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Tension/bending behaviour of buried pipelines subject to fault movements in earthquakes

T. Ariman & B.-J. Lee
University of Tulsa, Okla., USA

ABSTRACT: This paper deals with the tensile failure of buried pipelines subject to abrupt fault movements. The pipe is modeled as a thin cylindrical shell which is essentially semi-infinite. The Sanders' nonlinear shell theory is used with the inclusion of soil effects, and a simple flow theory of plasticity. A number of parametric studies are carried out and discussed to identify some design parameters of buried pipelines.

1 INTRODUCTION

Earthquake safety of utility systems and in particular buried pipelines have attracted a great deal of attention in recent years (Ariman 1979, Shibata 1980, Ariman 1983, ASCE 1977 and 1981). The most important characteristics that distinguish buried pipeline systems from other types of structure and facilities are: 1) their overall size which cover large areas and subject to a variety of geotechnical hazards and 2) they form networks so that optimal performance requires a system-wide evaluation for which probability and reliability techniques need to be utilized.

A pipeline system generally is built up over a large territory so that its response to permanent earthquake ground movements will be greater than that of a facility occupying a small area. Many water, oil and natural gas transmission pipelines in California must cross active faults, whereas individual buildings can be sited away from these features. Permanent ground movements should be considered during the design of new pipelines and for risk assessment and retrofitting strategies in existing systems. Measures for mitigating the effects of earthquake displacements should begin with understanding the principal forms of permanent movement.

During an earthquake, permanent differential movements of ground can be caused by faulting, soil liquefaction, slope instability and local compaction of the ground (O'Rourke 1980, O'Rourke 1984). Buried pipelines can be damaged either by permanent movements of this type and/or by seismic ground waves. For instance surface faults, landslides and local compaction of the ground in the 1972 San Fernando earthquake caused the rupture and/or buckling failures in water, gas, and sewage lines (O'Rourke 1980, O'Rourke 1984) with high concentration of pipeline damage along the Sylmar segment of the San Fernando fault (US Geological Survey Staff 1971, Youd 1978). Similarly, the 1972 Managua earthquake caused surficial displacement along four prominent strike-slip faults through the downtown area of the city and nearly all water mains crossing the faults ruptured. Although relatively old and/or corroded pipelines have been damaged by wave propagation (Steinbrugge 1970), seismic ground shaking alone generally cannot be expected to cause any major rupture and/or buckling failure in properly designed, manufactured and laid out welded steel pipelines (Muleski 1979, Chen 1980, Lee 1980, Ariman 1981). This outcome is in complete agreement with the investigation of Youd (Youd 1973). After examining the 1971 San Fernando earthquake in detail, he concluded that strong and ductile steel pipelines withstood ground shaking but were unable to resist the large permanent ground deformations generated by faulting and ground failure.

Furthermore, it is important to recognize that permanent differential movements may be caused by any earthquake and that the movements can assume a variety of patterns depending on local soil conditions and the presence of faults. Therefore, the response of buried pipelines to permanent ground movement is an important part of the lifeline earthquake engineering and its investigation is in line with the recommendations of a number of committees and individual researchers.

2 TENSION/BENDING BEHAVIOR

Frequently, a specific type of ground failure in a fault zone will cause both tension and compression failures, depending on the orientation of the pipeline and location within the zone of movement (Fig. 1). A thin cylindrical shell model of the pipeline may be required to simulate the local structural behavior, depending on the form of the buckling and tensile failure modes. Thus, a shell model is chosen herein to analyze tension and bending behavior.

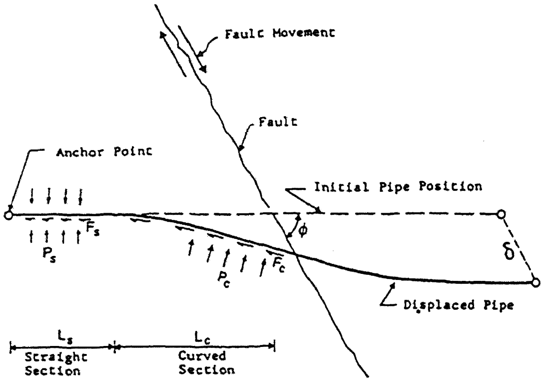

Figure 1. Buried pipe deformation due to strike-slip fault movement

Regarding tensile behavior due to large abrupt fault movements, a number of investigations have been conducted based on a beam model. Among these are three well-known procedures: Newmark-Hall procedure (Newmark 1975), Kennedy, et al. procedure (Kennedy 1977) and finite element approach (O'Rourke 1980). Wang (Wang 1984) extended Kennedy, et al. procedure based on a beam on an elastic foundation for the straight portion of the pipe, and the curved portion is again assumed to have a constant radius of curvature. However, it should be noted that under large fault displacements, the pipe axial stress may exceed the yield stress for quite a long distance away from the fault. Thus, the conjunction point between the elastic and inelastic zones may extend even into the straight portion of the pipe.

In this paper, a shell model is used to investigate the tensile and bending behavior of pipelines subject to abrupt fault displacements. The pipe is assumed to be placed in a shallow trench, and readily conforms to the transverse components of fault motion. Thus, the tension of fault motion plus an additional extension due to the geometric distortion resulting from the transverse component of fault motion, are investigated. The Sanders' nonlinear shell theory (Sanders 1963) is used by including soil effects, and a simple flow theory of plasticity (Murphy 1971) is introduced. Some typical result of the analysis for certain key variables, such as the crossing angle of pipeline/fault intersection, burial depth, pipe diameter, and soil effects are presented.

3 SELECTED RESULTS

A series of parametric studies are carried out to further understand the pipe tensile performance under the abrupt fault motion based on a cylindrical shell model. The X-60 grade pipes are considered to be 600 ft long, 42 in. in diameter, 0.562 in. in wall thickness, placed in loose to moderately dense sand with a depth cover of 3 ft with a fault crossing angle (ϕ) of 70 degrees.

Table 1. The influence of ϕ on ϵ_b (%)

δ (ft) \ ϕ	30°	40°	50°	60°	70°	80°
5	0.580	0.583	0.636	1.015	1.138	1.216
10	0.549	0.550	0.555	0.566	0.586	1.132
15	0.536	0.537	0.542	0.549	0.562	0.841
20	0.529	0.529	0.533	0.540	0.551	0.579

Some of the characteristic results for bending strains are shown by Tables 1-4. The effects of fault crossing angle (ϕ) and fault displacements (δ) on bending strains are shown in Table 1. It is clear that the bending strains do not vary significantly for smaller angles, $\phi = 30^{\circ}-40^{\circ}$, despite a large increase in fault displacements from 5 ft to 20 ft since the axial force reaches a plateau. It is found that the axial force is not affected significantly by the bending strain and the axial strain is more than the corresponding bending strain or the axial strain far exceeds the yield strain. On the other hand, the bending rigidity is strongly affected by the magnitude of the axial strain, i.e. under small axial strains the pipe would withstand larger bending strains for smaller fault displacements or larger crossing angles.

Table 2. The influence of ϕ_s on ϵ_b (%)

δ (ft) \ ϕ	20^{o}	25^{o}	30^{o}	35^{o}	40^{o}	45^{o}
5	0.202	0.366	0.621	1.015	1.509	2.548
10	0.171	0.258	0.374	0.566	0.810	1.339
15	0.167	0.251	0.363	0.549	0.787	1.297
20	0.164	0.246	0.357	0.540	0.774	1.276

Table 3. The influence of H_c on ϵ_b (%)

δ (ft) \ H_c (ft)	1	2	3	4	5	6
5	0.484	0.744	1.015	1.256	1.626	1.933
10	0.291	0.423	0.566	0.691	0.886	1.057
15	0.283	0.412	0.549	0.672	0.863	1.026
20	0.278	0.405	0.540	0.661	0.847	1.007

Table 4. The Influence of D on ϵ_b (%)

δ (ft) \ D (in.)	30	34	38	42	46	50
5	0.699	0.807	0.917	1.027	1.137	1.250
10	0.386	0.446	0.509	0.571	0.635	0.698
15	0.375	0.434	0.494	0.555	0.616	0.679
20	0.369	0.427	0.486	0.546	0.607	0.668

The effect of the soil angle of shearing resistance ϕ_s on the pipe bending strain is shown by Table 2 for a variation range of 20^{o} to 45^{o}. For large values of ϕ_s bending strains increase substantially and if the axial tension strain cannot compensate for the corresponding compressive bending strain, local buckling may occur even for small fault crossing angles and under small fault displacements. In other words, even if the fault crossing angle is below 80^{o} it would be possible that the pipe could be buckled by bending alone. Therefore, considering a small increase in axial strain and a substantial increase in bending strain, it is recommended to have ϕ_s as small as possible to accommodate transverse movement of the pipe in fault crossings.

The effect of the burial depth H_c (ft) of the pipe on the bending strains is shown in Table 3. An increase in H_c would provide larger longitudinal and lateral soil resistances on the straight as well as the curved sections of the pipe. An increase in lateral forces causes larger bending strains which are not desirable. Therefore, as in the case of the axial buckling (Lee 1985) again a shallow burial depth is recommended for pipes which are subjected to tension and bending in active fault crossings.

An increase in the pipe diameter for a constant thickness causes larger cross-sectional area and larger bending rigidity for the pipe. Thus frictional forces and lateral soil resistance would increase. As shown in Table 4, the stated factors result in considerable increases in bending strains. However, this situation is compensated by a substantial increase in the bending rigidity for larger diameter pipes.

REFERENCES

Ariman, T. (Ed.) 1983. *Earthquake Behavior and Safety of Oil and Gas Storage Facilities, Buried Pipelines and Equipment*, PVP-77, ASME, New York, 478 pgs.

Ariman, T., S.C. Liu, and R.E. Nickell (Eds.) 1979. *Lifeline Earthquake Engineering-Buried Pipelines, Seismic Risk and Instrumentation*, PVP-34, ASME, New York, 285 pgs.

Ariman, T. and G.E. Muleski (1981). *A Review of the Response of Buried Pipelines Under Seismic Excitations*, Earthquake Engineering and Structural Dynamics, Vol. 9, 133-151.

Chen, C.C., T. Ariman, and L.H.N. Lee 1980. *Elastic Buckling Analysis of Buried Pipelines Under Seismic Loads*, ASME Paper 80-C2/PVP-75.

Kennedy, R.P., A.W. Chow, and R.A. Williamson 1977. *Fault Movement Effects on Buried Oil Pipeline*, Transportation Engineering Journal of ASCE, Vol. 103, No. TE5, pgs. 617-633.

Lee, B.J. and T. Ariman 1985. *Buckling of Pipelines Crossing an*

Active Fault, Seismic Performance of Pipelines and Storage Tanks, PVP-Vol. 98-4, Edited by A.C. Singhal and T. Ariman, ASME.

Lee, L.H.N, T. Ariman, and C.C. Chen 1980. *On Buckling of Buried Pipelines by Seismic Excitation*, ASME Paper 80-C2/PVP-75.

Muleski, G.E., T. Ariman, and C.P. Aumen 1979. *A Shell Model of a Buried Pipe in a Seismic Environment*, J. Pressure Vessel Technology, ASME, 101, 44-50.

Murphy, L.M. and L.H.N. Lee 1971. *Inelastic Buckling of Axially Compressed Cylindrical Shells Subject to Edge Constraints*, Int. J. Solid Structures, 7, 1153-1170.

Newmark, N.M. and W.J. Hall 1975. *Pipeline Design to Resist Large Fault Displacement*, Proc. of the U.S. National Conference on Earthquake Engineering 1975, Earthquake Engineering Research Institute, Oakland, CA.

O'Rourke, T.D., and M.A. McCaffrey 1971. *Buried Pipeline Response to Permanent Earthquake Ground Movements*, Proceedings of the Eight World Conference on Earthquake Engineering, Vol. 8, 215-222.

O'Rourke, T.D. and C.H. Trautmann 1980. *Analytical Modeling of Buried Pipeline Response to Permanent Earthquake Displacements*, Geotechnical Engineering Report 80-4.

O'Rourke, T.D. and C.H. Trautmann 1980. *Buried Pipeline Response to Permanent Earthquake Ground Movement*, ASME Paper 80-C2/PVP-78.

Sanders, J.L., Jr. 1963. *Nonlinear Theories for Thin Shells*, Quarterly of Applied Mathematics, Vol. 21, 21-36.

Shibata, H.T., T. Katayama, and T. Ariman (Eds.) 1980. *Recent Advances in Lifeline Earthquake Engineering in Japan*, PVP-43, ASME, New York, 158 pgs.

Steinbrugge, K.V., W.K. Cloud, and H.N. Scott 1970. *The Santa Rosa, California Earthquake of October 1, 1969*, U.S. Department of Commerce, Rockville, MD.

The Current State of Knowledge of Lifeline Earthquake Engineering, ASCE 1977 and 1981. New York.

U.S. Geological Survey Staff 1971. *Surface Faulting, The San Fernando, California, Earthquake February 9, 1971*, U.S. Geological Survey, Professional Paper 733, 55-76.

Wang, L.R.L. and Y.H. Yeh 1984. *Seismic Analysis and Design of Buried Pipeline for Fault Movement*, unpublished manuscript.

Youg, T.L., R.F. Yerkes, and M.M. Clark 1978. *San Fernando Faulting Damage Its Effect on Land Use*, Proc. Conf. Earthquake Engineering and Soil Dynamics, ASCE, Vol. 11, 1111-1125.

Youd, T.L. 1973. *Ground Movements in the Norman Lake Vicinity During San Fernando, California Earthquake of February 9, 1971*, U.S. Dept. of Commerce, Vol. III, 197-206.

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