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3-D responses of buried pipeline systems under earthquake wave propagation

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ABSTRACT: In this paper, site responses of multilayered soil medias in half-space are deduced under propagation of earthquake surface wave—Love wave and Rayleigh wave. Then, regarding the site responses as earthquake multi-point inputs of buried pipelines, 3-D responses of buried pipeline systems are carried out. A mathematic model is put forward in which the pipeline systems are taken as space frames composed by continuous and segmented beams with joints and junctions, and the interaction between pipelines and soil in axial, transverse and distortional direction are taken into account by elasto-plastic springs. The computer programs are compiled, and the programs can evaluate the 3-D responses of any given buried pipeline systems. Some conclusions are obtained from a large amount of numerical calculation.

1 INTRODUCTION

As the rapid development of city, the prevention and reduction to the disasters of the facilities of municipal engineering have been paid more and more attention. A substantial percentage of these facilities are placed underground, and to form buried pipeline systems. Buried pipeline systems, which include water and sewer, natural gas and oil, power and communication pipelines, are lifelines of city. Interruption of these buried pipelines could cause major, even catastropic, disruption of essential services, and might break down the whole citylife seriously. If such disruption is caused by earthquake, the effect of the loss of vital service would be greatly amplified by impeding fire–fighting, preventing essential energy transmission, commuications, and transportation, and causing widespred diseae. For example, in the 1906 San Fernando earthquake , the lack of water was mainly responsible for the great fire following the earthquake, and the lack of potable water led to epidemics. It was eatimated that 80 percent of the damage was due to fire which resulting in destruction of an area covering 4.7 square miles. Similarly, the 1923 Kanto earthquake in Tokyo resulting the destruction of 40 percent of the city by fire. Buried pipeline systems have also been extensively damaged in severe earthquake, such at Kanto 1923, Long Beach 1933, Fukui 1948, Alaska 1964, San Fernando 1971, Managua 1972 and Tangshan 1976 (Liu 1985).

In general, there are three causes of seismic damages to buried pipelines: relative ground movement and faulting, travelling seismic waves, and liquefaction of sandy soil.

Because modern cities depend heavily on utility systems for their day–to–day operation, earthquake threats to utility systems become increasingly important in proportion with the level of urbanization. Furthermore, as a result of population growth and enviromental considerations, more and more structures for utilities and transportation systems are placed underground, and the need to maintain services after an earthquake becomes more critical every day. Since utility systems are networks having sources, transmission lines, and distrubution systems within themselves, damages to single locations in a utility network often affects significant portions of the entire systems.

Although major seismic damages have been observed to come from relative ground movement and faulting and liquefaction of sandy soil, the effects are localized and avoidance of crossing faulting and liquefaction zones may be possible. However, since seismic waves affects a large area, the design and construction of buried pipelines under a seismic environment is unavoidable.

It should be noted that all the previously studies deal mainly with a single long pipeline. Except for a system approach to lifeline (Wang 1988), very little work has been done on seismic general response behavior of entire buried pipeline systems,(Wang 1978 and Wang 1988) but the approach (Wang 1988) is only quasi–static analysis and only plane pipeline systems, and many studies (Ariman 1981, Kamiyama 1976 and Oishi 1982) have been indicate that the effective wave for asismic design of buried pipelines may not be the S–wave, but rather the surface wave, perticularly in homogeneous ground.

In this paper, 3–D responses of buried pipeline systems under eathquake surface wave propagation have been carried out, the computer programs are

compiled, and some conclusions are obtained from a large amount of numerical calculation.

2 MODEL FOR PIPELINE SYSTEMS

In order to simplify the problem, a simplified mathematic model is put forward in which the pipeline systems are taken as space frames composed by continuous and segmented beams with joints and junctions, and flexibility of the joint is taken into account by a axial spring, a bending spring and a distortional spring, and the interaction between pipeines and soil in axial, transverse and distortion direction are taken into account by elasto–plastic springs of soil.

The buried pipeline system model is shown in Figure 1. From reference (Wang 1988), there are five types of junctions in system plane (Figure 2). The elasto–plastic springs of soil (Takada 1988) are shown in Figure 3.

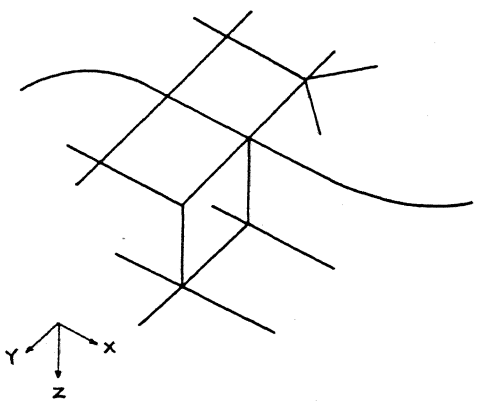


Figure 1. Buried pipeline systems model

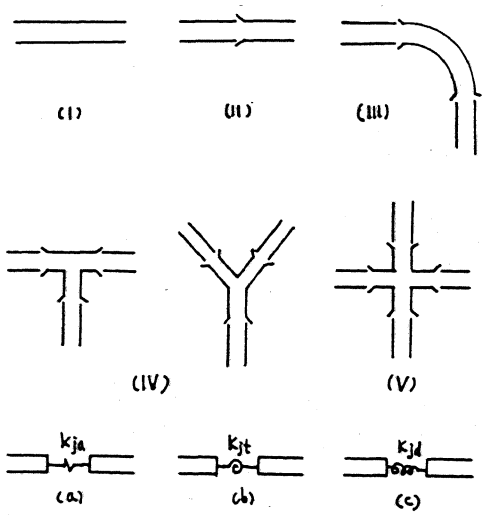
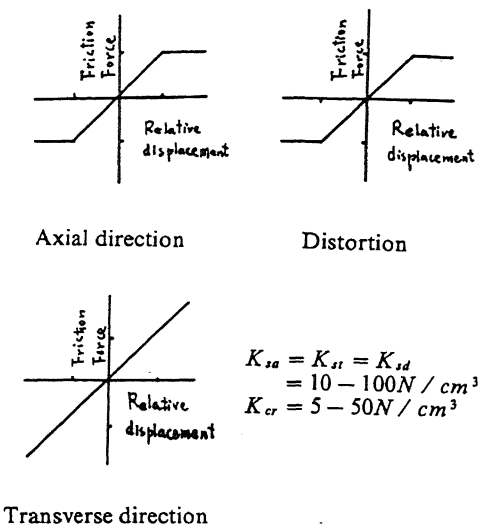


Figure 2. Types of joints and junctions



Axial direction

Distortion

Transverse direction

Figure 3. Springs of soil

3 EQUATIONS OF MOTION OF BURIED PIPELINE SYSTEMS

A lumped mass model is used here for equations of motion of buried pipeline systems.

The pipeline systems are divided into n slices of length, l, and the mass of each slice is lumped in the middle of it, and the mass matrix $[M]$and the stiffness matrix $[K]$of the pipeline systems can be formed with space bar–beam elements. If we only consider the steady responses of the buried pipeline systems, the soil damping can be neglected.

Since the resistance to the pipeline motion is generated by relative motion between the pipeline and the soil, u_l, the pipeline resistance come from the absolute displacements, U_l,the equations of motion of buried pipeline systems are

$$[M]\{U\} + [K_p]\{U\} + [K_s]\{u\} = 0 \tag{1}$$

Denotingthe abslute displacements

$$\{U\} = \{u_g\} + \{u\} \tag{2}$$

the equations of motions are in terms of the absolute displacements

$$[M]\{U\} + [K_p]\{U\} + [K_s]\{U\} = [K_s]\{u_g\} \tag{3}$$

in which, u_g is ground displacements.

4 DISPERSION OF LOVE WAVE AND RAYLEIGH WAVE IN MULTILAYERED HALF–SPACE

We consider plane waves of angullar frequency p and phase velocity c propagated in a hallf–space medium make up of n parallel, homogeneous, istropic layers (Haskell 1953) shown in Figure 4.

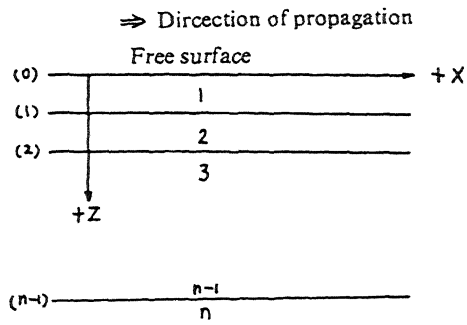


Figure 4. Multilayered soil in half–space

For the mth layers,

σ_m is density;
d_m is thickness;
λ_m and μ_m are Lame elastic constants;
α_m and β_m are velocity of propagation of dilatational and rotational waves respectively;
k is wave number, $k = p / c$;
$\gamma_m = 2(\beta_m / c)^2$;
u and w are displacement components in x and z directions;
σ is normal stress;
τ is tangential stress;
and let

$$\gamma_{m\alpha} = \begin{cases} +[(c/\alpha_m)^2 - 1]^{1/2} & c > \alpha_m \\ -i[1-(c/\alpha_m{}^2)]^{1/2} & c < \alpha_m \end{cases}$$

$$\gamma_{m\beta} = \begin{cases} +[(c/\beta_m)^2 - 1]^{1/2} & c > \beta_m \\ -i[1-(c/\beta_m)^2]^{1/2} & c < \beta_m \end{cases}$$

4.1 Rayleigh wave

For Rayleigh wave, periodic solutions of the elastic equations of motion for the mth layer may be found by combining dilational wave solutions,

$$\Delta_m = (\partial u/\partial x) + (\partial w/\partial z) = exp[i(pt - kx)][\Delta'_m exp(-ikr_{\alpha m} z) + \Delta''_m exp(ikr_{\alpha m} z)] \quad (4)$$

$$\omega_m = (1/2)[(\partial u/\partial z) - (\partial w/\partial x)] = exp[i(pt - kx)][\omega'_m exp(-ikr_{\beta m} z) + \omega''_m exp(ikr_{\beta m} z)] \quad (5)$$

where, Δ'_m, Δ''_m, ω'_m and ω''_m are constants.

The displacements and the pertinent stress components are,

$$u = -(\alpha_m / p)^2(\partial\Delta_m/\partial x) - 2(\beta_m / p)^2(\partial\omega_m/\partial z) \quad (6)$$

$$w = -(\alpha_m / p)^2(\partial\Delta_m/\partial z) + 2(\beta_m / p)^2(\partial\omega_m/\partial x) \quad (7)$$

$$\sigma = \rho_m[\alpha_m{}^2\Delta_m + 2(\beta_m)^2\{(\alpha_m / p)^2(\partial^2\Delta_m/\partial x^2) + 2(\beta_m / p)(\partial^2\omega_m/\partial x\partial z)\}] \quad (8)$$

$$\tau = 2\rho_m\beta_m{}^2[-(\alpha_m / p)^2(\partial^2\Delta_m/\partial x\partial z) + (\beta_m / p)^2\{(\partial^2\omega_m/\partial x^2) - (\partial^2\omega_m/\partial z^2)\}] \quad (9)$$

The boundary conditions to be met at an interface between two layers are that these four quantities shall be continuous. Since c is the same in all layers, we may take the dimensionless quantities $\dot{u}/c$ and $\dot{w}/c$ to be continous. Substituting the expressions (4) and (5) in equations (6) to (9), and expressing the exponential functions of $ikrz$ in trigonometric form, and placing the origin of z at the (m−1)th interface, the linear relationship between the values of $\dot{u}/c$, $\dot{w}/c$, ρ *and* τ at the (m−1)th interface and the constants $(\Delta'_m+\Delta''_m)$, $(\Delta'_m-\Delta''_m)$, $(\omega'_m-\omega''_m)$ *and* $(\omega'_m+\omega''_m)$ may be represented by the transformation

$$(\dot{u}_{m-1}/c, \dot{w}_{m-1}/c, \sigma_{m-1}, \tau_{m-1}) = E_m(\Delta'_m + \Delta''_m, \Delta'_m - \Delta''_m, \omega'_m - \omega''_m, \omega'_m + \omega''_m) \quad (10)$$

in which, E_m is matrix.

Letting $z = d_m$ gives the values of $\dot{u}/c$ etc. at the mth interface in terms of $\Delta'_m + \Delta''_m$ etc.

$$(\dot{u}_m/c, \dot{w}_m/c, \sigma_m, \tau_m) = D_m(\Delta'_m + \Delta''_m, \Delta'_m - \Delta''_m, \omega'_m - \omega''_m, \omega'_m + \omega''_m) \quad (11)$$

in which, D_m is matrix.

From equation (10) and (11), a linear relationship between the values of $\dot{u}/c$, $\dot{w}/c$, σ, *and* τ at the top and bottom of the mth layer may be expressed symbolically by the equation,

$$(\dot{u}_m/c, \dot{w}_m/c, \sigma_m, \tau_m) = D_m E_m^{-1}(\dot{u}_{m-1}/c, \dot{w}_{m-1}/c, \sigma_{m-1}, \tau_{m-1}) \quad (12)$$

Letting

$$A_m = D_m E_m^{-1}$$

and because the values of $\dot{u}/c$, $\dot{w}/c$, σ *and* τ at the top of the mth layer are the same as the values at the bottom of (m−1)th layer, we may write

$$(\dot{u}_m/c, \dot{w}_m/c, \sigma_m, \tau_m) = A_m A_{m-1}(\dot{u}_{m-2}/c, \dot{w}_{m-2}/c, \sigma_{m-2}, \tau_{m-2}) \quad (13)$$

By repeated application of equation (13), we have

$$(\dot{u}_{n-1}/c, \dot{w}_{n-1}/c, \rho_{n-1}, \tau_{n-1}) = A_{n-1}A_{n-2} \cdot \cdot \cdot A_1(\dot{u}_0, \dot{w}_0, \sigma_0, \tau_0) \quad (14)$$

and by application of the inverse of equation (10) for the nth layer,

$$(\Delta'_n + \Delta''_n, \Delta'_n - \Delta''_n, \omega'_n - \omega''_n, \omega'_n + \omega''_n) = E_n^{-1} A_{n-1} A_{n-2} \cdot \cdot \cdot A_1 (\dot{u}_0 / c, \dot{w}_0 / c, \sigma_0, \tau_0) \quad (15)$$

The case with which we are particularly concerned is that in which there are no stresses across the free surface, so that $\sigma_0 = \tau_0 = 0$, and there are no sources at infinity, so that $\Delta''_n = \omega''_n = 0$. The equation (15) can be write

$$(\Delta'_n, \Delta''_n, \omega'_n, \omega''_n) = G(\dot{u}_0, \dot{w}_0, 0, 0) \quad (16)$$

in which, $G = E_n^{-1} A_{n-1} A_{n-2} \cdot \cdot \cdot A_1$

or, explicitiy,

$$\begin{aligned} \Delta'_n &= G_{11} \dot{u}_0 / c + G_{12} \dot{w}_0 / c \\ \Delta'_n &= G_{21} \dot{u}_0 / c + G_{22} \dot{w}_0 / c \\ \omega'_n &= G_{31} \dot{u}_0 / c + G_{32} \dot{w}_0 / c \\ \omega'_n &= G_{41} \dot{u}_0 / c + G_{42} \dot{w}_0 / c \end{aligned} \quad (17)$$

By eliminating Δ'_n and ω'_n we have,

$$\frac{\dot{u}_0}{\dot{w}_0} = \frac{G_{22} - G_{12}}{g_{11} - G_{21}} = \frac{G_{42} - G_{32}}{G_{31} - G_{41}} \quad (18)$$

Since the elements of the matrix G are functions of the parameters c and k, equation (18) provides the implicit relationship between c and k, which is the desired phase velocity dispersion function.

4.2 Love waves

In the case of Love waves the boundary conditions to be satisfied at each interface are continuity of the transverse component of displacement, v, and of the transverse shear stress, Y_z. The pertinent plane–wave solution of the elastic equations of motion for a homogeneous layer is

$$u = w = 0$$

$$v = exp[i(pt - kx)][v' exp(-ikr_\beta z) + v'' exp(ikr_\beta z)] \quad (19)$$

where v' and v'' are constants.

The corresponding transverse shearing stress is

$$Y_z = \mu \partial v / \partial z = ik\mu r_\beta exp[i(pt - kx)][-v' exp(-ikr_\beta z) + v''(exp(ikr_\beta z)] \quad (20)$$

At the (m−1)th interface we are have

$$\begin{aligned} (\dot{v} / c)_{m-1} &= ik(v'_m + v''_m) \\ (Y_z)_{m-1} &= ik\mu_m r_{\beta m}(v''_m - v'_m) \end{aligned} \quad (21)$$

At the mth interface,

$$(\dot{v} / c)_m = (v'_m + v''_m) ik cos k r_{\beta m} d_m - (v''_m - v'_m) sin k r_{\beta m} d_m$$

$$(Y_z)_m = -(v'_m + v''_m) k\mu_m r_{\beta m} sin k r_{\beta m} d_m + (v''_m - v'_m) ik\mu_m r_{\beta m} cos k r_{\beta m} d_m \quad (22)$$

By eliminating v'_m and v''_m between equation (21) and (22),

$$(\dot{v}_m / c)_m = (\dot{v} / c)_{m-1} cos k r_{\beta m} d_m + (Y_z)_{m-1} \mu_m^{-1} r_{\beta m}^{-1} i sin k r_{\beta m} d_m$$

$$(Y_z)_m = (\dot{v} / c)_{m-1} i\mu_m r_{\beta m} sin k r_{\beta m} d_m + (Y_z)_{m-1} cos k r_{\beta m} d_m \quad (23)$$

As before, setting $A_{n-1} A_{n-2} \cdot \cdot \cdot A_1 = H$, the analog of equation (14) is

$$\begin{aligned} (\dot{v} / c)_{n-1} &= H_{11} (\dot{v} / c)_0 + H_{12} (Y_z)_0 \\ (Y_z)_{n-1} &= H_{21} (\dot{v} / c)_0 + H_{22} (Y_z)_0 \end{aligned} \quad (24)$$

From equation (21), we have

$$\begin{aligned} v'_n + v''_m &= H_{11} (ik)^{-1} (\dot{v} / c)_0 + H_{12} (ik)^{-1} (Y_z)_0 \\ v''_n - v'_n &= H_{12} (ik\mu_n r_{\beta n})^{-1} (\dot{v} / c)_0 + H_{22} (ik\mu_n r_{\beta n})^{-1} (Y_z)_0 \end{aligned} \quad (25)$$

The conditions for the existence of free surface wave are $(Y_z)_0 = 0$ and $v'' = 0$, with which, equation (25) lead to

$$H_{21} = -\mu_n r_{\beta n} H_{11} \quad (26)$$

5 RESULTS AND DISCUSSION

In order to discuss the responses of buried pipeline systems, a simplified example (Figure 5) with various parameters (Table 1) is used for parameter study.

The parameters of buried pipeline systems are:

Homogeneous half–space.
Pipeline material:steel ($E = 2.1 \times 10^{11}$pa)
Diameter of pipelines:0.3m
Thickness of pipelines:0.008m
Segmented length:5.0m

Earthquake waves inputs: as the earthquake records include various waves, in order to simplify the problem, we use two horizontal waves as Love–wave, and vertical wave as Rayleigh–wave.

Tianjin Waves (1976) are used for input.

Max. displacements(E–W):6.36cm
Max. displacements(N–S):7.1cm
Max. displacements(V):1.75cm
Duration:19.4sec.
Interval:0.01sec.

Because the parameters are too many, it is hard to express the results in a few figures and tables, we only state some statistical results and conclusions, details of the results can be found in reference (Liang 1991).

In order to compare the responses between single pipeline and pipeline systems, pipeline 5–8 is used for calculation. The results show that the difference between displacements in axial, transverse direction and earthquake records is not large, but the internal forces are very large, especially the bending

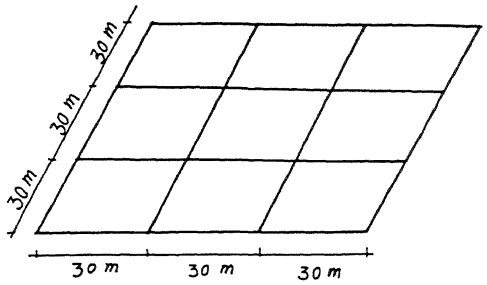


Figure 5. An example for calculation

Table 1. Parameters

Soil Stiff.	$k_s = 10-100N/cm^3$ $k_{cr} = 5-50N/cm^3$
Joint Stiff.	$k_j = 10-100N/cm^3$
Wave Veloc.	$v_p = 100-1000m/s$ $v_s = 50-500m/s$
Buried Depth	1.0m, 1.5m, 2.0m
Incident Angle	0°, 45°, 90°

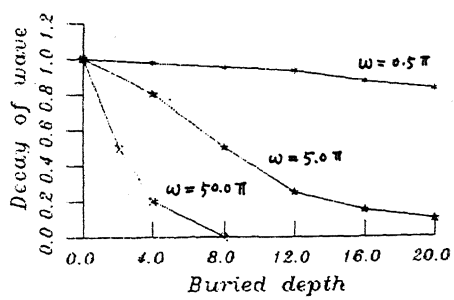


Figure 6. Decay of wave vs. frequency

stresses and in intersect of pipelines. The magnitude of stresses has great relations with incident angles of waves and stiffness of reference points and arrangements of pipeline systems.

For the same pipeline system and the same earthquake wave, if the velocity of wave is enlarged one times, the responses of pipeline system decresed, especially the axial strain. This indicates that the wave propagation velocity has important effects on the responses of buried pipeline systems.

The results show that the peak axial strain can be reduced by 15%–45%, the peak bending strain can be reduced by 5%–30% for regarding interaction between pipelines and soil than no interaction. This tells us that the interaction can not be neglected.

The results show that the flexibility of joints can reduce axial strain by 60%, and bending strain by 20%. This indicates that the flexible joints play an important role in aseismic engineering of buried pipelines.

As surface waves decay with depth quickly, the effects of the surface waves on deep buried pipelines are relatively small. Taking Love–wave as an example, the relations between frequency of wave and decay with depth are showed in figure 6.

Figure 6. shows that high frequency waves have smaller effects on deep buried pipelines, and the effects have relations with components of waves.

6 CONCLUSIONS

From a large amount of numerical calculation, we can obtain some conclusions.

For aseismic design of buried pipeline systems, it is not enough to analyze the pipelines one by one, and it is necessary to develop the 3–D general responses under propagation of earthquake wavea, espcially surface waves.

The wave propagation velocity has important effects on the responses of buried pipeline systems

The interaction between pipelines and soil can reduce axial strain and bending strain significantly.

The flexibility of joints and junctions can greatly reduce the axial strains and bending strains of pipelines.

The effects of buried depth on buried pipelines are not significant, this depends on frequency components of wave also.

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