PARAMETRIC INVESTIGATION OF BURIED PIPELINES UNDER SEISMIC ENVIRONMENTS

Leon Ru-Liang Wang (I)

SUMMARY

Recent studies have shown that buried water, sewer, gas and oil pipelines have been damaged heavily by earthquakes. This paper investigates seismic environments, which include ground straining and large ground movement. The analysis of buried pipeline responses under soil liquefaction environment will be outlined. Recommendations to mitigate pipeline damages will be made.

INTRODUCTION

Recent studies (1,2,3) have shown that buried gas, oil, water and sewer pipelines have been damaged heavily by earthquakes. The damages of these underground lifelines could cause major, even catastrophic disruption of essential services. Because of the importance of lifelines vis-a-vis the health, safety, service and supplies to the populace, lifeline earthquake engineering has become one of the most important areas of the earthquake engineering research. The state-of-the-art on lifeline earthquake engineering has been presented at the Seventh World Conference on Earthquake Engineering (4). In general, there are three causes of seismic hazards to these underground pipelines, namely, a) soil straining induced by seismic ground shaking, b) differential ground movement/rupture along fault zone and c) soil liquefaction induced by ground shaking. The paper will present the results of the parametric investigation on the responses of buried pipelines subjected to ground staining environments, which have been conducted by the author and his students for several years. Since there is no analytical study for buried pipeline under soil liquefaction environment, this paper will outline a preliminary analysis procedure, which upon modification, may lead to a meaningful solution for buried pipeline under adverse environment.

RESPONSE BEHAVIOR OF BURIED PIPELINES UNDER SEISMIC GROUND STRAINING ENVIRONMENT

Although the effects of wave propagation alone to the damages of buried pipelines located under uniform firm soil have been observed to be relatively minor (5), the affected area is rather large. To assist the development of future design criteria, this paper describes the response behavior of buried pipelines due to seismic ground shaking, which creates the ground straining environment for the pipelines.

Under ground shaking environments, the response behavior of buried pipelines during seismic shaking has been found to be predominant in the axial direction of the pipelines and the dynamic effect to be negli-

(I) Professor of Civil Engineering and Environmental Science, University of Oklahoma, Oklahoma, USA

gible (6), this paper is to present the response behavior of long buried pipelines due to seismic excitations in the direction of the pipeline axis by a simplified quasi-static analysis model (7). Fox (8) first implemented an elastic analysis computer program and the results have been presented elsewhere (9,10). Subsequently, Serna (11) modified the elastic formulations to include the yielding characteristics of the joint springs and the slippage strength of the soil. The results of this elasto-plastic analysis are given in a recent report (12). Since the details of the derivations and the computer results have been given in Reference 7 to 12. This paper briefly describes the formulations and conclusions of the analysis.

A long buried piping system model consisting of n-segments is shown in Fig. 1. A pipe segment has axial stiffness (Ea/L) and a node at each end. The joints are represented by elasto-plastic springs. The resistance forces that develop between the soil and the pipe segments are represented by distributed elasto-plastic soil resistance springs.

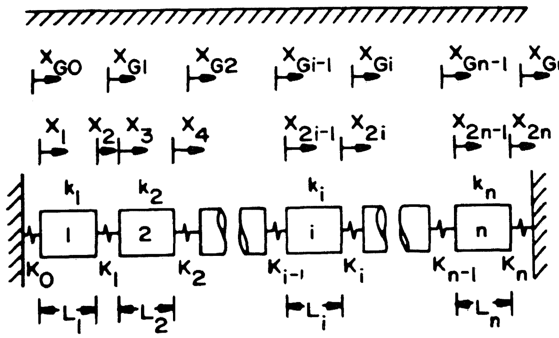

Fig. 1 Schematics of a Segmented Pipelines

The equation of static equilibrium, obtained from the variation of the total strain energy in the soil-structure interaction system, are as follows:

$$\underset{2n \times 2n}{[K_{system}]}\ \underset{2n \times 1}{\{X\}} = \underset{2n \times 2n}{[K_{soil}]}\ \underset{2n \times 1}{\{X_G\}} \qquad (1)$$

where $[K_{system}]$ and $[K_{soil}]$ are the symmetrical tridiagonal structural system and soil resistance matrices respectively, $\{X\}$ is the nodal axial displacement vector and $\{X_G\}$ is the ground displacement vector which varies with time. Note that this general model has 2n degrees of freedom. The solution of static pipe motion $\{X\}$ shown in Eqn. (1) depends on the inputs of the ground motion $\{X_G\}$. Since $\{X_G\}$ is a function of time, the solution of $\{X\}$ is also a function of time. Thus, the analysis is quasi-static.

The analysis model has the capabilities to accept various parameters such as variable length, cross sectional area and Young's modulus of pipe segments; variable joint spring stiffnesses and yield strengths; variable end conditions, variable soil spring constants and slippage strengths; variable time delay of travelling waves and waveforms. Since some of the early results have been published (9,10), this paper presents the parametric investigations given in the recent report (12).

One parametric investigation is to check the effects of geotechnical interfaces (change of soil stiffnesses), geological interfaces (change wave propagation speeds) and seismological interfaces (change of wave forms) within a pipeline. For this study, a 20 segment pipeline is divided into 2 10-segment regions and subjected to 1940 El Centro Earthquake. Only elastic response is considered and only one parameter is changed at one time. The results of pipeline strains for the changes of soil stiffnesses, wave propagation speeds and wave forms are presented in Figs. 2 to 4, respectively.

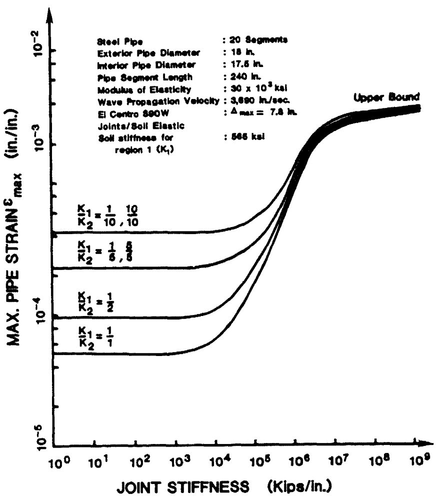

Fig. 2 Effect of Changing Soil Stiffness

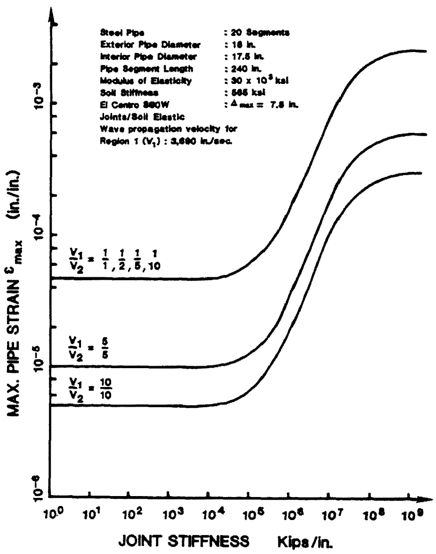

Fig. 3 Effect of Changing Wave Propagation Speed

In Fig. 2, the soil stiffness in Region 2, K_2, is varied from 1 to 10 times greater than K_1. The maximum pipe strain occurs near the interface and always in the region with higher soil stiffness. In Fig. 3, the traveling wave speed for Region 2, V_2 is varied from 1 to 10 times greater than V_1. The maximum strain occurs again near the interface, but in the region with lower traveling speed. Finally, in Fig. 4, three types of wave form changing are investigated: (1) the magnitude of the earthquake wave is increased or decreased 5% and 10% for Region 2 as compared to Region 1; (2) the wave form of Region 2 is reversed from that of Region 1 and (3) the wave in Region 2 is different from Region 1 by a time delay of 0.5 second and 1 second. One can see from Fig. 4 that the magnitude of ground displacement (increasing or decreasing by 5 to 10%) does not change the response very much. The reversed wave form gives the highest pipe strain. Similar conclusions have been found for relative joint displacements.

The second parametric investigation is to check the effects of ultimate joint spring strengths and soil slippage strengths on pipeline responses. In this study, all geotechnical, geological and seismological properties remain constant over the entire pipeline. Either joint spring or soil spring will yield at one time. The results of pipe strain responses for various ultimate values of joint and soil springs are shown in Fig. 5 and 6, respectively. One can see from these figures that the pipe strain will be smaller for smaller values of either joint or soil resistant strength. Again similar conclusions apply to the relative joint displacement responses.

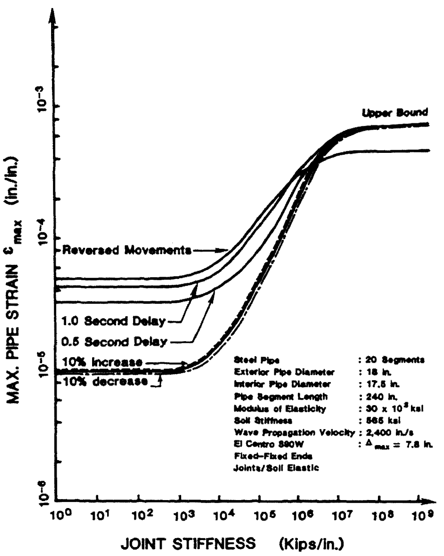

Fig. 4 Effect of Wave Forms

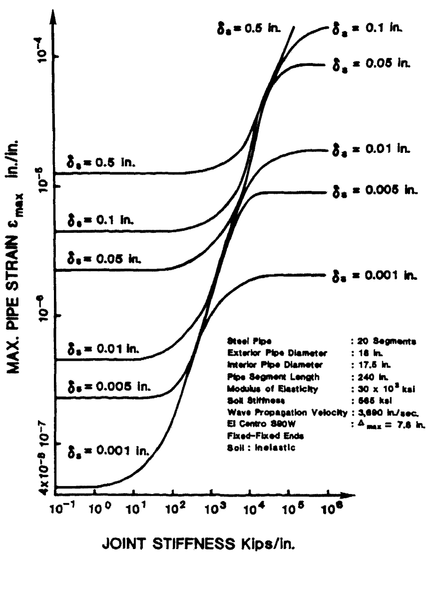

Fig. 5 Effect of Soil Strength

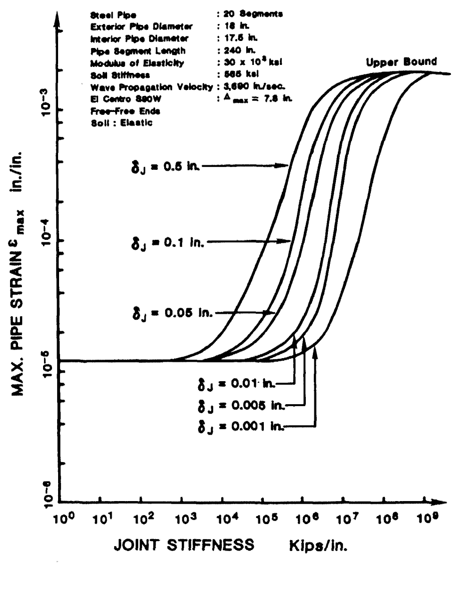

Fig. 6 Effect of Joint Strength

ANALYSIS OF BURIED PIPELINES UNDER FAULT MOVEMENT ENVIRONMENT

Damages of pipelines are frequently associated with fault movements. Only analysis for continuous buried pipelines subjected to tensive strike slips have been studied by Newmark and Hall (13) and later extended by Kennedy et al. (14). Similar analysis for segmented pipeline has been proposed by O'Rourke and Trautman (15). In the analysis, the pipeline is assumed to have only axial stiffness like a flexible cable. Without bending term, the results may be unconservative.

Under the direction of the author, Yeh (16) extends the Newmark-Hall-Kennedy approach to include bending stiffness and beam on an elastic foundation at the far end of the pipeline. Fig. 7 shows a schematic diagram of the proposed model for shallow buried pipeline deflection resulting from a strike-slip fault movement. This problem requires the equilibrium on the deformed position (large deflection theory) of the pipeline and the compatibility of the inelastic elongation (elasto-plastic pipe material) to geometric deformation. The governing equations are solved by an interative procedure. The parameters involved are area and moment of inertia of pipe, yield strength of material, elastic and passive resistance of surrounding soil, frictional force to axial pipe motion, fault movement and angle, buried depth etc.

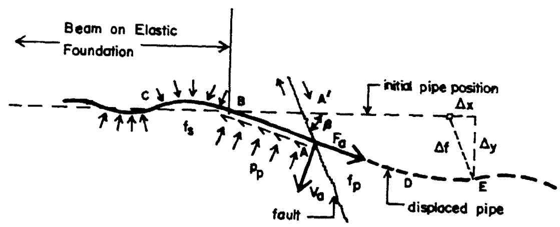

Fig. 7 Schematics of Pipeline Under Fault Movement

The effects of the soil parameters (represented by the buried depth) to a 42 in. in diameter, 0.652" thick, x-60 steel pipeline subjected to a 20 ft. fault movement are shown in Fig. 8. It is seen from this figure that both the axial stress at point A (mid-point of fault movement) and the combined axial and bending stress at point B (far end from fault at interface for beam on elastic foundation) increase with buried depth. Obviously, if we only consider axial stress, the pipeline is not critical under the conditions

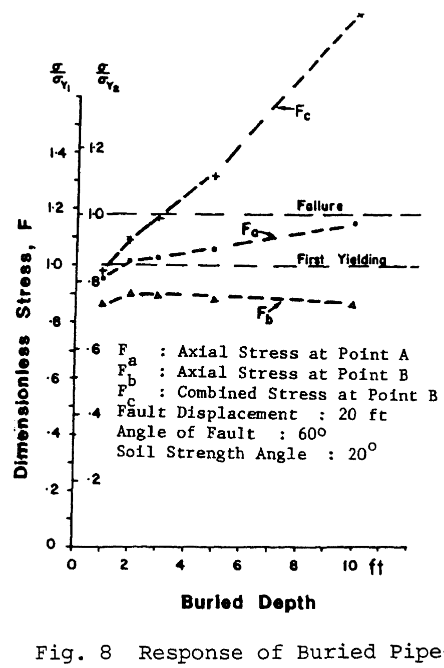

Fig. 8 Response of Buried Pipeline to Fault Movement

specified. However, the combined stress at point B shows that the pipeline will fail at buried depth up to 4 ft.

The general conclusions for buried pipeline subjected to large fault-movement are: (1) pipeline stress will increase with buried depth, (2) pipeline is more critical when buried under harder soil and (3) axial stress is more critical when pipeline is parallel to fault movement direction, which bending stress is dominant when pipeline is normal to fault movement.

PIPELINE UNDER SOIL LIQUEFACTION ENVIRONMENT

With regard to the underground pipelines subjected to soil liquefaction, the general failure modes can be found as pull-out, breaking, buckling, and crushing. An obvious example is the buckling damage of lifelines in a liquefied region during Tangshan Earthquake (17). Recently, attempts have been made to correlate pipeline damage due to geological and other conditions (6) (e.g. pipe size, etc.). but the influence of soil liquefaction to underground pipelines have been excluded in these investigations.

Although extensive amounts of research has been done in the past 10-15 years in various areas of soil liquefaction, most of these works, however, were related to evaluating liquefaction potential and prediction generation and dissipation of pore water pressure during earthquake. Very little work has been done towards analyzing or explaining the responses or failure mechanisms of buried lifelines subjected to earthquakes having potential for causing liquefaction.

To serve as a feasibility study, a simplified model (Fig. 9) for the Seismic response of buried pipelines in a soil liquefiable zone has been developed (16). In this model, the buried pipeline is considered as a beam (actually a column) embedded in two different elastic foundations subjected to an imposed external displacement function. The spring constant of one foundation remains constant (unliquefiable zone), while the stiffness of other foundation (liquefiable zone) decreases with time until liquefaction occurs (zero stiffness) during the earthquake period.

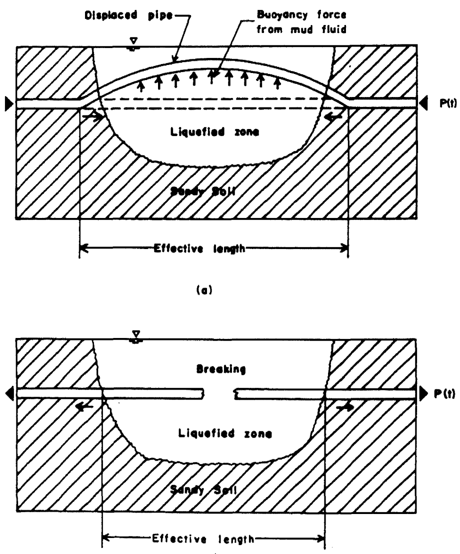

Fig. 9 Failure of Pipeline Under Soil Liquefaction Environment

Because the partial differential equations can be easily expressed in a difference form to a set of algebra equation which can easily be solved by computer, finite difference approach is adopted.

As a pilot test to the formulations and programming, a simply-supported column (beam without elastic foundations) subjected to a prescribed linear displacement function (with respect to both time and space) was evaluated. As given Ref. 16. the results was compared to that from Hoff (18). The agreement is extremely good. It is believed that the proposed approach would be promising for the further investigation.

The general recommendations to mitigate pipeline damages at this time when a rigorous analysis is still not available are (1) to avoid soil liquefiable zone when possible; (2) to select ductile material to give larger deformation capability without rupture; (3) to use restrained joints to avoid the separation of joints; (4) to densify the soil and to provide drainage in order to reduce liquefaction potential and (5) to anchor the pipeline to region below the liquefiable soil.

REFERENCES

1. Duke, C.M., "Damage to Water Supply Systems", The San Fernando, California Earthquake of Feb. 9, 1971, Geological Survey Professional Paper 733, U.S.G.S., and NOAA, 225-240, 1971.

2. Kubo, K. and Isoyama, R., "Damage to Buried Utility Pipes in the 1978 Miyagi-Ken-Oki Earthquake", Proc. of the 7th World Conference on Earthquake Engineering, Istanbul, Turkey, Vol. 8, Sept. 8-13, 1980, pp. 225-232.

3. Wang, L.R.L. and O'Rourke, M.J., "Overview of Buried Pipelines Under Seismic Loadings", Journal of the Technical Councils of ASCE, Vol. 104, No. TC1, November 1978, pp. 121-130.

4. Wang, L.R.L., Kubo, K., et al., "State-of-the-Art Report on Lifeline Earthquake Engineering", State-of-the-Art in Earthquake Engineering, 1981, Turkish National Committee on Earthquake Engineering, October 1981.

5. Isoyama, R. and Katayama, T., "Seismic Performance Evaluation of Water Supply Systems", Review Meeting, U.S.-Japan Cooperative Research on Seismic Risk and Lifelines, Jan. 1981.

6. Kubo, K., Katayama, T., and Ohashi, A., "Present State of Lifeline Earthquake Engineering in Japan", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, Aug. 1977, pp. 118-133.

7. Wang, L.R.L., "Static and Quasi-Static Seismic Analysis of Buried Pipelines", Technical Report (SVBDUPS Project) No. 11, Dept. of Civil Engineering, R.P.I., June 1980.

8. Fox, E.S.L., "Quasi-static Computer Analysis of Buried Pipelines", Master of Engineering, Project Report, Rensselaer Polytechnic Institute, January 1979.

9. Wang, L.R.L., "Seismic Analysis and Design of Buried Pipelines", Proc. of International Conference on Engineering for Protection from National Disasters, Bangkok, Jan. 1980.

10. Wang, L.R.L., "Parametric Seismic Responses of Buried Pipelines", Preprint, ASME Pressure Vessels and Piping Technology Conference, August 1980.

11. Serna, R., "Quasi-Static Elasto-plastic Analysis of Buried Pipelines", Master of Engineering Project Report, Rensselaer Polytechnic Institute, May 1981.

12. Wang, L.R.L., Olabimtan, A., "General Quasi-Static Seismic Analysis of Buried Straight Piping Systems", Technical Report LEE-006, School of Civil Engineering and Environmental Science, University of Oklahoma, Sept. 1983.

13. Newmark, N.M., and Hall, W.J., "Pipeline Design to Resist Large Fault Displacement", Proc. U.S. Nat'l Conf. on Earthquake Engineering, Ann Arbor, MI, 1975, pp. 416-425.

14. Kennedy, R.P., Darrow, A.D.C. and Short, S.A., "Seismic Design of Oil Pipeline Systems", Journ. of Tech. Councils, ASCE, TC1, 1979, pp. 119-134.

15. O'Rourke, T.D. and Trautmann, C.H., "Buried Pipeline Response to Permanent Earthquake Ground Movement", ASME Paper No. 80-C2/PVP-78, 1980.

16. Yeh, Y.H., "Failure Mechanisms of Buried Pipelines Under Various Seismic Environments", Ph.D. Thesis, School of Civil Engineering and Environmental Science, University of Oklahoma (in progress).

17. Sun, S.P., "Earthquake Damage to Pipelines", Proc. of 2nd U.S. National Conference on Earthquake Engineering, Stanford University, August 22-24, 1979.

18. Hoff, N.J., "The Dynamics of Buckling of Elastic Column", Transaction of the American Society of Mechanical Engineers, 1951, pp. 68-74.