SEISMIC VULNERABILITY, BEHAVIOR AND DESIGN OF BURIED PIPELINES

LEON RU-LIANG WANG[1]

SUMMARY

This paper summarizes the development and results of a research project entitled Seismic Vulnerability, Behavior and Design of Underground Piping Systems (SVBDUPS) (32) sponsored by the National Science Foundation for the past two years. The objectives and the overall aims of the project are to study thoroughly the seismic response behavior of buried water/sewer distribution systems, to develop a systematic way of assessing the adequacy in terms of vulnerability to seismic damage of these systems and to propose design criteria and a methodology to resist seismic wave propagation effects.

INTRODUCTION

Recent studies (9,10) have shown that buried gas, water and sewer pipelines have been damaged heavily by earthquakes. Other than the catastropic failures such as landslides and soil liquefactions, buried pipelines, if properly designed, may survive and remain serviceable when subject to ground shaking caused by the seismic wave propagation effects. Presently, there is no codified provisions in the United States for the design of buried pipelines to resist seismic loads. This research is to facilitate the developments of future design guidelines.

Following the steps of the research report (32), this paper presents a framework for seismic vulnerability evaluation and also design guidelines for buried pipelines.

BACKGROUND

Recent papers published in the subject may be grouped into six main areas as: 1. state of the art papers (11,30,31); 2. observations of earthquake damage and response behavior (8,15); 3. seismic risk analysis (16,23) and ground motion characteristics (18,22); 4. analyses of response due to seismic wave propagation (5,7,12,14,17,20,28); 5. studies of influential parameters (4,6) and 6. design considerations and design criteria (3,19,24,29).

Most of the existing literature concerning buried pipeline damage due to earthquakes gives a qualitative rather than quantitative description of the damage. In general, it was observed that pipelines with rigid (cement or lead caulked) joints failed more than those with flexible (rubber gasket) joints. Also, it was observed that 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.

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[1]Associate Professor of Civil Engineering, Rensselaer Polytechnic Institute, Troy, New York U.S.A.

As to the response behavior of buried pipelines, general observations are summarized as follows: 1. Most field data have indicated that buried pipelines and submerged tunnels move closely with the ground in both longitudinal and lateral directions during seismic wave propagation. There were no appreciable differences in displacements between these buried structures and the ground; 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 pipelines during earthquakes depends largely on the ground displacement characteristics along the route; 3. The axial strains were found to predominate over the bending strains in all cases. The flexural strains at the bends were of the same order of magnitude as in the straight sections. From the above discussions, it is concluded that the behavior of buried lifelines is governed by the relative displacements of the ground along the route.

Although no formal provision has been set by code organizations to design buried lifelines to resist earthquakes. However, passive physical design techniques are occasionally 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. 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 in the pipeline; 2. Pipeline construction on steep hillsides should be avoided when feasible due to the danger of landslides; 3. Redundancy in the distribution system is desirable; 4. Installation of blow-off valves near the fault line where higher seismic activity is anticipated should be considered; 5. Ductile pipe material such as steel, ductile iron, copper or plastic, should be considered to allow for larger pipeline deformations; and 6. Flexible joints using rubber gaskets and ball-socket-type connections should be considered in areas of potentially strong seismic activity. Extra long restraining sleeves can be provided for sliding type connections.

SIMPLIFIED APPROACH

Assuming that the seismic wave shape remains constant while traversing the pipeline, this simplified approach originally proposed by Newmark (13) results in maximum pipe strain/curvature and maximum joint displacement/rotation criteria. These two sets of upper bounds are developed by assuming either that the pipe segments are very rigid or the pipeline is very flexible with respect to soil. Actual pipe systems lie somewhere between these two extremes and have a non-zero value for joint stiffness representing some degree of physical restraint. Hence, a continuous pipeline would be required to satisfy the strain and curvature criteria in both tensile and compressive modes. A segmented pipeline with flexible joints would be required to satisfy the same strain criteria as well as the joint displacement/rotation criteria. Mathematically, these upper bounds of pipe strain, ε_{max}; curvature, χ_{max}; relative joint displacement, U_{max} and relative joint rotation, θ_{max} are given as:

$$\varepsilon_{max} = V_{max}/C_p \tag{1}$$

$$\chi_{max} = A_{max}/C_s^2 \tag{2}$$

$$U_{max} = V_{max}L/C_p \tag{3}$$

$$\theta_{max} = LA_{max}/C_s^2 \tag{4}$$

where V_{max} is the maximum ground velocity; A_{max}, the maximum ground acceleration; and C_p and C_s are the propagation velocities of seismic longitudinal and transverse waves in the surrounding environments relative to the pipeline axis.

Since the application of these upper bounds to seismic design of buried pipelines have been discussed elsewhere (17,18,32), details will not be repeated in this paper due to the limitation of space. In summary, Eqns. (1) to (4) provide a simple and conservative technique to calculate the maximum pipe strains and curvatures as well as maximum joint displacements and rotations if the earthquake accelerations and velocities can be predicted and if the propagation velocities with respect to the pipeline can be estimated.

QUASI-STATIC ANALYSIS APPROACH

For the simplified approach, upper bounds for pipe strains/curvatures and relative joint displacements/rotations are obtained by assuming that the pipeline is continuous and very flexible (upper bound for strains) or the pipeline consists of isolated rigid segments (upper bound for relative joint displacements). Actually, a buried pipeline reacts to the seismic wave propagation through the media of the surrounding soil. Thus, the response behavior of the buried pipeline will be influenced by a number of physical, geotechnical and seismological parameters.

Since the effects of pipeline inertia terms on the response behavior of buried pipelines (15,20) have been found to be negligible, the inertia and damping terms in the dynamic equations of motion will be dropped. Because the input ground motion is a function of time, the response will also be a function of time. Thus, the analysis is called "quasi-static analysis".

In an earlier investigation (28), a simple quasi-static model consisting of rigid pipe segments connected by elastic joint springs was used to study conservatively the relative joint motions of segmented pipelines due to seismic shaking. Based on the general formulation (25), this project is to develop a more rigorous quasi-static analysis model for the response of actual buried pipelines, segmented or continuous, subjected to earthquake motion in the axial direction. By comparing the pipe strains from the analysis with the seismic design criteria (29), the safety of buried pipelines subjected to a given set of earthquake loadings may be evaluated.

A long buried piping system consisting of n-segments is shown in Fig. 1. The equations of static equilibrium, obtained from the variation of the total strain energy in the soil-structure interaction system, are found to be:

$$[K_{system}] \quad \{X\} = [K_{soil}] \quad \{X_G\} \tag{5}$$

where $[K_{system}]$ and $[K_{soil}]$ are 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. The solution for pipe motion $\{X\}$ given in Eqn. (5) 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.

Note that a computer program for the general quasi-static analysis and

parametric studies of buried pipelines has been written by Fok (2) and other results have been presented elsewhere (26,27), this paper summarizes the conclusions as follows: 1. The most influencial parameters on the response behavior of buried pipelines are the maximum ground velocity and the wave propagation velocity of the seismic waves as suggested by the "Simplified" approach; 2. In general, longer pipe segment lengths and softer soil will produce both larger pipe strains and relative joint displacements; 3. Axial strains in continuous pipelines will be higher than those in segmented pipelines; 4. For a given value of joint stiffness, the difference in seismic response behavior for various commonly used pipeline materials is negligible.

GROUND MOTION CHARACTERISTICS

In this study, certain characteristics of earthquake ground motions which affect the behavior of buried pipelines are examined. Specifically, the simplified procedures note that for the critical case of a pipeline lying parallel to a radial line from the epicenter, maximum ground velocity in the radial direction governs the induced axial strain. For a pipeline with the same orientation, the induced curvature in the pipeline is governed by the maximum ground acceleration in the tangential direction. In this context, the question arises as to whether there is any difference between the radial and tangential components of the earthquake ground motion.

The second question addressed deals with the variation of the shpae of the seismic wave. In particular, the simplified procedures are based upon the assumption that the shape of the seismic wave remains unchanged as it traverses the pipeline.

Ground motion time histories recorded at 26 separate sites during the 1971 San Fernando Earthquake with their Cal Tech identifications were used to study the difference between the radial and tangential components of ground motion. The local site conditions, either rock, stiff soil or deep cohesionless soil, were taken from Seed et al. (21). The two original horizontal velocity time histories for each site were transformed into a radial and a tangential time history. The maximum ground velocities in the radial and tangential directions were then determined. The same procedure was used in processing the acceleration time histories. The study shows that there is little or no difference between the radial and tangential components. Considering the two components as paired data, there is no statistical difference at the 0.05 significant level between the radial and tangential maximums.

A total of 18 pairs of ground displacement time histories were used to study the constant wave shape assumption. Each pair of ground displacements are for two nearby stations which lie roughly along the same radial line from the epicenter. Of course, different pairs of stations may lie along different radial lines.

Three strains were calculated for each pair of stations as a function of the propagation speed of the seismic waves. The first strain value, corresponds to the maximum value of the average axial strain between the two stations assuming the wave shape remains constant. The second strain value corresponds to the maximum value of the average strain between the two stations using the actual radial displacement time histories of the two

stations. The third strain is that predicted by the simplified approach. In all cases, the effect of changes in the shape of the seismic waves as they traverse a pipeline was found to be significant. However, the effect is important only for high seismic wave velocities. Details of these investigations can be found in Refs. 17 and 18.

SEISMIC RISK ANALYSIS

The vulnerability analysis quantifies the probability of failure of a pipeline due to earthquakes. The satisfactory design of a pipeline based on certain failure criteria and risk level is achieved by repeating the vulnerability evaluation for a number of trials.

The project presents a procedure for determining design values for the peak ground acceleration for a particular location for given probability of occurrence and a return period.

In order to determine the source characteristics as well as other parameters, a list of historic earthquakes of the Albany, New York area was compiled. From the data base, the largest recorded earthquake within 200 miles (322 Km) of Albany has a magnitude of 5.5 on the Richter scale. Using five attentuation relationships developed by other researchers and using 0.02g maximum ground acceleration as the cut-off point for earthquake of engineering significance, O'Rourke and Solla (16) recommended the probability of exceeding particular ground acceleration for Albany, New York area. For example, a maximum ground acceleration of 228 cm/sec^2 has a 1 in 10 chance of being exceeded in 50 years, while a maximum ground acceleration of 205 cm/sec^2 has a 1 in 5 chance of being exceeded in 100 years.

It should be noted that peak ground acceleration values for particular return periods are available from other sources (1) for the United States. It is recommended that a detailed seismic risk analysis for a particular water system be undertaken only if the designer wishes to design for return periods other than those available from other sources of if the designer wishes to include a probabilistic error term in the attenuation relationship.

SEISMIC DESIGN CRITERIA

To aid in the design of buried pipelines against earthquakes, this project evaluates the reserve strength/strain of buried pipes beyond normal stress/strain conditions. This reserve strength is the capacity available in buried pipes to resist seismic loads. In buried pipelines under a combination of conventional and seismic loadings, bi-axial stresses are developed. Conventional loads produce mainly hoop stresses whereas seismic wave propagation produces predominantly longitudinal stress. To evaluate the failure of buried pipelines consisting of materials with different tensile and compressive strengths such as cast iron and concrete, under a bi-axial stress state, a modified Von Mises failure criterion is proposed.

For practical applications, this paper evaluates parametrically the reserve strength/strains of typical rigid pipes (cast iron or concrete) and typical flexible pipes (ductile iron or steel) with respect to several important parameters such as aging (corrosion effect), laying and loading conditions, buried depth and dynamic effect (earthquake induced water pressure). Details of these parametric studies are available in an earlier report (29).

In conclusion, the seismic reserve axial strength of buried pipes is influenced by all parameters investigated. The effects from corrosion and loading conditions for cast iron pipes are a little higher than those from buried depth, laying condition and dynamic load factor.

RECOMMENDED DESIGN PROCEDURES

Outlined below is a procedure which can be used to design "simple" buried pipelines for wave propagation effects: 1. The designer in consultation with other interested parties must select an acceptable level of risk for the design life of the pipeline system; 2. The peak ground velocity and acceleration for the design event must be established. These values can be determined by referring to seismic risk studies published in the technical literature or by performing a detailed seismic risk analysis for the particular site; 3. The simplified procedures can be used to estimate the maximum pipe strain and relative joint displacement. In this case, geotechnical information about the site is required to determine the wave propagation velocities with respect to the pipeline; 4. For a refined study, the "quasi-static" analysis approach is recommended. Then additional geotechnical information is required to determine the stiffness of the soil springs; and 5. By comparing these pipe strains and relative joint displacements with the reserve pipe strains and ultimate joint expansions and contractions one can determine the possibility of pipe failure or cracking, or joint separation/cursching.

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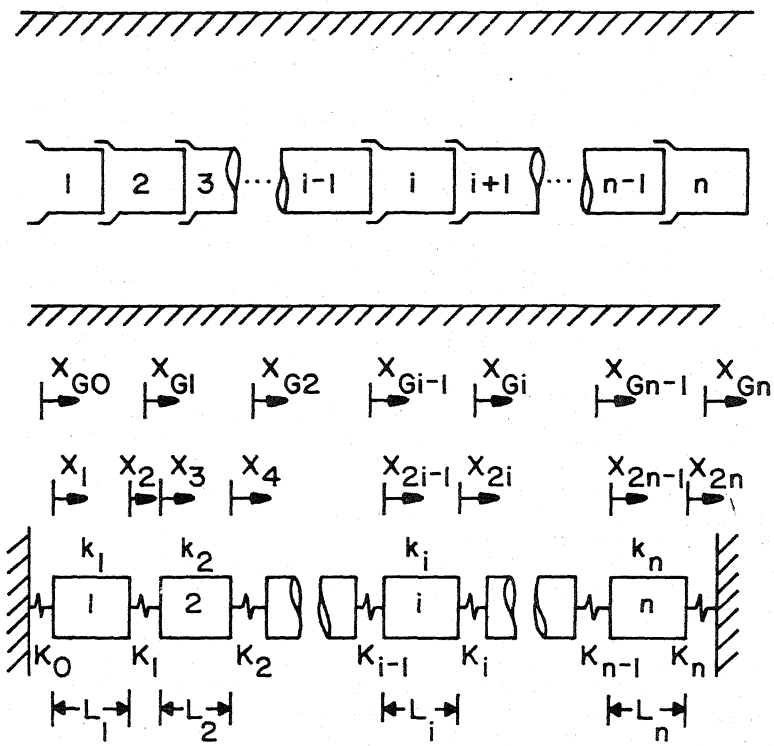

Fig. 1 - Seismic Analysis Model For Buried Pipeline