Seismic Vulnerability, Behavior and Design of Underground Piping Systems

An Overview of Buried Lifeline Earthquake Engineering

by

Leon Ru-Liang Wang

Michael J. O'Rourke

Sponsored by National Science Foundation

Research Applied to National Needs (RANN)

Grant No. ENV76-14884

Technical Report (SVBDUPS Project) No. 1A

January 1978

Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. NSF/RA-780338	2.	PB 291038

4. Title and Subtitle
Overview of Buried Lifeline Earthquake Engineering (Seismic Vulnerability Behavior and Design of Underground Piping Systems, Technical Report No. 1A)

5. Report Date January 1978

6.

7. Author(s)
L.R. Wang

8. Performing Organization Rept. No. 1A

9. Performing Organization Name and Address
Rensselaer Polytechnic Institute
Department of Civil Engineering
Troy, New York 12181

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G) ENV7614884

12. Sponsoring Organization Name and Address
Applied Science and Research Applications (ASRA)
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

13. Type of Report & Period Covered Technical

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Overall aims of this research are to develop a systematic way of assessing the adequacy and vulnerability of water/sewer distribution systems subjected to seismic loads and also to develop future design methodologies for water/sewer systems. This paper presents state of the art information on the behavior and design of buried lifelines such as submerged tunnels, gas, water, and sewer distribution lines subjected to earthquakes. Specifically, a survey of pipelines damage due to past earthquakes as well as current design practices, analysis procedures, code provisions, and the latest published research are discussed.

17. Document Analysis a. Descriptors

Design	Water pipes	Piping systems
Earthquakes	Water supply	Tunnels
Earthquake resistant structures	Sewer pipes	Subsurface structures
Dynamic structural analysis	Hazards	

b. Identifiers/Open-Ended Terms
Earthquake engineering
Buried lifelines

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
NTIS.	20. Security Class (This Page)	22. Price PC A02/MF A01

(See ANSI-Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4-77) (Formerly NTIS-35) Department of Commerce

ACKNOWLEDGEMENT

This is one in a series of reports under the general title of 'Seismic Vulnerability, Behavior and Design of Underground Piping Systems' (SVBDUPS). The research has been sponsored by the Earthquake Engineering Program of NSF-RANN under Grant No. ENV76-14884 and Dr. S.C. Liu is the Program Manager of this project. The overall aims of the research are to develop a systematic way of assessing the adequacy and vulnerability of Water/Sewer distributions subjected to seismic loads and to develop future design methodologies.

This report is written by Dr. Leon R.L. Wang, Associate Professor of Civil Engineering and Dr. Michael O'Rourke, Assistant Professor of Civil Engineering. Dr. Leon R.L. Wang is the Principal Investigator of the project.

Appreciation goes to the Advisory Panel which consists of Mr. Holly A. Cornell, President of CH2M Hill, Inc., Corvallis, Oregon; Mr. Warren T. Lavery, Superintendent of Latham Water District, Latham, N.Y.; Dr. Richard Parmelee, Professor of Civil Engineering, Northwestern University, and Drs. Jose Roesset and Robert Whitman, Professors of Civil Engineering, MIT for their helpful comments and suggestions.

The typing and proof-reading of this report by Mrs. Jo Ann Grega are also appreciated.

Please note that although our project is sponsored by The National Science Foundation, any opinions, findings and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of NSF.

AN OVERVIEW OF BURIED LIFELINE EARTHQUAKE ENGINEERING[a]

Leon Ru-Laing Wang[1], M., ASCE

Michael J. O'Rourke[2], A.M., ASCE

Abstract

This paper presents state of the art information on the behavior and design of buried lifelines such as submerged tunnels, gas, water and sewer distribution lines subjected to earthquakes. Specifically, a survey of pipelines damage due to past earthquakes as well as current design practices, analysis procedures, code provisions and the latest published research are discussed.

Introduction

Recent studies[5,11,18,22,23,35,37,42] have shown that buried gas, water/sewer pipelines have been damaged heavily by earthquakes. Because of the importance of lifelines vis-a-vis the health and safety of the populace, lifeline earthquake engineering is now beginning to draw the attention of the engineering profession[12]. This is evidenced by a number of papers[3,10,19,20,25,45,59] recently presented at a Specialty Conference on Lifeline Earthquake Engineering organized by ASCE's Technical Council on Lifeline Earthquake Engineering (TCLEE). These and other papers published within the last two years may be grouped into five main areas as: (1) state of the art papers[3,25,59]; (2) observations of earthquake damages and response behavior[19,21,31,55]; (3) analyses or mathematical models to study or explain the seismic shaking response behavior[1,20,36,39,45,47]; (4) studies of influencial parameters[4,6,16,58] and (5) design

---

(a) To be presented at ASCE Geotechnical Engineering Division Specialty Conference, at Pasadena, Calif., June 19, 1978.

(1) Associate Professor of Civil Engineering, Rensselaer Polytechnic Institute, Troy, New York 12181.

(2) Assistant Professor of Civil Engineering, Rensselaer Polytechnic Institute, Troy, New York 12181.

considerations and design criteria[30,47,49,51].

It should be noted that all the above papers deal mostly with a single long pipeline or tunnel. Except for a system approach to lifeline risk[60], very little discussion has been found on seismic response behavior or design of an entire buried lifeline network.

Presently, there are no codified provisions in the United States for the design of lifelines to resist seismic loads. More research is needed to facilitate the development of future design codes.

Observation of Buried Lifeline Behavior Due to Earthquakes

A. Observed Pipellne Damage

There are essentially two reasons for obtaining a record of pipeline damage due to earthquakes. First of all, by reviewing past damage records and noting the typical modes of failure, designers are better able to mitigate the effects of an earthquake. In developing analytical models for pipeline behavior, the more information that is available on how pipelines have failed, the more effective will be the check of the analytical model developed. Furthermore, analyses which deal with the modes of failure not likely to occur can be deemphasized. Also, through investigation of past damage records, it may be possible to establish statistical relationships between various failure mechanisms and parameters such as the type and size of pipe, soil conditions, joint details, etc.

Pipeline damage to mains, joints and branches can be attributed to either direct or indirect earthquake effects. The direct earthquake damaging forces are:

- Seismic shaking and vibration
- Fault displacement
- Tectonic uplift-subsidence

The indirect damaging forces refer to mass ground movements triggered by the earthquake such as:

- Landslides
- Soil Liquefaction
- Compaction of Sediment

The pipeline failure modes due to tectonic uplift-subsidence, landslide or liquefaction are catastrophic and cover a large area. Usually, such failures are accompanied by breakages of mains, branches, connections and joints of the entire or a large portion of the pipeline system in the failure area.

Failure from seismic shaking may result from large dynamic tension that can cause a pull-out at joints, compression that can cause crushing and/or buckling, shear that can cause cracks or breakages of connections, bending that can cause fractures, etc.

Most of the existing literature concerning buried pipeline damage due to earthquakes, gives a qualitative rather than quantitive description of the damages. This is due to the fact that a complete quantitative survey of buried pipeline damages is rather difficult and expensive.

It should also be noted that only the most recent severe earthquakes have been subjected to intensive investigations. Among them, the best documented is the San Fernando Earthquake (1971) which has been discussed by many investigators[11,18,22,23,35]. The others are the Alaska Earthquake (1964) which has been reported on by Richardson[42], the Managua Earthquake (1972) by Cajina[7] and Katayama et al[22] and several earthquakes in Japan by Katayama et al[22] and Okamoto[37]. Most of the failure mechanisms from these earthquakes have been tabulated in an earlier paper[59]; presented below is a brief summary.

Most damage in the San Fernando Valley area was due to seismic shaking. It was observed that pipelines with rigid joints failed more than those with flexible joints. The major failure mechanisms were crushing and flexural failure of pipe sections and pull-out and shear at joints.

During the 1964 Alaskaian earthquake, buried pipelines were destroyed completely in slide areas; differential settlement due to earthquake shaking caused breakages of mains and service lines while direct seismic shaking forces crushed and sheared pipes, broke bells and pulled joints apart.

Since 1920 in Japan, direct seismic shaking has caused most of the damages to buried pipes during earthquakes with Richter magnitude greater than seven. The exception is the Niigata Earthquake (1964) in which liquefaction occurred and caused most of the failures. The types of failure observed during these Japanese earthquakes were similar to those during the San Fernando and Alaska Earthquakes.

B. Parameters Affecting Damage

Unfortunately, the available pipeline damage data is not sufficient to completely correlate various types of pipeline damage with all of the pipe and soil parameters. However, attempts have been made to correlate similar pipeline damage to geological(21) and other conditions(15,22,25).

After reviewing damage data from the 1964 Alaska earthquake, the 1971 San Fernando earthquake and the Mechering, Western Australia earthquake on Oct. 14, 1968, Kachadoorian(21) concluded that the geologic environment under the buried pipeline influenced the intensity and frequency of the pipeline damages. Qualitatively, the damages occurred least in bedrock, moderately in coarse-grained soil and the most frequently in fine-grained soils such as caly or silt.

Using damage data from earthquakes in Japan, authors(22,25) have correlated pipeline damage to pipe size and concluded that smaller pipes are more liable to break. Others have taken an opposite view. Using 1971 San Fernando earthquake data(35), the damage statistics show no definite trend with respect to pipe size as shown in Reference 59. One possible explanation is that the damage data in these investigations are different. The number of joint loosenings was used in the Japan earthquake investigation while the number of breaks was used for San Fernando earthquake. It was observed in all investigations that the damages in main lines is proportional to the damages in service lines as one might expect.

Recently, Kubo et al[25] observed that the damage ratio's were highest in regions of transition from one type of soil to another. Also, damage statistics from Fukai Earthquake showed that pipes parallel to direction of propagation were more heavily damaged (by a factor of about 2.5) than pipeline normal to the direction of propagation.

C. Seismic Shaking Response Behavior

Several investigations including both field observations and model tests in Japan recently have reported the seismic response behavior of buried pipelines[24,27,30,32,44,55] and submerged tunnels[27,31,38,48,52,53]. General conclusions from these investigations are summarized as follows.

1. Most field data have indicated that buried pipelines[24,32,44] and submerged tunnels[38,48,52] move closely with the ground in both longitudinal and lateral directions during seismic shaking. There were no appreciable differences in displacements between these buried structures and the ground. Sakurai et al.[44] present the observed dynamic stresses induced by the Matsushiro earthquakes (1965). The observed stress in the underground pipes was discussed in connection with the observed deformation and wave character of the ground. The paper indicates the relative displacement between the pipe and the soil is small. Nakayama et al[31] observed that in earthquakes originated far from the site, the long period components were predominant in ground motion and the tunnel had almost the same behavior as the ground. However, where the epicenters are located near the site, the ground motion was governed by the short period components and the behavior of the tunnel did differ slightly from that of the ground.

Using model tests, Tumura et al[52,53] observed that in case of the vibration perpendicular to the tunnel axis, the model deforms nearly as much as the ground does, while in case of the vibration in the direction of the tunnel axis, the tunnel restricts the displacement of the ground surrounding the tunnel, because the rigidity of the tunnel in the axial direction is large.

2. The inertia force generated by motion of the buried lifeline was found to have very little effect upon the response of the structure itself. Thus, the response behavior (stresses or displacements) of buried lifelines during earthquakes depends largely on the ground displacement characteristics along the route. The ground displacement characteristics is hardly affected by the existence of the buried lines.

3. Both axial and bending strains of submerged tunnels[31,53] and buried pipelines[32,44] were observed during earthquakes. The axial strains were found to be predominant over the bending strains in all cases. The bending strains at the bends were of the same order of magnitude as in the straight sections.

Tamura et al[48,52,53] have concluded that all strains generated in the tunnel during earthquakes increased with an increase in earthquake acceleration but their magnitudes were mostly affected by the frequency characteristics of seismic motion of the ground.

In discussing axial pipeline strains, Nasu et al[32] observed that the pipeline moved with the ground as long as the adhesion/friction between the pipeline and surrounding soil was not lost. They also noted that axial strains were caused by longitudinal waves (P waves) for a pipeline laying along a radial line from the epicenter while transverse waves (S waves) caused axial strain for pipeline laying perpendicular to a radial line from the epicenter.

4. The frequency characteristics of axial pipeline strain differ from those of bending strain. These frequency characteristics of pipeline strain are closely related to those of the ground frequency characteristic but differ

according to the magnitudes of earthquakes. As the magnitude increases, low frequency component become more predominant[53].

D. Concluding Remarks on Seismic Response Behavior and Design

From above mentioned studies, it is obvious that the behavior of buried lifelines is governed by the relative displacements of the ground along the route and not the acceleration. Ductility or elongation to allow buried lifeline movement with the ground is the most important factor for the seismic design of such structures.

Current Design Practice

The structural design of most buried water and sewer pipes is based on static analysis. However, occasionally passive physical designs[13] are used to avoid damage due to seismic effects. The following is a list of common practices and considerations:

1) The pipeline should be located as far from fault lines as possible. At least, pipeline should not be parallel to the fault line. Thus, the location of fault lines is an important task as far as the planning of underground pipeline is concerned. For locations where the pipeline must cross an active fault, locating the pipeline at an oblique angle to the fault tends to reduce the shear on the pipeline[13].
2) Pipeline construction on steep hillsides should be avoided when feasible.
3) Redundancy in the distribution system is desirable. That is, more smaller pipes could be used in lieu of a single larger pipe to allow possible reduced capacity operation.
4) Installation of blow-off valves near the fault line where higher seismic activity is anticipated should be considered. In this system, water is lead to a nearby reservoir after the blow-off valve fails during an earthquake.

5) Ductile pipe material such as steel, ductile iron, copper or plastic, etc. should be considered to allow for larger pipeline deformations.

6) Flexible joints using rubber gaskets and ball-socket-type joints should be considered in areas of potentially strong seismic activity. Extra long restrained sleeves could be provided for sliding pipe connections.

7) Consideration should be given encasing the pipeline in a large tunnel in order to isolate the pipeline from ground motion.

8) For locations where main pipeline cross active faults, consider providing flexible expansion/contraction joints as suggested by Ford[8,13] and Okamoto[37]. Basically, the pipeline is designed to allow large seismic movements. For example, the so-called "Bellow joint" is capable of bending 15° whereas the simple mechanical joint can only be designed to bend 2°.

Similar to buried pipelines, submerged tunnels have been designed without concerning seismic effects. The first case where seismic resistance was taken into account in designing the longitudinal section of the tunnel was the BART System in San Francisco[26]. No formal design code provision was proposed, however.

<u>Design Criteria/Code Provisions</u>

In this country, no formal provision has been set by code organizations to design buried lifelines to resist earthquakes.

As to an overall system design approach, Duke and Moran[12] and Whitman et al.[60] have suggested the use of a reliability/damage level approach to the design of lifeline systems to resist various intensities of ground motion.

In Japan, Okamoto[37] suggested the seismic coefficients of 0.1g to 0.3g for the design of buried pipelines in Japan. The coefficients depend upon soil conditions, the softer the soil the larger the seismic coefficient. Recently, there are a number of papers proposing criteria for seismic design of buried pipelines[30,43] and submerged tunnels[20,49,50,51]. These criteria are mostly based on the observations that the buried lifelines behavior is governed by the relative displacement of the ground and the stresses in the buried structures can be calculated from the relative motion of grounds during earthquakes.

Analysis Procedures

A survey of most of the recently published literature in the areas of earthquake engineering and structural dynamics indicated that there is no single complete analytical model which is capable of predicting the behavior of an underground lifeline system under the attack of an earthquake. Standard text books[34,37,61] offer only brief discussions. There are, however, quite a few articles which, after making simplifying assumptions, provide models for analyzing the underground pipelines for particular types of earthquake damage.

In a recent paper, Newmark and Hall[33] present a method which can be used to analyze and design buried pipelines for large fault displacement. In this paper, the ductility (plasticity) of the material is used to allow for the large deformation. Using three possible grades of steel (X70.X65.X60), they concluded that all three types of steel can survive a 3 Meters (10 ft) fault motion, with deformation extending over a length of less than 50 Meters (160 ft) on each side of the fault.

Based on a plane strain formulation, Parmelee and Ludtke[40] presented a methodology for defining the soil stiffness, mass and damping ratios for a buried pipe system.

Treating the soil supports as elastic springs, above ground pipelines[1] and underground structures[17,34,46,57] have been studied. In a recent paper, Luscher et al.[28] discussed briefly the design of the below-ground portion of the Trans-Alaska pipeline.

As for failure behavior, both Cheney[9] and Forrestal and Hermann[14] present solutions for the buckling of underground tubes. In related fields, the imbedded cylindrical shells[41] have been studied experimentally as well as analytically. Azar[5] presented a static stress analysis for a simply suspended pipe. Dynamic analysis on related structures are also found[29,54,56].

Conclusions

State of the art information on the behavior and design of buried lifelines subjected to earthquake was presented. From a review of observed pipeline damage, the following general conclusions may be drawn;

1) Pipelines with flexible joints experience less damage during an earthquake than pipelines with rigid joints.
2) Pipelines in regions of transition from one soil type to another experience the most damage during an earthquake. Otherwise pipelines in soft soil experience more damage than those in firm soil.
3) The relative motion between the pipeline and the surrounding soil during seismic excitation is small.
4) There are conflicting reports as to the effect of pipe size vis-a-vis earthquake damage.

Various passive design practices are presently being used to mitigate the effects of earthquakes. These practices may be grouped into three general classifications:

1) reducing the earthquake hazard by placing the pipelines, if possible, away from active faults, steep hillsides and poor soil sties.
2) designing a flexible pipeline system by selecting ductile pipeline material and/or flexible joints.
3) providing "fail safe" systems at locations where damage is anticipated.

There is growing interest in the subject around the world and many papers have been published during the last two years. However, there are only a few analytical models which may be used to analyze a buried lifeline for specific types of earthquake excitation. For a single line, the structural behavior is governed by the relative displacement of the ground, which in turn, can be used as a design criterion. There is no information on the behavior and design of a network type buried lifeline system. Also current standard codes of practice do not present design procedure for buried lifelines with seismic loads.

Acknowledgement

The authors wish to thank the RANN Program of National Science Foundation for the financial support (Grant No. ENV76-14884) under the general title 'Seismic Vulnerability, Behavior and Design of Underground Piping Systems" from which this paper is developed.

Appendix - References

1. Anderson, A. and Singh, A., "Seismic Response of Pipeline on Friction Supports", Journ. of Engr. Mech. Div. ASCE, April 1976, pp. 275-291.

2. Aoki, Y. and Hayashi, S., "Spectra For Earthquake Resistive Design of Underground Long Structures", Proc. of 5th World Conference (1973) on Earthquake Engineering, IAEE, Rome 1974, pp. 558-568.

3. Ariman, T., "A Review of the Earthquake Response and Aseismic Design of Underground Piping Systems", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, Aug. 1977, pp. 282-292.

4. Audibert, J.M. and Nyman, K.T., "Soil Restraint Against Horizontal Motion on Pipes", Journ. of Geotechnical Eng. Div. ASCE, Oct. 1977, pp. 1119-1142.

5. Azar, J., Bomba, J. and Randolph, V., "Pipeline Stress Analysis", Transp. Engr. Journ. ASCE, Feb. 1975, pp. 163-170.

6. Bealey, M. and Lemons, J.D., "Concrete Pipe and The Soil Interaction System", Tech. Pub. #630, ASTM, Sept. 1977.

7. Cajina, A., "The Managua Earthquake and Its Effect on Water Supply System", Proc. of the Conference on Managua Earthquake, Vol. II, EERI, 1973, pp. 766-790.

8. Cast Iron Pipe Research Association, "Earthquakes and Other Geologic Hazards: Protective Design for Underground Pipe", Civil Engineering, ASCE, Sept. 1976, p. 35.

9. Cheney, J., "Buckling of Soil-Surrounded Tube", Journ. of Engr. Mech. Div. ASCE, Aug. 1971, pp. 1121-1132.

10. Dowding, C.H., "Lifeline Viability of Rock Tunnels - Empirical Correlations and Future Needs", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, Aug. 1977, pp. 320-336.

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

12. Duke, C.M. and Moran, D.F., "Guidelines for Evolution of Lifeline Earthquake Engineering", Proc. of U.S. National Conf. on Earthquake Engr., Ann Arbor, Mich., EERI, 1975, pp. 367-376.

13. Ford, D.B., "Design Considerations for Underground Pipelines in Geologically Hazardous Areas", Cast Iron Pipe News, Spring/Summer 1975.

14. Forrestal, Michael J. and Herrmann, George, "Buckling of a Long Cylindrical Shell Surrounded by an Elastic Medium", International Journal of Solids and Structures, vol. 1, no. 3, July 1965, pp. 298-309.

15. Golze, A.R., "Use of Pipelines in the California Water Project", Journ. of Pipeline Div., ASCE, Nov. 1967, pp. 25-32.

16. Goto, H., Takada, S. and Nagao, S., "Effect of Joint Parts on Aseismic Strength of Buried Pipeline", Proc. of 6th World Conference on Earthquake Engineering, New Delhi, 1977.

17. Hemant, S. and Chu, S.L., "Seismic Analysis of Underground Structural Elements", Journ. of Power Div. ASCE, July 1974, pp. 53-62.

18. Housner, G. and Jennings, P., "The San Fernando, California Earthquake", Int. Journ. of Earthquake Engr. and Struct. Dynamics, John Wiley and Sons, Vol. 1, No. 1, July-Sept. 1972, pp. 5-31.

19. Hradilek, P.T., "Behavior of Underground Box Conduits in the San Fernando Earthquake", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, Aug. 1977, pp. 308-319.

20. Isenberg, J., Weidlinger, P., Wright, J.P. and Baron, M.L., "Underground Pipelines in A Seismic Environment", Proc. of ASCE First Specialty Conference on Lifeline Earthquake Engineering, UCLA, Aug. 1977, pp. 267-281.

21. Kachadoorian, R., "Earthquake: Correlation Between Pipeline Damage and Geologic Environment", Journ. of AWWA, March 1976, pp. 165-167.

22. Katayama, T., Kubo, K. and Sato, N., "Earthquake Damage to Water and Gas Distribution Systems", Proc. of U.S. National Conf. on Earthquake Engr., Ann Arbor, Mich., EERI, 1975, pp. 396-405.

23. King, P.V. and Betz, J.M., "Earthquake Damage to a Sewer System", Journ. of Water Pollution Control Federation (WPCF), May 1972, pp. 859-867.

24. Kubo, K., "Behavior of Underground Waterpipes During An Earthquake", Proc. of 5th World Conference (1973) on Earthquake Engineering, IAEE, Rome, 1974, pp. 569-578.

25. 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.

26. Kuesel, T.R., "Earthquake Design Criteria for Subways", Journ. of Struct. Div., ST6, ASCE, June 1969.

27. Kuribayashi, E., Iwasaki, T. and Kawashima, K., "Dynamic Behavior of A Subsurface Tabular Structure", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 7, No. 4, Dec. 1974, pp. 200-209.

28. Luscher, V., Black, W. and Nair, K., "Geotechnical Aspects of Trans-Alaska Pipeline", Trans. Engr. Journ. ASCE, Nov. 1975, pp. 669-680.

29. McClure, G.M., Atterbury, T.J. and Frazier, N.A., "Analysis of Blast Effects on Pipelines", Journ. of Pipeline Div., Vol. 90, No. PL2, ASCE, Nov. 1964, pp. 25-47.

30. Miyajima, N., Miyachi, J., Shirakawa, K. and Aono, Y., "An Example of Seismic Design and Earthquake Response Measurement of Buried Pipeline", Proc. of US-JAPAN Seminar on Earthquake Engineering Research With Emphasis on Lifeline Systems, Tokyo, Nov. 1976, pp. 177-196.

31. Nakayama, S., Kiyomiya, O. and Tsuchida, H., "Observation of Dynamic Behavior of Kinuura Submerged Tunnel During Earthquakes", Preprint, 9th Joint Meeting US-JAPAN on Wind and Seismic Effects, Tokyo, May 1977.

32. Nasu, N., Kazama, S., Morioka, T. and Tamura, T., "Vibration Test of the Underground Pipe With A Comparatively Large Cross-Section", Proc. of 5th World Conference (1973) on Earthquake Engineering, IAEE, Rome, 1974.

33. Newmark, N.M. and Hall, W.J., "Pipeline Design to Resist Large Fault Displacement", Proc. of U.S. National Conf. on Earthquake Engr., Ann Arbor, Mich., EERI, 1975, pp. 416-425.

34. Newmark, N.M. and Rosenblueth, E., "Fundamental of Earthquake Engineering" Prentice-Hall, Inc., 1971.

35. NOAA/EERI Subcommittee on Water and Sewerage Systems, "Earthquake Damage to Water and Sewer Facilities", San Fernando Earthquake of 1971, Vol. 2 - Utilities, Transportation and Sociological Aspects, Ed. by C.M. Murphy, National Oceanic and Atmospheric and Administration, 1973, pp. 73-193.

36. Novak, M. and Hindy, A., "Seismic Response of Buried Pipelines", Proc. of 2nd Annual Engineering Mech. Div. Specialty Conf. on Advances in Civil Engineering Through Eng. Mech., ASCE, April 1977, pp. 44-47.

37. Okamoto, S., "Introduction to Earthquake Engineering", John Wiley & Sons, 1973.

38. Okamoto, S. and Tamura, C., "Behavior of Subaqueous Tunnel During Earthquakes", Int. Journ. of Earthquake Engr. and Struct. Dynamics, John Wiley & Sons, Ltd., Vol. 1, No. 3, Jan.-Mar. 1973, pp. 253-266.

39. O'Rourke, M. and Wang, L.R.L., "Earthquake Response of Buried Pipeline", Accepted for presentation to ASCE Geotechnical Division Specialty Conference, Pasadena, Calif., June 1978.

40. Parmelee, R.A. and Ludtke, C.A., "Seismic Soil-Structure Interaction of Buried Pipelines", Proc. of U.S. National Conf. on Earthquake Engr., Ann Arbor, Mich., EERI, 1975, pp. 406-415.

41. Parnes, R., "Dynamic Response of Imbedded Cylindrical Shell", Journ. of Engr. Mech. Div., ASCE, April 1971, pp. 421-440.

42. Richardson, C.B., "Damage to Utilities", The Great Alaska Earthquake of 1964 - Engineering, Written by Committee of the Alaska Earthquake, National Academy of Science, 1973, pp. 1034-1073.

43. Sakurai, A., Kurihara, C. and Takahashi, T., "A Proposal For Earthquake Response Analysis of Long Structures and Aseismic Design Criteria of Pipelines", Proc. of 5th World Conference (1973) on Earthquake Engineering, IAEE, Rome, 1974, pp. 603-606.

44. Sakurai, A. and Takahashi, T., "Dynamic Stresses of Underground Pipelines During Earthquakes, Proc. of 4th World Conference on Earthquake Engineering, Chilean Asso. on Seismology and Earthquake Engineering, Santiago, 1969, pp. 811-895.

45. Shinozuka, M. and Kawakami, H., "Underground Pipe Damages and Ground Characteristics", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering, Los Angeles, Aug. 1977, pp. 293-307.

46. Tajimi, H., "Dynamic Analysis of a Structure Embedded in An Elastic Stratum", Proc. of 4th World Conf. of Earthquake Engr., Santiago, Chile, 1969, pp. 53-56.

47. Takada, S. and Nagao, S., "Dynamic Frictional Force and Efficiency of Joint Parts for Aseismic Strength of Buried Pipelines", Proc. of US-JAPAN Seminar on Earthquake Engineering Research With Emphasis on Lifeline Systems, Tokyo, Nov. 1976, pp. 211-222.

48. Tamura, C., "Dynamic Behavior of A Submerged Tunnel During Earthquake", Trans. of JSCE, Vol. 7, 1975, pp. 197-200.

49. Tamura, C., "Design of Underground Structures by Considering Ground Displacement During Earthquakes", Proc. of US-JAPAN Seminar on Earthquake Engineering Research With Emphasis on Lifeline Systems, Tokyo, Nov. 1976, pp. 417-434.

50. Tamura, C. and Okamoto, S., "A Study on the Earthquake Resistant Design of Subaqueous Tunnels", Proc. of 5th European Conf. on Earthquake Engineering, Istanbul, 1975.

51. Tamura, C. and Okamoto, S., "On Earthquake Resistant Design of A Submerged Tunnel", Proc. of International Symposium on Earthquake Structural Engineering, Univ. of Missouri, Aug. 1976, pp. 809-822.

52. Tamura, C., Okamoto, S. and Hamada, M., "Dynamic Behavior of A Submerged Tunnel During Earthquakes", Report of the Institute of Industrial Science, Univ. of Tokyo, VOl. 24, No. 5, Serial No. 154, March 1975.

53. Tamura, C., Okamoto, S. and Kato, K., "Observations on Dynamic Strains of Submerged Tunnel During Earthquakes", Bulletin of Earthquake Resistant Structure Research Center, No. 6, Univ. of Tokyo, Dec. 1972, pp. 1-21.

54. Toki, K. and Takada, S., "Earthquake Response Analysis of Underground Tabular Structures", Bull. of the Disaster Prevention Research Institute, Kyoto Univ., June 1974.

55. Tsuchida, H. and Kurata, E., "Observed Earthquake Ground Displacements Along a 2500 Meter Line", Proc. US-JAPAN Seminar on Earthquake Engineering Research With Emphasis on Lifeline Systems, Tokyo, Nov. 1976, pp. 29-42.

56. Tsutsumi, H., Kamiya, Y., Kudoh, T. and Taguchi, S., "Dynamic Analysis of Ground-Structure System Based on Elastic Wave Theory", Proc. of 5th World Conference (1973) on Earthquake Engineering, IAEE, Rome, 1974, pp. 2113-2116.

57. Wang, L.R.L., "Dynamics of Buried Pipelines", Tech. Report (SVBDUPS Project) No. 2, Dept. of C.E., R.P.I., April 1977.

58. Wang, L.R.L., "Discussion on Soil Restraint Against Horizontal Motion of Pipes by Audibert and Nyman in ASCE Journ., GT Div., Oct. 1977", Submitted to ASCE for consideration of possible publication.

59. Wang, L.R.L. and O'Rourke, M.J., "State of the Art of Buried Lifeline Earthquake Engineering", Proc. of ASCE Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, August 1977, pp. 252-266.

60. Whitman, R.V., Cornell, C.A. and Taleb-Agha, G., "Analysis of Earthquake Risk for Lifeline Systems", Proc. of U.S. National Conf. on Earthquake Engr., Ann Arbor, Mich., EERI, 1975, pp. 377-386.

61. Wiegel, R.L., "Earthquake Engineering", Prentice Hall, Inc., 1970.