.0026144	0.0039606	0.0039606	0.0039606
0.70	0.0026144	0.0042779	0.0042779	0.0042779

TABLE 5–VIIb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.2040345	0.2040345	0.2040345	0.2040345
0.20	0.1019097	0.1018634	0.1018634	0.1018634
0.30	0.0000000	0.0678747	0.0678747	0.0678747
0.40	0.0000000	0.0508932	0.0508932	0.0508932
0.50	0.0000000	0.0407084	0.0407084	0.0407084
0.60	0.0000000	0.0339202	0.0339202	0.0339202
0.70	0.0000000	0.0290724	0.0290724	0.0290724

TABLE 5–VIIc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 12 in (30.5 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)

δ (m)	L(m) 200	400	600	800
0.10	0.0016703	0.0016703	0.0016703	0.0016703
0.20	0.0023687	0.0023687	0.0023687	0.0023687
0.30	0.0028208	0.0029037	0.0029037	0.0029037
0.40	0.0028208	0.0033544	0.0033544	0.0033544
0.50	0.0028208	0.0037514	0.0037514	0.0037514
0.60	0.0028208	0.0041102	0.0041102	0.0041102
0.70	0.0028208	0.0044401	0.0044401	0.0044401

TABLE 5–VIIIa Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.0016795	0.0016795	0.0016795	0.0016795
0.20	0.0023752	0.0023752	0.0023752	0.0023752
0.30	0.0028208	0.0029090	0.0029090	0.0029090
0.40	0.0028208	0.0033590	0.0033590	0.0033590
0.50	0.0028208	0.0037555	0.0037555	0.0037555
0.60	0.0028208	0.0041140	0.0041140	0.0041140
0.70	0.0028208	0.0044436	0.0044436	0.0044436

TABLE 5–VIIIb Maximum Pipe Strain for a Rigid Block 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)

δ (m)	L(m) 200	400	600	800
0.10	0.5531722	0.5531719	0.5531719	0.5531719
0.20	0.2759169	0.2754672	0.2754672	0.2754672
0.30	0.0000000	0.1833962	0.1833962	0.1833962
0.40	0.0000000	0.1374539	0.1374539	0.1374539
0.50	0.0000000	0.1099183	0.1099183	0.1099183
0.60	0.0000000	0.0915737	0.0915737	0.0915737
0.70	0.0000000	0.0784765	0.0784765	0.0784765

TABLE 5–VIIIc Percent difference in Maximum Pipe Strain between Simplified and Complete Models. ϕ = 30 in (76.2 cm), t = 0.25 in (6.4 mm), C = 9 ft (2.74 m)