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GENERAL ELASTIC RESPONSES OF BURIED PIPELINE SYSTEMS DUE TO GROUND WAVE PROPAGATION

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SUMMARY

This paper is to report the general response behavior of buried pipeline systems under a seismic shaking environment. In order to aid the general design of such lifeline systems, this study includes continuous as well as segmented pipes with joints and junctions. The resistant behavior of the surrounding soils (longitudinal and lateral) and the pipe joints (axial and bending) are assumed to be linearly elastic. Both longitudinal and lateral responses due to compression and shear ground wave propagation are investigated. The interactions of various parameters are presented.

INTRODUCTION

Buried pipelines, which include water, sewer, oil and gas pipelines, have been damaged by recent earthquakes (Refs. 1,2) including the most recent Whittier California Earthquake of October 1, 1987 (Ref. 3). Despite the fact that the losses from fires due to earthquake damage to water mains in San Francisco in 1906 and in Tokyo in 1923 were much higher than the losses directly resulted from the earthquake itself, lifeline earthquake engineering which studies the behavior and design of long life-supported water and sewer systems, oil and gas pipelines, among others, has not been emphasized until after the 1971 San Fernando Earthquake.

In general, there are three causes of seismic hazards to buried pipelines namely: a) soil straining induced by seismic ground waves, b) fault movement/ground rupture and c) soil liquefaction induced by ground shaking. Although major seismic hazards have been observed to come from large ground movement/rupture along fault or soil liquefaction zones, the effects are localized and avoidance of crossing active faults or liquefaction zones may be possible. However, since seismic shaking affects a large area, the design and construction of buried pipeline under a seismic shaking environment is unavoidable. This paper concentrates on the response behavior due to seismic ground wave effects. At the present time, there are studies [Ref 4,5] for straight pipelines under seismic shaking. There is very limited information on response behavior and there is no seismic code for the design of buried pipeline systems available. The paper is to study the effects and interactions of various soil and pipe design parameters. In short, the scope of the study consists of (1) development of a general computer program that can evaluate the response behavior of any given buried pipeline system under any given seismic ground shaking condition and (2) investigation of the effects of various parameters in order to recommend future design criteria.

SYSTEM MODEL

The system model is shown in Figure 1. It consists of mains and branches of a buried pipeline system. For each pipe element, it is bonded by the continuous axial (K_{SA}) and lateral (K_{SL}) soil springs. There are five types of junctions considered in the system involving both axial (K_{JA}) and bending (K_{JR}) joint springs. They are (I) Continuous, (II) Linear, (III) Elbow, (IV) Tee, (V) Cross Junctions. The system is subjected to a horizontal ground wave, compression or shear type, with a traveling speed c, at an incident angle ϕ, with respect to the x-axis. Since both the loading function and the system geometry are in the same plane, the system may be considered as a plane frame from the structural analysis point of view.

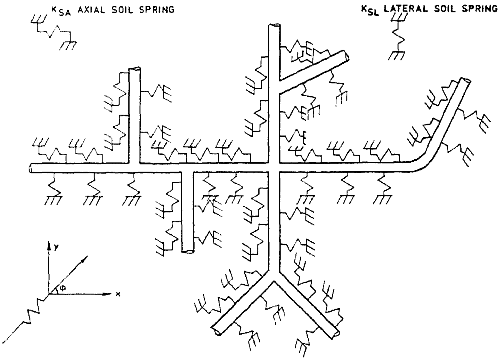

Figure 1 System Model

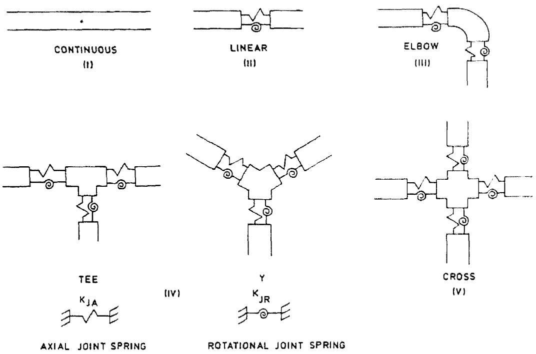

Figure 2 Type of Joints and Junctions

FORMULATION OF PROBLEM

The formulation of the problem is based on an energy approach for a quasi-static analysis. Since the dynamic effects on the response behavior of buried pipelines have been found to be negligible (Ref. 4) due to heavy soil constraint and damping, the inertia and damping term in the dynamic equations of motion can be dropped. Because the ground motion input is a function of time, the response will also be a function of time. Thus, the analysis is called quasi-static analysis.

As the details of the formulation are given in Ref. 6, the following only gives brief descriptions. The pipe element is modeled as a beam on two elastic foundations (one axial and one lateral) with three-degree-of-freedom (axial, lateral and rotational) at each end. Along with the surrounding soil (Fig. 1) and the joints (Fig. 2) springs, the total potential energy of the system is as follows:

$$
\begin{aligned}
U_{\text{Total}} &= U_{\text{Pipe}}^{\text{Total}} + U_{\text{Soil}}^{\text{Total}} + U_{\text{Joint}}^{\text{Total}} \\
&= \sum_{i=1}^{NM} \left(\frac{1}{2} \{u_i\}^T [K_P^i] \{u_i\} + \frac{1}{2} \{u_i^*\}^T [K_S^i] \{u_i^*\} \right) \\
&\quad + \sum_{i=1}^{NJ-NBJ} \frac{1}{2} \{u_{Ji}\}^T [K_J^i] \{u_{Ji}\} + \sum_{i=1}^{NBJ} \frac{1}{2} \{u_{Ji}\}^T [K_J^i] \{u_{Ji}\} \qquad (1)
\end{aligned}
$$

where $\{u_i\}$ is nodal displacement vector; $\{u_i^*\}$, relative nodal displacement vector between the pipe and the ground of ith pipe element; $\{u_{Ji}\}$, relative displacement vector of ith joint; NM, number of elements; NJ, number of joints; and NBJ, number of boundary joints. $[K_p^i]$ and $[K_s^i]$ are the ith element stiffness matrices of the pipe and the surrounding soil, respectively; and $[K_J^i]$, stiffness matrix of ith joint. Based on the principle of variation, the first variation of the total potential energy of an equilibrium system should be equal to zero, the quasi-static equation of equilibrium is found:

$$[K_{SYS}]\{u\} = [K]\{X_G\} = \{F(t)\} \tag{2}$$

where

$$[K_{SYS}] = [K_{Pipe}] + [K_{Soil}] + [K_{Joint}]$$

$$[K] = [K_{Soil}] + [K_{BJ}] \tag{3}$$

and $[K_{SYS}]$ is the system stiffness matrix, which includes the stiffness of pipe, $[K_{Pipe}]$, surrounding soil $[K_{Soil}]$ and joints, $[K_{Joint}]$; $\{u\}$, the system nodal displacement vector; $[K]$, forcing function stiffness, which includes the stiffness of the surrounding soil, $[K_{Soil}]$ and the boundary joints, $[K_{BJ}]$, and $\{X_G\}$, ground displacement vector. The details of these matrices can be found in Ref. 6.

A computer program written in FORTRAN has been completed to solve Eqn. (2) for the system response, $\{u\}$, for given system parameters shown Eqn. (3). Readers are referred to Ref. 6 for further details. In order to study the parametric responses, one has to know the range of the values of some physical parameters described below.

<u>Soil Resistant Parameters</u> As indicated in Figs. 1 and 2 as well as in Eqn. (1), the most important physical parameters are the axial soil resistant spring, K_{SA}, (from friction) and the lateral soil spring, K_{SL}, (passive soil reaction) from longitudinal and lateral motion of pipes. Although these parameters need to be investigated at the site for any important project, a value varying from 0.1 to 100 kips/in/in for various soils can be found in the literatures as reported by several investigators (Refs. 7, 8, 9). This range of K_{SA} and K_{SL} values would be reasonably used in the parametric study.

<u>Pipe Joint Resistant Parameters</u> For segmented pipeline, the axial (K_{JA}) and rotational (K_{JR}) joint resistant spring constants that affect the pipeline response behavior are two important parameters required in the developed system model. At the present time, there is very limited information on pipe joint resistant characteristics available. Recently, Singhal presented some pull-out and bending test data of rubber gasket joints (Ref. 10). Currently, the senior author (Ref. 11) and his colleague are conducting an experimental project on the dynamic performance of a very flexible joint developed recently in Japan. For rubber gasket joint, the joint spring constant is approximately 1 kip/in while the rotational spring constant is about 1 kip-in/degree.

For the parametric study, joint axial spring constants varying from 0.1 to 10,000 kip/in and rotational spring from 0.1 to 10,000 kip-in/degree would be used to represent very flexible to very rigid (almost continuous) pipe joints.

<u>Ground Wave Propagation Velocities</u> The ground wave propagation velocity, either compression or shear wave, is the most important site parameter that influences the seismic response behavior of buried pipelines. It varies tremendously according to the geological and soil conditions at the site. From various investigators, (Refs. 4, 9, 12, 13), the shear wave velocity varies from less than 100 ft/sec for banking top soil to more than 5000 ft/sec for sandstone clay. The compression wave velocity is at least twice higher than the shear wave. For the parametric study, shear wave velocities varied form 50 ft/sec to 500 ft/sec were used.

PARAMETRIC STUDY

To study the effects of various parameters in a buried pipeline system, a cross type pipeline with 10 segments for each leg under a sinusoidal ground motion (amplitude = 1 in, period = 0.8 sec, duration = 4 sec, $\Delta T = 0.1$ sec) is used for the parametric study. The referenced and the parametric conditions set for the comparison of results are given in Table 1 below:

Table 1 Study Parameters

Physical Parameter	Referenced Condition	Parametric Conditions
Pipe Material (Steel)	E = 30,000 ksi	Concrete E = 3,000 ksi C.I. E = 13,000 ksi
Segment Length	L = 20 ft	L = 10, 20, 40 ft
Diameter	OD = 6"	12", 18", 24", 36", 48"
Soil Stiffness	$K_{SA} = K_{SL} = 1$ ksi	$K_{SA} = 0.1$ to 10,000 ksi $K_{SL} = 0.1$ to 10,000 ksi
Joint Stiffness	Continuous	$K_{JA} = 0.1$ to 10,000 k/in $K_{JR} = 0.1$ to 10,000 k-in/degree
Wave Velocity	$C_p = 2400$ in/sec $C_s = 1200$ in/sec	$C_p = 1200$ in/sec - 12,000 in/sec $C_s = 600$ in/sec - 6,000 in/sec
Incident Angle	$\phi = 0°$	$\phi = 0°, 15°, 30°, 45°$
Boundary Condition	all edges free	combination of free and fixed

RESULTS AND DISCUSSION

While the details of the results can be found in Ref. 6, the following only discusses some of the important parametric effects on the response behavior of buried pipeline systems. It is noted that two independent methods have been used to verify the correctness of the formulations and to debug the computer program; one is based on the continuous and the other, segmented system formulated with longitudinal and rotational joint stiffnesses approaching infinite. Results of both continuous and segmented pipeline systems are reported below.

Continuous Pipeline System Responses The pipe strain and pipe curvature responses of a continuous pipeline system are given in Figs. 3 and 4. Since pipe strains are influenced mostly by the compression ground wave and the longitudinal soil stiffness, while the pipe curvatures, by the shear wave and the lateral soil stiffness, these parameters are used to plot the behavior curves shown in Figs. 3 and 4, respectively. One can see from these figures that as the soil stiffness increases, the pipe responses increase also. However, the increase in pipe strains is much more pronounced than the curvatures.

In Fig. 3, one can see the effect of the pipe size under a given seismic environment. It is shown that the smaller the pipe, the larger the pipe strain response will be. Similar conclusion can be applied to pipe curvature. The effect of wave propagation velocity is shown in Fig. 4. From the responses shown in Fig. 4, one can conclude that the lower propagation velocity of the

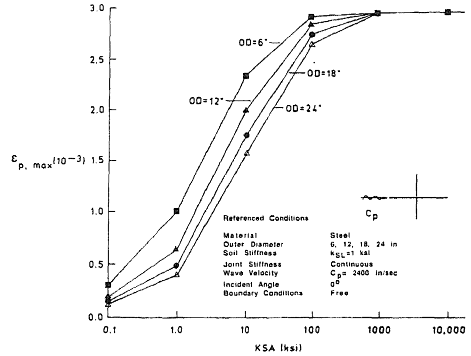

Figure 3 Pipe Strain Response

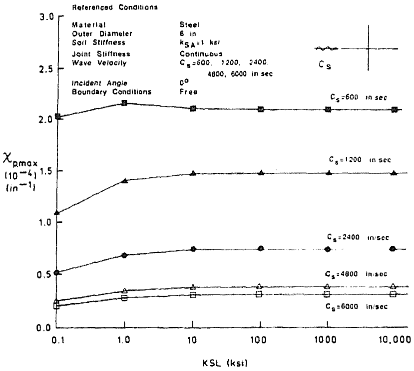

Figure 4 Pipe Curvature Response

soil at the site (soft soil) will produce higher pipeline responses. The effect of the ground wave incident angles to the pipe responses is given in Fig.5. For this study, P-wave is used and the maximum pipe strains are obtained for vertical (N-S) and horizontal (E-W) pipelines. One can see from this figure that when ϕ=0°, E-W pipe has the highest strain, while N-S the lowest. At ϕ=45°, both E-W and N-S pipes have the same maximum pipe strains. For other parametric effects, readers are referred to Ref. 6.

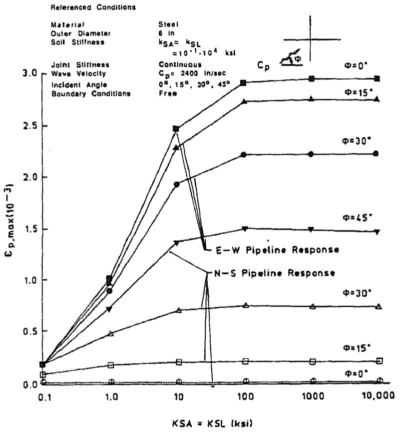

Figure 5 Effect of Incident Angle

Segmented Pipeline System Responses The relative joint displacement and rotation responses of the segmented pipeline systems are shown in Figs. 6 and 7, respectively. One can see from these figures that the longitudinal soil stiffness plays a major role, while the lateral soil stiffness does not seem to have much effect in segmented pipeline responses. One can see from Figs. 3 and 6 that for different diameters of pipe, the smaller pipe will have larger pipe strains, but smaller relative joint displacements and vice versa. Due to limited space other parametric behavior of segmented pipelines are not shown but can be founded in Ref. 6.

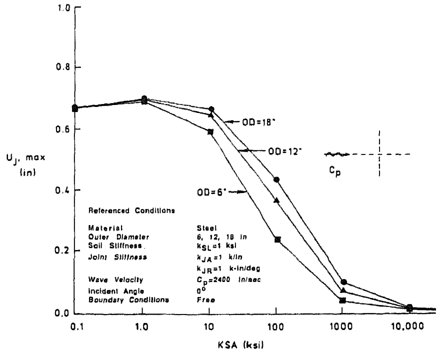

Figure 6 Relative Joint Displacement Response

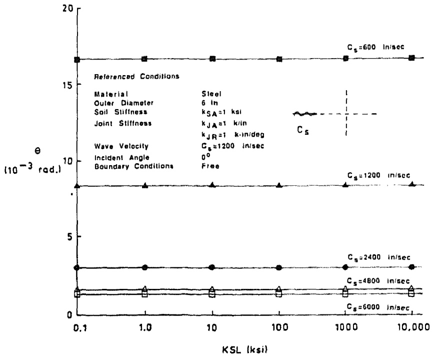

Figure 7 Relative Joint Rotation Response

CONCLUSIONS

For continuous pipeline systems, longitudinal soil stiffness dominates the pipe strain responses, while lateral soil stiffness affects the curvatures the most. However, the effect of longitudinal soil stiffness is more pronounced. Lateral soil stiffness will affect pipe strain response when $k_{SL} > k_{SA}$.

For segmented pipeline systems, as longitudinal soil stiffness increases, the pipe strain also increases, but relative joint displacement will decrease.

In general, higher propagation velocity of the ground wave will give lower pipeline responses. For various pipe sizes, smaller pipe will have larger strain, but smaller relative joint displacement responses. Design for safer pipeline should consider both pipe material and joint flexibility.

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