FAILURE CRITERION FOR BURIED PIPE SUBJECT TO LONGITUDINAL PGD: BENCHMARK CASE HISTORY

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ABSTRACT

The effects of longitudinal Permanent Ground Deformation (PGD) on a buried continuous steel pipeline is considered. Longitudinal PGD, (ground movement parallel to the pipe's axis) is characterized by the amount of movement, δ and its spatial extent, L. Local compressional buckling of the pipe wall and tensile failure of pipeline are taken as the failure modes of interest. Critical values for the amount of ground movement and the spatial extent, which lead to compressive failure, δ_{cr} and L_{cr}, are determined for five grades of steel, various R/t ratios and burial conditions.

Three buried pipelines which were subject to longitudinal PGD during the 1994 Northridge California event are used to benchmark the proposed failure criterion. The proposed analytical procedure suggests that two of the three pipes, the Los Angeles Dept of Water and Power Granada Trunk Line and the So. Cal. Gas (SCG) Line 120; both located along Balboa Blvd. at the Northern end of the San Fernando valley would suffer damage. The observed behavior matches the predicted behavior. The third line, the newer SCG line along McLennan Ave., is also considered. For the third line, we postulate as to why it was not damaged. There are two other lines along Balboa which were undamaged by the PGD. These two lines are excluded from consideration because of a lack of information on certain parameters.

Finally the effects of an expansion joint which was installed in the LADWP line after the 1971 San Fernando earthquake are discussed in detail.

INTRODUCTION

Permanent ground deformation refers to non-recoverable soil movement due to landslides, surface faulting or liquefaction induced lateral spreading. In general a pipeline would be exposed to some combination of transverse PGD (ground movement perpendicular to the pipe's axis) and longitudinal PGD. The longitudinal PGD leads to axial tension and compression in a pipe whereas transverse PGD leads to flexural. O'Rourke and Nordberg (1992) conclude that longitudinal PGD is more likely to result in failure in continues pipeline. Herein we restrict our attention to longitudinal PGD due to lateral spreading induced by liquefaction of a subsurface layer.

Based on observed patterns of longitudinal PGD from Japan, we use an idealized Block pattern (uniform movement δ of a mass of soil having length L) to evaluate pipe strain. Assuming constant friction force per unit length at the soil pipe interface, the stress and strain in a pipeline are investigated using a Ramberg-Osgood model for the steel pipe material. Critical values for δ and L which result in wrinkling of the pipe wall in compression are determined for five grades of steel, various R/t ratios and various burial conditions.

The analysis method is applied to pipelines along Balboa Blvd., which were subjected to longitudinal PGD during 1994 Northridge event.

ANALYSIS PROCEDURE FOR LONGITUDINAL PGD

There are two cases to be considered for a buried pipeline subject to a Block pattern of longitudinal PGD. In Case I, the amount of ground movement δ is large and the pipe strain is controlled by the length, L, of the PGD zone. In Case II, L is large and the pipe strain is controlled by δ.

The distribution of pipe axial displacement, force and strain are shown in Figure 1 for Case I and in Figure 2 for Case II, where f_m is the friction force per unit length at the pipe-soil interface and L_e is the effective length over which f_m acts. The friction force can be expressed by:

$$f_m = (c + \mu \Upsilon H)\, \pi D \tag{1}$$

where c is the soil cohesion or the undrained shear strength, μ is the coefficient of friction at the soil-pipe interface, Υ is the effective unit weight of soil, H is the depth to centerline of the pipeline and D is the diameter of pipe.

Over the segment AB, the force in the pipe is linearly proportional to the distance from Point A. Using a Ramberg Osgood model for the pipe material, the pipe strain and displacement can be expressed as follows:

$$\varepsilon_{max} = \frac{\beta_p L_e}{2E} \left\{ 1 + \frac{n}{1+r} \left(\frac{\beta_p L_e}{2\sigma_y} \right)^r \right\} \tag{2}$$

$$\delta_{max} = \frac{\beta_p L_e^2}{E}\left\{1 + \frac{2}{2+r}\cdot\frac{n}{1+r}\cdot\left(\frac{\beta_p L_e}{\sigma_y}\right)^r\right\} \tag{3}$$

where n and r are Ramberg-Osgood parameter, E is the modulus of elasticity of the steel pipe, σ_y is the effective yield stress, β_p is the pipe burial parameter and Le is the distance from point A to point B in Figure 1 and Figure 2.

For sandy soil (c=0), the pipe burial parameter β_p and the frictional coefficient μ can be computed by:

$$\beta_p = \frac{\mu \Upsilon H}{t} \tag{4}$$

$$\mu = k\tan\phi \tag{5}$$

where ϕ is the angle of shear resistance of sand and k is a coefficient which depends upon the condition at soil pipe interface.

Hall and Newmark (1977) suggest that compressional wrinkling in a pipe normally begins at a strain of 1/3 to 1/4 of the theoretical value of ε_{theory}=0.6 t/R, where t is the pipe wall thickness and R is the pipe radius. Herein we assume that the onset of wrinkling occurs at the midpoint of the range established by Hall and Newmark, that is:

$$\varepsilon_{cr} = 0.175\frac{t}{R} \tag{6}$$

The strain associated with tensile rupture is on the order of 3% to 5% (Newmark and Hall, 1975). In this study we use an ultimate tensile value of 4%, beyond which the pipeline is considered to have failed in tension.

The critical length L_{cr} is established from Equation 2. Setting the peak strain equal to the critical strain, we solve for the corresponding effective length. The critical length, the length of the PGD zone leading to failure, is then twice this effective length The critical displacement δ_{cr} is established from Equation 3 by setting the effective length L_e equal to half the critical length L_{cr}.

The critical values, δ_{cr} and L_{cr}, which result in wrinkling of the pipe wall in compression are given in Figure 3 for grade-B steel and in Figure 4 for X-60 steel for various combination of the pipe burial parameter β_p and the pipe radius over thickness ratio R/t. The analysis procedure suggests that the pipeline will be damaged if both L and δ are larger than their critical values (that is if the actual L and δ are above and to the right of the δ_{cr}, L_{cr} point).

Note that the potential for damage decreases (δ_{cr} and L_{cr} become larger) as the pipe burial parameter decreases. Also for a given value of the pipe burial parameter, the potential for damage decreases as the R/t ratio decreases. Finally the beneficial effects of higher grade steel are most noticeable at small R/t ratios.

For the pipes considered herein, the R/t values are large enough that the wrinkling strain from Equation 1 is in all cases smaller than the strain associated with tensile rupture. Hence the wrinkling occurs first in the straight pipeline crossing the longitudinal PGD zone considered here. Once wrinkling occurs, a determination of wether an additional tension failure would occur at the head of the PGD zone is complicated, and will not be discussed in detail here. That is, once a failure (in our cases when wrinkling occurs) we do not attempt to determine if additional failure occur in the line.

BALBOA BLVD. CASE HISTORY

The Northridge earthquake occurred on January 17, 1994 in the San Fernando Valley. The epicenter was about 1 mile south-southwest of Northridge or 20 miles west-northwest of Los Angeles at a focal depth of 12 miles (15 km). The surface wave magnitude assigned by the National Earthquake Information Center was Ms=6.7. The maximum horizontal and vertical ground acceleration recorded closest to the Balboa Blvd. site were 0.98g and 0.52g, respectively (Hall, 1994).

Figure 5 shows the map of major pipelines, ground deformation zones and locations of pipeline damage on Balboa Blvd. An area between the two shadowed belts in Figure 5 moved to the south due to Northridge event. The ground movement (essentially directly south or downslope) was parallel to Balboa which is a North/South street. According to O'Rourke and Palmer (1994), the pattern of ground deformation suggests that lateral spreading of the alluvial fan sediments took place. Nearby boreholes show loose silty sands at depths of 30 to 40 feet (9 to 12 m).

A total length of the PGD zone was about 500 yards (457 m). At the southern end of the zone, sidewalk overlapping and sidewalk buckling as shown in Figure 6 suggest an abrupt compressive ground movement of roughly 21 inches (0.53 m, O'Rourke, 1994). At the northern end of the zone, gaps in sidewalks and ground cracks as well as gaps in curbs as shown in Figure 7 suggest a tensile ground movement of at least 18 inches (0.46 m). Hence for the purpose of analysis we use L=457 m and δ=0.50 m.

Three out of five gas and water main pipelines along Balboa Blvd. were damaged by the Northridge earthquake. There were compressive and tensile failures in the 49 inch (1240mm) diameter Granada Trunk Line, the 68 inch (1730 mm) diameter Rinaldi Trunk Line and the 22 inch (550 mm) diameter gas line (old Line 120) in the compressive and tensile zones of ground deformation, respectively. The other lines are a 30 inch (750 mm)-diameter gas transmission line and 16 inch (400 mm)-diameter petroleum pipeline, which survived in the Northridge earthquake. In addition there is a new 24 inch (600 mm) gas line (new Line 120) located along McLennan Ave. which was subject to similar PGD as along Balboa but was apparently undamaged. Herein we consider only the Granada Trunk Line and both the old and new Line 120 because of a lack of information for the other lines.

Granada Trunk Line

As shown in Figure 5, the Granada Trunk Line installed in 1956 is 49 inch (1240 mm) in diameter and has 5/16 inch (7.9 mm) wall thickness with butt welded joints. Based on field observations by the first author, the pipe was buried with 5 feet (1.5 m) of cover over its top and had 1/2 inch (13 mm) inside and 1 inch (25 mm) outside mortar coatings. After the 1971 San Fernando earthquake, a 10 inch (254 mm) Dresser Coupling with 2 to 3 inches (51 to 76 mm) allowable movement was installed at a location a "couple hundred" feet north of Lorillard St. The grade of steel for this pipe is unknown.

As summarized in Table 1 herein we assume Grade B steel with σ_y=33 ksi, n=10, r=100, burial depth to top of pipe =5.0 feet (H=7 feet) and unit weight of soil Υ=105 lb/ft^3, angle of shearing resistant ϕ=35^o. Based on Elhmadi and O'Rourke (1989), we take k=1.0 for concrete mortar/soil interface, which results in a friction coefficient μ=0.7 and a pipe burial parameter β_p=11.5 psi for the Granada Trunk Line.

Using β_p=11.5 psi and R/t=78 for the Granada Trunk Line, the critical length of the PGD zone is about 150m and the critical amount of the PGD is about 0.1 m from Figure 3 for a compressive failure strain of 0.0022. Both of the length of the PGD zone L=1500 feet (457 m) and amount of the PGD δ =20 inch (0.5 m) are larger than the critical values. Hence the analysis procedure indicates that, at least, the Granada Truck Line fails in compression. This computation for the Granada Trunk Line is shown in Table 2.

As noted above, the state of strain and stress in the line after a wrinkling failure is complex, and a detailed discussion is not attempted here. However it can be noted that if the lines were locally reinforced in the abrupt ground compression zone such that wrinkling would not occur, the analysis procedure suggests that the Granada Trunk line would suffer tensile failure since the actual values of L=457 m and δ=0.5 m are larger than δ_{cr} and L_{cr} for tensile failure in Table 2. In addition once wrinkling occurs, the tensile strain at the tension zone tends to increase since the wrinkled zone can no longer take its full share of the applied load ($f_m L/2$).

Line 120

Old Line 120 (transmission gas pipeline) is 22 inch (550 mm) in diameter, 0.281 inches (7.2 mm) in wall thickness and was constructed in 1930 with unshielded electric arc girth welds. It was made of Grade B steel. The line was operated at about 175 psi (1.2 MPa) at the time of the earthquake. Line 120 had been scheduled for replacement in the Granada Hills area before the 1994 Northridge earthquake. Old Line 120 had a compressive shortening at the ground compression zone, and a separation between the failed ends at the ground tension zone of approximately 10 inch (250 mm). The compressive shortening and tensile failure occurred at welded joints. The new 24 inch (600 mm)-diameter pipeline (new Line 120), with electric arc girth welds, X-60 steel, and 0.25 inch (6.4 mm)-thick wall, had been constructed parallel to the older 22 inch-diameter line (old Line 120) along McLennan Avenue as shown in Figure 5. It had not been opened for gas flow at the time of the earthquake. It crossed similar zones of tensile and compressive PGD, however it was not damaged.

The properties of both old Line 120 along Balboa Blvd. and new Line 120 along McLennan Ave. are shown in Table 1. The buried depth of 4 feet (1.2 m, ground surface to top of pipe) for the old Line 120 was measured by the first author. That same value is assumed to the new Line 120. Assuming k=0.9 for gas pipeline without concrete/mortar coating, computations for both old and new of Line 120 (following the same procedure as that for Granada Trunk Line) are shown in Table 2.

The actual length of PGD zone and the amount of PGD are 457 m and 0.5 m which are larger than failure criteria for old Line 120. Hence the analysis procedure suggests that old Line 120 would likely be damaged in both the compressive and tensile zones of PGD. For new Line 120, the critical length and displacement for compressive failure are 331 m and 0.38 m respectively. Hence the analysis procedure indicates that this line should have failed by wrinkling. Apparently the line did not fail. This discrepancy could be due to a combination of effects. First the actual buried depth may be less than 4 feet (1.2 m) assumed herein. Secondly the length and amount of PGD movements along McLennan Ave. may have been less than that along Balboa Blvd. Finally and somewhat more likely, the pipe may well have followed under the street, that is a 90^{o} elbow installed south of the ground compression zone. The presence of such an elbow or bent would reduce the compression axial stress and strain in that leg. Note that the possible presence of an elbow is not currently included in the analysis procedure. In addition because the actual displacement of the tensile PGD zone (0.5 m) is less than the critical value of 1.68 m, the analysis procedure suggests that no tensile failure for new Line 120 occur, which matches the observed behavior.

DISSCUSSION

The calculation for the Granada Trunk Line presented above does not take into consideration the presence of an expansion joint, which according to LADWP personnel, is located "a couple of hundred" feet north of Lorillard St.(possibly 140 m away from the location of tensile failure). The expansion joint was a Dresser type with an allowable relative movement of 2 to 3 inches (51 to 76 mm). Based on the calculation shown above, the critical length of PGD zone for Granada Trunk line is 150 m. Hence an expansion joint located about 140 m to the North of the ground tension zone would have no influence on the response of the pipeline because the expansion joint would be located outside the interaction region (140 m > 150 /2 =75 m). Even if the expansion joint is installed in the tensile zone of PGD, it would not greatly improve the performance of the pipeline because the allowable movement of the joint is too small relative to the amount of PGD.

If a single unlimited movement expansion joint is installed in a location near the margin of PGD zone, one can see from the distribution of pipe axial forces, shown in Figure 8 for case I, that the expansion joint actually make the situation worse.That is, if the single expansion joint is located just North of the PGD zone, the pipe strain at the compression zone increase since the total load, $f_m L$, is no longer shared equally at both the compression and tension zones.

Installation of two expansion joints, one to the North of the ground tension zone and another to the South of the ground compression zone, would reduce stress and strain in the pipe. However such an approach would require a prior knowledge of the actual location of the PGD zone as well as reasonable estimates of both L and δ. Hence, the use of high grade steel with modern welding technique, shallower burial depths, reduced friction at the soil pipe interface and/or decreased R/t ratios are probably somewhat better methods to reduce pipeline damage.

CONCLUSION

In this paper, an analysis procedure for pipeline subject to longitudinal PGD is reviewed. The failure criteria are used to predict damage in the Los Angeles DWP Granada Trunk Line and gas pipeline (Line 120) along Balboa Blvd. The analysis shows that the failures of DWP Granada Trunk Line and old Line 120 in 1994 Northridge earthquake are predicted by the analysis procedure.

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Table 1 Properties of Three of the Pipeline in Balboa Lateral Spread Zone

Item	D (inch)	t (inch)	Material	Location	Installed Data	Performance
Granada Trunk Line	49	0.313	Grade-B	Balboa Blvd.	1956	Damaged
Old Line-120	22	0.281	Grade-B	Balboa Blvd.	1930s	Damaged
New Line-120	24	0.250	X-60	McLennan	After 1971	Survived

Table 2 Computation of Pipe Parameters

Item	Frictional Coeff. μ	R / t	β_p (pci)	Compression L_{cr}	Compression δ_{cr}	Tension L_{cr}	Tension δ_{cr}
Granada Trunk Line	0.70	78	11.5	149 m	0.09 m	154 m	0.15 m
Old Line-120	0.63	39	8.2	211 m	0.13 m	217 m	0.21 m
New Line-120	0.63	48	9.2	331 m	0.38 m	422 m	1.68 m

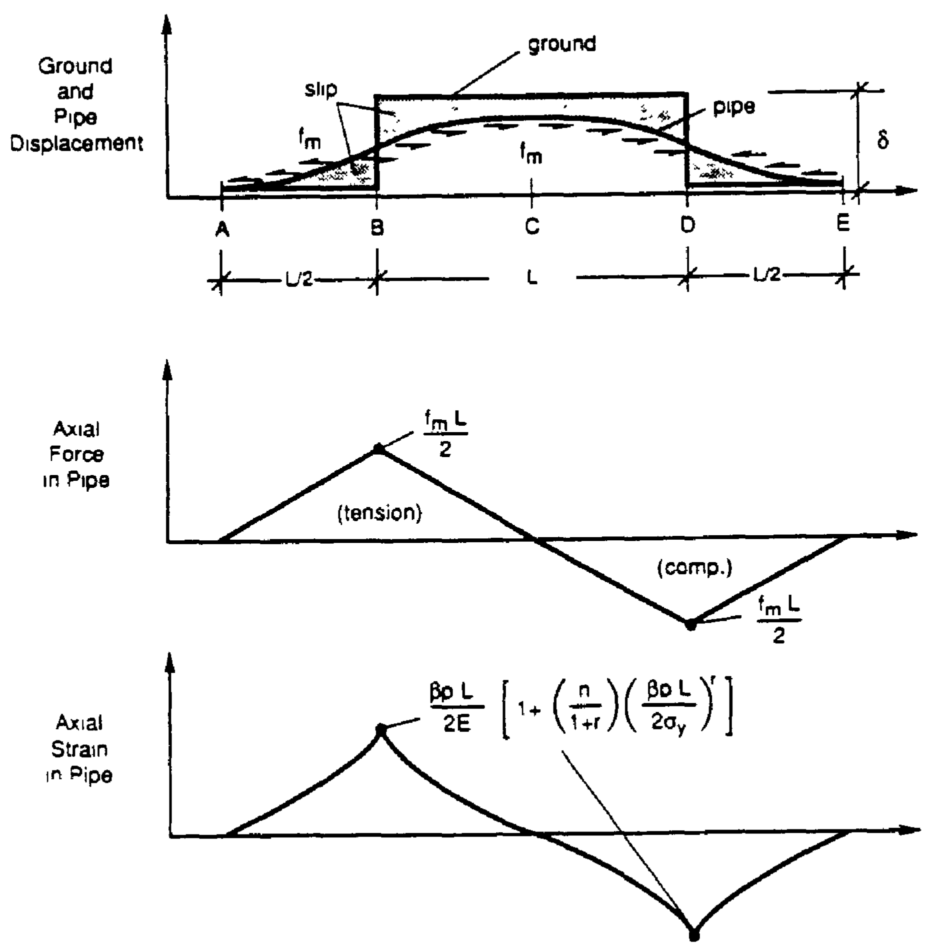

Figure 1 Pipe Axial Displacement, Force and Strain Due to Longitudinal PGD for Case I

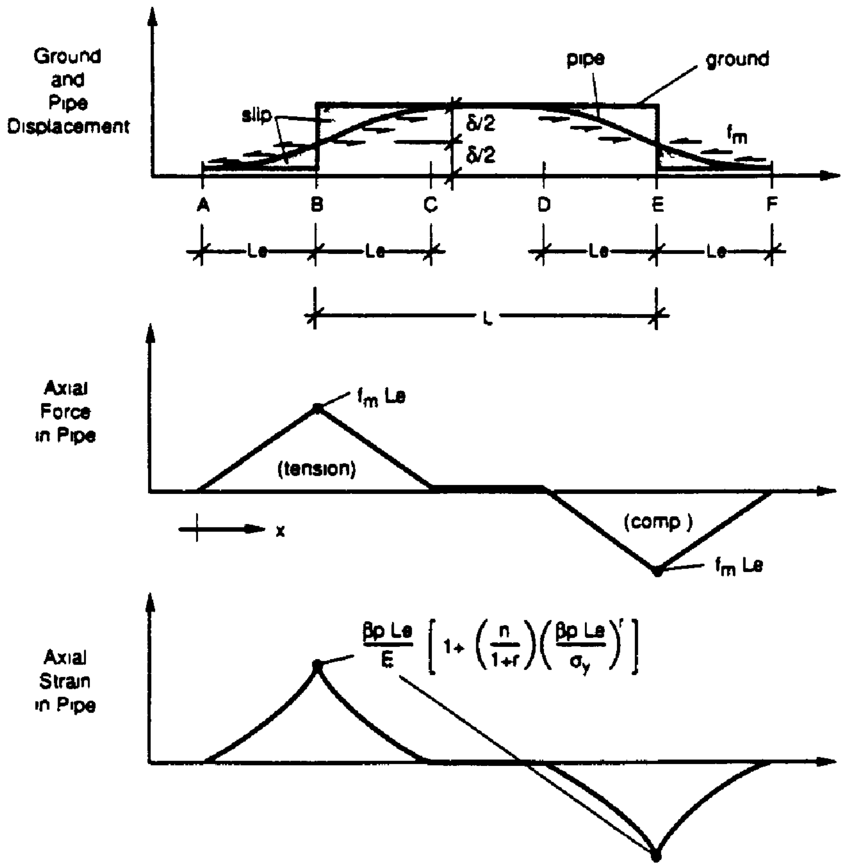

Figure 2 Pipe Axial Displacement, Force and Strain Due to Longitudinal PGD for Case II

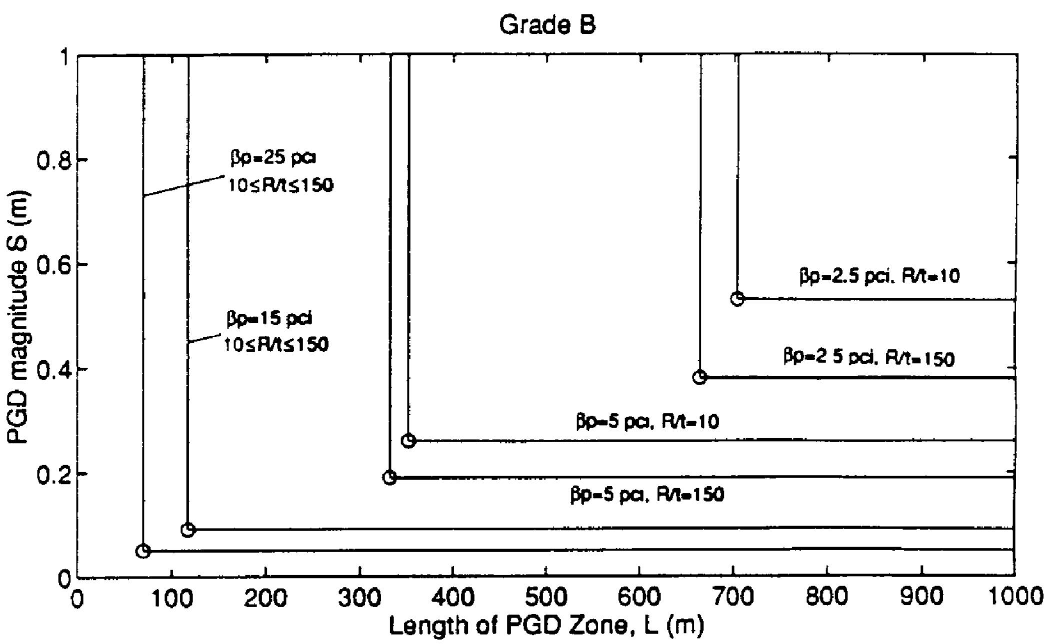

Figure 3 Critical Length L_{cr} and Displacement δ_{cr} for Grade-B steel in Compression

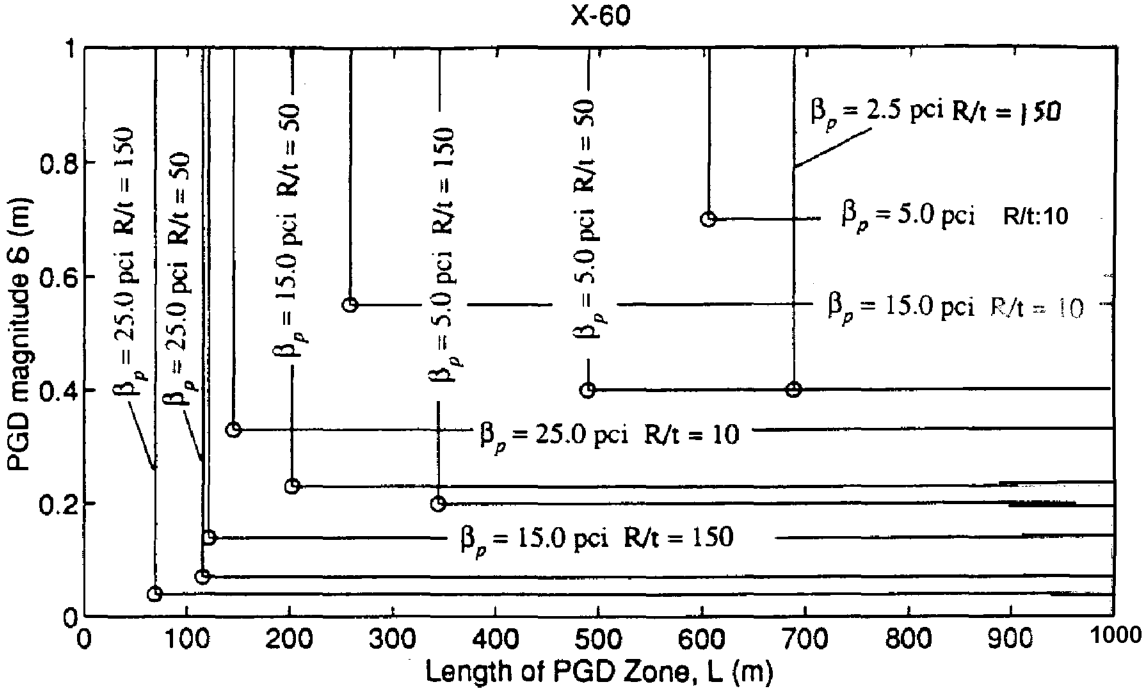

Figure 4 Critical Length L_{cr} and Displacement δ_{cr} for X-60 Steel in Compression

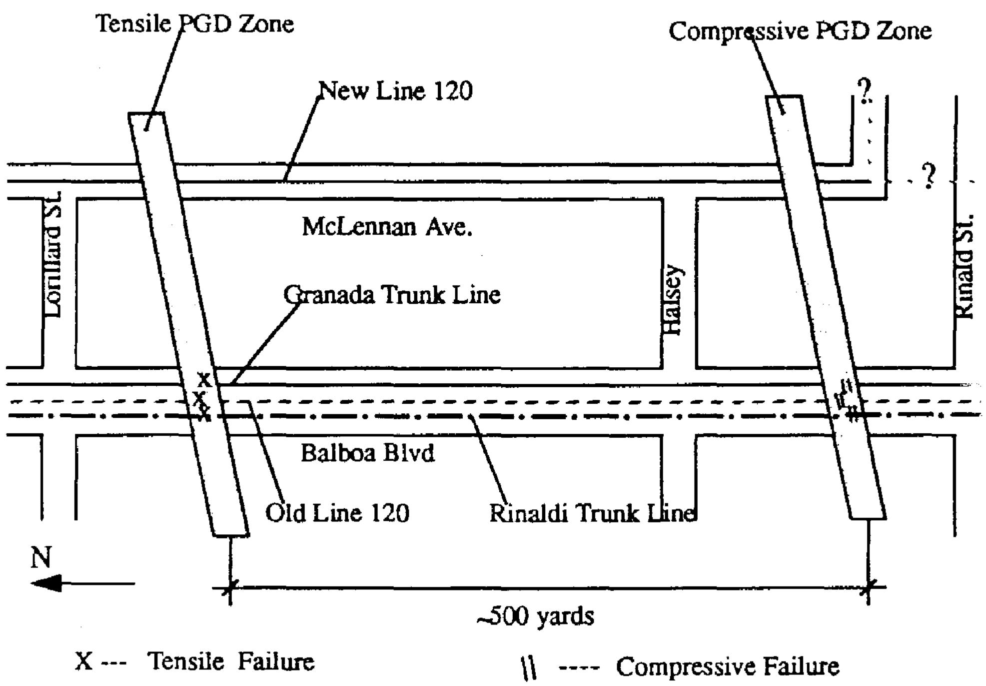

Figure 5 Map of Major Pipelines, Ground Deformation Zones and Locations of Pipeline Damage on Balboa Blvd.