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EFFECTS OF PARAMETER VARIABILITY ON RESPONSE OF BURIED SEGMENTED PIPELINES

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SUMMARY

The behavior of straight buried pipeline subject to seismic wave propagation is investigated in this paper. Analytical models which incorporate the variability of system characteristics are used to evaluate system response.

INTRODUCTION

Information on the performance of segmented pipelines during past earthquakes indicates that damage most often occurs at the pipeline joints (Refs. 1,2). In particular, extension in the longitudinal direction is a major mode of failure. Other modes of failure such as crushing of the pipe bells, or opening of the joints under a combination of extension and rotation, have also been observed.

This damage can have serious consequences. For example, as a result of the 1985 Michoacan earthquake, approximately 3.5 million residents of Mexico City were left without running water. For this earthquake, water system damage was primarily due to leaks in the segmented water supply system caused by seismic wave propagation. In the Lake (or soft soil) Zone of Mexico City, the damage ratio was about 0.45 leaks/km with approximately one third of the leaks occurring at joints in nominally straight runs of piping. The other leaks occurred close to "T" or elbow junctions and other such hard spots (Ref. 3). Using a 6 meter spacing as the distance between joints, about one out of every thousand joints in straight runs of piping in the Lake Zone leaked. That is, although there were over 5000 leaky joints (ie, joints requiring repair), only a very small fraction of <u>all</u> the joints leaked.

Analytical models in which the system characteristics are uniform along the pipeline have been used in the past to determine pipeline response to wave propagation. However experimental results show a pronounced variability of joint properties. In addition, soil properties are expected to vary along the pipeline. In the present study, information on the seismic environment, the mechanical properties of pipe segments and joints, and the soil resistance to pipeline movements are combined to establish a realistic model. The model formulation takes into account the <u>nonlinearity</u> as well the <u>variability</u> of the system characteristics. The inclusion of <u>variability</u> of the joint and soil properties is considered a first step towards developing realistic models capable of estimating damage which observation indicates occurs only at a small fraction of all joints.

The results in this paper are based upon two simplifying assumptions. It is assumed that a static formulation is appropriate for evaluating pipeline response. Several studies have shown that inertia effects can be neglected (Refs. 4,5). This is primarily due to the fact that the mass of a fluid filled pipe is typically smaller than the mass of the insitu soil it replaces.

The second assumption limits this study to wave propagation effects. Although it is recognized that faulting, liquefaction and landsliding are potential causes of damage to pipelines, there are certain cases such as Mexico City in 1985 where damage was exclusively due to wave propagation effects.

Results from a sensitivity analysis which quantify the effects of joint and soil variability on response parameters such as the relative displacement at joints are presented. Results indicate that the response parameters are more influenced by variations in joint properties than by variations in soil properties. Finally, a simplified Monte Carlo simulation technique is used to develop histograms for the response parameters at different levels of ground strain. Emphasis is placed on joint displacement since damage usually occurs at the joints.

SEGMENTED PIPELINE MODEL

The purpose model for straight buried segmented pipelines is shown in Figure 1. It consists of a number of pipe segments surrounded by axial and lateral soil spring–sliders. The soil spring–sliders are treated as continuous rather than discrete in the formulation. Each pipe segment is modeled by a number of truss and beam elements. Joints exist between the pipe segments and are represented by nonlinear axial and rotational springs. Figure 2 shows the axial force/displacement curve for a lead caulked joint in a cast iron pipe system. The other type of system considered is a ductile iron system with rubber gasketed joints.

As mentioned previously, parameters defining the force deformation characteristics of the joints as well as the soil spring–sliders, are assumed to be random variables. For example, Figure 3 shows a histogram (Ref. 6) for the axial slippage force, Fs, for a 76cm (30in) diameter lead caulked joint in a cast iron pipe. The stress/strain relationship of the pipe segment material, on the other hand, is assumed to be deterministic. A complete methodology for determining these relationships for the two pipeline systems considered, is found in Ref. 7.

The quasistatic approximation to the seismic wave propagation environment is modeled by displacing the base of the soil spring–sliders.

MATHEMATICAL FORMULATION

A finite element formulation is used to develop the governing algebraic equation.

$$[K]\,\{d\Delta\} = \{dFg\} \qquad (1)$$

where [K] is the total stiffness matrix of the system, $\{d\Delta\}$ represents an increment of the nodal displacement vector and {dFg} is an increment of the applied load vector. The stiffness of the two end joints are doubled to account for the presence of the actual system beyond the length of the model considered.

The formulation includes cases where all the system characteristics are deterministic as well as cases where the soil and joint characteristics are random. When any of the response parameters enter the nonlinear range, Eq. 1 is solved incrementally. The resulting nodal displacement vector, $\{\Delta\}$, is used to compute the pipeline response parameters which include the joint displacements and rotations, pipe segment strains and relative displacements between the soil and the pipeline. The deterministic case is used herein for a sensitivity analysis.

A simplified Monte Carlo simulation technique is incorporated into the model to include cases where the soil and joint characteristics are assumed to be random. Histograms for the mechanical properties of the joints are used in conjunction with a random number generator, to establish the axial force/displacement and bending moment/rotation relationships for each joint along the pipeline model. The axial and lateral forces per unit length/displacement relationships for the soil spring–sliders along each pipe segment, are established in a similar manner. Equation (1) is solved for a number of generated models. The response parameters for each model are then combined to establish histograms for these response parameters.

SENSITIVITY ANALYSIS

Results from a sensitivity analysis highlight the effect of variable system characteristics upon pipeline response. Results are presented herein for three cases of a 76 cm (30 in) diameter cast iron pipeline, with 10 pipe segments in the models, subject to a ground strain $\epsilon_g = 0.001$. For case I, all joints have the same axial stiffness of 68.5×10^6 kgf/cm which is the average value from available laboratory tests. For this first case, the resulting joint displacements were all about 0.56 cm. Case II was identified to Case I except the middle joint is assigned a stiffness of 33.3×10^6 kgf/cm. This middle joint stiffness is towards the low end of the range of available tests. For case II the largest joint displacement of 0.72 cm occurred at the middle joint. For Case III the middle joint was assigned a stiffness of 137×10^6 kgf/cm which is towards the high end of available tests. In this case the two joints adjacent to the middle joint had the largest joint displacement of 0.65 cm. These results for cast iron pipe with lead caulked joints are summarized in Table I.

Table I shows that variations in stiffness from joint to joint result in variations in the maximum joint displacement as one might expect. The variation in joint displacement for ductile iron pipe with rubber gasketed joints is much less. This is due to the relatively low value of the average axial stiffness of these systems. For example, a 76 cm (30in) ductile iron joint has an average stiffness of 2.7×10^2 kgf/cm which is about 5 orders of magnitude lower than the corresponding cast iron joint.

Results were also obtained for cases where the soil properties are not uniform along the pipeline model. For both the cast iron and ductile iron systems considered, the joint axial displacements, uj, were not significantly affected by the variation in soil properties. This suggests that the joint parameter variability is more important than the soil parameter variability for the cast iron pipes with lead caulked joints system. For the ductile iron pipe with rubber gasketed joints system, both the variability of joint properties and that of the soil properties have a small influence on the results.

It should be mentioned that the system as a whole remained in the linear–elastic range for a tensile ground strain of $\epsilon g = 0.001$. However for the Monte Carlo simulation presented in the next section, the system enters the nonlinear range.

SIMPLIFIED MONTE CARLO SIMULATION

Simplified Monte Carlo simulation was applied to the two pipeline systems considered under a range of uniform ground strain, $1 \times 10^{-4} \leq \epsilon g \leq 7 \times 10^{-3}$. Histograms for each of the response parameters are established from models where joint and soil properties were randomly distributed. Figure 4 shows a histogram of the joint axial displacement, uj, for cast iron pipe with lead caulked joints under a uniform tensile ground strain, $\epsilon g = 0.001$. The same histogram for the ductile iron with rubber gasketed joints gives a mean joint axial displacement, uj = 0.59 cm and a coefficient of variation, $\mu = 1.7\%$. Thus, the variability of caulked joint properties has a stronger influence on the axial displacement at joints than the variability of rubber joints properties. This is mainly due to the fact that caulked joints are relatively rigid, while rubber joints are relatively flexible.

Results shown in Fig. 4 were used to generate the probability of exceedence for various values of the joint displacement as a function of ground strain. Typical results for a 76 cm (30in) diameter cast iron system with lead caulked joints is shown in Fig. 5. That is, at a tensile ground strain of 0.003, the probability of exceeding a joint displacement of 5.0 cm is about 0.002 (0.2% or one in 500).

The behavior of segmented systems under compressional ground strain was also studied. For cast iron systems with lead caulked joints, contact between pipe segments occurs at compressional ground strains between 0.0005 and 0.0007. The corresponding range for ductile iron systems in 0.001 to 0.002. At ground strain less than those identified above, the system response in tension and compression are similar. After compressional contact occurs, the response parameter of interest is the force in the joint, which is related to the possibility of crushing at the bell.

Table 2 presents the joint force for a 76 cm(30in) diameter system in compression with probabilities of exceedence of 1% and 0.1%. For a system at a given level of ground strain larger than that causing contact between some pipe segments, ($\epsilon g > 0.0007$ for cast iron or $\epsilon g > 0.002$ for ductile iron), there is only minor variability in the maximum joint force. For a system at a given level of ground strain less than that causing some contact ($\epsilon g < 0.002$ for ductile iron), there is substantial variability in the maximum joint force.

CONCLUSION

It is shown that the variability of joint properties can have a significant influence upon the response of straight buried segmented pipelines to seismic wave propagation. The influence is stronger for stiff systems such as cast iron with leads caulked joints than for flexible systems such as ductile iron with rubber gasketed joints. This partially explains why caulked joints tend to experience more seismic damage than rubber gasket joints. This highlights the advisability of using flexible joints in buried segmented systems subject to seismic wave propagation effects. It is also felt that this is a first step in developing analytical models capable of predicting seismic wave propagation damage.

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Table 1. Maximum Joint Displacement for Cast Iron System wih Lead Caulked Joints (tensile ground strain $\epsilon g=1.0x10^{-3}$).

CASE	$(U_j)_{max}$ (cm)
Case I; all with average stiffness.	0.56
Case II; middle joint with low stiffnes.	0.72
Case III; middle joint with high stiffness.	0.65

Table 2 Maximum Joint Force (kgf) for Various Exceedence Probabilities (compressional ground strain)

Material	ϵg	Prob. = 1%	Prob. = 0.1%
Cast Iron	$1x10^{-3}$	$3.35x10^{5}$	$3.57x10^{5}$
Cast Iron	$5x10^{-3}$	$1.67x10^{6}$	$1.68x10^{6}$
Ductile Iron	$1x10^{-3}$	$5.26x10^{4}$	$1.10x10^{5}$
Ductile Iron	$5x10^{-3}$	$1.13x10^{6}$	$1.14x10^{6}$

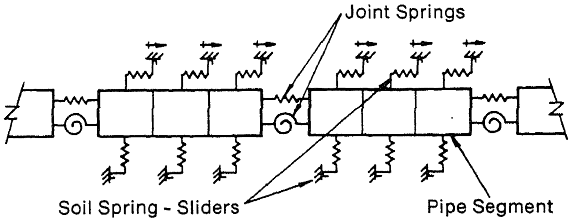

Figure 1. Mechanical Model

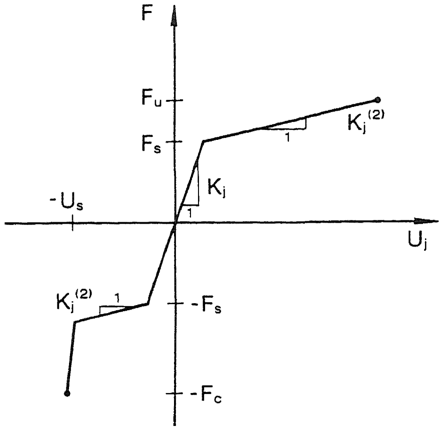

Figure 2. Typical force deformation relationship for lead caulked joint.

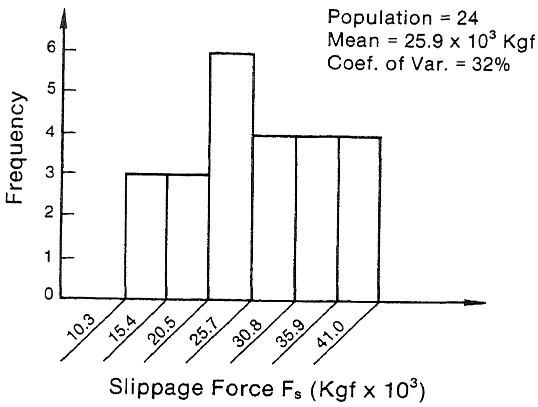

Figure 3. Histogram for slippage force for 76 cm diameter lead caulked joint.

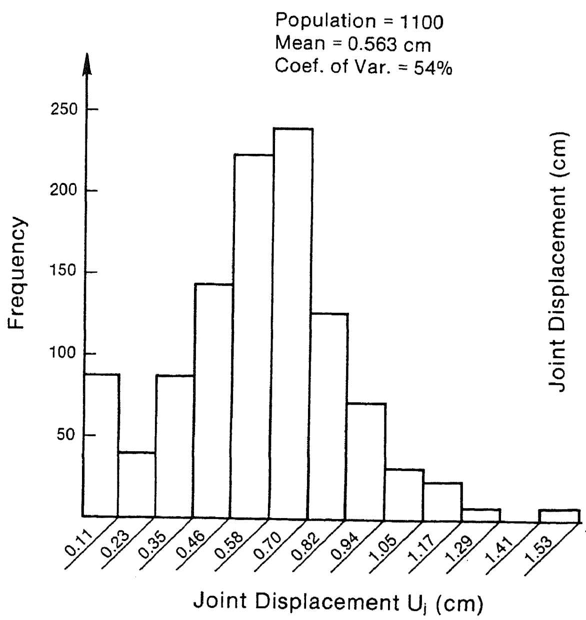

Figure 4. Histogram for joint displacement of 76 cm diameter cast iron pipe (tensile ground strain = 0.001)

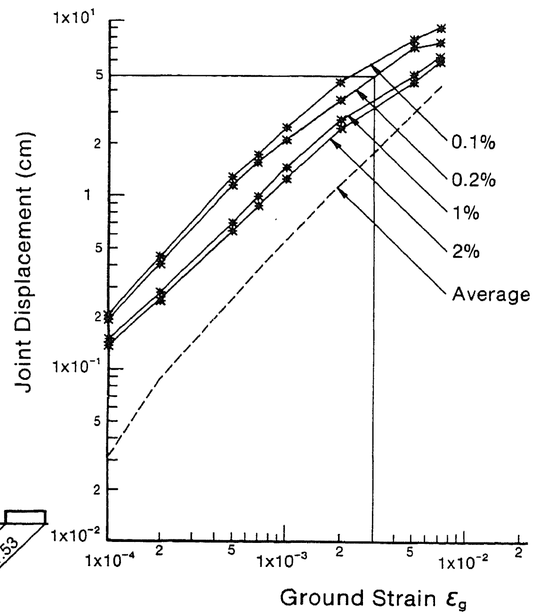

Figure 5. Joint displacement of 76 cm diameter cast iron pipe with various exceedence probabilities.