USING NON-LINEAR SOIL MODEL TO ANALYZE SEISMIC RESPONSE OF UNDERGROUND PIPELINES

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SUMMARY

Two-dimension finite element method is adopted to analyze dynamic response of straight continuous buried pipeline. The soil surrounding the pipeline is supposed of equivalent linear viscoelastic model. Goodman contact elements are added between pipe elements and soil elements in order to simulate relative slip between pipe and soil. Wilson-θ method is utilized to compute dynamic time-history response of soil-pipe system. The effects of wave amplitude, pipeline buried depth, soil-pipe friction, soil materials and input angles are also studied in the paper.

INTRODUCTION

With the development of economy and urbanization, the damage of pipeline system, which resulted in severe effect on living and manufacture, drew more and more extensive attention. Many investigations have indicated that underground pipeline is vulnerable and second damage is serious during earthquakes. Data from Michoacan earthquake (Mexico, 1985), Northridge earthquake (USA, 1994) and Kobe earthquake (Japan, 1995) showed that underground pipeline systems such as gas, water supply and sewage system were damaged heavily.

Seismic response of underground pipeline is related to dynamic deformation of surrounding soil. The damage mechanisms are mainly composed of permanent ground deformation and seismic wave propagation. Permanent ground deformations including faulting, landslides, liquefaction and settlements frequently happen during or past earthquake. Wave propagation occurs during earthquake and affects on extensive areas. The influential areas may be near epicenter such as Northridge earthquake or far away from epicenter such as Mexico City in Michoacan earthquake.

Seismic response analysis of buried pipeline made great progress during twenty years. Pipeline weight compared with surrounding soil is small, and restriction force of soil is large, thus dynamic amplification effect is not large under the load of seismic wave. Relative displacement of surrounding soil results in buried pipeline stress. Therefore, dynamic effect is often ignored in calculation of pipeline seismic behavior. The pseudo-static method is used [2]. The oldest and simplest method was proposed by Newmark [7]. The method assumed that the maximum axial strain of buried pipeline was equal to the maximum strain of the surrounding ground. In order to simulate pipe-soil system more actually, soil is modelled as the combination of linear elastic spring or ideal elasto-plastic spring and damper [4].

Underground pipeline response is caused by soil-pipe interaction. The pseudo-static method and spring soil model are not able to fully reflect non-linear and non-elastic soil characteristics. FEM is used to numerically analyze straight buried pipeline response caused by wave propagation in the paper. In the discrete finite element of the system, the pipe segments are presented by elastic beams. The soil surrounding the pipes is presented by 4-node quadrilateral finite elements. Relative slip between soil and pipe is simulated by Goodman contact element. The effects of wave amplitude, pipeline buried depth, soil-pipe friction, soil materials and input angles are also studied in the paper.

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COMPUTATIONAL MODEL

Three kinds of finite element are used in the program: two dimensional isoparametric quadrilateral element for soil [8], two-node beam element for pipes and Goodman contact element for interface between pipe and soil.

Motion Equation

Considering horizontal and vertical seismic loads, the equation of the pipe-soil motion is in terms of relative displacement [1],

$$[M]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K]\{u\}=-[M]\{\ddot{u}_g\}-[K_p]\{u_g\} \tag{1}$$

in which $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the vectors of the relative node accelerations, velocities and displacements, respectively; $\{\ddot{u}_g\}$ and $\{u_g\}$ are the vectors of seismic acceleration and displacement, respectively; $[M]$ is the system mass matrix obtained from lumped mass; $[C_s]$ is the damping matrix from soil; $[K]$ is the global stiffness matrix changing with dynamic shear stresses.

Denoting the global stiffness

$$[K]=[K_p]+[K_s] \tag{2}$$

where $[K_p]$ is the pipe stiffness matrix; $[K_s]$ is the soil stiffness matrix.

According to Rayleigh assumption, damping matrix is

$$[C]^e=\alpha[M]^e+\beta[K]^e \tag{3}$$

where $\alpha=\xi\omega$, $\beta=\xi/\omega$, ξ is damping ratio, which is changing with dynamic shear strain; ω is fundamental frequency of system.

The above motion equation is solved by the means of step-by-step integration method. Wilson-θ method is used and θ is equal to 1.40 in order to keep the equation unconditional stability.

Equivalent Linear Viscoelastic Model for Soil

Soil model adopts equivalent linear viscoelastic model. The model connects parallel with springs and dampers. Both elastic resilience and viscous damping force take on dynamic soil stresses, but soil stiffness and damping, which are concerned with dynamic strain amplitude, are not constant. Equivalent linear model considers soil as visco-elasticity. Equivalent Young's modulus E or shear modulus G and equivalent damping ratio λ are employed to show two basic characteristics of the relationship between dynamic stress and strain, namely non-linearity and hysteresis. Modulus and damping ratio are expressed as the functions of dynamic strain (dynamic normal strain ε_d or shear strain γ_d), namely $E_d=E(\varepsilon_d)$ and $\lambda=\lambda(\varepsilon_d)$ or $G_d=G(\gamma_d)$ and $\lambda=\lambda(\varepsilon_d)$. Average static consolidated principal stress is considered in the above relationship.

Soil skeleton curve that is regressed by cycling load test and shows the relationship between dynamic shear stress τ and shear strain γ can be approximately expressed by hyperbola. Then the function of shear modulus G and shear strain γ can be deduced.

$$G=\frac{G_{\max}}{1+\gamma/\gamma_r} \tag{4}$$

in which $\gamma_r = \frac{\tau_{ult}}{G_{\max}}$, τ_{ult} is the ultimate stress when $\gamma \to \infty$; $G_{\max}$ is the maximum shear modulus. Shear modulus G is confined by $G_{\max}$ and γ_r which are related to average initial static soil stress σ_0.

$$G_{\max} = k_1 \cdot Pa \cdot \left(\frac{\sigma_0}{Pa}\right)^{n_1} \tag{5}$$

$$\gamma_r = k_2 \cdot \left(\frac{\sigma_0}{Pa}\right)^{n_2} \tag{6}$$

in which Pa is an atmosphere, which unit is the same as σ_0; parameters k_1, k_2, n_1 and n_2 can be obtained from tests.

Equivalent damping ratio λ_{eq} is computed by

$$\lambda_{eq} = \frac{1}{4\pi}\frac{A_L}{A_T} \tag{7}$$

where A_L is hysterisic loop area of stress-strain, namely total energy dissipation in a cycle; A_T is maximum elastic deformation energy in a stress-strain cycle.

Beam Element

Pipe is simplified as beam element. There is a node in each end of beam element. Each node includes axial displacement U, normal displacement V and rotational angle θ, corresponding to axial force T, shear force Q and bending moment M, respectively. The relationship between nodal displacements and forces in partial coordinate can be expressed in matrix as follows

$$\begin{bmatrix} \frac{EA}{L} & & & & & \\ 0 & \frac{12EI}{L^3} & & & symmetry & \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & & & \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & & \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \begin{Bmatrix} U_1 \\ V_1 \\ \theta_1 \\ U_2 \\ V_2 \\ \theta_2 \end{Bmatrix} = \begin{Bmatrix} T_1 \\ Q_1 \\ M_1 \\ T_2 \\ Q_2 \\ M_2 \end{Bmatrix} \tag{8}$$

in which E is the Young's modules of beam, L is the beam length, A is the beam sectional area, I is the inertial moment of beam. The stresses of upper edge and lower edge in the midspan of beam are

$$\sigma_u = \frac{T_1}{A} + \frac{Q_1 L}{2W} - \frac{M_1}{W}$$

$$\sigma_l = \frac{T_1}{A} - \frac{Q_1 L}{2W} + \frac{M_1}{W} \tag{9}$$

in which σ_u is the stress of upper edge, σ_l is the stress of lower edge, W is sectional modulus. If hinge exists in an end, rotational freedom should be released.

Goodman Element [5]

Deformation moduli of pipes are hundreds of times higher than that of ground soil. The interface between pipe and soil results in shear slip in strong earthquake. Therefore, non-thickness contact element proposed by Goodman is used to solve the relative slip. Goodman element assumes contact surfaces of soil element and beam element are connected by countless tiny tangent springs and normal springs. Two contact surfaces totally coincide before loading forces, and may slip, penetrate and separate after loading forces.

Stresses at the center of Goodman element is,

$$\begin{Bmatrix} \tau \\ \sigma_n \end{Bmatrix} = \begin{bmatrix} K_s & \\ & K_n \end{bmatrix} \begin{Bmatrix} \Delta u \\ \Delta v \end{Bmatrix} \tag{10}$$

where τ , σ_n are tangent stress and normal stress in the contact element, respectively; K_s and K_n are tangent and normal stiffness coefficient per unit length, respectively; Δu is the tangent relative displacement, Δv is the normal relative displacements.

The mechanical property of Goodman contact element is very complicated. It is the key for Goodman element how to choose dynamic parameters K_s and K_n. J.S.Wu and P.Jiang used the vibrational simple shear apparatus to study dynamic shear characteristics of concrete and soil [6]. They considered the relationship between shear stiffness and relative displacement as hyperbola. That is

$$K_s = \frac{K_{s\max}}{1 + \dfrac{K_{s\max}}{\tau_f} u_r} \tag{11}$$

in which u_r the relative slip; $K_{s\max}$ is the maximum shear stiffness; τ_f is the shear strength. $K_{s\max}$ can be obtained from empirical formula.

$$K_{s\max} = 22 \times 10^3 \sigma_n^{0.7} \quad KPa/m \tag{12}$$

Dynamic shear strength τ_f is

$$\tau_f = tg\phi \cdot \sigma_n \quad KPa \tag{13}$$

in formula (12) and (13), σ_n is the normal stress, unit is KPa; ϕ is the frictional angle.

Experiments demonstrated shear stiffness rapidly attenuate with the increase of relative displacement. When relative displacement reaches to a certain value, shear stresses on the contact surfaces approach to shear strength and yield. Residual shear stiffness should be used at that time.

RESULTS AND ANALYSIS

Several factors are considered in order to study seismic response of continuous straight buried pipeline caused by wave propagation. The numerical results are presented for these input data:

Pipeline: pre-stressed concrete, length 5.0m, diameter 1.0m, thickness 0.08m. Buried depth 2m or variable. Finite element discrete figure shows in Fig. 1.

Soil: dynamic parameters of soils in Table 1, the relationship curves between normalized shear modulus $G/G_{\max}$ and shear strain γ, damping ratio h and shear strain γ in Fig. 2(a) and Fig. 2(b) [3].

Seismic excitation: El-centro seismic wave (Fig. 3), peak acceleration 0.16g or variable, peak displacement 8cm or variable, time interval 0.01s.

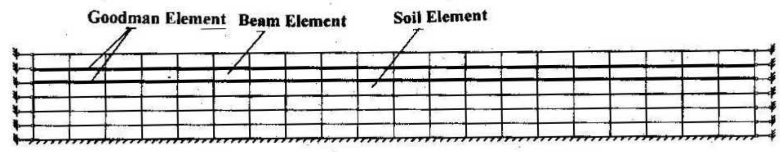

Fig. 1 Finite Element Discrete Figure

Table 1 Dynamic Parameters of Soils

	Soil 1	Soil 2	Soil 3
k_1	203.0	567.0	800.8
n_1	0.47	0.69	0.60

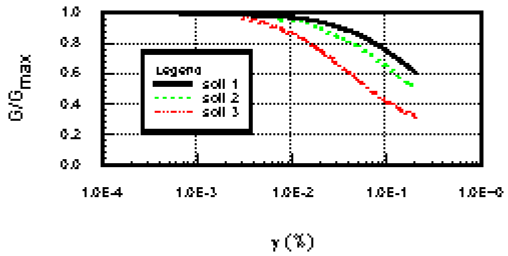

Fig. 2(a) $G/G_{\max} \sim \gamma$ **Curve**

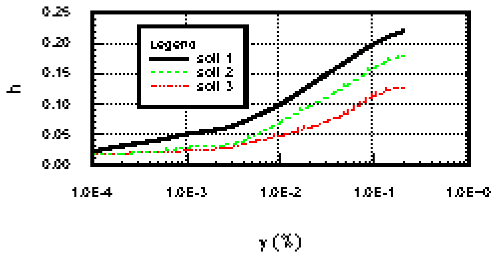

Fig. 2(b) $h \sim \gamma$ **Curve**

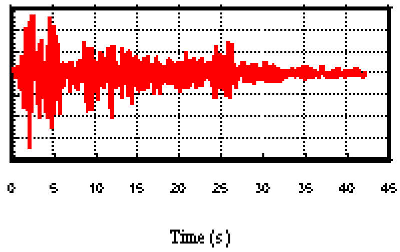

Fig. 3(a) El-centro Acceleration Time History

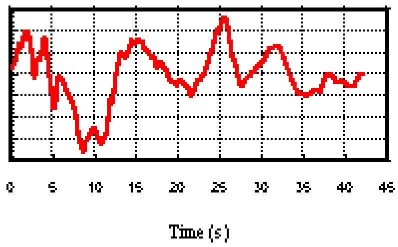

Fig. 3(b) El-centro Displacement Time History

The Effect of Soil-Pipe Friction

Goodman elements are used to simulate the relative slip between soil and pipe. The friction between soil and pipe is an important factor for pipe axial stress. Fig. 4 shows friction force can enhance axial stress of pipeline.

The Effect of Surrounding Soil

The interaction between soil and pipe causes pipe stress, and soil has the characteristics of non-linearity and hysteresis. It is important for pipe analysis to create a rational soil model. The dynamic soil parameters of equivalent linear model in Table 1 are adopted. Fig. 5 shows axial stress of soft soil is lower. Because of the complexities of soils, different soils should be analyzed separately.

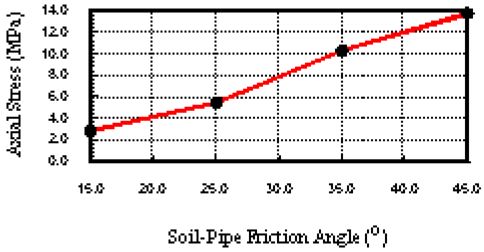

Fig. 4 The Effect of Soil-Pipe Friction

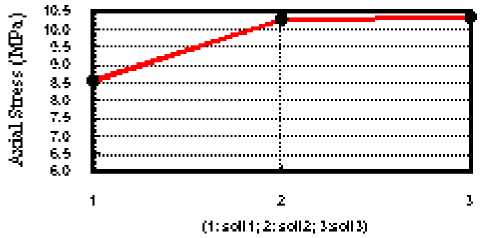

Fig. 5 The Effect of Soil Materials

The Effect of Seismic Input

From equation (1), the response of pipeline is related to seismic acceleration and displacement. Table 2 shows the load combinations of maximum input acceleration and displacement. Fig. 6 shows the maximum axial stresses of pipeline. With the increase of input acceleration and displacement, the response of pipe increases. But the trend is not linear. In order to analyze the effects of acceleration and displacement, it is feasible to keep displacement and acceleration unchangeable, respectively. Fig. 7(a) shows the influence of acceleration, and Fig. 7(b) represents the influence of displacement. The contribution of acceleration to axial stress is nearly constant, but the seismic displacement plays an important role in axial stress.

Table 2 Load Combinations

Load Combination Number	1	2	3	4	5
Maximum Displacement (cm)	1.0	2.0	4.0	8.0	16.0
Maximum Acceleration (g)	0.02	0.04	0.08	0.16	0.32

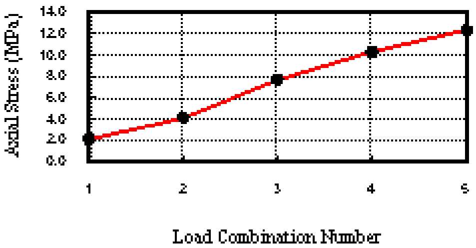

Fig. 6 The Effect of Seismic Input

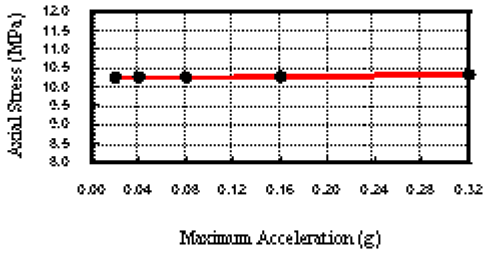

Fig. 7(a) The Effect of Seismic Acceleration

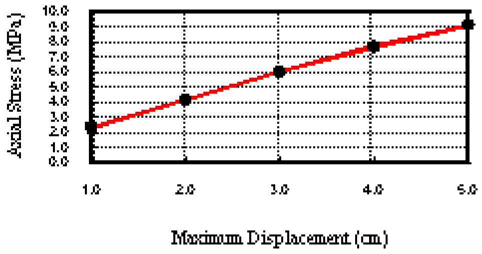

Fig. 7(b) The Effect of Seismic Displacement

The Effect of Buried Depth

The buried depth of 1m, 2m, 3m, 4m and 5m is calculated respectively. From the results in Fig. 8, the deeper the pipe is buried, the slower the axial stress increases in shallow conditions.

The Effect of Seismic Wave Input Angles

The motion of the soil particle depends on the type of waves but can always be resolved in an axial component and a lateral component relative to the pipeline. The lateral components of the soil motion generate lateral response of the pipe and the longitudinal motions generate axial response of the pipe. The angle between soil motion and pipe axial direction is defined as input angle. Fig. 9 shows axial stress decreases with the increase of input angle.

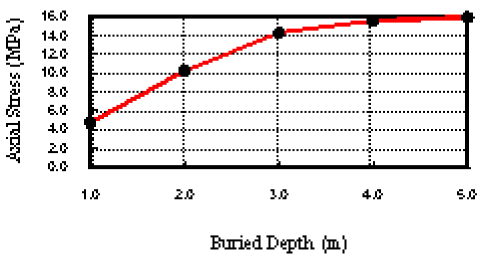

Fig. 8 The Effect of Buried Depth

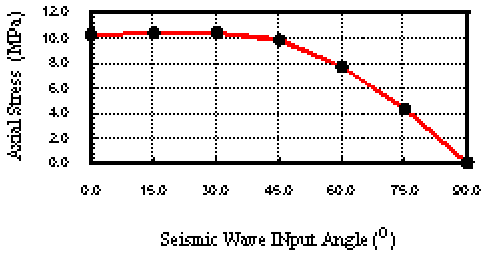

Fig. 9 The Effect of Input Angle

CONCLUSIONS

1. Using Goodman contact element is ideal to simulate the interaction between soil and pipe. The key to reach the high accuracy of the method is to obtain the reasonable shear stiffness. Thus, the shear stiffness of contact element should be confirmed through tests. The contacts between different materials should be tested on different experiments.
2. It is feasible for soil to use equivalent non-linear model. Computing parameters have clearly physical meanings. The model is more actual than that of which is simplified as bi-linear spring model.
3. Soil surrounding pipes plays a key role with pipe stress. But soil characteristics are very complicated, different soil should be analyzed separately.
4. Seismic input is decisive to affect the pipeline response. The pipe stresses increase with the augment of seismic input, especially for ground displacement. The tendency of the pipe stresses increasing is nonlinear.
5. The depth of buried pipeline can increase pipe stress, but it is not very obvious in shallow depth.
6. The friction between soil and pipe can enhance pipe stresses, it is not beneficial for anti-seismic design.

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