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# Earthquake response analysis of above-ground pipelines

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ABSTRACT: Based on a stochastic model for ground motion including its spatial variation, differential axial and lateral response of the soft joints of straight above-ground cross-country pipelines is studied. The elevation difference between soil surface and pipeline axis, neglected in previous studies, and compliance of the foundation-soil are considered. The axial response is found to be significantly larger than lateral response even if the ground motion components along and perpendicular to the pipeline axis have identical intensities. Joint distress is found to be greater for pipelines running through softer soil sites or having longer spans. Although higher damping at joints reduce differential joint movements, higher soil damping does not necessarily produce the same effect, especially for axial pipeline vibration. Joint distress in pipelines supported at higher elevations is less due to isolation of the spatial variation (incoherence) in ground motion.

## 1 INTRODUCTION

*Pipeline failure during past earthquakes has* principally been attributed to excessive stresses developed at joints between pipeline segments because of differential displacements at these joints (see Wang and Cheng (1979)). This type of joint failure has been attributed to two causes: spatial variation of ground motion along the length of the pipeline, and flexibility of the foundation soil medium. Therefore, any earthquake response analysis of cross-country pipelines should take into consideration these two critical aspects of the problem.

Anderson and Johnston (1975) analysed the lateral response of above-ground pipelines subjected to earthquake ground motion. They considered the spatial variation of ground excitation to be given by out-of-phase support motions, where the phase difference is the time lag due to the earthquake wave propagating through the foundation-soil medium along the pipeline axis at a given velocity. They, however, did not consider the foundation flexibility in their formulation, with the principal objective being the analysis of the effect of non-linear friction supports and initial stresses on pipeline response. They concluded, surprisingly, that the effect of out-of-phase motion of supports were almost completely negated by friction forces, and therefore spatial variation of ground motion was unimportant. Powell (1978) extended the work of Anderson and Johnston to the analysis of pipeline response considering *lateral and axial motion to occur* simultaneously. He concluded that out-of-phase support motions have a significant effect on response, and should, therefore, be considered.

Zerva, et al. (1988) analysed the response of above-ground pipelines to stochastic ground motion considering both the spatial variation of ground motion and the foundation flexibility. The former was accounted for by describing a correlation function between two support motions, which was obtained statistically from SMART-1 array data for the 1981 earthquake at Lotung, Taiwan. They concluded that it was spatial variation of ground motion that contributed totally to differential motions between pipeline segments, and that lateral responses of the structure were comparable to the axial responses and should, therefore, be analysed also.

This study, in a manner, is an extension of the work done by Zerva and others. The pipeline response to stochastic ground motion is analysed assuming spatial variation to be given by an idealized correlation function developed by Hindy and Novak (1980). The elevation of the pipeline axis above the ground surface is considered in the formulation, and the influence of this and other pipeline and soil parameters on the axial and lateral r.m.s. differential displacements at joints between pipe segments is analysed.

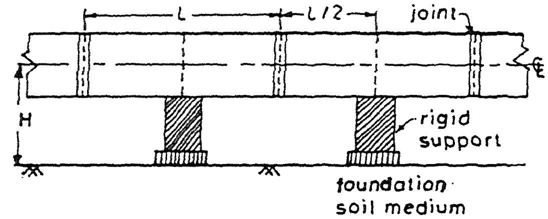

Figure 1. Typical above-ground pipeline.

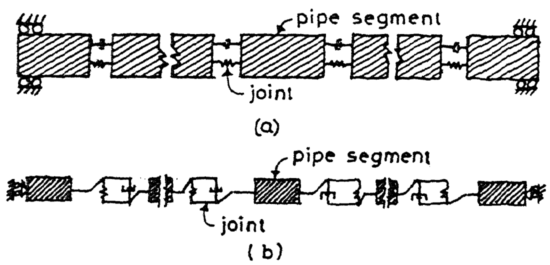

Figure 2. Structural idealization for (a) axial and (b) lateral joint differential response.

## 2 SYSTEM AND GROUND MOTION IDEALIZATION

A typical representation of a straight above-ground cross-country pipeline is shown in Figure 1 above: each pipeline segment of length L is supported at midspan by a rigid support that rests on the foundation-soil medium; each segment is connected to another on either end through a soft joint; and the pipeline longitudinal axis is at a height H above the ground surface.

This pipeline is modelled as an assemblage of finite number of rigid uniform straight line segments connected through soft flexible joints as shown in Figure 2, with each segment supported at midspan on a rigid square footing resting on the surface of a flexible foundation-soil medium. The line segments are at an elevation H above the ground surface, and the number of segments considered in the analysis is decided by the number, say $N$, required to obtain an asymptotic estimate of the differential response at a joint with the pipeline stretching infinitely on either side. In this study it was seen that for axial response analysis $N=9$ was sufficient, whereas for lateral response analysis $N=19$ was required.

Each flexible joint is idealized as a viscoelastic axial or shear spring, depending on whether the axial (see Figure 2(a)) or lateral/transverse (see Figure 2(b)) response of the pipeline is being analysed. This is different from the spring-dashpot system used by Zerva et al. (1988) and Wang and Cheng (1979) in that hysteretic damping, which is frequency-independent, is considered instead of viscous damping. Therefore the viscoelastic joint spring constant can be written as

$$\tilde{K}_p = K_p \ (1+i\eta_p) \qquad (1)$$

where $K_p$ and $\eta_p$ are the elastic stiffness constant and hysteretic damping ratio of the joint, respectively; and i is the notation signifying an imaginary number.

The foundation-soil medium is idealized as a viscoelastic half-space (see Veletsos and Verbic (1973)) with frequency-dependent impedance functions defined with respect to the lateral displacement and rotation of each footing, which are coupled to each other, as given by Veletsos and Wei (1971) and Goyal and Chopra (1989). The direction of the footing displacements considered depend on the type of pipeline response being analyzed: for axial response they are along the longitudinal axis of the pipeline, whereas for lateral response they are transverse to it. The coupling between displacements of adjacent footings is neglected since pipeline spans are generally significantly larger than footing dimensions. Therefore, the foundation-soil flexibility is considered by defining complex impedance functions $K_{VV}(\omega)$, $K_{MM}(\omega)$ corresponding to footing displacement and rotation, respectively, and $K_{VM}(\omega)$ as the coupling term with respect to each component of footing excitation, along and transverse to pipeline axis, for each support considered in the analysis.

This study is restricted to the consideration of earthquake waves travelling along the pipeline axis, and each support being subjected to two components of horizontal ground motion along principal orthogonal directions aligned with and tranverse to pipeline axis. The advantage of considering the principal directions in this manner is the uncoupling of the axial and lateral pipeline responses, since the support excitations along and transverse to pipeline axis are uncorrelated in the statistical sense.

Each free field earthquake ground motion component is idealized as a stationary, Gaussian wide-banded stochastic process of limited duration, such that the power spectral density function (PSDF) of the ground acceleration a is characterized by the modified Kanai-Tajimi PSDF given by Clough and Penzien (1975) as

$$S_{aa}(\omega) = S_0 \ / \ |H_1(\omega)|^2 \ |H_2(\omega)|^2 \qquad (2)$$

where $S_0$ is the spectrum of white noise bed acceleration given by

$$S_0 = \sigma_a^{\,2} / \int_0^{\infty} |H_1(\omega)|^2 \, |H_2(\omega)|^2 \, d\omega \qquad (3)$$

in which $\sigma_a$ is the root mean square (r.m.s.) ground acceleration that is assumed to be identical for all supports considered; and $|H_1(\omega)|$ and $|H_2(\omega)|$ are the magnitudes of the complex frequency response functions of the first and second filters, respectively, representing dynamic characteristics of soil medium above bedrock given by

$$|H_1(\omega)|^2 = \frac{1 + (2\eta_g \omega/\omega_g)^2}{[1-(\omega/\omega_g)^2]^2 + (2\eta_g \omega/\omega_g)^2} \qquad (4a)$$

$$|H_2(\omega)|^2 = \frac{(\omega/\omega_f)^4}{[1-(\omega/\omega_f)^2]^2 + (2\eta_f \omega/\omega_f)^2} \qquad (4b)$$

in which $\omega_g$ and $\omega_f$ are the resonant frequencies, and $\eta_g$ and $\eta_f$ are the viscous damping ratios of the first and second filters, respectively. The PSDF of ground displacement d is related to the PSDF of ground acceleration through the relationship

$$S_{dd}(\omega) = S_{aa}(\omega) / \omega^4 \qquad (5)$$

where $S_{aa}(\omega)$ is as given by equation (2).

The spatial variation of ground motion is given by defining a cross spectral density function between the excitations at two supports i and j to be given as

$$S_{a_i a_j}(\omega) = R(r_{ij}, \omega) \, S_{aa}(\omega) \qquad (6)$$

where again $S_{aa}(\omega)$ is given by equation (2), and $R(r_{ij}, \omega)$ is the cross-correlation function suggested by Hindy and Novak (1980), which is given as

$$R(r_{ij}, \omega) = \exp[-C r_{ij} \, \omega / 2\pi V_f] \qquad (7)$$

in which $V_f$ is the foundation-soil shear wave velocity, $r_{ij}$ is the distance between the two supports as measured along the direction of earthquake wave propagation, and C is a dimensionless factor that is dependent on soil conditions.

## 3 EQUATIONS OF MOTION

Based on the above idealizations the equations of motion for the pipeline can be developed considering the dynamic equilibrium of the structure-soil system in both axial and transverse lateral directions subjected to the multiple-support excitation defined above. However, since the axial and lateral motions of the pipeline are uncoupled, the equations of motion for the response analysis can be developed separately for the two cases.

### 3.1 Axial Motion

The degrees of freedom considered for analysing the axial response of the pipeline are the total inplane horizontal and rotational displacements of the supports defined at their base. Therefore, for N pipe segments there are 2N degrees of freedom -- $u_i$ and $\theta_i$, i=1,...,N, where i denotes the ith support. Then the governing equations for the ith pipeline segment, considering inplane axial force and moment dynamic equilibrium at the pipeline axis level, are given by

$$M_i \ddot{u}_i + M_i H \ddot{\theta}_i + \tilde{K}_p (u_i + H\theta_i - u_{i+1} - H\theta_{i+1}) + \tilde{K}_p (u_i + H\theta_i - u_{i-1} - H\theta_{i-1}) + K_{VV} u_i + K_{VM} \theta_i = K_{VV} d_i \qquad (8a)$$

$$M_i H \ddot{u}_i + (J_i + M_i H^2)\ddot{\theta}_i + \tilde{K}_p H(u_i + H\theta_i - u_{i+1} - H\theta_{i+1}) + \tilde{K}_p H(u_i + H\theta_i - u_{i-1} - H\theta_{i-1}) + K_{VM} u_i + K_{MM} \theta_i = K_{VM} d_i \qquad (8b)$$

where $M_i$ and $J_i$ are the total mass and mass moment of inertia, respectively, of the ith pipeline segment; $\tilde{K}_p$ is the complex joint spring constant given in equation (1); $H$ is the pipeline elevation (see Figure 1); $K_{VV}$, $K_{VM}$, and $K_{MM}$ are the soil impedance functions that are identical for all supports; and $d_i$ is the ground displacement under the support.

### 3.2 Lateral Motion

The degrees of freedom considered for analysing the lateral response of the pipeline are the total transverse horizontal and rotational displacements of the supports defined at their base, in addition to the rotation of the pipeline segments about their vertical axis. Therefore, for N pipe segments there are 3N degrees of freedom -- $u_i$, $\theta_i$, and $\alpha_i$, i=1,...,N, where i denotes the ith support or segment, as appropriate. The governing equations for each pipeline segment, considering dynamic equilibrium of transverse force and moment and moment about vertical axis of pipeline, can be developed similarly to equation (8) except that there are three equations per segment in this case. These equations can be written in the form

$$[M]\ \{\ddot{u}\} + [\tilde{K}]\ \{u\} = [\tilde{K}_f]\{d\} \qquad (9)$$

where [M] denotes the mass matrix that includes the mass moments of inertia about the two axes of rotation considered; $[\tilde{K}]$ denotes the system stiffness matrix that contains both joint and soil impedance functions; $[\tilde{K}_f]$ has terms identical to the right hand side of equation (8), i.e. only lateral and coupling soil impedance functions; {u} is the vector of 3N degrees of freedom; and {d} is the vector of N support excitations.

## 4 RESPONSE ANALYSIS

Since the pipeline response is a stationary, Gaussian stochastic process, the PSDF matrix for the displacements corresponding to the defined degrees of freedom of the pipeline can be obtained from standard stochastic analysis procedures (see Clough and Penzien (1975)), given the PSDF of multiple support displacements (see equation (5)) and their cross-spectral density functions (see equation (6)). From this matrix it is possible to obtain the covariance matrix of the displacements, as each term in the covariance matrix is the area under the corresponding cross-spectral density function curve in the PSDF matrix.

Furthermore, the differential response, whether axial or lateral, at any joint is linearly related to the total response of the two pipeline segments connected at that joint. For example, the axial differential displacement at joint i, i.e. the joint between pipeline segments i and i+1, can be expressed as

$$\Delta u_i = u_i + H\theta_i - u_{i+1} - H\theta_{i+1} \qquad (10)$$

where u and θ are the total axial responses of the pipeline as defined in equation (8). Similarly, the lateral differential displacement at joint i can be expressed in terms of the total lateral response of segment i and i+1 as

$$\Delta u_i = u_i + H\theta_i + (L/2)\alpha_i - u_{i+1} - H\theta_{i+1} - (L/2)\alpha_{i+1} \qquad (11)$$

Therefore, the variance and hence the root mean square (r.m.s.) value of the differential joint displacements can be obtained from the covariances of the pipeline displacements through standard procedures.

## 5 RESULTS AND DISCUSSION

An example above-ground cross-country pipeline is considered here to study the effects of the various pipeline, joint and soil parameters on the r.m.s. differential displacements at the joints. The following data is assumed to be given and constant in this study : pipeline mass density = 2500 N-sec$^2$/m ; soil mass density = 1700 N-sec$^2$/m ; soil poisson's ratio = 0.25 ; footing dimensions = 1.5m x 1.5m ; r.m.s. ground acceleration = 0.61 m/sec$^2$ ; soil parameter C in equation (7) = 0.5 ; and the Kanai-Tajimi filter properties : $\omega_g$ = 5π rad/sec; $\eta_g$ and $\eta_f$ = 0.6; and $\omega_f$ = 0.1$\omega_g$ . The footing is assumed to be a thin massless rigid equivalent circular plate for analysis. The other system properties and their values chosen for this study are given in Table 1 below.

Table 1. Values of system parameters that are varied in the pipeline analysis.

| Parameter | Values |
|---|---|
| Segment length L | 10 m or varied |
| Pipeline elevation H | 1.25 m or varied |
| Joint stiffness $K_p$ | 0.1$K_{vv}$ (ω=0) or varied |
| Joint damping ratio $\eta_p$ | 0.10 or varied |
| Soil damping ratio $\eta_f$ | 0.80 or varied |
| Soil wave velocity $V_f$ | 100 m/sec or varied |

$K_{vv}$(ω=0) denotes the static soil lateral stiffness value.

The results of the analysis of the effect of the six system parameters listed in Table 1 on both axial and lateral differential joint displacements of the example above-ground pipeline are presented in Tables 2 and 3, and Figures 3 to 6.

Table 2. Influence of normalized joint stiffness on r.m.s. joint differential displacement.

| $K_p/K_{vv}$ | Axial resp. | Lateral resp. |
|---|---|---|
| 0.1 | 4.787 | 0.9177 |
| 0.25 | 3.692 | 0.3652 |
| 0.5 | 2.900 | 0.1818 |

All displacements in mm.

Table 3. Influence of joint hysteretic damping ratios on r.m.s. joint differential displacement.

| $\eta_p$ | Axial resp. | Lateral resp. |
|---|---|---|
| 0.02 | 4.830 | 0.9555 |
| 0.10 | 4.787 | 0.9177 |
| 0.20 | 4.731 | 0.8692 |
| 0.40 | 4.611 | 0.7731 |

All displacements in mm.

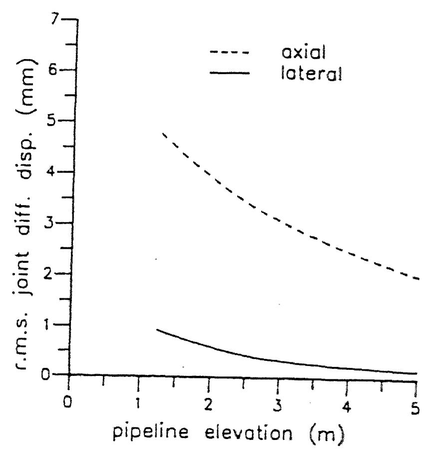


Figure 3. Influence of pipeline elevation on r.m.s. axial and lateral joint differential displacements.

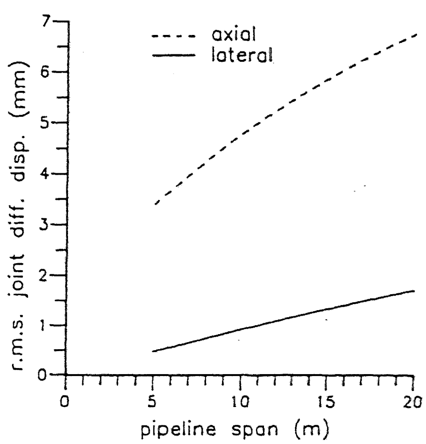


Figure 4. Influence of pipeline span on r.m.s. axial and lateral joint differential displacements.

This analysis reemphasises the fact that although lateral differential joint response is always smaller than the axial one, it is significant and cannot be ignored.

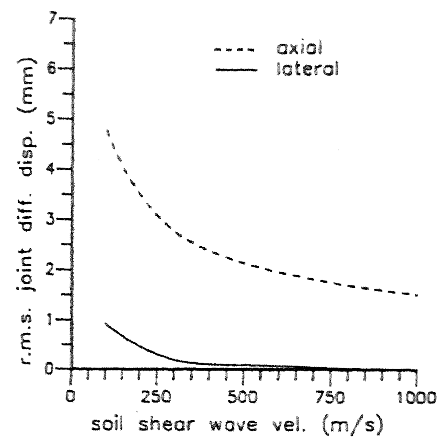


Figure 5. Influence of soil shear wave velocity on r.m.s. axial and lateral joint differential displacements.

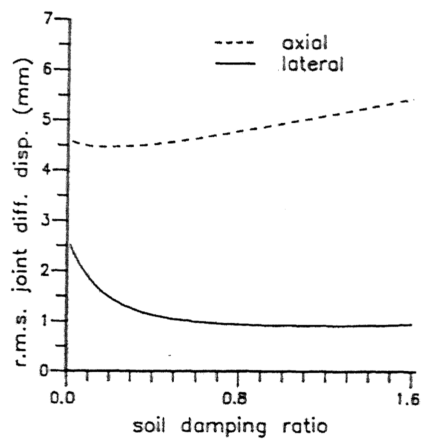


Figure 6. Influence of soil hysteretic damping ratio on r.m.s. axial and lateral joint differential displacements.

Analysing the results in Table 2 shows that increasing joint stiffness decreases both axial and lateral differential joint displacements, and the reasons for this is obvious. However, if the joint differential forces are studied it can be seen that the lateral forces are practically invariant of the lateral stiffness, whereas the axial forces increase significantly with increase in joint stiffness. Furthermore, the results in Table 3 imply that the joint material damping has an insignificant effect on the differential response of a pipeline, unless it is very large when it reduces the differential response by dissipating more energy. Therefore, it can be concluded that softer joints attract lesser differential response, since these joints are flexible, and have more energy dissipation capacity.

The significance of the effect of pipeline elevation on joint differential response is obvious from Figure 3, with higher elevations reducing the response significantly. The reason for this is the increased effect of footing rotation in the total response of each pipeline segment with increasing height. Since, adjacent footing rotations are almostly perfectly correlated, i.e. they are in-phase, this reduces the differential response at the joint between the segments. Therefore, above-ground pipelines at high elevations have a lower risk of joint failure due to excessive differential response being developed.

The reason for increasing joint differential response with increasing pipeline spans, as illustrated in Figure 4, is the decreasing level of correlation between adjacent pipeline support excitations as the distance between the supports increase.

The joint differential response also significantly reduces with increasing shear wave velocity of the foundation-soil medium, as demonstrated by Figure 5. This is because of a combination of two factors. As the foundation becomes more rigid, the total pipeline displacement closely corresponds to the ground displacement. Furthermore, as the velocity increases, the lack of correlation, i.e. the out-of-phase nature, between support excitations reduces significantly leading to a large reduction in differential response. In fact, for a soil shear wave velocity > 750 m/sec, the lateral response is insignificant.

The effect of soil damping on pipeline joint differential response shows markedly different trends for axial and lateral motion (see Figure 6). Whereas increasing soil damping reduces lateral response, it increases axial response. For understanding the reason for this behaviour, it is instructive to investigate the cause of differential joint response in the two cases. For lateral response, the contribution to differential motion comes from three sources (see equation (11)): the difference between the adjacent total footing displacements, footing rotations, and segment rotations about vertical axis. Increased soil damping reduces the effect of the footing displacements with respect to segment rotations, which are in-phase with each other thus reducing differential joint response. For axial response, the contribution to differential motion comes from two sources (see equation (10)): the differences between the total footing displacements and rotations. Increased soil damping reduces both response quantities, but has a more severe effect on rocking. Therefore, the relief from the in-phase nature of rocking motion is lost increasing differential motion at the joint.

## 6 CONCLUSIONS

The main conclusions from the study are the following:

1. Softer joints attract less differential response, and are therefore safer for use in above-ground cross-country pipelines.
2. Joint distress is found to be greater for pipelines running through softer soils or having longer spans.
3. Joint distress in pipelines supported at higher elevations is less due to isolation of the spatial variation in ground motion.
4. Higher soil damping does not necessarily reduce differential pipeline joint response, especially for axial motions.

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