SEISMIC ANALYSIS OF UNDERGROUND TUBULAR STRUCTURES

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SUMMARY

Results of research conducted into the response of underground pipelines to seismic ground motion are reported. The study is theoretical and treats the following problems: deterministic analysis of pipe response to travelling waves acting under arbitrary angle of incidence in homogeneous medium and in two different media separated by a vertical boundary; stochastic response to ground motion which is random in time and space; and reduction of pipe stresses due to pipe insulation or slippage between the soil and the pipe. Some of the results also apply to tunnels.

INTRODUCTION

The seismic design of buried pipes carrying water, gas or other substances is very important as damage to pipelines can result not only in considerable economic loss but in widespread human suffering. Special risks are faced in nuclear powerplants where all the systems of underground piping must be designed to remain functional in the event of a safe shutdown earthquake.

This paper reports the results of research into seismic response of buried pipes conducted by the authors at the University of Western Ontario. The study is theoretical and formulated in terms of both deterministic and random vibrations using lumped mass as well as distributed mass models. The lumped mass model is used to investigate the pipe response to deterministic travelling waves while the distributed models are employed in the random vibration analysis. Only some of the main findings are reported here. Some aspects of the research are described in more detail in (1,2, 3,7 to 10). The theoretical approaches described can also be applied to tunnels.

Three different bedding conditions are considered: uniform soil, two different soil media separated by a vertical boundary and embedment in uniform soil with a soft insulation layer surrounding the pipe. The study is limited to the effects of ground shaking, ignoring kinematic interaction and the theory is linear.

RESPONSE TO TRAVELLING WAVES

The response of the pipe to travelling waves can be analyzed using the lumped mass model (Fig. 1). Such a model can be exposed to the effect of different waves that can produce both axial and lateral (bending) response depending on the angle of incidence (Fig. 2).

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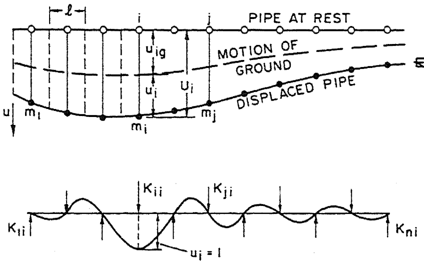


Fig. 1 - Lumped mass model and generation of pipe stiffness

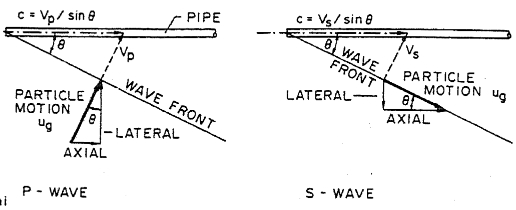


Fig. 2 - Pipe excitation due to P-wave and S-wave

The lateral response of the pipe is described in terms of the absolute displacements by the equation

$$\lceil m \rfloor\{\ddot{U}\} + [C_s]\{\dot{U}\} + [K]\{U\} = [C_s]\{\dot{u}_g\} + [K_s]\{u_g\} \tag{1}$$

In the above equation $\lceil m \rfloor$ is the diagonal mass matrix, $[C_s]$ the soil damping matrix, $[K]$ is the soil stiffness matrix and the vector of the ground displacements is

$$\{u_g\} = [u_{1g} u_{2g} \ldots u_{ng}]^T \tag{2}$$

Similarly, $\{U\}$, $\{u\}$ are the vectors of the absolute and relative pipe displacements, respectively. The dots indicate differentiation with respect to time. The equations of motion contain ground displacement and ground velocity.

For axial vibration, the equation of motion is formally the same; only the stiffness and damping matrices and the components of ground motion are replaced by the magnitudes pertinent to the axial direction.

The soil stiffness and soil damping matrices are evaluated from the reactions of soil to the motion of the ground. These reactions are complex and frequency dependent and are established approximately by combining the exact dynamic plane strain solution (10) with the static three dimensional solution due to Mindlin (6). In this way, the propagation of waves away from the pipe is approximately accounted for.

The free vibrations of the pipe are also of interest and can be obtained from Eq. 1 by ignoring the ground motion. The modal damping associated with individual modes of free vibration can be evaluated for use in modal analysis using an energy consideration. The modal damping ratio of the embedded pipe becomes

$$D_j = \sum_i \sum_k C_{ik} u_{kj}^2 / 2\omega_j \sum_k m_k u_{kj}^2 \tag{3}$$

in which ω_j is the natural frequency of mode j, C_{ik} the damping coefficient of mass m_i associated with vibration velocity of mass m_k (the i x k element of the damping matrix $[C_s]$) and u_{kj} the modal displacement of mass m_k in mode j; ω_j and u_{kj} are obtained by solving the eigenvalue problem of Eq. 1. The summations extend over the whole pipe. Eq. 2 applies to both lateral and axial vibrations with the pertinent C and u substituted.

The modal damping obtained from Eq. 3 is quite high. For a typical buried pipe, the damping of the first fifteen modes may range from more than 100 per cent for the first mode to 50 per cent for the fifteenth mode. The very low values of damping assumed sometimes in models that do not allow the calculation of damping do not appear to be justified and may lead to misleading conclusions.

Response to ground motion can be obtained from Eq. 1 using various descriptions of the seismic input. The basic case is that of a fully correlated travelling wave described by a single time history travelling along the pipe axis with a phase velocity $c = V/\sin\theta$, where θ is the angle of wave incidence with the pipe axis (Fig. 2) and V is the wave velocity. Extensive parametric studies of the pipe response were conducted by integrating the equations of motion in the time domain using the Wilson-θ method. Three different earthquake time histories were used in the study; two artificial earthquakes and the 1971 San Fernando Valley earthquake.

The analysis indicates that axial stresses are much higher than bending stresses. For a shear wave, maximum pipe bending stress occurs at θ=90° while maximum axial stresses occur at θ=40-45°. For a P-wave, maximum bending stresses occur at θ=50-60° while maximum axial stress occurs when θ=90°. The maximum pipe strains calculated with respect to soil-pipe interaction are plotted in a dimensionless form in Fig. 3 which summarizes the effect of different parameters for the two critical cases of the P-wave and S-wave excitation.

Using the strain parameters from Fig. 3, the maximum axial and bending stresses in the pipe can be obtained for any condition providing the following data are available: pipe parameters (Young's modulus E_p, pipe outer radius R and wall thickness t); soil parameters (mass density ρ, Poisson's ratio ν, shear wave velocity V_S and P-wave velocity V_P); earthquake parameters (maximum horizontal ground acceleration $\ddot{u}_g$, maximum horizontal ground velocity $\dot{u}_g$ and predominant period T). With these data, the maximum axial stress due to P-waves at θ=90° is

$$f_a^P = E_p \psi_a \dot{u}_g / V_P \quad (4a)$$

and the maximum bending stress due to shear waves at θ=90° is

$$f_b^S = E_p \psi_b R \ddot{u}_g / V_S^2 . \quad (4b)$$

The strain parameters ψ_a, ψ_b (Fig. 3, Eqs. 4) can be viewed as reduction factors accounting for the effects of soil-pipe interaction.

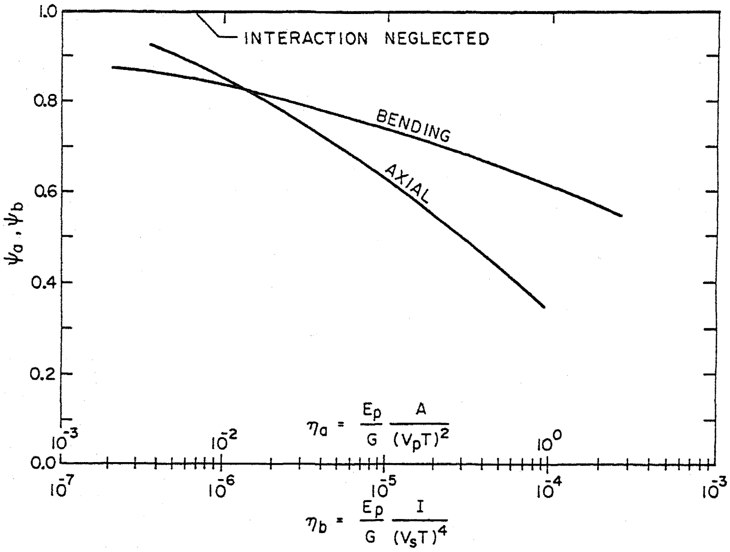


Fig. 3 - Normalized pipe axial strain ψ_a due to P-waves and bending strain ψ_b due to S-waves. (For Rayleigh waves V_P and V_S are replaced by V_R; A = pipe cross sectional area, I = pipe moment of inertia.

It can be seen from Fig. 3 that pipe strains calculated neglecting soil-pipe interaction represent the upper bound and that the interaction reduces pipe strains. The effect of interaction is greatest for rigid pipes buried in soft soil and subjected to high frequency seismic waves.

If soil-pipe interaction is neglected, $\psi_a = \psi_b = 1$ and Eqs. 4 take on the well known form. Often, the wave velocity is derived from seismic considerations of the overall motion of the ground that suggest a much higher shear wave velocity than soil properties of the top layer would indicate. In such cases, soil-pipe interaction effects are quite small.

Horizontally polarized shear waves also produce axial strain as can be inferred from Fig. 2. When soil-pipe interaction is ignored, the maximum axial strain due to shear waves occurs at the angle of incidence θ=45° and is

$$f_a^S = E_p \, \dot{u}_g/(2V_S) \tag{5}$$

This is a formula often used in practice to predict the most critical axial stress. This stress can be higher than the axial stress f_a^P due to P-wave (Eq. 4a) if $2V_S < V_P$. However, even higher axial stress can result from Rayleigh waves.

Pipe stresses caused by Rayleigh waves can be obtained by resolving the wave into a horizontal compression component and a vertical shear component. Both wave components travel with the R-wave velocity V_R and have amplitudes v_R and w_R in the horizontal and vertical directions, respectively. The shear wave component produces only bending stresses in the pipe while the compression component acts like the P-wave (Fig. 2) and produces axial as well as bending stresses depending on the pipe orientation with respect to the direction of wave propagation. For the critical direction of the wave front following the pipe (θ=90°), the axial and bending stresses due to R-waves may be obtained from Eqs. 4 and Fig. 3 by replacing both V_P and V_S with V_R for the axial as well as the bending cases. Since V_R is much lower than V_P and slighly lower than V_S, the pipe stresses due to Rayleigh waves are higher than those due to other types of waves having the same maximum acceleration and velocity and the reduction of the stresses due to soil-pipe interaction can be more significant. If soil-pipe interaction is neglected, the pipe axial stress from Rayleigh waves becomes

$$f_a^R = E_p \dot{u}_g / V_R \tag{6}$$

which is more than twice the axial stress due to shear waves given by Eq. 5.

Effect of pipe embedment on axial and bending stresses for different types of waves is shown in Fig. 4. In the case of P-waves and S-waves, the

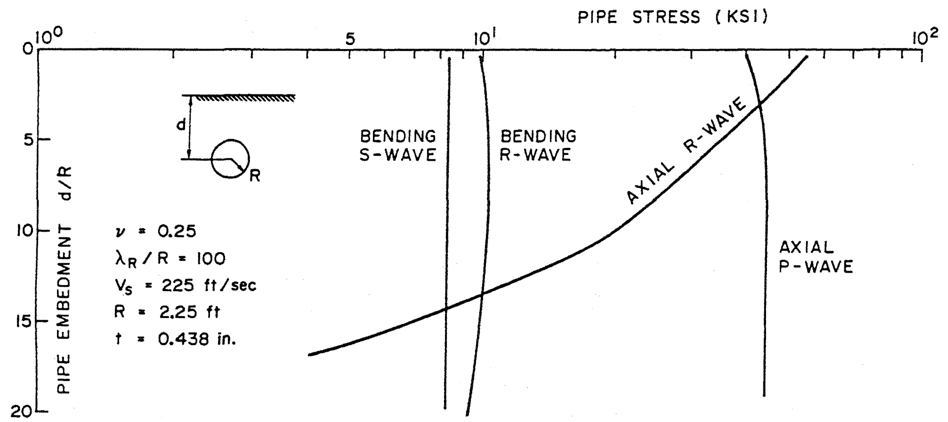
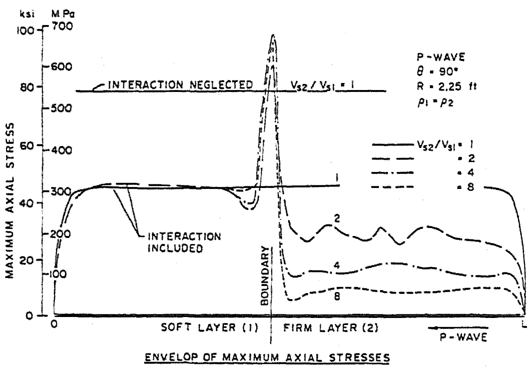


Fig. 4 - Variation of pipe stresses with embedment.

only parameter assumed to vary with depth was the soil reaction to pipe motion while wave amplitudes were assumed to be constant. In the case of R-waves, variations of the horizontal amplitude v and vertical amplitude w with depth were also considered using the well known relations including $\lambda = V_R T$ = the predominant length of the R-wave. Because the horizontal amplitude of the R-wave diminishes quickly with depth, the axial pipe stresses caused by R-waves decay rapidly with increasing pipe embedment. For the very low values of λ/R and V_s used in the sample, the axial stresses caused by R-waves become smaller than those produced by P-waves for embedment ratio $d/R>3.0$ and $d/R>6.2$ if interaction is neglected. Thus, the maximum stress decisive for design may be caused by different types of waves depending on conditions.

Two different media separated by a vertical plane can also be treated using the lumped mass model described by Eq. 1. The soil stiffness and damping matrices have to be adjusted and both wave refraction and reflection from the interface between the two media must be accounted for. The reflected wave is superimposed on the oncoming wave and the combined effect of both waves can amplify or attenuate the pipe response depending on the wave type, the direction of wave front propagation and the ratio of wave velocities in the two media. The case of two media was studied assuming the waves travelling along the pipeline and the reference time history is represented by the seismic wave in the weaker medium.



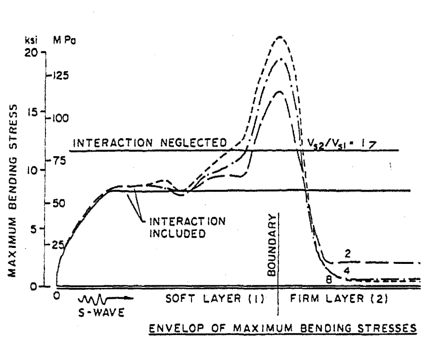


Fig. 5 - Maximum axial stresses in pipe due to P-wave propagating from firm soil to soft.

Fig. 6 - Maximum bending stresses in pipe due to S-wave propagating from soft soil to firm.

Examples of the results are shown in Figs. 5 and 6. Pipe stresses are highest close to the boundary and their peaks can exceed values calculated in the homogeneous medium ignoring soil-pipe interaction. Maximum axial stresses occur when the wave travels from firm soil to soft but this situation is reversed when considering bending stresses.

RESPONSE TO PARTIALLY CORRELATED RANDOM EXCITATION

One useful observation resulting from the analysis of the lumped mass system is that the effect of off diagonal terms of the soil stiffness and soil damping matrices is quite small and that the diagonal terms alone yield sufficient accuracy. This means that the soil reactions acting at a certain station can approximately be considered as independent of the soil reactions at other stations. This observation can be exploited in formulating the pipe response problem in terms of a distributed mass system suitable to examine the response of the pipe to partially correlated ground motions. For the solution in terms of random vibration, the displacement of the ground is described by the cross-spectrum

$$S_{u_g}(y_1,y_2,f) = \frac{S_{\ddot{u}_g}(f)}{(2\pi f)^4} R(y_1,y_2,f) \qquad (7)$$

where $S_{\ddot{u}_g}(f)$ = the local power spectrum of ground acceleration, f = frequency and $R(y_1,y_2,f)$ = the normalized cross-spectrum of ground acceleration at stations y_1 and y_2. For a moderately long pipeline section, the local spectrum can be considered as common for all stations y and the normalized cross-spectrum as depending rather on separation $|y_2-y_1|$ than on stations y_1,y_2. Realizing that $R(y_1,y_2,f)$ can be expected to diminish with both frequency and separation $|y_2-y_1|$ the ground motion cross-spectrum may be described similar to atmospheric turbulence as

$$R(y_1,y_2,f) = e^{-\frac{cf}{V}|y_2-y_1|} \qquad (8)$$

in which c = constant depending on the distance from the focus, magnitude of the earthquake, geology of the area and other factors, V = wave velocity (most often shear wave velocity); V/f = wave length and $f|y_2-y_1|/V$ = dimensionless frequency.

Using Eqs. 7 and 8, the pipe response was analyzed in the frequency domain using modal analysis. The analysis indicates that lack of correlation of the seismic excitation can produce stresses well in excess of those resulting from fully correlated travelling waves. The effect of the parameter c on the most critical axial response is shown in Fig. 7 (2,7).

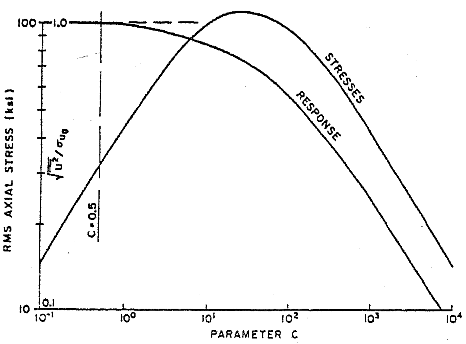


Fig. 7 - Pipe axial response and stress vs parameter c.

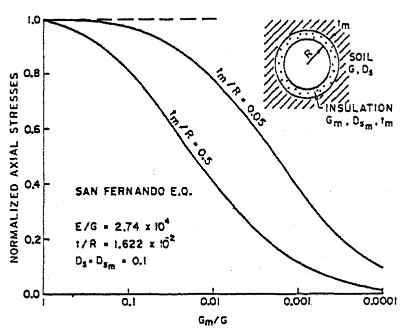


Fig. 8 - Effect of insulation on peak pipe axial stress due to fully correlated travelling wave.

With increasing c correlation decreases. Realistic values of c appear to be about 0.5 or less. More research into c is needed.

EFFECTS OF PIPE INSULATION AND SLIPPAGE

For the most critical axial stress these effects were examined using the theories outlined above with the only change being that the soil reactions to pipe motion were derived from a composite medium indicated in Fig. 8. This composite medium consists of a cylindrical layer of insulation around the pipe and the outer homogeneous medium representing the soil and extending to infinity. Examples of pipe stresses calculated are shown in a dimensionless form in Fig. 8. The results are plotted for different ratios G_m/G = shear modulus of insulation/shear modulus of soil and t_m/R = thickness of insulation/pipe radius. Pipe stresses decrease with a decrease in insulation rigidity and with an increase in its thickness. However, this decrease is less than might be expected (3).

Pipe slippage between the pipe and soil may be expected to produce pipe stress reductions very similar to those resulting from the effect of pipe insulation. Judging by Fig. 8, the reduction of pipe stresses due to slippage may be small and much less than is often assumed.

CONCLUSIONS

Soil-pipe interaction reduces pipe stresses but this reduction is significant only for very soft soils. Buried pipes are overdamped and consequently resonance type amplification does not occur. Axial pipe stresses are much higher than bending stresses for all types of excitation including random excitation. Lack of correlation of the seismic ground motion may result in pipe stresses in excess of those produced by fully correlated travelling waves. Pipe stresses are not reduced very much by insulation or slippage between the pipe and soil.

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