IJE TRANSACTIONS C: Aspects Vol. 28, No. 3, (March 2015) 338-349

International Journal of Engineering

Journal Homepage: www.ije.ir

A Continuum Shell-beam Finite Element Modeling of Buried Pipes with 90-degree Elbow Subjected to Earthquake Excitations

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PAPER INFO

Paper history:
Received 07 July 2014
Accepted in revised form 18 December 2014

Keywords:
Buried Pipe Elbow
Finite Element Method
Hybrid Model
Continuum Model

ABSTRACT

In the current work, the seismic analysis of bent region in buried pipes is performed, and effects of soil properties and modeling methods on pipe's response are investigated. To do this task, beam, beam-shell finite element modeling, and a continuum shell FE model of a 90-degree elbow are employed. In the beam model, the pipe is simulated by beam elements while combined shell-beam elements are used for the continuum shell finite element model. The surrounding soil is simulated by nonlinear springs and solid elements; moreover, soil hardening behavior and soil-pipe slippage are considered in the models. In addition, an equivalent boundary condition has been employed at the end of each elbow leg to simulate far field effects more closely. From these analyses, it can be revealed that axial strain at bends is larger in stiffer soil due to smaller slippage. In addition, a full three dimensional soil-pipe interaction using continuum shell FE model causes a substantial increase of elbow strain.

***doi**: 10.5829/idosi.ije.2015.28.03c.02*

1. INTRODUCTION

Buried pipeline systems thought as one of lifeline systems are generally used to transport sewage, water, oil, natural gas and other materials. Possible relative displacements between soil and pipe make the buried pipelines seismic behavior distinct from the most above ground structures. A pipeline system which traverses a large geographical area with different soil conditions is susceptible to experience a wide variety of seismic hazards. The major seismic hazards which significantly affect a pipeline system are ground failure (Permanent Ground Deformation; (PGD)) and ground motion (Transient Ground Deformation; (TGD)). When the seismic waves excite the ground, the buried piping components such as bends used to follow the pipeline geometry experience additional stresses. The behavior of buried pipe with elbow under ground motions is studied in the current study.

The seismic behavior of buried pipelines has been investigated by many researchers, and various analytical and numerical solutions were proposed to evaluate their responses under wave propagation incorporating soil-pipe interaction. The early studies on buried pipelines behavior subjected to ground excitations assumed the straight part of pipeline would follow the deformation of the ground resulting in the fact that the soil-pipe interaction was not considered [1].

Since the soil-pipe interaction could not be taken into account in Newmark approach, Sakurai and Takahashi [2], Shinozuka and Koike [3] and also O'Rourke and El Hamdi [4] have presented a quasi-static analysis using beam elements to consider soil-pipe interacting forces (O`Rourke and Liu [5]). The influence of wave propagation on bent pipes employing beam on elastic foundation theory were studied by Shah and Chu [6], Shinozuka and Koike [3] and Goodling [7]. For more precise consideration of soil-pipe interaction effects on elbows subjected to seismic waves, Ogawa and Koike [8], and O'Rourke and Mclaughlin [9, 10] used numerical methods to derive closed form solutions for the pipe response. Hosseini and Tafreshi [11] presented a physical model for flexible pipes under vertical excitations. In their study, using a number of experiments, effects of soil's unit weight, pipe depth and boundary conditions were evaluated.

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Please cite this article as: M. Saberi, F. Behnamfar, M. Vafaeian, A Continuum Shell-beam Finite Element Modeling of Buried Pipes With 90-degree Elbow Subjected to Earthquake Excitations, International Journal of Engineering (IJE), TRANSACTIONS C: Aspects Vol. 28, No. 3, (March 2015) 338-349

Lee et al. [12] performed a numerical study for buried pipes under seismic ground motions. It has been noticed from past earthquakes that the buried pipelines suffered severe damages due to ground shaking following large deformations in the pipe section resulting in a very large strain. Since it is difficult for the beam model to analyze the large deformation in the pipe cross section, the shell FEM model has been proposed by some researchers (Datta et al. [13] & Wang et al. [14], Takada and Tanabe [15], Takada and Higashi [16], Takada and Katagiri [17] and Kouretzis et al. [18]). Consideration of straight buried pipe behaviors, as relatively rigid and flexible pipes, is another course of study, which has been followed by O`Rourk et al. [19], Wang et al. [14] and Shi et al. [20]. Xie et al. [21] presented a new Winkler model using centrifuge testing and 3D finite element analysis for investigation of straight pipes under normal faulting.

Interaction of pipe with the surrounding soil in all aforementioned investigations has been simulated using the Winkler theory. A detailed investigation into such an interaction is needed to ensure that the response of both pipeline and soil components is properly understood during design. In this regard, Halabian et al. [22], Symans and Xie [21], Hatzigeorgiou and Beskos [23], Vazouras et al. [24] and Trifonov and Cherniy [25] studied soil-structures interaction by modeling soil medium around the underground systems. On the other hand, the majority of the works cited in the relevant literature have focused on quasi-static analyses of straight buried pipelines; whereas, due to the seismic load, the stress typically concentrates at elbows of a pipeline system. As a result, time history analysis of buried pipes at the elbow seems to be necessary. Furthermore, due to the complicated soil behavior and pipeline geometry, the influence of soil-pipe interaction on bent pipes has not been fully understood. Thus, the necessity of the development of a more accurate and efficient 3D model to simulate far field effects and a more closely modeling of slippage of pipe in surrounding soil under seismic loading appears to be required. The current study aims to consider dynamic time history analysis of bent pipes using a finite element (FE) simulation. In order to reach a more accurate approach for elbow pipe modeling, numerical 3D FE models for simulating the surrounding soil as semi-infinite medium are employed.

TABLE 1. Mechanical properties of pipe [26].

Pipe type	Diameter (mm)	Thickness (mm)	Mass density (kg/m^3)
Steel- API-X65	400	9.5	7850
Elasticity modulus E(GPa)	Poisson ratio (υ)	Yield stress σ_y (MPa)	Ultimate stress σ_u (MPa)
210	0.3	465.4	517.7

TABLE 2. Material properties of selected soil types [27]

	Soil type		
	Loose sand	**Medium sand**	**Dense sand**
Unit weight (kN/m^3)	14	18	22
Internal friction angle φ (degree)	28	35	45
Friction angle between pipe and soil (degree)	17	21	27
Average shear wave velocity V_S (m/s)	75	220	450
	Soft clay	**Medium clay**	**Stiff clay**
Unit weight (kN/m^3)	16	18	21
Shear strength S_u (kPa)	10	50	200
N'_{70}	0-2	6-10	20-30
Average shear wave velocity V_S (m/s)	75	220	450

Subsequently, pipe strain response and pipe-soil slippage values in Beam, hybrid Beam-Shell, and Continuum Shell FE models are compared. In addition, effect of the soil type on pipe response is taken into account.

2. NUMERICAL ANALYSIS OF BENT PIPE

Various types of numerical modeling of soil-pipe interaction are employed to examine the nonlinear performance of buried pipelines in the elbow area and effect of the characteristics of surrounding soil. Three different FE models named as Beam model, Hybrid Beam-Shell model and general Finite Element model are utilized within Abaqus software. A steel pipe of API 5L grade X65, whose mechanical specifications are summarized in Table 1, is selected for the present analyses. Moreover, the embedment depth (H) and elbow radius are assumed 1.5m and 3D, respectively, in which D is the pipe diameter. Since the right angle elbow is the most common bend in the actual piping configurations, the bend angle is fixed at 90˚. It is noteworthy that material damping, which is treated as Rayleigh type for the 3D FE models, is also utilized in this research.

2. 1. Beam and Hybrid Beam-shell Models

In this paper, two numerical models named Beam and Hybrid Beam-Shell models are first developed for the analysis of buried pipe. In the mentioned models, six various types of soil are assumed as the burial domain: loose, medium and dense sand; and soft, medium, and stiff clay (see Table 2).

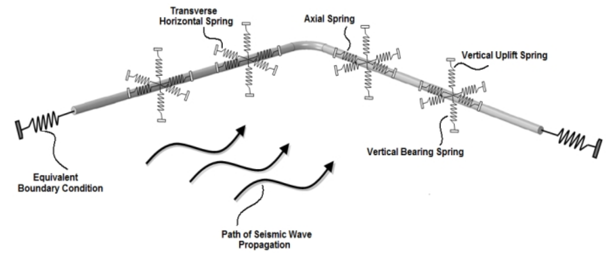


Figure 1. Schematic arrangement of the soil spring around the pipe and boundary condition

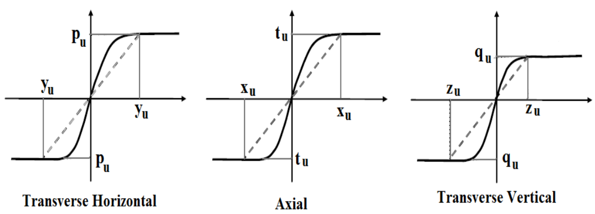


Figure 2. The force-displacement behavior of soil springs

2. 1. 1. Soil-pipe Interaction in the Beam Model

In the Beam model, the pipe is modeled using beam elements, adopting Winkler theory to take soil-pipe interaction into account. It can be predicted that interaction of soil and pipe has a remarkable effect on the behavior of buried pipe subjected to earthquake excitations. According to the Winkler theory, the surrounding soil is simulated by a number of nonlinear spring elements to represent the elasto-plastic nature of the soil-pipeline interaction. These nonlinear springs are located around the pipe in three perpendicular directions. The springs act only in compression to properly simulate the soil-pipe interaction. Thus, they are imposed on both sides of the pipeline in the model. Consequently, there are six nonlinear spring elements around each node of the model (Figure 1). Nonlinear load-displacement relationships of soil springs proposed by ALA [28] are employed for the simulation of soil behavior. The maximum soil resistance *(t_u)* per unit length of pipe in axial direction can be calculated as:

$$t_u = \pi D c \alpha + \frac{\pi D}{2} \bar{\gamma} H (1 + K_0) \tan \delta \tag{1a}$$

$$\alpha = 0.608 - 0.123c - \frac{0.274}{c^2 + 1} + \frac{0.695}{c^3 + 1} \tag{1b}$$

where, D is the pipe outer diameter, c is the soil cohesion, α is adhesion factor, $\bar{\gamma}$ is effective unit weight, H is burial depth, K_0 is coefficient of lateral pressure at rest and finally δ is angle of friction at the pipe-soil interface. According to ALA standard, displacement at t_u (Δ_t) is 3 to 5 mm for dense to loose sand, and 8 to 10 mm for stiff to soft clay. The maximum lateral soil resistance per unit length of pipe (p_u) and the transverse displacement corresponding to p_u (Δ_p) are given by:

$$p_u = N_{ch} c D + N_{qh} \bar{\gamma} H D \tag{2a}$$

$$\Delta_p = 0.04\left(H + \frac{D}{2}\right) \le 0.1D \text{ to } 0.15D \tag{2b}$$

where N_{ch} and N_{gh} are soil capacity factors given by ALA [28]. The properties of soil springs are different in upward and downward directions. The relationship between vertical uplift load (Q_u) and displacement at which maximum soil resistance in vertical upward is developed (Δ_{qu}), is calculated as:

$$Q_u = N_{cv} c D + N_{qv} \bar{\gamma} H D \tag{3a}$$

$$\Delta_{qu} = \begin{cases} 0.01H \text{ to } 0.02H & \text{for dense to loose sands} < 0.1D \\ 0.1H \text{ to } 0.2H & \text{for stiff to soft clays} < 0.2D \end{cases} \tag{3b}$$

where, N_{cv} and N_{qv} are vertical capacity factors given by ALA standard. The maximum force (Q_d) of vertical soil bearing springs per unit length of pipe can be determined by:

$$Q_d = N_c c D + N_q \bar{\gamma} H D + N_\gamma \gamma \frac{D^2}{2} \tag{4}$$

where, γ is total unit weight of sand, and N_c, N_q and N_γ are bearing capacity factors which are suggested by ALA [28]. The displacement, at which maximum soil resistance in downward direction is developed (Δqd), is equal to 0.1D for sandy and 0.2D for clayey soils. The aforesaid force-displacement relationships are shown in Figure 2.

Another interesting point to note is the fact that nonlinear soil springs, which are employed in this research, are able to simulate hardening behavior of soil and soil-pipe slippage under cyclic loading.

2. 1. 2. Soil-pipe Interaction in the Hybrid Model

The second numerical model used in the present investigation for evaluation of seismic pipe strains, is the hybrid Beam-Shell model. This means that some parts of pipe are modeled by shell elements and the rest of pipe, by beam elements [5, 19, 29]. To simulate the pipe cross-section deformation more accurately, the elbow region and its vicinity are modeled by shell elements. The rest of the pipe, in the straight part of each elbow leg, is simulated by beam elements and linked to shell elements. It is noteworthy that a number of sensitivity analyses for evaluation of optimized length of straight pipe away from the bend are performed. Consistency of deformations is enforced at the junction of beam and shell parts. As proposed in a previous investigation, [30], the dimensions of elements must be less than 1/8 of the wave length with the highest important frequency.

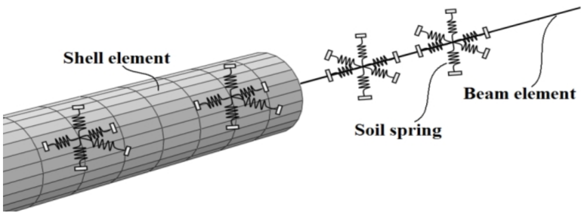


Figure 3. Schematic view of Hybrid model.

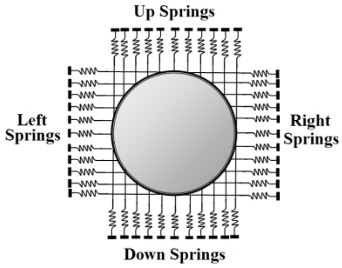


Figure 4. Arrangement of soil springs around pipe circumstance

This condition results in employing 24 elements around the pipe circumstance in the shell elements region. The minimum aspect ratio is increased from 1/5 in straight segments to 1/3 at the bend in order to observe high possibility of stress and strain concentration at this location. Again, the springs are active only in compression so that the sum of springs' capacities just on one side equals the total soil capacity in the direction of sets of springs; i.e., at any time only the springs on the compression sides of pipe are active.

Another point that should also be noted is that the contribution of each transverse spring to the total lateral stiffness is proportional to its share of the perimeter when projected onto the diameter. It is concluded that the lateral springs located nearest to the center on each side are the stiffest, whereas the transverse spring stiffness decreases as the distance from the center lengthens. The strength per unit length for each axial spring in the beam model is distributed equally around the perimeter of the pipe and is assigned to each separate axial soil spring. Where the shell elements part terminates, and the beam elements begin, deformations of the cross section are associated with the node on the longitudinal axis or the center of section at the same place. This accounts for the consistency of displacements in the model. The schematic modeling of connection between shell and beam parts of the model and arrangements of nonlinear soil springs around the pipe circumstance are presented in Figures 3 and 4, respectively.

2. 1. 3. Modeling of the Far Field and Seismic Input To reach an accurate simulation, the length of each elbow leg should be taken to be very large. However, due to computational problems, the modeling of the pipeline with this assumption could be time consuming; therefore, a different assumption for the far field should be considered. That is why, to simulate the infinite length of bend legs and avoid the analysis error caused by the forced boundary, instead of using a fixed boundary at the end of the beam segment of the pipeline, the equivalent boundary condition proposed by Takada et al. [29] is adopted in this study. They assumed that the lateral deformations of pipe far from the part under study do not affect the mentioned part, and only the longitudinal friction exists.

The total axial deformation of the buried pipe (ΔL) under axial force F is equivalent to a nonlinear elongated spring force. The relationship between the axial force F and the longitudinal extension ΔL is indicated by Equation (5):

$$F(\Delta L)=\begin{cases}\sqrt{\dfrac{3EAf_s}{2}}U_0^{-\frac{1}{6}}\Delta L^{\frac{2}{3}} & 0\le \Delta L\le U_0\\ \sqrt{2EAf_s(\Delta L-\dfrac{1}{4}U_0)} & U_0\le \Delta L\le \dfrac{\sigma_y^2 A}{2Ef_s}+\dfrac{U_0}{4}\end{cases} \tag{5a}$$

$$f_s = 0.75\pi DH\gamma_s\mu = KU_0 \tag{5b}$$

where E is the soil modulus of elasticity, A is the pipe cross section area, U_0 is yield relative displacement between the soil and the pipe, σ_y is the yield stress of the pipe material and f_s is the sliding soil friction per unit length. In addition, H is burial depth, γ_s is the weight density of surrounding soil and μ is the frictional coefficient. The aforesaid equations can be applied to ends of each elbow leg as nonlinear springs.

3D elbow pipeline models introduced in this study are subjected to different earthquake excitations to examine the effect of wave propagation on bend behavior. The ground motions characteristics including the frequency content, the soil shear wave velocity and the Peak Ground Acceleration (PGA) are given in Table 3 [31]. In this study, to highlight the severity of the ground motions, the pipes are assumed to be buried in soil with shear wave velocities consistent with the selected ground motions sites. The records are also chosen in a way such that the frequency content of each individual record matches the pipeline-soil system's important frequencies that are up to 10 Hz. A material damping ratio equal to 4% of critical damping has also been considered. It includes Rayleigh type damping with α and β coefficients for mass and stiffness proportional damping, respectively. Modal analysis was performed to discover the modes with important contributions; consequently, the aforesaid coefficients have been computed through the results obtained from the modal analysis.

It is worth mentioning that the propagation medium is assumed to be homogeneous and the energy source (the causative fault) is taken as very far such that the wave front can be regarded as parallel lines. The wave propagation parallel to a pipe branch leads to inducing out-of-phase motions along a pipe axis, consequently, axial and flexural strains are produced in the buried pipe considered in the current work.

2. 2. The Continuum-shell FE model When a buried pipeline is subjected to a severe earthquake, the relative displacement between pipe and soil will be large enough to cause a significant strain in the bent pipe. As can be seen from previous studies, in the majority of cases, strain in buried pipes under propagating waves are caused by soil-pipe slippage. Thus, to reach a more accurate modeling of slippage, and a full 3D analysis of bent buried pipeline under wave propagation, a continuum shell finite element model was developed in the current study. In this 3D numerical model that is referred to as the Continuum-Shell FE model, soil medium is simulated as a half space using continuum solid elements.

The determination of equilibrium initial stress field in the onset of dynamic analysis of soil-pipe model is normally required. Accordingly, a static analysis is performed first to apply the gravity load and establish the initial stress state. This stress state then is used as the initial stress field in a subsequent wave propagation dynamic analysis.

2. 2. 1. Soil-pipe Interaction Modeling using the Continuum Shell FE Model In the continuum model, the surrounding soil in the shell part of the hybrid model is modeled by solid (brick) elements instead of discrete nonlinear springs, and the rest of the model is simulated in the same way as the hybrid model.

TABLE 3. Characteristics of input ground motion

Earthquake	Station	Shear wave velocity Vs (m/s)	Peak ground acceleration (g)
Chichi	CHY041	Vs<180	0.639
Chichi	CHY028	180 <Vs< 360	0.821
Chichi	CHY080	360 <Vs< 750	0.968
Northridge	Montebello-Bluff Rd	Vs<180	0.179
Northridge	LA-Centinela St	180 <Vs< 360	0.465
Northridge	Santa Monica City Hall	360 <Vs< 750	0.883

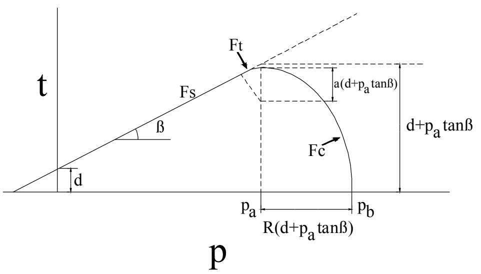


Figure 5. Yield surfaces in meridional plane of modified Drucker-Prager/Cap model

A contact surface algorithm is employed for modeling of soil-pipeline interface in which slide and soil-pipe separation is made possible using this contact function. This contact capability allows finite sliding and separation between two surfaces based on Coulomb friction criterion. The reduced interface friction angle between the soil and pipe is set at 0.75 of internal friction angle of the soil (φ), as suggested elsewhere [32].

2. 2. 2. Soil Behavior Modeling in the Continuum Shell FE Model The soil is simulated using the modified Drucker-Prager/Cap plasticity model which is appropriate in considering the elasto-plastic soil behavior. This model is also capable of considering the effect of stress history, stress path, dilatancy and the effect of intermediate principle stress.

Additionally, the yield surface in hydrostatic compression is considered, and also an inelastic hardening mechanism for representing the plastic compaction is offered by this model. As the material yields in shear, volume dilatancy controlling can be achieved by taking softening into account. For this, the softening law is defined as a function of the inelastic volume increase; created as the material yields on the Drucker-Prager shear failure surface.

As depicted in Figure 5, the yield surface in the meridian (*p*-*t*) plane is divided to three main parts: a pressure-dependent Drucker-Prager shear failure segment F_s, a compression elliptical cap with constant eccentricity F_c, and a transition surface F_t, which are presented in Equations (6), (7) and (8), respectively.

$$F_s = t - p\tan\beta - d = 0 \quad (6)$$

$$F_c = \sqrt{(p-p_a)^2 + \left(\frac{Rt}{1+\alpha-\alpha/\cos\beta}\right)^2} - R(d + p_a\tan\beta) = 0 \quad (7)$$

$$F_t = \sqrt{(p-p_a)^2 + \left[t - \left(1-\frac{\alpha}{\cos\beta}\right)(d + p_a\tan\beta)\right]^2} - \alpha(d + p_a\tan\beta) = 0 \quad (8)$$

where t is the deviatoric stress measure, p is the equivalent pressure stress, β is the angle of friction, d is the material cohesion, R is the ratio of the horizontal axis of the elliptical cap to the vertical axis of the elliptical cap, p_a represents the volumetric inelastic-strain-driven hardening and/or softening, and α represents the ratio of the radius of the transition surface to the radius of the vertical axis of the elliptical cap in the *p*-*t* plane.

In terms of cap surface, the elliptical cap depends on the third stress invariant in the deviatoric plane. Furthermore, plastic flow on the aforesaid surface, which causes the material to compact, is defined by a flow potential that is associated in the deviatoric plane, associated in the cap region in the meridian plane, and nonassociated in the failure surface and transition regions in the meridan plane. It is worth mentioning that the constitutive parameters of the Cap plasticity model for the used soils in this section are calibrated by triaxial tests, and are summarized in Table 4. The mechanical properties of studied pipe are also as Table 1.

2. 2. 3. Boundary Conditions and Input Ground Motion To have a realistic assessment of the soil-pipe dynamic response, a suitable boundary condition should be defined to model the impedance of the far-field soil region including the radiation damping effect. For this purpose, in the present study the soils in the near field and far field regions are modeled using the conventional 3D finite elements and 3D infinite elements, respectively. According to Wolf [33], modeling of soil medium up to a distance equal to 4 times the diameter from the center of pipe leads to an accurate response of pipe-soil system analysis. In the current paper, the aforementioned condition is also considered for the near field modeling of soil region.

In order to simulate the far field effect, the infinite elements are employed instead of absorbing boundary conditions such as springs and dampers. This approach overcomes some difficulties of absorbing boundary conditions, and takes less memory space and computing time. The nodal points in each infinite element are located on the interface with the finite element region. Furthermore, the nodes pointing to the infinite direction are positioned far enough to enhance the performance of infinite elements. The aforesaid descriptions are illustrated in Figure 6. It is notable that the boundary conditions of the rest of the continuum numerical model are the same as the hybrid model.

TABLE 4. The parameters of Cap plasticity soil model used in 3D continuum shell FE model.

Soil type	Mass density ρ (kg/m³)	Elasticity modulus E (MPa)	Poisson` ratio Υ
Sand	1923	182	0.28
Soil's angle of friction (β) (deg)	**Cap eccentricity (R)**	**Transition yield surface parameter (α)**	
55.7	0.4	0.05	

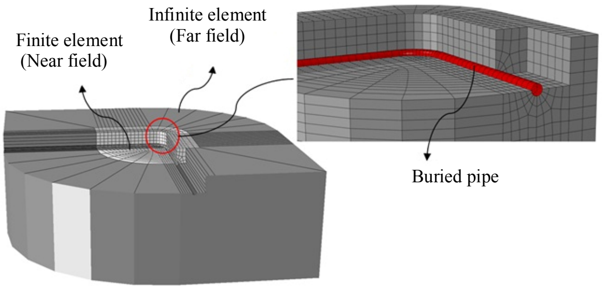


Figure 6. A view of the 3D continuum part of FE modeling of soil-pipe interaction

Note that assumptions considered in the previous sections for the simulation of travelling seismic waves are again employed in the current model. The bottom of soil medium is assumed to be bedrock; therefore, pipe-soil modeling system is subjected to seismic ground motion at the bedrock to all three acceleration components of the Chichi (CHY028 station) and Northridge (LA-Centinela St) earthquakes. The selection of these input ground motions are according to corresponding shear wave velocity of the used soil that is described in sec. 2.1.3.

2. 2. 4. The Evaluation of Finite Element Mesh Adequacy In order to ensure stability and accuracy of the numerical solution, the size of elements should satisfy some criteria. Thus, in addition to the mentioned criteria in the previous sections, another criterion has also been developed in the present work. For a more close description of wave propagation in the solid medium, the ratio (q) of wavelength (L_w) to element length (L_e) should be between 6 and 12 [23, 34]. The critical (upper) frequency (f_{cr}), which can be accurately transmitted by the finite element model, is calculated as Equation (9).

$$q = \frac{L_W}{L_e} \tag{9a}$$

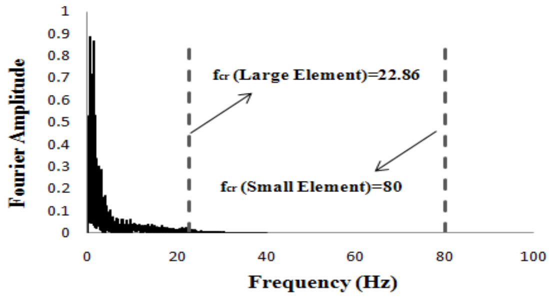
$$f_{cr} = \frac{V_S}{L_W} = \frac{V_S}{qL_e} \tag{9b}$$

where V_s is the shear wave velocity. In order for the computational efforts to reduce, six elements per wavelength (q=6) are assumed. The majority of the used solid elements have a length of 0.4m, but the length of the largest finite element is 1.4m. The shear wave velocity (V_s) of the selected soil is 192 m/s, and finite elements being 0.4 and 1.2 m long are selected for adequacy mesh evaluation. Consequently, the frequencies equal to 80 and 22.86 Hz are the highest frequencies which can be transmitted accurately by the mentioned element sizes, respectively. The Fourier spectra of the used earthquake ground motions and the upper frequency thresholds are presented in Figure 7.

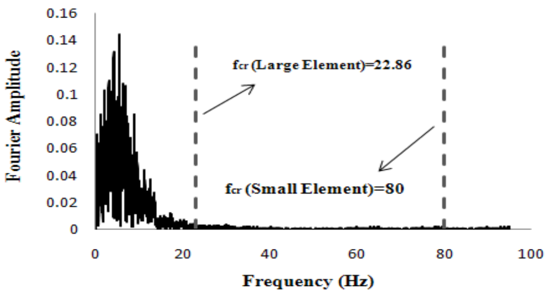
3. NUMERICAL RESULTS

In order to identify the major parameters affecting the structural response of the bent area under wave propagation, a number of analyses on the soil-pipe system are carried out using the approaches explained in this study. To assess the magnitude of strains induced in the elbow region and pipe slippage, the influences of the soil type and soil-pipe interaction modeling are illustrated as follows.

3. 1. Sensitivity Analysis There is no consensus on the minimum length of straight part of the pipe away from the elbow which is required for analyzing the bend. In order to evaluate the influence of the boundary condition on the pipeline's response, a number of models with various lengths and the far field boundary conditions are analyzed.



(a) Transverse component of the Chichi earthquake



(b) Transverse component of the Northridge earthquake

Figure 7. Fourier spectra of selected seismic input; a) Chichi earthquake and b) Northridge earthquake

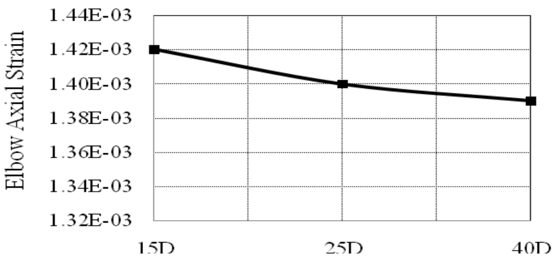


Figure 8. Pipe response under sensitivity analysis of shell length

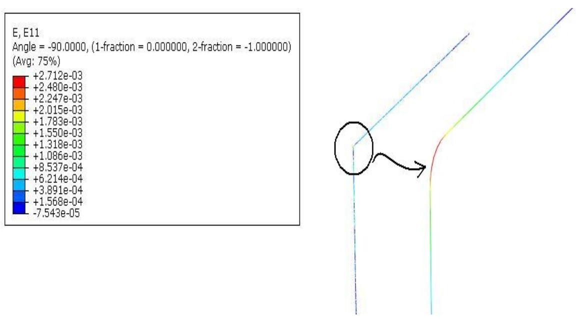


Figure 9. Contour presentation of the axial strain for the pipe in dense sand under Chi-Chi earthquake

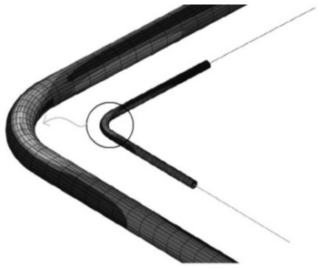


Figure 10. Contour presentation of the principal strains for the pipe in dense sand under Chi-Chi earthquake.

The length of straight part of the pipeline was evaluated using some preliminary analyses, and the results showed that if the end boundary condition was assumed to be fixed, 800D was a sufficient length for accurate evaluation of the elbow's response. The preliminary analyses also stated that the 400D was the case when the nonlinear axial spring was used as the end boundary condition. In this study to optimize the cost of computations, the length of 400D for the straight parts of the models along with the equivalent boundary is employed.

As mentioned in Sec. 2.1.2, a series of sensitivity analyses are employed to determine the sufficient length of the pipe's legs in the modeling. In this context, various straight lengths such as 15D, 25D and 40D are selected to simulate shell parts in elbow's branches. The effect of shell's length on the maximum axial strain in the elbow are presented in Figure 8, which shows that the differences between axial strains in three various lengths for the shell part of the model are less than 4%. As a result, in the current work, a length equal to 15D, is considered to optimize the computational time and to provide a satisfactory accuracy.

3. 2. Maximum Strain Response of Bend in the Beam and Hybrid Models

In order to predict the variation of seismic pipe response with different surrounding soils, both the Beam and Hybrid models are analyzed. The contour of axial strain for the pipe in dense sand under Chi-Chi earthquake is shown in Figure 9. Also, contour of the principal strains is shown in Figure 10. Both figures demonstrate that the bend is a critical place along a pipeline. Figure 11 shows the maximum and minimum principle strains at the elbow. As can be seen from the figure, there is a direct dependency between soil stiffness and strain value in the bend region response. In the other words, if the soil becomes stiffer, the elbow strain will increase, as depicted in Figure 11. What's more, the embedded pipe in stiff soil approximately follows the ground deformation, so it can be expected that the pipe experiences higher strains. Note that although the Beam and Hybrid models predict a similar trend for pipe response, the Hybrid model yields greater values for higher principal strains at the elbow in all cases. This is due to the presence of hoop strains in shell elements which cannot be simulated by beam elements. Finally, the largest principal strains of the buried elbow pipe, subjected to wave propagation in tensile and compressive situations, are far below the rupture and critical levels.

3. 3. Maximum Relative Displacement Response of Pipe in Beam and Hybrid Models In this section, the effect of wave propagation on pipe slippage into surrounding soil is evaluated.

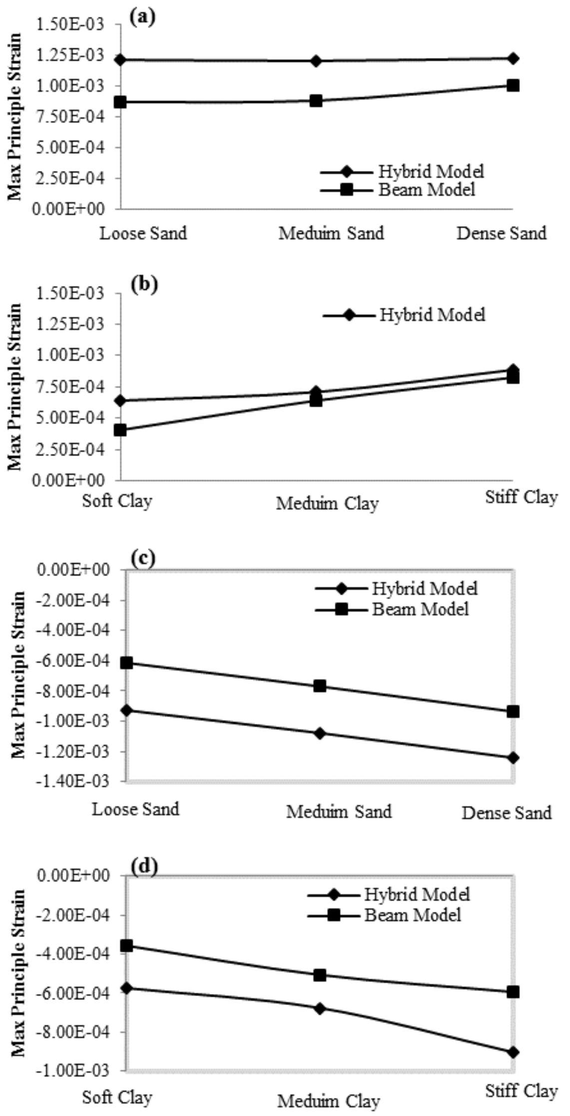


Figure 11. Effect of the surrounding soil and pipe modeling on the principal strains of bent buried pipes subjected to Chichi and Northridge earthquake: (a) maximum tensile strain in sandy soil; (b) maximum tensile strain in clayey soil; (c) maximum compressive strain in sandy soil and (d) maximum compressive strain in clayey soil

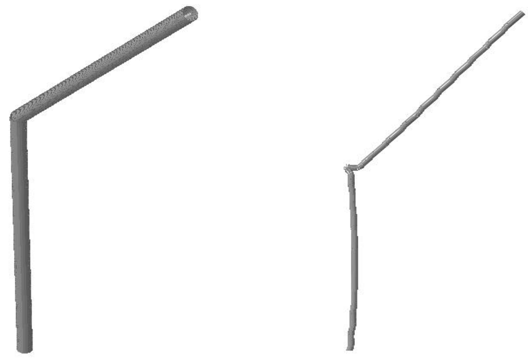


Figure 12. Pipe deformation at bend, in dense sand under Chi-Chi earthquake

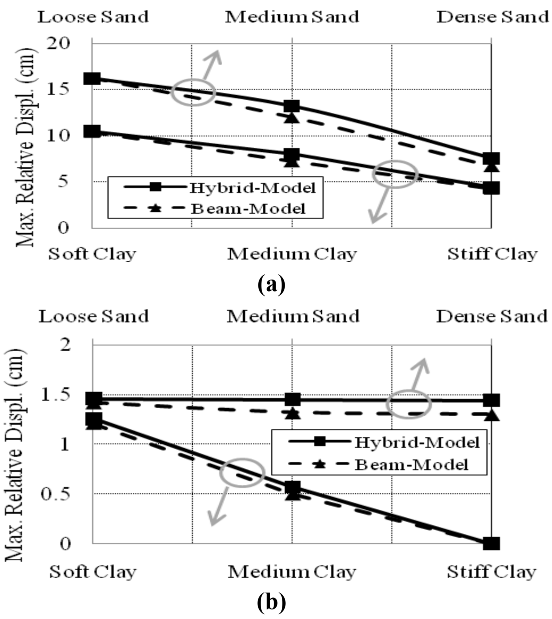
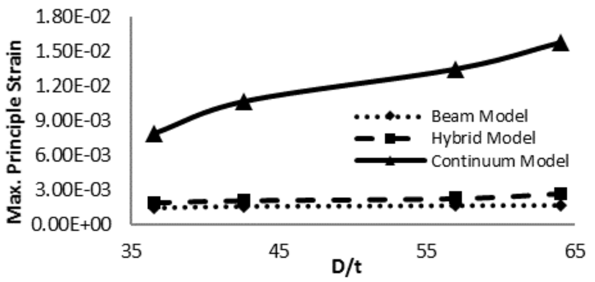
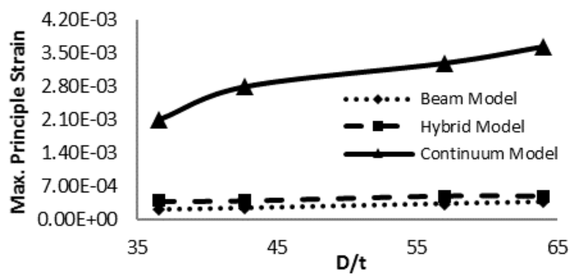


Figure 13. Effect of soil type on soil-pipe slippage in Beam and Hybrid model under Chichi and Northridge earthquake: (a) Chichi earthquake and (b) Northridge earthquake

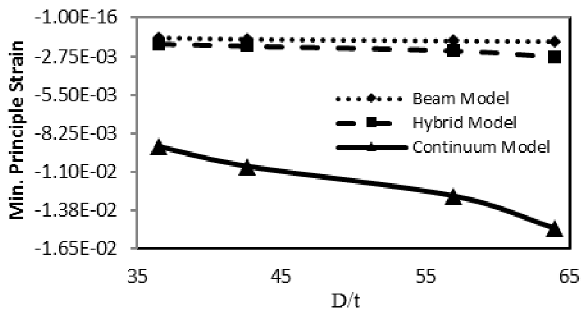
The results indicate that the maximum relative displacement response in the axial direction appears to be affected by the soil condition. The maximum relative displacement between soil and pipe belongs to the soil with a lower stiffness. An interesting point to note is that the cases with low strain responses in the previous section have higher slippage values. This confirms the calculation consistency of the current study. Moreover, it can be observed that the sliding is significantly affected by cohesion properties of the soil. Figure 12 shows the pipe deformation in dense sand under Chi-Chi earthquake, again confirming the above observations. The aforementioned descriptions are supported by Figure 13 which also expresses that the minimum relative displacement response mainly occurs in a cohesive soil (such as clay) in comparison with a non-cohesive soil (such as sand). Therefore, as presented in Figure 13, the buried pipe slippage values under wave propagation phenomenon will decrease from soft to stiff clay due to cohesion characteristic. There is also a good agreement between Beam and Hybrid Beam-shell models in predicting the maximum soil-pipe relative displacement; however, a slight discrepancy is observed between responses.



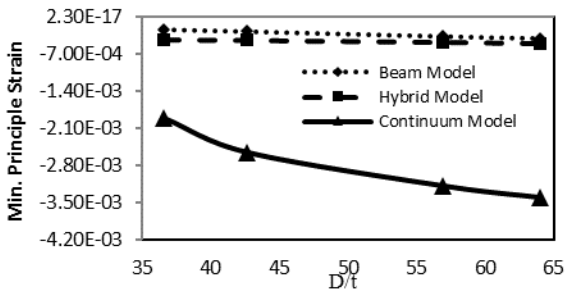
(a)



(b)

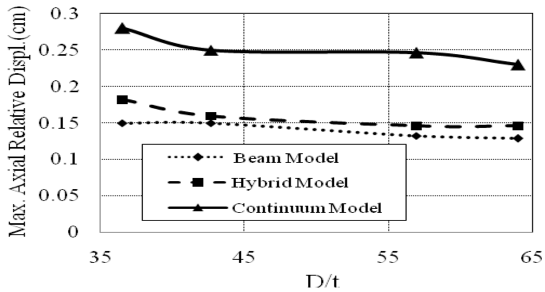


(c)

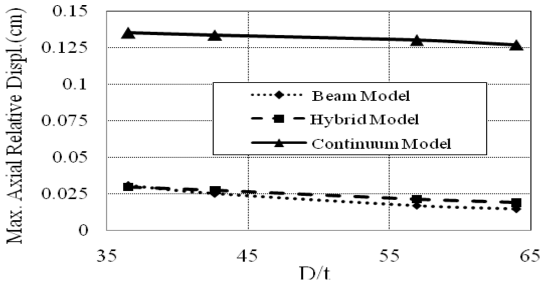


(d)

Figure 14. The influence of different soil-pipe interaction modeling on elbow principle strains under seismic loading: (a) maximum strain under Chichi earthquake; (b) maximum strain under Northridge earthquake; (c) minimum strain under Chichi earthquake and (d) minimum strain under Northridge earthquake



(a)



(b)

Figure 15. Effect of soil-pipe interaction modeling on maximum relative displacement between soil and pipe under earthquake records: (a) Chichi earthquake and (b) Northridge earthquake

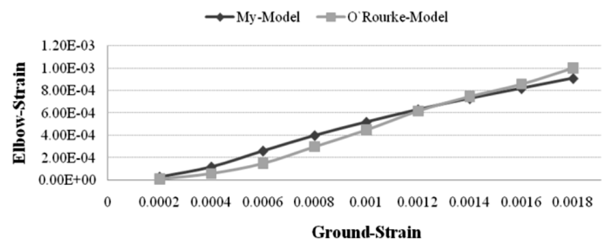


Figure 16. Effect of ground strain on the pipe's strain at bend

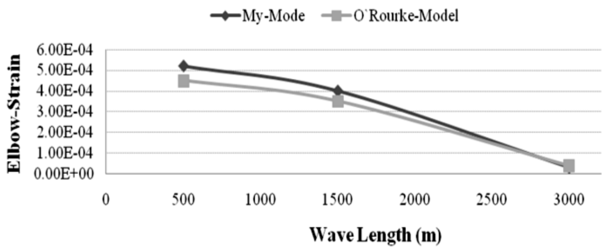


Figure 17. Effect of wave length of the propagating waves on the pipe's strain at bend

3. 4. Effect of Full 3D Soil-Pipe Interaction Modeling on the Elbow Strain Response

This section examines the ability of the continuum-shell elements to simulate soil-pipe interaction under seismic loads. Results of three types of soil-pipe system modeling (Beam, Hybrid and Continuum-Shell FE models) are shown in Figure 14. The pipe diameter to thickness ratio (*D*/*t*) is also selected as a representative mechanical property of pipe for the aforesaid comparative analyses. A relatively high discrepancy is observed between the elbow strains in the Continuum Shell FE model and the two other models, as presented in Figure 14. Furthermore, there is again a slight difference in the pipe response between the Beam and Hybrid models similar to the previous section. However, the pipe bend strains rise highly in the full 3D simulation of the soil-pipe interaction using the continuum elements.

When a large slippage between the pipe and soil occurs, sliding along the interface of pipe and surrounding soil results in turn in an excessive strain in the pipe. This phenomenon can be simulated only via the Continuum Shell FE model which is developed in the current research. Therefore, it can be expected that maximum and minimum principal strains will increase in comparison with the Winkler models, as clearly illustrated in Figure 14. Note that, predicting soil behavior using a continuum soil medium with a constitutive plasticity model is more different than the use of soil springs for soil behavior simulation. The used soil plasticity model in the current study extremely depends on several parameters which are depicted in Table. 4, whereas in the Winkler model the soil spring elements work by a bilinear force-displacement relationship. It is worth mentioning that a large difference in modeling of far field and boundary conditions around the elbow region can be another important factor which mainly affects the pipe response.

Figure 14 shows that the results obtained from three soil-pipe interaction modeling types follow a similar trend for the effect of pipe diameter-to-thickness (D/t) ratio. Thus, a raise in D/t ratio leads to an increase in pipe strain response in all cases. It is noteworthy that although with the more accurate simulation of soil-pipe interaction the strain levels will grow, they do not reach the rupture limit, as can be seen in the results of this section.

3. 5. Effect of Full 3D Soil-Pipe Interaction Modeling on Maximum Soil-Pipe Slippage The influence of various types of soil-pipe interaction simulation and pipe mechanical properties on maximum relative displacement between soil and pipe is considered in this section. As shown in Figure 15, the maximum slippage along the soil and pipe interface in the Continuum Shell FE model is higher than the Beam and Hybrid models. There is also an inverse relationship between diameter-to-thickness ratio and pipe sliding so that as the D/t increases, the soil-pipe relative displacement decreases. In other words, all three numerical models present a similar trend for relative displacement response of the buried pipeline. Note that the values of slip for cases with larger principal strains are smaller. Therefore, this confirms the obtained results in previous sections. Finally, the actual value of the relative displacement between soil and pipe is larger than what has been offered by the Winkler models.

3. 6. Validation of the Analytical Models To show the validity of the developed models, their performance is evaluated in estimating pipe responses compared with previous studies. In this regard, the studies on the pipe bend response by O`Rourke and Mclaughlin [9, 10] are considered. The results of the above study on the effects of ground strain and wave length of the propagating wave on the pipe response are simulated again in the current study and compared. Figures 16 and 17 demonstrate a good consistency between the results of the two studies.

4. CONCLUDING REMARKS

A numerical methodology was developed to calculate the seismically induced strains at the elbow of buried pipelines. Three different FE models were proposed to simulate soil-pipe interaction, employing Beam, Hybrid Beam-Shell and 3D Continuum theory in the analysis of the pipes. These models were used towards a better understanding of the effect of soil-pipe interaction modeling on the behavior of buried elbow pipes subjected to seismic motions. Therefore, pipe response characteristics such as strain in the elbow region and soil-pipe slippage in the bend area were compared in different models. Influence of the soil type on pipe's elbow response was also accounted for. The finite element results showed that the buried pipes in the soil with higher stiffness experienced larger strains at their bend. The results also depicted that pipe slippage was significantly affected by the soil type. In fact, the elbow pipes embedded in stiffer soil follow the ground displacement under seismic ground motions and consequently experience minor axial relative displacements between soil and pipe. Moreover, increasing cohesion properties of soil, leads to a decrease in pipe slippage values.

Another main result from the numerical study is that the elbow strain response that is evaluated by a full 3D soil-pipe interaction via the Continuum Shell FE model causes a substantial increase of elbow strain. This can be due to a more accurate simulation of full contact between soil and pipe interface which leads to excessive strains. Furthermore, the observed discrepancy in pipe response between Continuum Shell FE and Winkler models is caused by a large difference in the constitutive model for simulating the surrounding soil as a medium and the force-displacement relationship for soil modeling by discrete springs. It has also been shown that the bend strain and the soil-pipe relative displacement are directly and inversely proportional to the D/t ratio, respectively.

Finally, the results illustrate that strain response of the elbow pipe under wave propagation is remarkably below the pipe failure strain.

5. ACKNOWLEDGEMENT

Assistance of Mr. Mehdi Ghandil from Isfahan University of Technology in formatting and finalizing the paper is gratefully acknowledged.

6. REFERENCES

1. Newmark, N.M., "Problems in wave propagation in soil and rock", in Selected Papers By Nathan M. Newmark@ sCivil Engineering Classics, ASCE. (1967), 703-722.
2. Sakurai, A. and Takahashi, T., "Dynamic stresses of underground pipelines during earthquakes", in Proceedings of the Fourth World Conference on Earthquake Engineering. Vol. 81, (1969).
3. Shinozuka, M. and Koike, T., "Estimation of structural strains in underground lifeline pipes, Columbia University, Department of Civil Engineering and Engineering Mechanics, (1979).
4. O'Rourke, M.J. and Hmadi, K.E., "Analysis of continuous buried pipelines for seismic wave effects", ***Earthquake engineering & structural dynamics***, Vol. 16, No. 6, (1988), 917-929.
5. O'Rourke, M.J. and Liu, X., "Response of buried pipelines subject to earthquake effects", (1999).
6. Shah, H.H. and Chu, S.L., "Seismic analysis of underground structural elements", ***Journal of the Power Division***, Vol. 100, No. 1, (1974), 53-62.
7. Goodling, E., "Buried piping—an analysis procedure update", in Proceedings international symposium on lifeline earthquake engineering, Portland, Oregon, ASME, PVP-77. (1983), 225-237.
8. Ogawa, Y. and Koike, T., "Structural design of buried pipelines for severe earthquakes", ***Soil Dynamics and Earthquake Engineering***, Vol. 21, No. 3, (2001), 199-209.
9. McLaughlin, P.M., "Seismic response and behavior of buried continuous piping systems containing elbows", (2003).
10. Mclaughlin, P. and O'Rourke, M., "Strain in pipe elbows due to wave propagation hazard", ***Lifeline Earthquake Engineering in a Multihazard Environment, ASCE***, (2009).
11. Hosseini, S. and Tafreshi, S.M., "Soil-structure interaction of buried pipes under cyclic loading conditions", ***International Journal of Engineering Transaction B: Applications***, Vol. 15, No. 2, (2002), 117-124.
12. Lee, D.H., Kim, B.H., Lee, H. and Kong, J.S., "Seismic behavior of a buried gas pipeline under earthquake excitations", ***Engineering structures***, Vol. 31, No. 5, (2009), 1011-1023.
13. Datta, T., "Seismic response of buried pipelines: A state-of-the-art review", ***Nuclear Engineering And Design***, Vol. 192, No. 2, (1999), 271-284.
14. Wang, Y., O'Rourke, T. and Shi, P., "Seismic wave effects on the longitudinal forces and pullout of underground lifelines", in Proceedings of the 100th anniversary earthquake conference: commemorating. (1906), 18-22.
15. Takada, S. and Tanabe, K., "Three-dimensional seismic response analysis of buried continuous or jointed pipelines", ***Journal of Pressure Vessel Technology***, Vol. 109, No. 1, (1987), 80-87.
16. Takada, S. and Higashi, S., "Seismic response analysis for jointed buried pipline by using shell fem model", ***Proceedings of the Tenth World Confrence on Earthquake Engineering***, (1992), 5487-5492.
17. Takada, S., Katagiri, S. and Shinmi, T., Shell model response analysis of buried pipelines., American Society of Civil Engineers, New York, NY (United States). (1995)
18. Kouretzis, G.P., Bouckovalas, G.D. and Gantes, C.J., "3-d shell analysis of cylindrical underground structures under seismic shear (s) wave action", ***Soil Dynamics and Earthquake Engineering***, Vol. 26, No. 10, (2006), 909-921.
19. O'Rourke, T., Wang, Y., Shi, P. and Jones, S., "Seismic wave effects on water trunk and transmission lines", in Proceedings of the 11th international conference on soil dynamics and earthquake engineering and 3rd international conference on earthquake geotechnical engineering. Berkeley, CA. Vol. 2, (2004), 420-428.
20. Shi, P., O'Rourke, T., Wang, Y. and Fan, K., "Seismic response of buried pipelines to surface wave propagation effects", in The 14th world conference on earthquake engineering. Beijing, China, (2008).
21. Xie, X., Symans, M.D., O'Rourke, M.J., Abdoun, T.H., O'Rourke, T.D., Palmer, M.C. and Stewart, H.E., "Numerical modeling of buried hdpe pipelines subjected to normal faulting: A case study", ***Earthquake Spectra***, Vol. 29, No. 2, (2013), 609-632.
22. Halabian, A., Hokmabadi, T. and Hashemolhosseini, S., "Numerical study on soil-hdpe pipeline interaction subjected to permanent ground deformation", in The 14th world conference on earthquake engineering, Beijing, China. (2008).
23. Hatzigeorgiou, G.D. and Beskos, D.E., "Soil–structure interaction effects on seismic inelastic analysis of 3-d tunnels", ***Soil Dynamics and Earthquake Engineering***, Vol. 30, No. 9, (2010), 851-861.
24. Vazouras, P., Karamanos, S.A. and Dakoulas, P., "Finite element analysis of buried steel pipelines under strike-slip fault displacements", ***Soil Dynamics and Earthquake Engineering***, Vol. 30, No. 11, (2010), 1361-1376.
25. Trifonov, O.V. and Cherniy, V.P., "A semi-analytical approach to a nonlinear stress–strain analysis of buried steel pipelines crossing active faults", ***Soil Dynamics and Earthquake Engineering***, Vol. 30, No. 11, (2010), 1298-1308.
26. Specification, A., "5l, 2000,"", ***Specification for line pipe***, Vol. 42, (2000).
27. Bowles, J.E., "Foundation analysis and design, (1988).
28. Alliance, A.L., "Guidelines for the design of buried steel pipe, American Society of Civil Engineers. (2001).
29. Takada, S., Hassani, N. and Fukuda, K., "A new proposal for simplified design of buried steel pipes crossing active faults", ***Earthquake Engineering & Structural Dynamics***, Vol. 30, No. 8, (2001), 1243-1257.
30. Lysmer, J., "Finite dynamic model for infinite media", in Proc. of ASCE. (1969), 859-877.
31. "Peer; http://peer.Berkeley.Edu/ ,pacific earthquake engineering research center", (2014).
32. Yimsiri, S., Soga, K., Yoshizaki, K., Dasari, G. and O'Rourke, T., "Lateral and upward soil-pipeline interactions in sand for deep embedment conditions", ***Journal of geotechnical and geoenvironmental engineering***, Vol. 130, No. 8, (2004), 830-842.
33. Wolf, J.P., "Dynamic soil-structure interaction, Prentice Hall int., (1985).
34. Beskos, D.E. and Anagnostopoulos, S.A., "Computer analysis and design of earthquake resistant structures: A handbook, WIT Press, (1997).

A Continuum Shell-beam Finite Element Modeling of Buried Pipes with 90-degree Elbow Subjected to Earthquake Excitations

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PAPER INFO

Paper history:
Received 07 July 2014
Accepted in revised form 18 December 2014

Keywords:
Buried Pipe Elbow
Finite Element Method
Hybrid Model
Continuum Model

چکید

در این مقاله، تحلیل لرزه ای ناحیه خم در لوله های مدفون موردنظر است و اثرات مشخصات خاک و روش مدل سازی نیز بر واکنش لرزه ای لوله بررسی خواهد شد. به این منظور سه روش مدل سازی شامل مدل های تیر، تیر–پوسته، و پوسته–محیط پیوسته از یک خم ۹۰ درجه مورد بحث قرار می گیرد. در مدل تیر، لوله توسط المانهای تیر جزء بندی می شود در حالیکه از ترکیبی از المانهای تیر و پوسته در روش دوم و از المانهای پوسته در یک محیط سه بعدی در روش سوم استفاده می گردد. خاک اطراف در دو روش اول به وسیله فنرهای غیرخطی با قابلیت مدل سازی لغزش بین لوله و خاک و در روش سوم با المانهای سه بعدی مدل می گردد. به علاوه، در دو انتهای لوله شرایط مرزی سازگار با طول نامحدود لوله و انتشار امواج تا بی نهایت درنظر گرفته می شود. با انجام تحلیل های دینامیکی غیرخطی نتیجه گرفته می شود که کرنش محوری در ناحیه خم در خاکهای سخت بیشتر است که به علت لغزش کمتر بین خاک و لوله می باشد. از سوی دیگر، در تحلیل سه بعدی سیستم لوله–خاک، کرنش های بزرگتری در ناحیه خم به دست می آید.

***doi**: 10.5829/idosi.ije.2015.28.03c.02*