9

Response of Segmented Pipelines to PGD

In this chapter, the response of segmented pipelines subject to PGD will be discussed. Segmented pipes typically have bell and spigot joints and can be made of cast iron, ductile iron, steel, concrete or asbestos cement. As indicated in Section 4.2, there are three main failure modes for segmented pipelines: axial pull-out at joints, crushing of the bell and spigot joints, and round flexural cracks in the pipe segment away from the joints.

Similar to the response of continuous pipelines, the behavior of a given buried segmented pipeline is a function of the type of PGD (e.g. longitudinal or transverse), the amount of ground movement δ, the spatial extent of the PGD zone and the pattern of ground movement within the zone.

In reference to the type, Suzuki (1988) concluded that damage due to longitudinal PGD was more common than damage due to transverse PGD based on the observed damage to segmented gas pipelines during the 1964 Niigata earthquake. In these cases, the joints were pulled out in the tension region and buckled in the compression region.

In terms of the pattern, if the ground movement within the PGD zone is relatively uniform (i.e., an idealized block pattern of longitudinal PGD in Figure 6.1(a)), one expects that a few pipe joints near the head and toe of the zone would have to accommodate essentially all the abrupt differential ground movement. On the other hand, if the ground movement varies within the PGD zone (i.e., an idealized ridge pattern of longitudinal PGD in Figure 6.1(c)), the rate of change along the segmented pipeline leads to an "equivalent" ground strain. One expects that all joints within the zone, to a greater or lesser extent, would then experience relative axial displacement.

In this chapter, the response of segmented pipe to longitudinal and transverse PGD as well as fault offsets are discussed.

LONGITUDINAL PGD

As with continuous pipeline, longitudinal PGD induces axial effects in segmented pipeline, specifically axial strain in the pipe segments and relative axial displacement at the joints. However, in contrast to the response of continuous pipelines, damage to segmented pipelines subject to longitudinal PGD typically occurs at pipe joints since the strength of the joints is generally less than the strength of the pipe itself. Whether the joints fail depends on the strength and deformation capacity of the joints as well as the characteristics of the PGD

One particularly important characteristic is the pattern of longitudinal PGD. Herein, two types of patterns are considered in detail For the distributed deformation case (such as the idealized ridge pattern in Figure 6.1(c)), ground strain exists over a significant portion of the PGD zone. For the abrupt deformation case (such as the idealized block pattern in Figure 6.1(a)), relative movement exists only at the margins of the PGD zone, and the ground strain between the margins is zero.

9.1.1 DISTRIBUTED DEFORMATION

The response of segmented pipelines subject to a distributed deformation pattern of longitudinal PGD is similar to that for segmented pipelines subject to wave propagation in that the spatially distributed PGD results in a region of ground strain. That is, the ridge, asymmetric ridge and ramp patterns in Figure 6 1 result in ground strain over the whole length of the PGD zone, while the Ramp-Block pattern results in uniform ground strain over a portion (i.e , length βL) of the zone. For example, the ground strain for the ridge pattern is:

$$\varepsilon_g = \frac{2\delta}{L} \tag{9.1}$$

By assuming that pipe segments are rigid and all of the longitudinal PGD is accommodated by the extension or contraction of the joints, the average relative displacement at the joints is given by the ground strain times the pipe segment length, L_o.

$$\Delta u_{avg} = \frac{2\delta L_o}{L} \tag{9.2}$$

Although Equation 9.2 represents the average behavior, the joint displacements for uniform ground strain varied somewhat from joint to joint due to variation in joint stiffness. That is, a relatively flexible joint is expected to experience larger joint displacements than adjacent stiffer joints. Using realistic variations of joint stiffness, El Hmadi and M. O'Rourke (1989) determined, as presented in Table 9.1, the mean joint displacement, Δx, in centimeters, and coefficients of variation, μ, in percentage, as a function of ground strain for various diameters of Cast Iron pipe with lead caulked joints (CI) and Ductile Iron pipe with rubber gasketed joints (DI). The values in Table 9.1 assume that the pipe segment length L_o for all types was 6.0 m (20 ft).

Table 9.1 Mean Joint Displacement and Coefficient of Variation for Segmented Pipe Subject to Uniform Ground Strain

Ground Strain	CI D=40 cm (16 in)		CI D=76 cm (30 in)		CI D=122 cm (48 in)		DI D=40-122 cm (15-48 in)	
	$\Delta\bar{x}$ (cm)	μ(%)	$\Delta\bar{x}$ (cm)	μ(%)	$\Delta\bar{x}$ (cm)	μ(%)	$\Delta\bar{x}$ (cm)	μ(%)
0.001 (1/1000)	54	64	.56	54	.58	52	.59	2
0.002 (1/500)	1.14	56	1.17	49	1.17	43	1.19	2
0.005 (1/200)	2.92	39	2.95	24	2.97	14	3.00	[illegible]
0.007 (1/150)	4.12	26	4.16	19	4.16	16	4.19	1

Note that the mean values for both CI and DI pipes are about equal to the value given in Equation 9.2 (that is $\varepsilon_g L_o$).

As shown in Table 9.1, μ for DI joints is quite small in comparison to that for CI joints. This is due to the fact that DI joints are substantially more flexible than CI joints. As a result, the joint opening for DI pipelines would be relatively constant over the length of the PGD zone.

To gauge the effects of a distributed deformation pattern of longitudinal PGD on segmented pipe, expected joint openings are calculated. M. O'Rourke et al. (1995) present a summary of longitudinal PGD pattern observed in Noshiro City after the 1983 Nihonkai Chubu event. The minimum ground strain due to the distributed longitudinal PGD is 0.008. The corresponding joint opening is 5 cm (2 in), which is larger than the joint capacity of typical segmented pipelines as noted in Section 4.2 (i.e., segmented joints typically leak for relative displacement on the order of half the total joint depth). Hence, typical segmented pipelines are vulnerable and consideration should be given to replacement by continuous pipelines or segmented pipelines with special joints (having large contract/expansion capacity and/or anti-pull-out restraints) when crossing a potential longitudinal PGD zone.

The potential for damage due to something other than joint pull-out of simple bell and spigot joints is more difficult to evaluate. For example, tensile failure of various types of restrained joints or crushing of simple bell and spigot joints typically involves some slippage in the joint before significant load is transferred across the joint. In this regard, the expected behavior of concrete pipe joints in compression is discussed in Chapter 11

9.1.2 Abrupt Deformation

As used herein, abrupt longitudinal PGD refers to ground movements with large relative offsets at localized points. The block pattern in Figure 6.1(a) is an example. In this case, the ground strain is zero away from the margins of the PGD zone, there is a tensile opening or gap at the head of the zone and a localized compressive mound at the toe. The ramp and ramp-block patterns in Figure 6.1 (b) and (d) also have an abrupt offset, but for these patterns at only one end of the PGD zone.

At the head of the zone (i.e., the tension gap), pipeline failure for typical bell and spigot joints is probable. In the simplest model, one expects joint leakage or pull-out if the relative joint displacement corresponding to leakage or pull-out respectively is less than the ground offset (that is δ in Figure 6.1).

For the 17 idealized block, ramp or ramp-block patterns studied by M. O'Rourke et al. (1995), the abrupt offset, δ, was 1.2 m (4 ft) or larger. Hence, one expects joint pull-out in typical segmented pipe at tension gaps at least for the examples of longitudinal PGD considered by M. O'Rourke et al. (1995).

An axially restrained pipe at a tension gap or a restrained or unrestrained pipe at a compression mound behaves like a continuous pipe subject to longitudinal PGD as discussed in Chapter 6 That is, in the simplest model, the flexibility at the joint itself (i.e., due to stretching of bolts for a restrained joint in tension, or joint push-in for a joint in compression) is neglected. Failure is possible in the pipe segment or at the joint closest to the tension gap or compression mound. For the "no-joint-flexibility" assumption, the pipe segment behaves like a continuous pipe Potential failure modes and strains are discussed in detail in Chapter 6 The axial force at the joint closest to the abrupt offset is the smaller of $t_u L/2$ or $t_u L_e$ as shown in Figures 6 5 and 6.6.

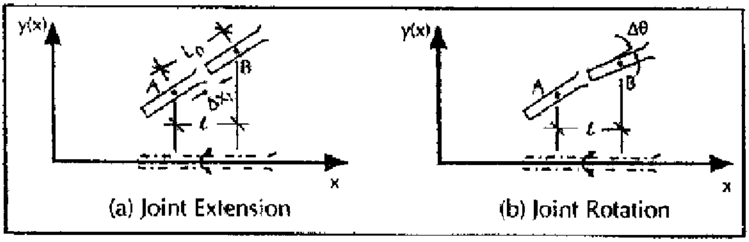
9.2 TRANSVERSE PGD

In considering the response of segmented pipelines subject to transverse PGD, one must differentiate between spatially distributed transverse PGD and localized abrupt transverse PGD as sketched in Figure 7.1. Localized abrupt PGD is a special case of fault offset (intersection angle of 90°).

9.2.1 SPATIALLY DISTRIBUTED PGD

For segmented pipelines subject to spatially distributed transverse PGD, the failure modes include round cracks in the pipe segments and crushing of bell and spigot joints due to the bending, and pull-out at the joint due to axial elongation (i.e., arc-length effects).

For an assumed sinusoidal variation of ground movement across the width of the PGD zone as given by Equation 7.3 and shown in Figure 7.23, M. O'Rourke and Nordberg (1991) studied the maximum joint opening due to both joint rotation and axial extension of segmented pipelines. Figure 9.1(a), (b) present a pipeline subject to transverse PGD, where Δx_t and $\Delta\theta$ are the joint extension and relative joint rotation between the adjacent segments



After M. O'Rourke and Nordberg, 1991

■ **Figure 9.1 Plan View of Segmented Pipeline Subject to Distributed Transverse PGD**

Assuming that the pipe segments are rigid (i.e., EA=∞, EI= ∞) and that the lateral displacement at the midpoint of the rigid pipe segment exactly matches the spatially distributed PGD at that point, they developed the relative axial displacement at a joint.

$$\Delta x_t = \frac{L_0}{2}\left(\frac{\pi\delta}{W}\sin\frac{2\pi x}{W}\right)^2 \qquad (9.3)$$

where x is the distance from the margin of the PGD zone and L_0 is the pipe segment length.

The axial displacements are largest for joints near $x = W/4$ and $3W/4$. Hence, a pure joint-pull-out failure mode is most likely at the locations $W/4$ away from the center of the PGD zone. The peak axial displacement is given by:

$$\Delta x_t = \frac{L_0}{2}\left(\frac{\pi\delta}{W}\right)^2 \qquad (9.4)$$

Assuming that the slope of the rigid pipe segment exactly matches the ground slope at the segment midpoint, the joint opening due to the joint rotation, Δx_r, is as follows:

$$\Delta x_r = \begin{cases} \dfrac{\pi^2\delta D L_0}{W^2}\cos\dfrac{2\pi x}{W} & \Delta x_t > \Delta\theta \cdot D/2 \\[2ex] \dfrac{2\pi^2\delta D L_0}{W^2}\cos\dfrac{2\pi x}{W} & \Delta x_t < \Delta\theta \cdot D/2 \end{cases}$$

(9.5)

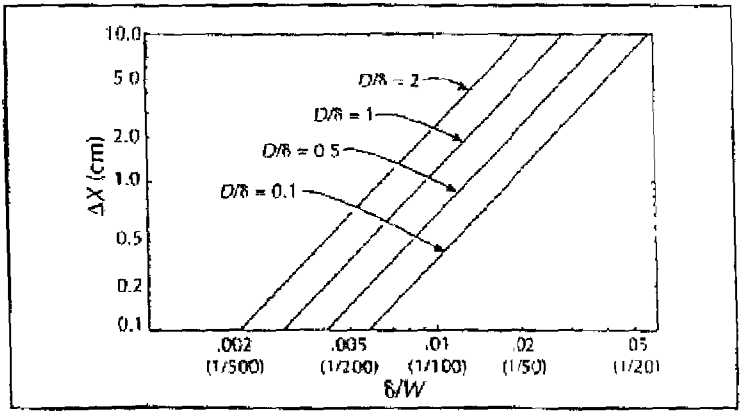
where D is the pipe diameter.

This function is a maximum at $x = 0$, $W/2$ and W. Hence, a pure joint rotation failure and/or flexural round cracks are more likely at the margins and middle point of the PGD zone.

The total maximum opening at one side of a joint, Δx, due to transverse PGD, is simply the sum of axial extension plus rotation effects. However, the axial and rotational components are largest at different points as discussed previously. Combining these effects, the resulting maximum joint opening is:

$$\Delta x = \begin{cases} \dfrac{\pi^2 L_o \delta^2}{W^2}\left[\dfrac{2D}{\delta}\right] & 0.268 \le D/\delta < 3.73 \\ \dfrac{\pi^2 L_o \delta^2}{2W^2}\left[1 + (D/\delta)^2\right] & \text{Others} \end{cases} \tag{9.6}$$

This relation for the maximum joint opening is plotted in Figure 9.2. Note that the maximum joint opening is an increasing function of both the δ/W ratio and the D/δ ratio.



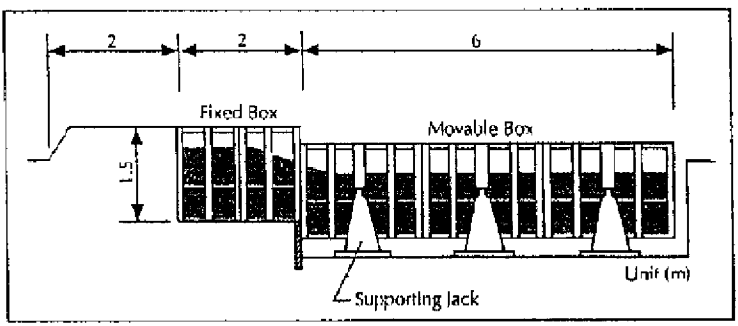
After M. O'Rourke and Nordberg, 1991

Figure 9.2 Maximum Joint Opening for Segmented Pipe Subject to Distributed Transverse PGD

Consider the observed spatially distributed transverse PGD during the 1964 Niigata and 1983 Nihonkai Chubu events (Suzuki and Masuda, 1991) shown in Figure 2.8. Observed values for the δ/W ratio range from 0.001 to 0.01 with 0.003 being a typical value. The amount of ground movement δ ranged from 0.2 to 2.0 m (0.66 to 6.6 ft) with 1.0 m (3.3 ft) being a typical value. Hence, from Figure 9.2, the corresponding maximum joint opening (i.e., using upper bound values of δ/W=0.01 and δ=2.0 m) would be 2.5 cm (1 in) or less for pipe diameter of 4.0 m (157 in) (i.e., D/δ=2) or less. Hence, significant leakage or pull-out failure at these joints due to the axial movement is unlikely to occur for segmented pipelines subject to spatially transverse PGD shown in Figure 2.8. However, for segmented pipelines with rigid joints, some leakage at joints is likely to occur since leakage may occur at joint opening of 2.0 mm (0.08 in) based on the laboratory tests (Prior, 1935).

9.2.2 Fault Offsets

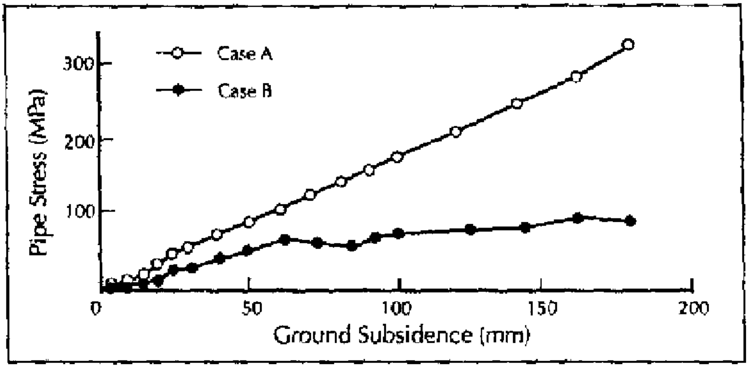
Both experimental and analytical results are available for segmented pipelines subject to fault offset (i.e., local abrupt differential ground movement transverse to the pipe axis). For example, Takada (1984) performed a laboratory test to analyze the response of segmented pipelines subject to transverse PGD. Figure 9.3 presents a sketch of the sinking soil box (dimension 10 m×1 m×1.5 m), in which a 169 mm (nominal 6 in) diameter Ductile Iron pipeline is surrounded by loose sand. The vertical offset is produced by decreasing the height of the six jacks which support the movable box. Two cases were studied in their tests. In Case A, the pipeline is composed of three longer segments, while in Case B it is composed of five shorter segments.



After Takada 1984

■ Figure 9.3 Model Box for Segmented Pipeline Subject to Transverse PGD

Figure 9 4 shows the maximum pipe stress, which occurs directly over the offset, versus the ground subsidence for both cases.



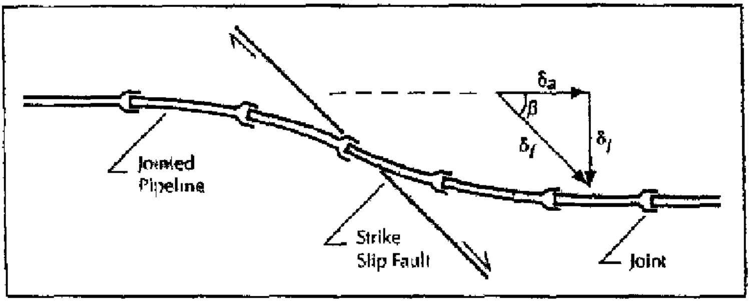
After Takada, 1984

■ **Figure 9.4 Maximum Pipe Stress vs. Ground Subsidence for Case A and Case B**

As shown in Figure 9.4, the stresses in the pipeline with smaller-length segments (Case B) are much less than those for large-length segments (Case A) particularly for large values of the offset.

For the geometry studied by Takada, that is, a pipe at 90° with respect to the fault or offset plane, flexural stresses in the pipe dominate. If one assumes rotationally flexible joints (i.e , no moment transfer across the joint), the portion of the pipe segment on one side of the fault plane acts as a cantilever beam subject to a distributed loading along its length due to transverse pipe-soil interaction forces and a concentrated load at its end (i.e., at the joint) due to shear transfer across the joint. Smaller pipe stress in Case B are due, in part, to the shorter cantilever length.

Analytical results for segmented pipes are also available T. O'Rourke and Trautmann (1981) developed a simplified analytical method for evaluating the response of segmented pipelines subject to fault offset. They assume that segments are rigid and joints accommodate the ground deformation. Figure 9.5 shows the plan view of a segmented pipeline subject to fault offset.



After T O'Rourke and Trautmann, 1981

■ Figure 9.5 Plan View of Segmented Pipeline Subject to Fault Offset

The tolerable fault displacement can be obtained by:

$$\delta_f = min\begin{cases}\delta_a \sec\beta \\ \delta_l \csc\beta\end{cases} \quad (9.7)$$

where δ_a is the pull-out capacity of the joint (axial deformation) near the fault offset, δ_l is the lateral deformation capacity, which depends on the joint rotation ability and is calculated by finite element simulations for typical ductile and cast iron pipelines

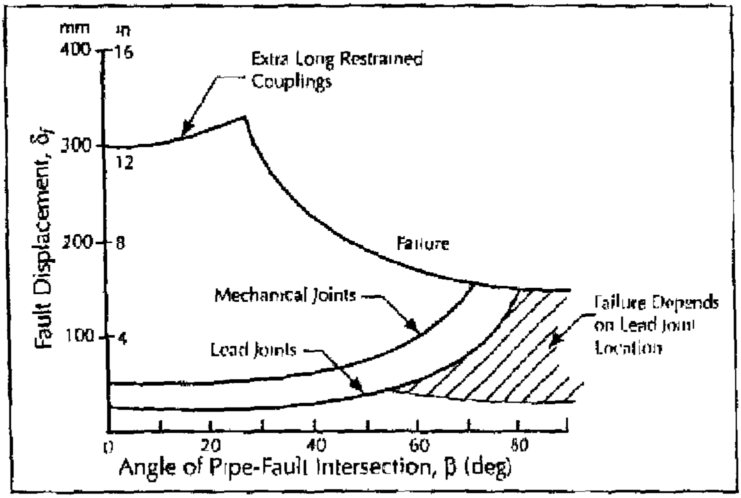
The optimal orientation of the pipeline, $\beta_{optimal}$, can be defined by:

$$\beta_{optimal} = \frac{\delta_l}{\delta_a} \quad (9.8)$$

A pipeline would fail by joint pull-out when the intersection angle between the pipe axis and the fault trace is less than $\beta_{optimal}$, while the pipeline would fail by bending when the intersection angle is larger than $\beta_{optimal}$.

T. O'Rourke and Trautmann (1981) plotted the tolerable fault offset for segmented pipelines as a function of the intersection angle as shown in Figure 9.6. Similar to the response of continuous pipelines subject to fault offset, the tolerable fault offset for pipelines with either restrained or unrestrained joints is an increasing function of β for the intersection angle less than the optimal value, and decreases thereafter. For example, the optimal intersection angle for pipe with mechanical joints is about 70°. According to T.

O'Rourke and Trautmann, the decrease in capacity for $\beta > \beta_{optimal}$ is caused by the larger bending moments developed in the pipeline for large intersection angles.



After T O'Rourke and Trautmann, 1981

■ **Figure 9.6 Tolerable Fault Offset vs. Intersection Angle**

Note that pipe with extra long restrained coupling are particularly effective only when the intersection angle is small At these small intersection angles, axial effects dominant and the expansion capability of the special joints is useful. However, at large intersection angles (β > 60°), where flexural effects govern, the capacity of mechanical and special joints is similar.

Post earthquake observation of segmented pipe response to fault offsets would be useful for case history verification of available analytical procedures.