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SEISMIC RESPONSE ANALYSIS OF UNDERGROUND PIPELINES USING EFFECTIVE STRESS METHOD

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SUMMARY

Seismic response of underground pipeline is correlative closely with the characters of surrounding soil and soil-pipe mutual contact interface. Based on the principles of effective stress method and the non-linear soil mode, the development of pore water pressure, the reduction of soil effective stress and the change of soil dynamic properties can be considered simultaneously. The contact interface element between soil and pipeline is adopted to simulate interactive response. With the finite element method, Seismic response of underground pipelines can be numerically simulated. The effects of some factors on the response are also studied.

INTRODUCTION

City underground pipeline systems have been suffered severely destroys in recent earthquakes, such as Horthridge earthquake of California [1] (USA, 1994), Kobe earthquake (Japan, 1995) and Ji-Ji earthquake (Taiwan, 1999) [2]. Not only normal usage functions of underground pipeline systems are damaged directly, but also derivative calamities are brought.

For the seismic response of the underground pipelines, great progress has been acquired [3-4]. The pseudo-static method has been used widely in analyzing the soil-pipe mutual system. This method only changes the soil as springs simply, and cannot consider the reduction of soil intensity. According to soil dynamics, because of the remarkable nonlinear behavior and the solid-liquid two-phase character of the soil under a seismic action, the soil dynamic properties will be changed significantly.

Research shows [5-6], the dynamic intensity and the deformation of soil are mostly depended on the development of pore water pressure. Both of them will influence the dynamic response of the soil-pipeline system. Therefore, the increase of vibrant pore water pressure and the reduction of effective stress should be considered for their effects on soil dynamic properties. On the other hand, the coupling between the dissipation and the re-distribution of pore water pressure and the soil frame response should also be considered.

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In this paper, the finite element method is adopted to study the seismic response of underground pipeline and surrounding soil. The soil that surrounds the pipeline is regarded as a solid-liquid two-phase medium. A drainable effective stress method and nonlinear constitutive relation model of soil are used to study the increase and the dissipation of pore water pressure during the seismic process. At the same time, the contact interface between the pipeline and the surrounding soil is also included in this paper. A full-process response of the underground pipeline can be simulated numerically.

EFFECTIVE STRESS METHOD

Terzaghi advanced the effective stress principle, and he figured that the total stress of any point in the saturated soil should be a sum of the effective stress and the pore water pressure of this point. The development of pore water pressure under vibrant loads is a fundamental factor for the soil deformation and the intensity, and it is also a key to the dynamic analysis of the effective stress method. The effective stress method not only considers the effect of vibrant pore water pressure's rising on the soil dynamic properties, but also considers the dissipation of pore water pressure generated by the vibration.

Increase of Pore Water Pressure Under Vibration

Based on the vibration tri-axis experiment, Seed [7] established the stress mode of pore pressure, which showed the relationship between vibrant pore water pressure and vibrant circular times. The increment expression of pore water pressure is,

$$\Delta p_g = \frac{\sigma_v' \left(1 - m\dfrac{\tau_0}{\sigma_v'}\right)}{\pi \alpha N_L \sqrt{1 - \left(\dfrac{N}{N_L}\right)^{\frac{1}{\alpha}}}} \left(\frac{N}{N_L}\right)^{\frac{1}{2\alpha}-1} \Delta N$$

Where, Δp_g is the vibrant pore water pressure; σ_v' is the perpendicular effective stress; τ_0 is the original shear stress; N is equivalent vibrant circular times of earthquake load; N_L is vibrant circular times of initial liquefaction without the original horizontal shear stress; α is a coefficient related with soil type and density; ΔN is equivalent vibrant circular times of this period of time; m is a experiential parameter.

Dissipation Equation of Pore Water Pressure

According to Biot concretion theory [8], it is assumed that the soil is a complete saturated isotropy body, its deformation is minute, and the soil grain and the pore water is uncompressed. Then the basic equations can be constructed,

Effective stress principle: $\{\sigma\} = \{\sigma'\} + \{M\} p$ (1)

Soil equilibrium equation: $[\partial]^T \{\sigma'\} + [\partial]^T \{M\} p = \{T\}$ (2)

Soil constitutive equation: $\{\sigma'\} = [D]\{\varepsilon\} - \{M\} p_g$ (3)

Soil geometry equation: $\{\varepsilon\} = -[\partial]\{u\}$ (4)

Darcy law: $\{V\} = -[K]\left([\partial]^T \{M\} p - \{\bar{T}\}\right)$ (5)

Seepage continued equation: $\{M\}^T [\partial]\{V\} = \dfrac{\partial}{\partial t}\left(\{M\}^T \{\varepsilon\}\right) = -\dfrac{\partial}{\partial t}\left(\{M\}^T [\partial]\{u\}\right)$ (6)

Where, $\{\sigma\}$ is the total stress; $\{\sigma'\}$ is the effective stress; p is the remained pore water pressure; $\{T\}$ is the physical force of soil frame; $[D]$ is the elastic matrix; p_g is the vibrant pore water pressure; $\{\varepsilon\}$ is the total strain; $\{u\}$ is the displacement of soil frame; $\{V\}$ is the velocity of flow that liquid relative to soil frame; $[K]$ is the seepage coefficient matrix; $\{\bar{T}\}$ is the physical force of liquid ; $[\partial]$ is the partial differential matrix; $\{M\} = (1 \quad 1 \quad 0)^T$.

The solution region is dispersed with finite elements. The displacement $\{u\}$ of soil and the pore pressure p of any point in a certain element can be express as an approximate function of the displacement $\{\delta\}^e$ and the pore pressure $\{p\}^e$ of this element nodes, $\{u\} \approx \{\tilde{u}\} = [N]\{\delta\}^e$, $p \approx \tilde{p} = [\bar{N}]\{p\}^e$, where $[N]$ and $[\bar{N}]$ are the matrixes of shape function of the soil element and the pore pressure element respectively.

The basic equations are combined into simultaneous equations. The Galerkin weighted residual method is used to disperse the space region with the shape function as weighted function. Simultaneously, the displacement bound, the stress bound, the pore pressure bound and the flow velocity bound are leaded in, then manipulative equations can be gained. More, using the increment method to disperse the time region, the increment form of manipulative equations in the FEM matrix can be expressed as

$$\begin{vmatrix} [K_u] & [K_c] \\ [K_c]^T & -\theta\Delta t[K_p] \end{vmatrix} \begin{Bmatrix} \{\Delta\delta\}^e \\ \{\Delta p\}^e \end{Bmatrix} = \begin{Bmatrix} \{\Delta F\}^e \\ \{\Delta R\}^e \end{Bmatrix} \tag{7}$$

Where $[K_u] = \iint_\Omega [B]^T [D][B] dxdy$

$$[K_c] = \iint_\Omega [B]^T \{M\}[\bar{N}] dxdy$$

$$[K_p] = \iint_\Omega [B_w]^T [K][B_w]^T dxdy$$

$$\{\Delta F\}^e = \iint_\Omega [N]^T \{\Delta T\} dxdy + \iint_\Omega [B]^T \{M\} \Delta p_g dxdy$$

$$\{\Delta R\}^e = \Delta t \left(\iint_\Omega [\bar{N}]^T \{M\}^T [\partial][K]\{\bar{T}\} dxdy + [K_p]\{p\}_n^e \right)$$

Where $[B]$ is the stress matrix of element; $[D]$ is the elasticity matrix; θ is a constant for integral (value is 0.5~1). Based on above equations, the displacement of soil and the pore pressure of any point in any time can be got in this wise.

Analytic Process of Seismic Response Using Effective Stress

Using the step-by-step integration method and considering the development and the dissipation of pore water pressure simultaneously, the process can be figured as follows:

1. The seismic analysis is done by time-share. Dynamic shear module G and Damping ratio λ are calculated with the dynamic constitutive relationship of soil.
2. The increment of vibrant pore water pressure Δp_g is calculated using the vibrant pore pressure model and transformed into an equivalent load at nodes. Using the dissipation equations, the pore water pressure is dissipated. Then the displacement u and the pore pressure p of every node at the end of this period of time are calculated.

3. Calculate the effective stress σ_e' of each element, then judge whether or not the elements are liquefied. If some elements are liquefied, because of the stress transfer, static calculation should be carried through at the end of this period of time.
4. For the next period of time, step 1 to step 3 are repeated until the earthquake action is ended.
5. After the earthquake action has finished, the dissipation of pore pressure should be calculated sequentially until the excess-static pore water pressure has been dissipated completely and the residual stress won't increase anymore.

NUMERICAL SIMULATION OF SEISMIC RESPONSE ANALYSIS

In this paper, the soil-pipeline system is studied as a whole structure. To investigate this coactive system, there are three aspects should be simulated.

Simulation of Soil Model

The dynamic model of soil is simulated with above-mentioned effective stress method. Hardin-Drnevich model, which has a hyperbolic skeleton curve, is adopted to describe the soil constitutive relationship. The dynamic shear module is expressed as $G = \dfrac{G_{\max}}{1+\gamma/\gamma_r}$, where, $G_{\max}$ is the maximal shear module; γ is the shear strain; γ_r is the reference shear strain and $\gamma_r = \tau_{\max}/G_{\max}$, where $\tau_{\max}$ is the maximal dynamic shear stress. Actually, $\tau_{\max}$ is the limit value of τ, which has shear intensity as its asymptotic value when γ is big enough. When shear stress τ is applied at the horizontal surface, according to the Mohr-Coulomb failure theory, $\tau_{\max}$ can be numerated in term of the following formula,

$$\tau_{\max} = \sqrt{\left(\frac{1+K_0}{2}\sigma_V Sin\phi + C\cdot\cos\phi\right)^2 - \left(\frac{1+K_0}{2}\sigma_V\right)^2}$$

Where, K_0 is the still lateral compression coefficient; σ_V is the still vertical effective positive stress; ϕ and C are indexes of effective intensity of soil.

Damping ratio, $\lambda = \lambda_{\max}\dfrac{\gamma/\gamma_r}{1+\gamma/\gamma_r}$, where $\lambda_{\max}$ is the maximum of damping ratio.

Simulation of Pipeline Model

Since the underground pipeline is a long structure, the pipeline is simulated as a plane beam with two nodes. Each node concludes three freedoms, which are the axial displacement, the normal displacement and the corner. Accordingly, the node force includes the axial force, the shear force and the moment of flexion. Due to the steel material of underground pipeline, the constitutive model of pipeline is described as linear elastic.

Simulation of Contact Interface

The contact element not only simulates the deformation of contact interface, such as a fault, a slip or a crack between both sides of the contact interface, but also simulates the force transfer between two contact sides. Goodman [9], at the base of four-node rectangular element, got rid of the thickness along the normal direction of contact interface. The element is degenerated into two tangent line elements. The assumption of such an element is, there are innumerable minute tangential and normal springs connecting two contact sides, and the force relationship only appears at the node position between the contact element and the adjacent element. The stress in a contact element can be expressed as, $\tau = K_s\cdot\Delta u$, $\sigma = K_n\cdot\Delta v$, where K_s and K_n are the tangential and normal stiffness of the contact element respectively, Δu and Δv are the difference of tangential and normal displacement between contact sides respectively, τ and σ is the tangential and normal stress components respectively.

For the constitutive relationship of the contact element, Clough and Duncan thought that [10], the relationship between the shear stress and the relative slip could be figured with a hyperbolic line. When the contact interface is in tension, no force would be transferred upon the contact interface, K_s and K_n are chosen with a less value; when the contact interface is in compression, in order to avoid the superposition of two contact sides, the normal stiffness K_n should be chosen with a very big value, and the tangential stiffness is calculated as $K_s = k_{st}\gamma_w\left(\sigma_n / Pa\right)^n\left(1-\dfrac{R\cdot\tau}{\sigma_n \tan\delta}\right)^2$, where, γ_w is the bulk density, Pa is the atmospheric pressure, k_{st} and n are the contact parameters, δ is the contact intensity parameter and R is the contact interface destruct ratio.

Seismic Response Analysis of Integral Structure

The soil and pipeline system comprises three kinds of element: the soil element, the pipeline element and the contact element. Assembling the mass, the stiff and the damping matrix of these three kinds of elements, the integral mass, stiff and damping matrices of the structure system can be obtained.

The dynamic equation of the integral structure is,

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{\ddot{u}_g\} \tag{8}$$

Where, $\{u\},\{\dot{u}\},\{\ddot{u}\}$ are the displacement, the velocity and the acceleration vectors of the structure nodes respectively; $\{\ddot{u}\}_g$ is the input acceleration vector; $[M],[C],[K]$ are the mass, the stiff and the damping matrices of the structure respectively. The damping is chosen with Rayleigh proportion damping, that is, the damping will change with the change of damping ratio and the fundamental frequency.

The dynamic equation is solved by the step-by-step integration method (Newmark- β), and the dynamic response of the soil, the pipeline and the contact element can be obtained respectively. According to above, the finite element program (SRUPFE) is compiled. Using this program, the full-time seismic response of the underground pipeline and the surrounding soil can be simulated numerically.

CALCULATION EXAMPLE

Calculation Model

Using the program SRUPFE, examples have been carried out. The site is designed with a 50*25m uniform saturated sandy soil space, ground water is set at the ground surface, and a steel pipe is buried at the depth of 5m. Fig. 1 is the Finite element discrete model.

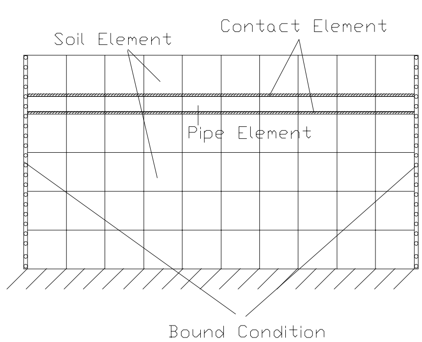

Fig.1 Finite Element Discrete Model

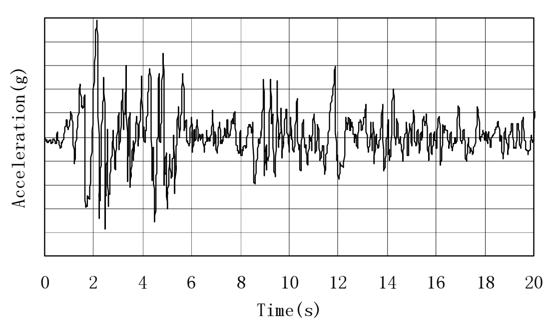

Fig.2 EI-CENTRO Acceleration Curve

The acceleration curve of EI-CENTRO wave is chosen as the input seismic curve. Fig.2 is the earthquake acceleration curve. The earthquake is inputted from the bottom horizontally and the duration is 20s. The peak value of acceleration will be adjusted according to the needs.
The seismic wave is inputted from the bottom nodes. The boundary adopts Lysmer viscous boundary, which can eliminate the numerical error aroused by the limited region. Besides, the pore water pressure boundary is designed as a complete drain boundary. The soil dynamic parameters and the contact parameters are showed as follows

Table 1 Soil Dynamic Parameters

Soil Parameters	Density(kg/m^3)	ϕ	C	$\lambda_{\max}$	Seepage Coefficient(m/s)	m	α
	2000	30^0	0	0.3	1×10^{-5}	1.1	0.7

Table 2 Contact Parameters

Contact Parameters	k_{st}	n	δ	R_f
	45000	0.9	36	0.7

Result and Analysis
Fig.3 shows when the earthquake peak value is adjusted to 0.2g (g is the acceleration of gravity, units is m/s^2), the development of pore water pressure changes with the seismic duration for different depth. From the result of Fig.3, for the flat soil, the liquefaction will happen after10s of the earthquake, and for other depth, the pore pressure has also developed significantly. So it is not accurate if the effects of the development and the dissipation of pore water pressure on soil dynamic properties and soil response has not been considered.

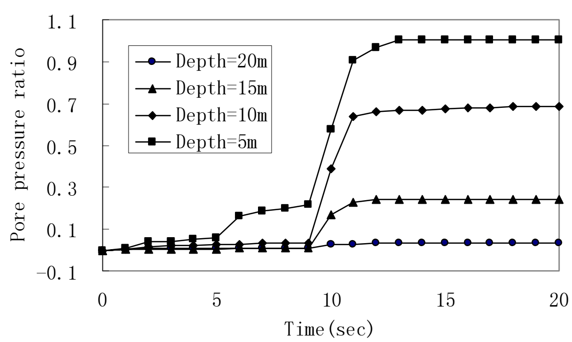

Fig.3 Pore Water Pressure Development

There are many factors that will influence the seismic response of underground pipeline. Here four factors are investigated: the earthquake peak value, the relative density of soil, the shear wave speed and the diameter of pipeline. Here the maximal bend stress represents the seismic response of pipeline.
In order to study the effect of earthquake peak value, its value is adjusted to 0.1g, 0.2g, 0.3g and 0.4g; the relative density of soil is 70%; the shear wave speed at the position where the pipeline is buried is 236m/s; the diameter of pipeline is 1m. From the result of Fig.4, the maximal bend stress of pipeline will increase with the increase of earthquake peak value remarkably.
For the saturated sandy soil, the relative density of soil is an important index that explains the soil compaction degree and it will influence the development of pore water pressure directly. Then, the relative density of soil is chosen as 50%, 60%, 70% and 80% respectively; the earthquake peak value is 0.2g; the shear wave speed at the position where the pipeline is buried is 236m/s; the diameter of pipeline

is 1m. From the result of Fig.5, the maximal bend stress of pipeline will increase at a certain extent with the reduction of relative density.

The soil shear wave speed would influence shear module straight. Fig.6 shows, when the shear wave speed at the position where the pipeline is buried is different, other factors are chosen as the earthquake peak value is 0.2g, the relative density of soil is 70% and the diameter of pipeline is 1m, the maximal bend stress of pipeline will increases along with the increases of shear wave speed.

In Fig.7, the change of the maximal bend stress of pipeline with the diameter of pipeline is showed fluctuant. Other factors are chosen as, the earthquake peak value is 0.2g, the relative density of soil is 70% and the shear wave speed at the position where the pipeline is buried is 236m/s.

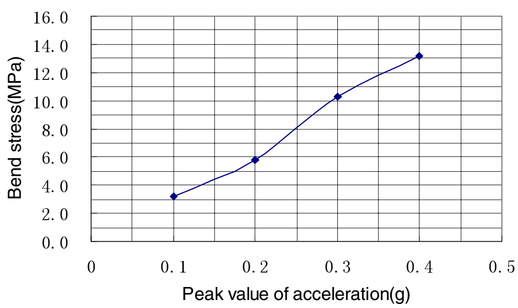

Fig.4 Pipe Stress-Earthquake Peak Value

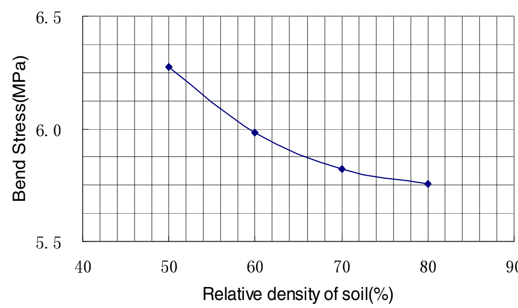

Fig.5 Pipe Stress- Relative Density of Soil

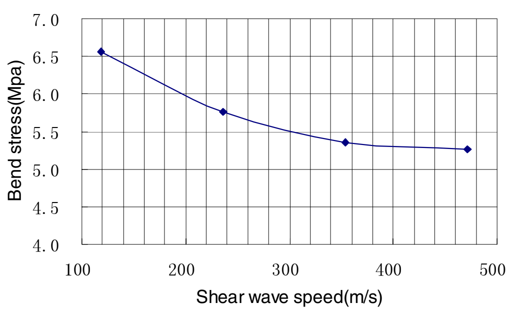

Fig.6 Pipe Stress- Soil Shear Wave Speed

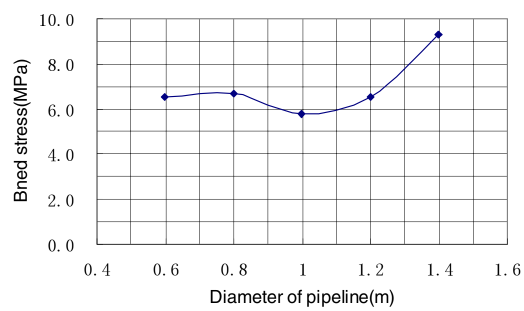

Fig.7 Pipe Stress- Diameter of Pipeline

CONCLUSION

In this paper, the soil that surrounds the pipeline is regarded as a solid-liquid two-phase medium. A drainable effective stress method and nonlinear constitutive relation model of soil are used to study the development and the dissipation of pore water pressure during a seismic process. Because the change of soil dynamic properties under the seismic action is considered adequately, the actual characters of the soil can be illuminated much more. At the same time, the contact interface model is adopted to simulate the interaction between pipeline and surrounding soil. Using the program SRUPFE based on the theory of this paper, a numerical simulation of the full-process analysis for an underground pipeline can be gained accurately.

Some influence factors related with the maximal bend stress of pipeline are investigated, including the earthquake peak value, the relative density of soil, the shear wave speed at the position where the pipeline is buried and the diameter of pipeline. Conclusions can be educed, that is: the maximal bend stress of pipeline will increase with the increase of earthquake peak value remarkably; the maximal bend stress of pipeline will reduce at a certain extent with the increase of relative density; the maximal bend stress of pipeline will increases along with the increases of shear wave speed; the change of the maximal bend stress of pipeline with the diameter of pipeline shows fluctuant.

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