RESPONSE ANALYSIS OF BURIED PIPELINES DUE TO LARGE GROUND MOVEMENTS *

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ABSTRACT :
A three dimensional finite element model is developed for response analysis of buried pipelines under faults induced by permanent ground deformation, considering the interaction between the pipeline and soil around. The buried pipeline is divided from the earth medium together with the soil around, and the calculated area including the pipeline and the soil is established. The pipe is regarded as the space structure, and modeled by the four nodes thin-shell elements, while the soil solid elements. The 3-D nonlinear contact elements are used to simulate the slip and isolation phenomena between the pipe and the soil. The initial stress state in the pipeline-soil system is also estimated for response analysis. The nonlinear seismic responses of buried pipelines and surrounding soil under permanent ground deformation are analyzed using pseudo-static analysis method without considering the fracture of the soil. Some influential factors, such as crossing angle, soil displacement, ratio of diameter and wall-thickness, friction coefficient and buried depth are researched, and some regular conclusions are drawn.

KEYWORDS:
buried pipeline, ground deformation, pipeline-soil interaction, nonlinear response, finite element model

1. INTRODUCTION

Pipeline systems, served as water supply and wastewater facilities, natural gas and liquid fuel lines, power and communication lines, generally play an important role in not only modern life but also disaster control and mitigation after earthquake. Most pipelines are built underground, it has been illustrated repeatedly that these buried pipelines are vulnerable during the earthquake. Damages and disruptions of the buried pipeline systems in the earthquake could threaten seriously social life and property, and prolong economic recovery during post earthquake construction and rehabilitation. So earthquake performance and safety of the buried pipeline systems are very important.

Field observations and various studies indicate that major seismic hazards to the buried pipeline systems are: (1) excessive axial and bending stresses and deformations in the pipelines created mainly by the phase difference and change of wave shape between different points along the pipeline; (2) large displacements due to the ground deformation during an earthquake if the pipeline crosses a major fault; (3) landslides and buoyancy caused by soil liquefaction. Earthquake induced permanent ground deformations are one of the main reasons why the buried pipelines destroy, and most of them caused by fault movements. The response of the buried pipeline under the ground deformation is investigated first by Newmark N. M. and Hall W. J. (Newmark and Hall 1975), and then the Newmark-Hall method is developed by some researches (Kennedy 1977, Wang 1998, Liu 2002). However, these analysis procedures for the buried pipelines response are established on the basis of the foundation beam model, and generally 2-D analysis. In fact, the interaction between the buried pipelines and soils around the pipeline is an important problem for safety of the buried pipelines during the earthquake ground deformation. Although the affects of the soil around the pipeline may be simulated by a group of springs, the parameters of these soil springs are estimated difficultly. Another way to consider the interactive affects of the pipeline-soil system is developed recently (Parmelee and Ludtke 1975, Liang 1992, Feng 2001), that is, the

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buried pipeline is regarded as the shell structure and modeled by finite element method, but the soils replaced still by the soil springs.
Based on above research achievements, a 3-D model is developed for the seismic response analysis of the buried pipeline-soil system due to the fault generated large ground deformation in this paper. The buried pipeline is considered as a space shell structure, and the soil around the pipeline also taken out for analysis in the model. Therefore, the interactions between the pipeline and the soil deal with by solving the contact problem, and the responses of both the pipeline and the soil around can be computed.

2. NONLINEARITIES IN THE PIPELINE-SOIL SYSTEM

2.1. Constitutive behavior

The responses of buried pipeline and soil under ground deformation are nonlinear which includes material nonlinearity, geometry nonlinearity and contact nonlinearity. Tri-linear model is adopted to simulate the stress-strain relationship of pipe material, while Mohr-Coulomb plastic model is employed to simulate the soil around pipeline.

Mohr-Coulomb damages and intensity criteria which is widely used in geotechnical engineering is a kind of constitutive relationship model with quite maturation and high precision. Elastic-plastic deformations are generally divided into two parts, elastic and plastic. Elastic deformation is calculated with Hooker's law, while plastic deformation is explained by plastic theory.

2.2. Contact nonlinearity

The relatively large deformation takes place at the interface between pipeline and soil under ground deformation for the difference of mechanical properties between pipe structure and soil medium. Then the nonlinear contact phenomenon of normal relative separation and tangential sliding movement will occur at the interface. The interaction between contacting surfaces consists of two components: one normal to the surfaces and one tangential to the surfaces. The tangential component consists of the relative motion (sliding) of the surfaces and, possibly, frictional shear stresses. Contact issue is a kind of highly nonlinear behavior, and there're two problems required to be solved: (1) Determinations of contact regions and contact state at the interface; (2) constitutive relations of contact behavior.

The contact constraint is applied when the clearance between two surfaces becomes zero. There is no limit in the contact formulation on the magnitude of contact pressure that can be transmitted between the surfaces. The surfaces separate when the contact pressure between them becomes zero or negative, and the constraint is removed.

Three-node contact element adopted in this paper can be used to explain the contact state of pipeline and soil. Normal-force and tangential-force are delivered at the interfaces when contact behavior occurs. In addition to determining whether contact has occurred at a particular point, the analysis also must calculate the relative sliding of the two surfaces. If the two interacting surfaces are rough, the analysis may need to take frictional forces, which resist the relative sliding of the surfaces, into account. Coulomb friction is a common friction model used to describe the interaction of contacting surfaces. The model characterizes the frictional behavior between the surfaces using a coefficient of friction, μ .The relationship of shear-stress and normal-stress can be expressed as

$$\begin{cases} \tau = K_s \omega, \omega \prec \omega_s \\ \tau = \mu p, \omega \geq \omega_s \end{cases} \tag{1}$$

Where τ is shear-stress, p is normal-stress, K_s is shear rigidity, ω is the relative displacement at the interface, μ is the friction coefficient of the interface, ω_s critical elastic relative displacement.

3. MODELING OF THE PIPELINE-SOIL SYSTEM

3.1. Dimensions and Boundaries of the modeling

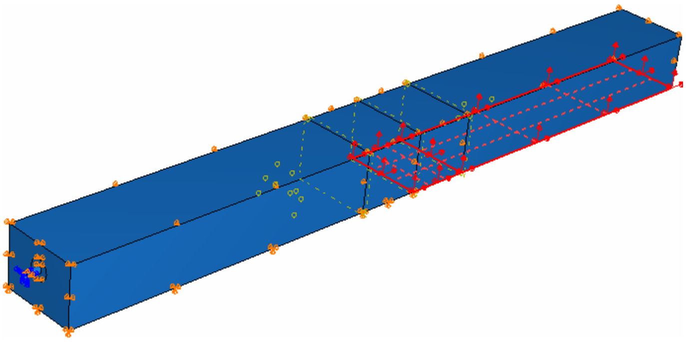


Fig. 1 Interaction model of buried pipeline and soil

In order to consider the pipeline-soil interaction in detail, a three dimensional finite element model is developed, shown in Figure 1. In this model, the soil around the pipeline is also taken out together with the buried pipeline; the soil springs are not adopted. According to this model, the calculated area consists of the pipeline structure and the soil medium, and enclosed by 6 boundaries. Besides the ground surface boundary, the other 5 boundaries are artificial, they cut the soil medium off in the calculated area from those outside. Obviously determination of the 5 artificial boundaries' location or the calculated area range should be studied. However, in this paper the calculated area is selected as 120m length, 12m width and 9m depth, while the length of the buried pipeline is 124m.

The top face of the soil model is free, and the front and behind surface being restrained in horizontal direction. The left end face also is constrained in horizontal direction, and the right one being free. The left underside is held in all directions, and the right one being the boundary of displacement input, while end face of the pipe is restrained in horizontal direction.

The soil is modeled as solid elements, while the pipe structure simulated by four nodes thin shell elements, and nonlinear contact elements are used to simulate the interaction between the pipeline and the soil. The seismic responses of buried pipeline and surrounding soil under permanent ground deformation are analyzed using pseudo-static analysis method without considering the fracture of the soil.

3.2. Parameters of pipe and soil medium

Pipe material makes use of Tri-linear constitutive model whose Young's module is $2.1\times10^{11}Pa$ and Poisson's ratio is 0.3 in elastic stage, and pipe material comes into elastic-plastic phase when the effective stress reaches $418MP_a$, and the pipe turns to absolutely plastic when the stress and strain arrives $516Mpa$ and 0.016 respectively. The soil medium uses Mohr-Coulomb model, whose parameters are listed in table 1.

Table 1 Parameters of the soil medium around the pipe

$\gamma(:kN/m^3)$	$\varphi(:^0)$	$E(:Pa)$	υ	$\sigma_s(:Pa)$	$\phi(:^0)$
20	33	8×10^6	0.3	50000	0

Where γ is soil gravity, φ is the internal friction angle of the soil, E is Young's module, υ is Poisson's ratio,

σ_s is the yield stress of the soil, and ϕ is the dilation angle.

3.3. Calculation of the initial stress field

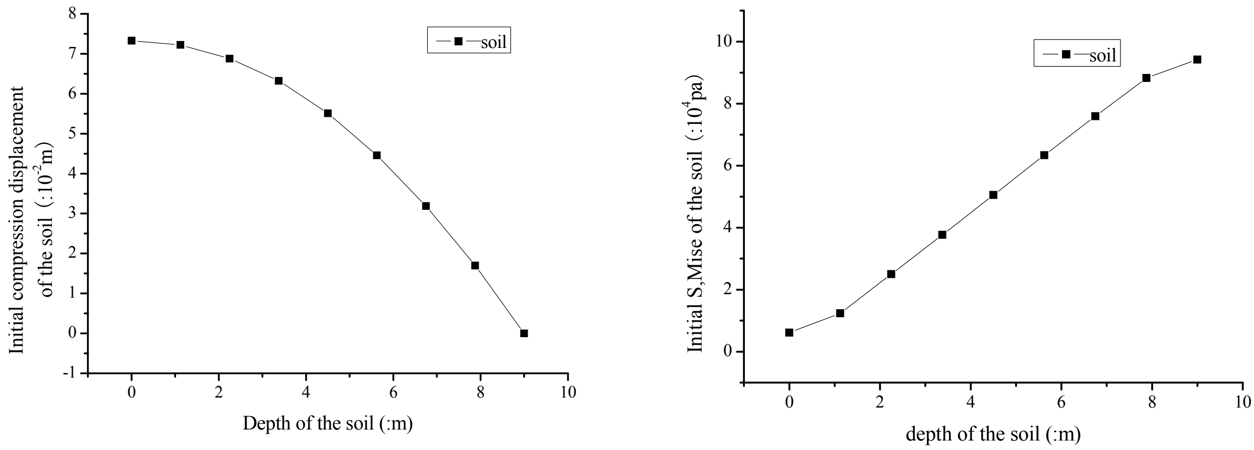
Initial stress field problem is very important to simulate the initial state and contact issues of structures in geotechnical engineering. In this paper, initial stress field is the gravity stress field (no considering the gravity of the thin-wall pipe). The vertical stress varies linearly along the depth, and the relationship between horizontal stress and vertical stress is

$$\sigma_z = \gamma z , \quad \sigma_x = \sigma_y = k_0 \sigma_0 \tag{2}$$

Where k_0 is the static lateral pressure coefficient which takes the worth 0.6.

4. RESPONSE OF THE PIPELINE AND THE SOIL

4.1. Initial condition and the responses of pipeline



(a) initial compression-displacement of the soil

(b) initial Stress-Mise of the soil

Fig 2 Initial conditions of the soil along the perpendicular direction

The seismic responses of the buried pipeline and soil are analyzed with finite element theory under ground deformation whose displacement is 0.5m in horizontal and vertical direction. The responses of the soil under the action of ground movement include the longitudinal compression displacement of the soil and stress-Mise along depth direction as shown in figure 2. From figure (a) we can see that the displacement of the top-surface reaches almost 7.5 centimeters. Figure (b) shows the initial stress-Mise state of the model. From the figures, it’s uneasy to see that initial stress field is very important and reasonable for the calculations of the practical mechanical model. So it can’t be ignored in the calculation.

Figure 3 to 5 show the responses of the pipeline under the permanent ground deformation. Figure 3 shows the shear-stress and normal-stress distribution curve of the pipe along axial direction, from which we can see that the pipe bears the shear-stress significantly in the middle part. And reverse-direction shear takes place at the place about 5m from the centre because of the force that the soil applies to the pipe. The shear stress reaches the maximum in reverse-direction at the place about 10m from the centre, and then decreases to both sides gradually, and becomes zero at the place 20 meters away from the middle for no relative slip produces here. This also can be seen from the stress distribution curve of figure 4.

Figure 4 presents the normal stress distributions curve along the axial. As is shown in the figure, the max normal-stress of the pipe doesn't occur at the middle position but the place about 10 meters from the centre, because this is the place where the sum of stresses generated by axial stretch and flexure of the pipeline reaches the maximum.

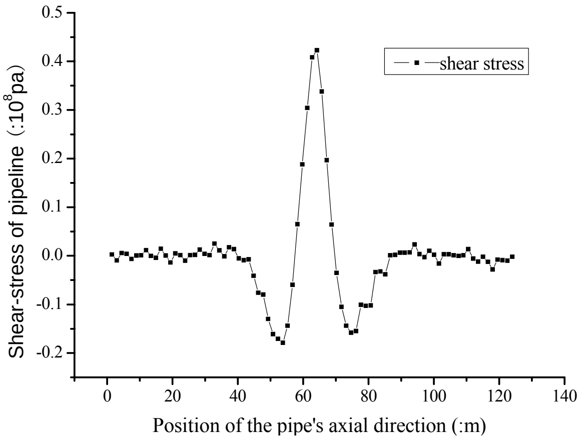


Fig 3 Shear-stress of the pipeline along axial direction

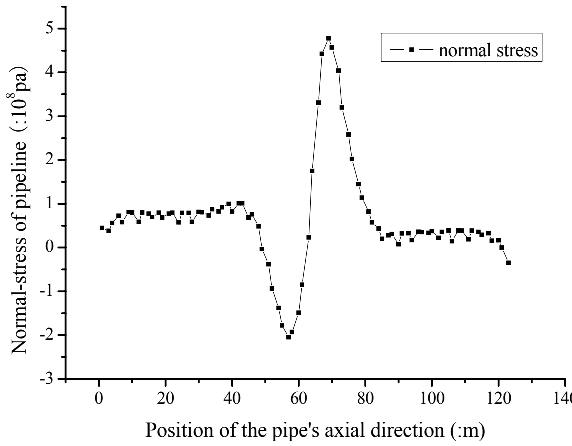


Fig 4 Normal-stress of the pipeline along axial direction

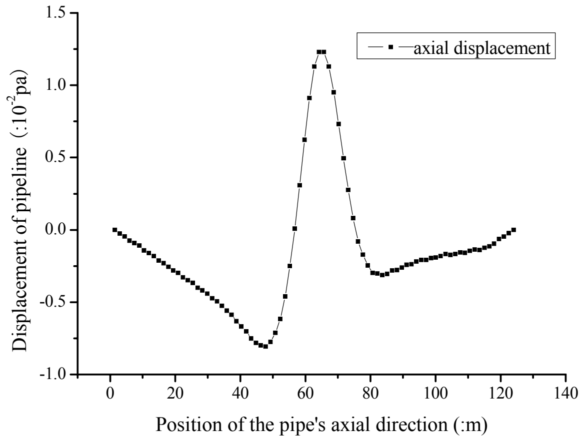


Fig 5 Axial displacement of the buried pipeline

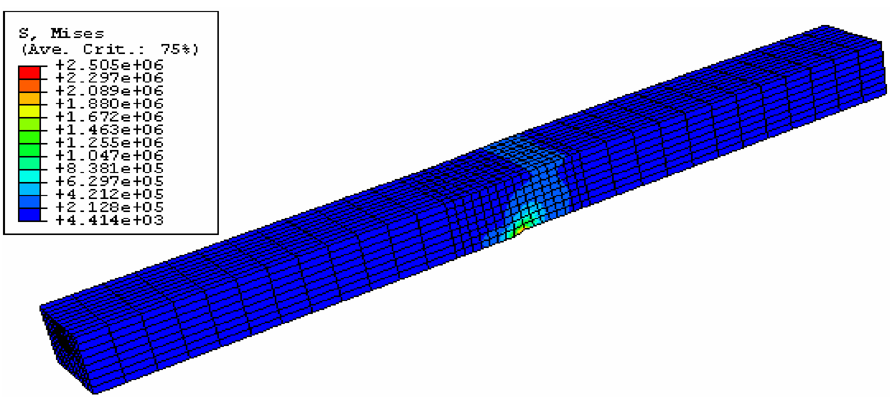


Fig 6 S, Mise of the soil around the pipeline

Figure 5 is the axial displacement (U3) distribution curve of the buried pipeline. Great axial displacement takes place in the middle part, and decreases to both sides gradually because of the frictional behavior generated at the interface. The displacement turns to zero at the place about 10 meters from the centre, and the negative-direction displacement generates on both sides as a result of the negative friction.

Figure 6 is the seismic response of the soil under ground deformation. As is seen from the picture, great response takes place in the middle-part of the soil model, and decreases to the exterior gradually. Here, we assume that no fracture generates or we deem the maximum effective stress doesn't reach the yield point.

4.2. Analysis of influence parameters

In order to know the general regulation of buried pipelines under permanent ground deformation, it's necessary to study the factors that influence the seismic performance of the buried pipeline with numerical simulation, which will provide theory basis for the design and construction of pipe engineering. Some influential factors are shown in table 2, and variable situations are analyzed in the next part.

Table 2 Calculated influence-parameters of the model

	$\Delta(:m)$	$\beta(:^{0})$	D/t	μ	$H(:m)$
$\Delta(:m)$	——	45	60	0.3	3.5
$\beta(:^{0})$	1.2	——	60	0.3	3.5
D/t	1.2	45	——	0.3	3.5
μ	1.2	45	60	——	3.5
$H(:m)$	1.2	45	60	0.3	——

Where Δ means the displacement imposed by the soil, β is the crossing angle of the pipeline, D/t is ratio of pipe diameter and thickness (here the diameter is 1m, while the wall-thickness t is variable), μ is friction coefficient at the interface between pipe and soil, and H is buried depth of the pipeline.

The relationship between the soil input displacement and the Peak S, Mise (equivalent stress) of pipe is shown in figure 7. From the figure, it's not hard to see that the response of the buried pipeline takes on linear increase tendency, which illustrate the inverse relation between seismic performance of buried pipe and input displacement. The greater the displacement input, the more serious the response of the pipeline.

Figure 8 shows the seismic responses of the pipeline under the same loading condition but different crossing angles, and from the figure we can see that the peak-S, Mise of the pipeline increases with the increase of crossing angle. We know that axial stress of the pipeline under the same displacement decreases with the increase of crossing angle, but the shear-stress and curvature of the pipeline takes on the increase tendency with angle increase, which induces the augment of equivalent stress with crossing angle increase at last.

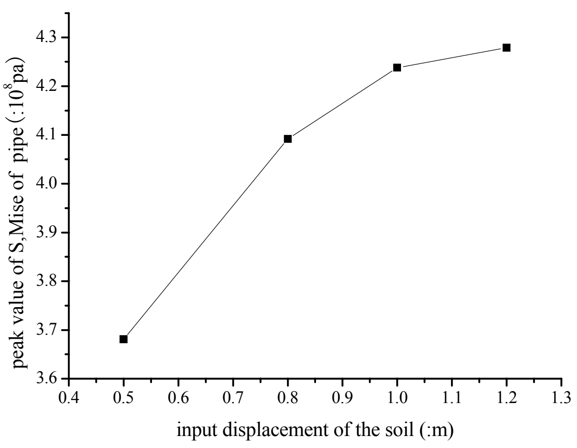


Fig 7 The influence of displacement on the max S, Mise

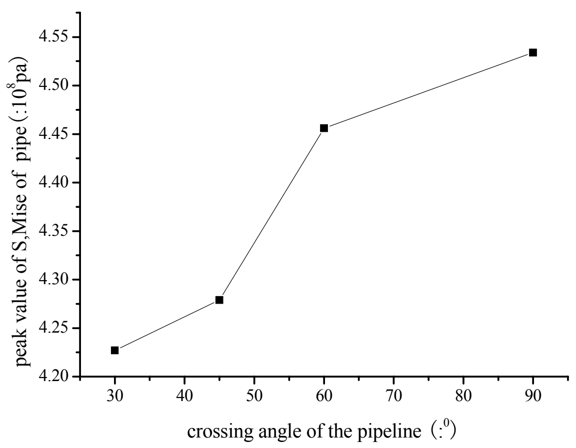


Fig 8 The influence of crossing angle on the max S, Mise

Therefore, the large crossing angle goes against the earthquake-resistance capability of buried pipelines under the actions of normal movement. But due to the indetermination of movement direction and in order to avoid buckling failure of pipeline under reverse movement, we recommend 90^0 to be suitable.

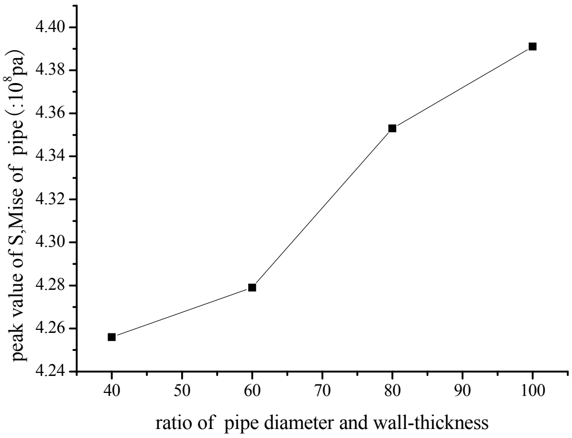


Fig 9 The influence of ratio between diameter and thickness on the max S, Mise

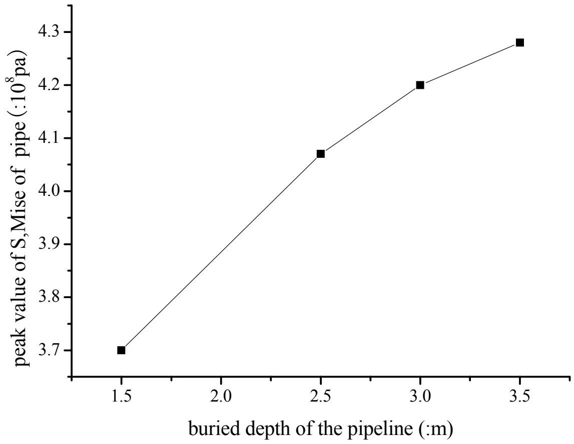


Fig 10 The influence of buried depth on the max S, Mise

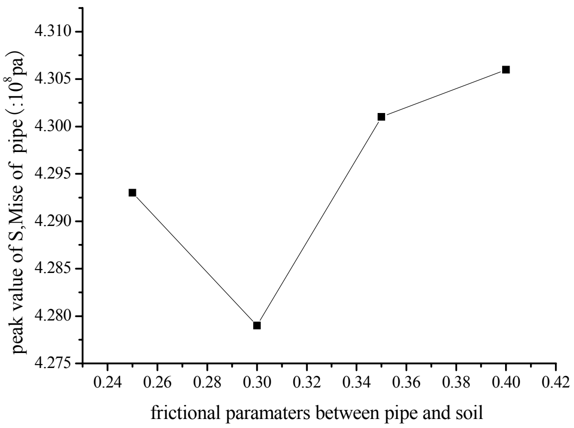


Fig 11 The influence of friction coefficient on the max S, Mise

The relationship between the ratio D/t and the Peak S, Mise of pipe is shown in figure 9, from which we find that the ratio has great effect to seismic performance of the pipeline. Peak-S, Mise of the pipeline increases promptly with the augment of the ratio. As we know that the friction-force between pipe and soil is proportional to pipe perimeter almost and the axial force is proportional to cross-section of the pipe. As a result, the pipe ability to resist soil movement is proportional to the wall-thickness of pipe when the diameter is the same.

Figure 10 shows the relationship of buried depth and the peak S, Mise of the pipeline. Peak stress grows with the increase of buried depth, which states that the capacity to resist ground movement becomes inverse ratio with buried depth of the pipeline. Due to their easy deformation and absorbing more energy, buried pipeline has good performance to resist earthquake when buried depth is shallow. In a word, the deeper buried depth, the poorer performance of the pipe.

Figure 11 shows the responses of pipeline when the frictional parameter is different at the interface of pipe and soil. As can be seen from the figure, the response reaches to minimum when the friction coefficient is 0.3, and the response is larger when the coefficient is more than or less than the value 0.3. The reason is that when the friction coefficient is 0.3, the friction of pipeline and soil can be offset by external load, while less than or greater than the value, the external force plays an important role or friction makes side effect in the model, leading to larger peak stress. This should be given attention during the design and construction of the pipe engineering.

5. CONCLUSIONS

(1) With the increase of the ratio D/t the peak S, Mise increases rapidly. The pipe performance to resist vertical ground movement is proportional to the wall-thickness of pipe with the same diameter.

(2) The greater the crossing angle, the greater response of the pipe under normal-movement. But in order to avoid the action of reverse-movement, we should make the angle to be 90 degrees as far as possible to improve the seismic performance during the pipe design and construction.

(3) Seismic response of buried pipeline increases with the increase of the soil displacement. The greater buried depth, the poorer performance of the pipe. Shallow embedment can improve pipe performance.

(4) The earthquake-resistant performance is the best when frictional coefficient is 0.3, which should be given attention during the pipe design and construction.

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