NUMERICAL STUDY ON SOIL-HDPE PIPELINE INTERACTION SUBJECTED TO PERMANENT GROUND DEFORMATION

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ABSTRACT :

Earthquake-induced Permanent Ground Deformation (PGD) could be occurred due to fault movements, land sliding and also liquefaction-induced soil displacements. This kind of deformation can significantly affect underground lifelines, such as buried gas pipelines. To assess the integrity of the pipelines against fault deformation, it is important to quantitatively evaluate the interaction between the pipelines and the surrounding soil. The simplified analysis procedures for buried pipelines crossing active faults consider a bilinear force-displacement relationship curve to represent the soil-pipeline interaction specified in the major seismic design guidelines for pipelines. In a case of fault's large movement or existing relatively soft soil, the soil adjacent to the pipe could behave in a nonlinear fashion and affects the pipe's response and also changes the pipeline-soil interface behavior significantly. In this study, the effect of the soil non-linearity as well as geometric and material non-linearity in soil-pipe interaction due to large ground deformation on the earthquake-resistance of buried pipelines were investigated. A new hybrid approach was developed to reduce the number of degrees of freedom of the soil-pipeline system accounting for real soil-pipeline interaction. The approach combines the finite-element method (FEM) modeling the pipeline and near-field soil around the pipe and the consistent infinitesimal finite-element cell method (CIFECM) to represent the far-field soil around the pipe. The pipeline near fault is modeled using large deformation shell elements, while the segment located far away from the fault, is considered as elastic beam elements. The developed method was used to evaluate the maximum strains for the fault-crossing steel and High Density Polyethylene (HDPE) pipes subjected to various fault movements. Parametric responses for different fault crossing angles and pipe diameters are presented.

KEYWORDS: soil-pipe interaction, permanent ground deformation, HDPE pipe

1. INTRODUCTION

The heavily destruction of buried pipeline networks in number of severe earthquakes in recent years such as 1995 Kobe in Japan, the 1999 Chi-Chi in Taiwan and the 1999 Kocaeli in Turkey showed that the damage mechanism of buried pipelines could be caused less by Transient Ground Deformations (TGD) due to wave traveling and mainly by post-earthquake hazards such as fault movement, land sliding and also liquefaction-induced soil displacements all so-called Permanent Ground Deformations (PGD). After liquefaction, large abrupt differential ground movement is the most reported damage causes to buried lifelines as consequences of the occurrence of an earthquake. The huge deformation in the pipe section always creates the very large amount of strain in the pipeline, and then could cause buckling, cracking or fracture in the pipe body. The early studies on buried pipelines behavior subjected to fault displacements were focused on the movements that cause tensile failure of the pipeline (normal fault) using cable theory (Newmark-Hall [1], Kennedy *et al.* [2]). Some observations of the damages (V-shape and Z-shape) caused by earthquakes showed that pipelines could undergo out of plane axial and bending deformations due to ground displacements at normal faults and in plane axial and bending deformations at reverse faults. Since the cable theory could not satisfy the equilibrium condition for a pipeline crossing a reverse fault, the beam model was developed to consider the bending stiffness of the pipe (O'Rourke and Trautmann (1980), Wang and Yeh (1985)). In the beam model, the large deflection part of the pipe was modeled as a constant curvature curved segment and the remaining part of the pipe, which is small deflection was treated as a semi-infinite beam on elastic foundation. For the cases that the pipe is subjected to fault's moderate and large movements, this model yielded more realistic than cable model. It has been noticed from past earthquakes that the buried pipelines suffered severe damages due to surface faulting following huge deformations in the pipe section that creates the very large amount of strain. Therefore, the pipe response near the fault zone is a complicated nonlinear behavior. Since it is difficult for the cable or beam model to analyze the large deformation in the pipe crossing section, the shell FEM model has been proposed in the analysis of fault-crossing pipeline in order to consider the effect of local buckling and wrinkle in the pipe's section (Ariman and Lee (1992)).

Most of the researches conducted on soil-pipe interaction are focused on steel pipes; however, there are a few studies on seismic behavior of underground pipelines with materials other than steel, and in particular high density polyethylene (HDPE). With HDPE pipelines now becoming the industry standard for natural gas distribution systems, a detailed investigation into the interaction of these types of pipes with the surrounding soil is needed to ensure that the response of both pipeline and soil components is properly understood during design. The present study uses a new hybrid shell-beam model with an equivalent boundary developed by the authors (2008) to examine the response of buried pipelines subjected to large fault movements. The length of affected pipeline under fault movements is usually too long for a shell-mode calculation because of the limitation of memory and costly computations. Therefore, in the new approach, only the pipeline segment near fault is modeled with large deformation shell elements in order to consider the effect of local buckling and large section deformation, and then beam elements are used to model far-fault parts of the pipeline. To assess the integrity of the pipelines against such a large ground movements, it is important to quantitatively evaluate the interaction between the pipelines and the surrounding soil. The soil-pipeline interaction specified in the major seismic design guidelines for pipelines has a bilinear force-displacement relationship curve, where the actual experimental results showed due to large ground deformations the soil-pipe interaction decreases as the relative displacement between the soil and pipe increases (Trautmann and O'Rourke [6]). The material property of the pipeline segment far away from the fault is considered as elastic and nonlinear spring elements at the equivalent boundaries are obtained and applied at the ends of the shell model. To take into account actual soil-pipe interaction using substructure method, the near field soil around the pipe is also modeled by finite-element method (FEM) that accounts soil non-linearities.

In this paper, the new approach is adopted to study the seismic response of underground HDPE pipelines and surrounding soil under three-dimensional movements of crossing faults. In order to understand the main features of the damage of the HDPE pipeline crossing fault, a parametric numerical study on damage to buried HDPE pipeline subjected to large fault displacement was carried out. A 3-D pipe-soil interaction model was developed. Then, attention was paid to determine the contributing factors and key parameters influencing the behavior of HDPE pipe buried in soil accounting for both material and geometric non-linearities. The relation between the maximum axial strain and fault movement considering different pipe-fault crossing angles and different fault movements are examined.

2. SOIL-PIPELINE MODELING

During large abrupt ground movements of an active fault, the crossing buried pipeline experiences large inelastic deformations including material non-linearity as well as geometric non-linearities. These sources of non-linearities tend to change the seismic response of buried pipelines. The elastic and inelastic seismic response behavior of these underground structures also depends highly on the characteristics of the input earthquake records. Several simplified design methods have been proposed to evaluate the maximum stresses or strains in pipelines subjected to large abrupt differential ground movements of an active crossing fault.

For buried pipelines crossing strike-slip faults that cause tensile effects on the line, Newmark and Hall (1975) modeled the pipe as a cable and developed a procedure to evaluate the effect of fault movement on the pipeline. They used the soil pressure at rest (K_0) to represent the pipe-soil interaction and no consideration of passive soil resistance was assumed. Assuming small deflection theory they found the resistant capacity of a buried pipeline subjected to the faulting deformation depends to the soil dynamic properties, pipe-fault crossing angle, slip length and material property. Taking uniform passive soil pressure and bending deformations in the vicinity of the fault into consideration, the cable model was modified by Kennedy *et al*. (1977). They assumed the pipeline is a cable deformed into the single constant curvature curve from bending point B (Figure 1) approaching asymptotically to the undeformed part of the pipeline (Point A). Based on the elongation of the pipe and the variation of the pipe's axial force, the location of the bending moment can be found through an iterative calculation. In the Kennedy's approach the flexural rigidity and also compression in reverse strike-slip or oblique-slip faults can no still be considered.

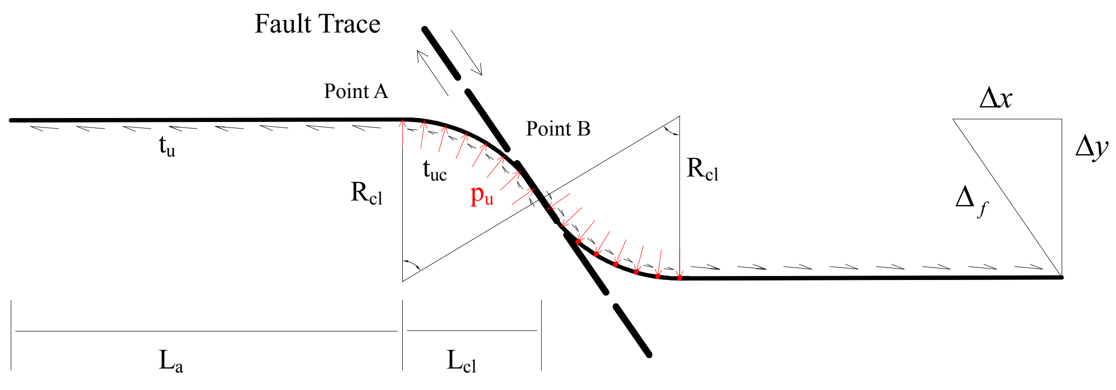

Figure 1. Soil-pipeline model using Kennedy's approach

For situations a strike-slip fault causes compression in the pipeline, Wang and Yeh [6,7] developed beam model considering large deflection theory. In the beam model a large deflection pipe is modeled as a constant curvature curved segment and the remaining small deflection pipe as a semi-infinite beam on elastic foundation. This model includes the bending rigidity of the pipe, a shear force at the point of inflection of the curve pipe crossing the fault zone, and a boundary condition related to semi-infinite beam on elastic foundation at some distance away from the fault zone. For the cases that the pipe is subjected to moderate and large movements, this model yielded more realistic than cable model. It has been noticed from past earthquakes that the buried pipelines suffered severe damages due to huge deformations in the pipe section that creates the very large amount of strain. Therefore, the pipe response in some areas is a complicated nonlinear behavior. Since it is difficult for the cable or beam model to analyze the large deformation in the pipe crossing section, the shell FEM model has been proposed in the analysis of fault-crossing pipeline in order to consider the effect of local buckling and wrinkle in the pipe's section (Ariman and Lee, 1992).

In the current study, to investigate the effect of large deformation in the HDPE pipe's sections and also non-linear behavior of the soil surrounding the pipe during earthquake, a hybrid model proposed by the authors (2008) was adopted to represents the long geometry of soil-pipe system. As the length of affected pipe under fault movements is usually long (about 200 to 500m), for investigation the effect of section deformation, in the new proposed approach, a beam-shell-soil model is used for the FEM analysis (Figure 2). The pipe-soil segment (about 30*pipe's diameter) near the fault is modeled. In this segment, 4-node curved shell elements having six degrees of freedom at each node, namely, three translations and three rotations were used to represent the pipeline. The element takes into account large membrane strains and arbitrary

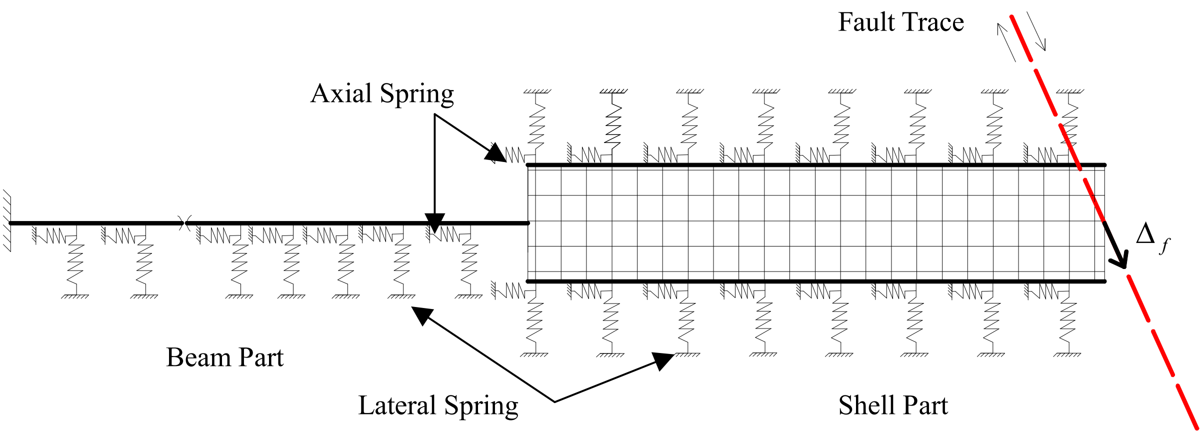

Figure 2. Soil-pipeline FEM model

large rotations and has one integration point. The length of pipe-soil segment was evaluated using the concept of the bending point of the pipe proposed by Kennedy's method. In this method, it is assumed that the deformed geometry of the pipe is approximately a part of a circle (Figure 1). According to this method, the maximum radius curvature that pipe can have is calculated by

$$R_{CL} = \frac{Q}{P_u} \tag{1}$$

where $Q=AF_u$ is the maximum possible axial force in the pipe, in which A and F_u are the pipe's cross-section area and ultimate strength of the pipe's material, respectively. The location of the bending point is in a distance of L_{CL} from the crossing fault as

$$L_{CL} = \sqrt{R_{CL}\Delta y} \tag{2}$$

where Δy is the lateral component of the fault displacement. Since the pipe can have sliding, it is recommended that the shell-soil model should be extended some length beyond the bending point (Takada *et al.* 2001).

In the proposed hybrid finite element model, as it was mentioned the pipe part located in the area crossing the fault is modeled by shell elements, while beam elements are used for the side part, which is between the far end point and end point of the shell segment. Assuming that the principle of the superposition is valid, it is computationally more efficient to subdivide the soil medium around the pipe modeled by shell elements into the near field zone and far field medium (Figure 3). The static or dynamic analysis of the pipeline and near field soil is performed using the impedance functions of the far field medium. Any accurate analysis for pipe-soil system requires that the unbounded nature of the far-field soil region and the nonlinear behavior of the near-field zone be suitably modeled. As a hybrid model developed based on the substructure method, the near field soil and pipe in the soil-pipe segment is modeled by finite-element method (FEM) that accounts material non-linearities in the pipe and soil adjacent to the pipe as well. The reaction of the far field soil on the near-field far-field interface is represented by a boundary condition in the form of a force-displacement relationship.

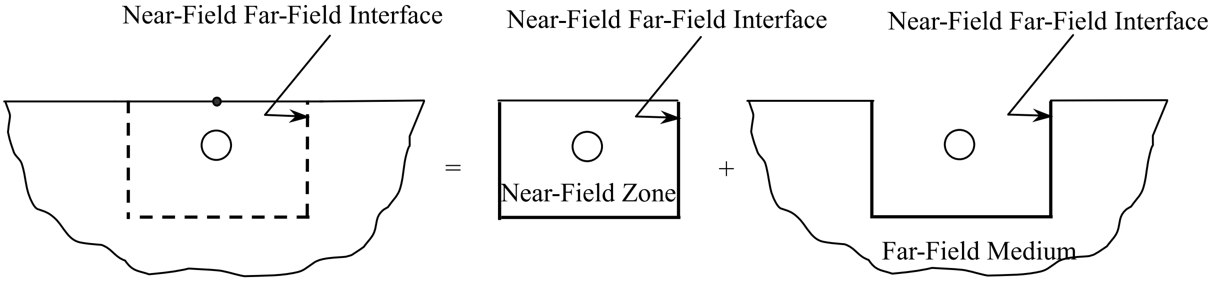

Figure 3. New hybrid model for soil pipe segment (Halabian *et al*. (2008))

Soil-pipeline interaction in the side part (pipe's beam element) in response to relative displacement between pipe and soil is modeled with discrete spring elements using a bilinear force-displacement relationship to represent the elasto-plastic nature of the soil-pipeline interaction. Theses springs represent the axial, transverse horizontal and transverse vertical soil restraints. The soil-pipeline interaction specified in the major seismic design guidelines for pipelines has a bilinear force-displacement relationship curve, where the actual experimental results showed due to large ground deformations the soil-pipe interaction decreases as the relative displacement between the soil and pipe increases. However, in this study as the side part could be subjected less deformation, bilinear representations are sufficiently adequate. Using the load-deformation characteristics for soil-pipeline interaction recommended in ALA, the parameters for mutually perpendicular Winkler's springs are obtained from Table 1. In the Table 1, D and H are the pipe's diameter and embedded depth, respectively. C is the soil cohesion and $\bar{\gamma}$ is used as effective unit weight. N_{ch} and N_{qh} can be obtained from the charts recommended by ALA (2001). N_c, N_q and N_γ are the soil capacity factors given by ALA (2001).

The part of the pipe, which is located far away from the pipe-fault crossing point, assumed to have only axial elongation and can be modeled using beam element supported by spring elements representing the pipe-soil interaction. The far end of the pipeline is assumed to have fixed boundary, as in this region the pipe experiences very small axial strains. To avoid the analysis error caused by the forced boundary, instead of using fixed boundary at the end of the beam segment of the pipeline, the equivalent boundary developed by Liu *et al.* (2004) was adopted in this study.

$$F_{(\Delta L)} = \sqrt{2EAt_u \Delta L} \tag{3}$$

3. GOVERNING EQUATIONS

The displacements and tractions within the soil around the pipe and also inside the pipe are obtained from the governing equation

$$\begin{bmatrix} \mathbf{M}_{pp} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{ii} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{ss} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_p \\ \ddot{\mathbf{u}}_i \\ \ddot{\mathbf{u}}_s \end{Bmatrix} + \begin{bmatrix} \mathbf{C}_{pp} & \mathbf{C}_{pi} & \mathbf{0} \\ \mathbf{C}_{ip} & \mathbf{C}_{ii} & \mathbf{C}_{is} \\ \mathbf{0} & \mathbf{C}_{si} & \mathbf{C}_{ss} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{u}}_p \\ \dot{\mathbf{u}}_i \\ \dot{\mathbf{u}}_s \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{pp} & \mathbf{K}_{pi} & \mathbf{0} \\ \mathbf{K}_{ip} & \mathbf{K}_{ii} & \mathbf{K}_{is} \\ \mathbf{0} & \mathbf{K}_{si} & \mathbf{K}_{ss} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_p \\ \mathbf{u}_i \\ \mathbf{u}_s \end{Bmatrix} = -\begin{bmatrix} \mathbf{M}_{pp} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{ii} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{ss} \end{bmatrix} \begin{Bmatrix} \mathbf{0} \\ \mathbf{0} \\ \ddot{\mathbf{u}}_g \end{Bmatrix} \tag{4}$$

Table 1. Bilinear soil-pipeline interaction springs parameters (ALA (2001))

Component	Ultimate soil force	Yield soil displacement
Axial (t-x curves)	$t_u = \pi D \alpha C + \pi D H \bar{\gamma} \frac{1+K_0}{2} \tan \delta$ $\alpha = 0.608 - 0.123 C - \frac{0.274}{C^2+1} + \frac{0.695}{C^3+1}$	$\Delta_t = 0.05 \quad cm$
Transverse Horizontal(p-y curves)	$p_u = N_{ch} CD + N_{qh} \bar{\gamma} HD$	$\Delta_p = 0.04(H + D/2) \le (0.1 - 0.15)D$
Transverse Vertical (q-z curves)	Upward Direction: $Q_u = \begin{vmatrix} N_{cv} C_u D & for\ Clays \\ N_{qv} \bar{\gamma} HD & for\ Sands \end{vmatrix}$ $N_{cv} = 2(H/D) \le 10$ $N_{qv} = (\frac{\varphi H}{44D}) \le N_q$ Downward Direction: $Q_d = N_c CD + N_q \bar{\gamma} HD + N_\gamma \gamma \frac{D^2}{2}$	Upward Direction: For Sands: $\Delta q_u = (0.01 - 0.02)H < 0.1D$ For Clays: $\Delta q_u = (0.1 - 0.2)H < 0.2D$ Downward Direction: For Sands: $\Delta q_u = 0.1D$ For Clays: $\Delta q_u = 0.2D$

where **M**, **C** and **K** are the mass, damping and stiffness matrices obtained by the finite-element formulation. The common nodes at the interface of the pipeline and soil are defined with "*i*"; the nodes of shell and beam elements representing the pipeline and the nodes within the soil around the pipeline and springs representing the soil in the side part are defined with "*p*" and "*s*", respectively. The mass, the stiffness and the damping at the interface nodes are the sum of the contribution from the pipeline (*p*) and the soil (*s*), and are given by

$$\mathbf{M}_{ii} = \mathbf{M}_{ii}^{p} + \mathbf{M}_{ii}^{s} \quad ; \mathbf{C}_{ii} = \mathbf{C}_{ii}^{p} + \mathbf{C}_{ii}^{s} \qquad \text{and} \qquad \mathbf{K}_{ii} = \mathbf{K}_{ii}^{p} + \mathbf{K}_{ii}^{s} \tag{5}$$

As it was noted the end point of the pipe crossing the fault and adjacent soil can experience very large amount of strains during the earthquake. Having this kind of local non-linearity and also geometric non-linearities of the pipe, solving implicit algorithm can be followed with some difficulties in terms of convergences. Therefore, in this study, the explicit approach as a computational efficient approach was adopted to solve the governing equations. The static geometric non-linear analysis under the static situation is essential as a starting point for the non-linear seismic analysis using explicit algorithm, taking the initial conditions at rest for the soil and accounting the initial induced strains to the pipeline due to surcharge loads. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment, *t*; The accelerations calculated at time t are used to advance the velocity solution to time $t + \frac{\Delta t}{2}$ and the displacement solution to time $t + \Delta t$ as

$$\{\dot{u}\}^{N}_{i+\frac{1}{2}} = \{\dot{u}\}^{N}_{i-\frac{1}{2}} + \frac{\Delta t_{i+1} + \Delta t_i}{2} \{\ddot{u}\}^{N}_{i} \tag{6}$$

$$\{u\}^{N}_{i+1} = \{u\}^{N}_{i} + \Delta t_{i+1} \{\dot{u}\}^{N}_{i+\frac{1}{2}} \tag{7}$$

The subscript *i* refers to the increment number in an explicit dynamics step. $\{u\}^N$ is the displacement vector, $\{\dot{u}\}^N$ is the velocity vector and $\{\ddot{u}\}^N$ is the acceleration vector, where *N* is the number of degrees of freedom in the model. The explicit integration rule is quite simple but by itself does not provide the computational efficiency associated with the explicit dynamics procedure. The accelerations at the beginning of the time increment using D'Alambert's principle are computed by

$$\{\ddot{u}\}_i^N = [M]^{-1\,NJ}(\{P\}_i^J - \{I\}_i^J) \tag{8}$$

where $[M]^{-1\,NJ}$ is the inverse mass matrix, $\{P\}_i^J$ is the applied load vector, and $\{I\}_i^J$ is the internal force vector including stiffness and damping forces and J is a numerator. A lumped mass matrix is used because its inverse is simple to compute and because the vector multiplication of the mass inverse by the inertial force requires only N operations. The explicit procedure requires no iterations and no tangent stiffness matrix. The internal force vector, $\{I\}_i^J$ is assembled from contributions from the individual elements such that a global stiffness matrix need not be formed. The explicit procedure integrates through time by using many small time increments. The central-difference operator is conditionally stable, and the stability limit for the operator with damping is given in terms of the highest frequency of the system as

$$\Delta t \le \frac{2}{\omega_{\max}}\left(\sqrt{1+\zeta_{\max}{}^2} - \zeta_{\max}\right) \tag{9}$$

where $\omega_{\max}$ is the highest natural frequency and $\zeta_{\max}$ is the fraction of critical damping in the mode with the highest frequency.

4. NUMERICAL RESULTS

To better understand the fracture mechanism of buried HDPE pipelines crossing the slip faults, using the approach explained in this study a series of non-linear analysis of soil-pipeline system were carried out. The effect of geometric characteristics of pipe, fault displacement, pipe-fault-crossing angle and fault slope angle on the response of buried HDPE pipeline crossing the reverse fault were considered. The pipe consisted in this study is the HDPE pipe with the outside diameter of 41 cm and wall thickness of 2.34 cm. The main characteristics of HDPE pipe material used in the analyses are given in Table 2, while its stress strain relation is shown in Figure 4.

A series of analyses were performed for the above parameters to study the effect of the slip fault movements on nonlinear response of the HDPE pipe. Five cases of pipe-fault crossing angle at 30, 65, 90, 115 and 150^0 are considered. For the assumed fault angle, the pipe were analyzed under different amount of fault displacements ranging from 0.1m to 1.2 m. the longitudinal and sectional deformations of the pipe for the crossing angle of 65^0 and fault movement equal to 1.2m are shown in Figure 5.

Figures 6 and 7 show the variation of the maximum and minimum axial strains (compression and tension) of the HDPE pipeline crossing the assumed fault angles versus the different fault displacements. As it was pointed out the section which contains the shell element with maximum and minimum strains is shown in Figure 5. As it can be noted from Figures 6 and 7, by increasing the fault movement incrementally, local buckling has been occurred. However, the axial strain increase is more pronounced for the bigger fault crossing angles. Figures 8 and 9 present variations of the induced axial strains resulting from fault displacement of 1.22 m and dip-fault crossing angles equal 65^0 and 115^0 along the pipe from the crossing point. The axial strains are shown for top, bottom, left spring line and right spring line of the pipe's cross section. The results show the crossing angle could be one of the most effective parameters on the distribution of axial strain along the pipe and around its cross section.

Table 2. HDPE pipe material characteristics

Mass density *(kg/m^3)*	Modulus of elasticity *(Mpa)*	Poisson's ratio
960	760	0.35

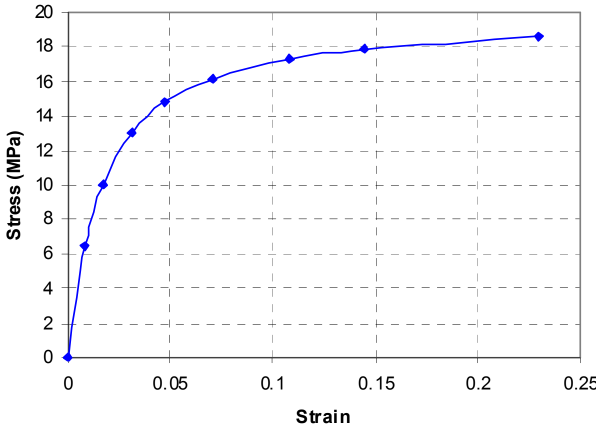

Figure 4. Stress-strain relationship for the HDPE Pipe material

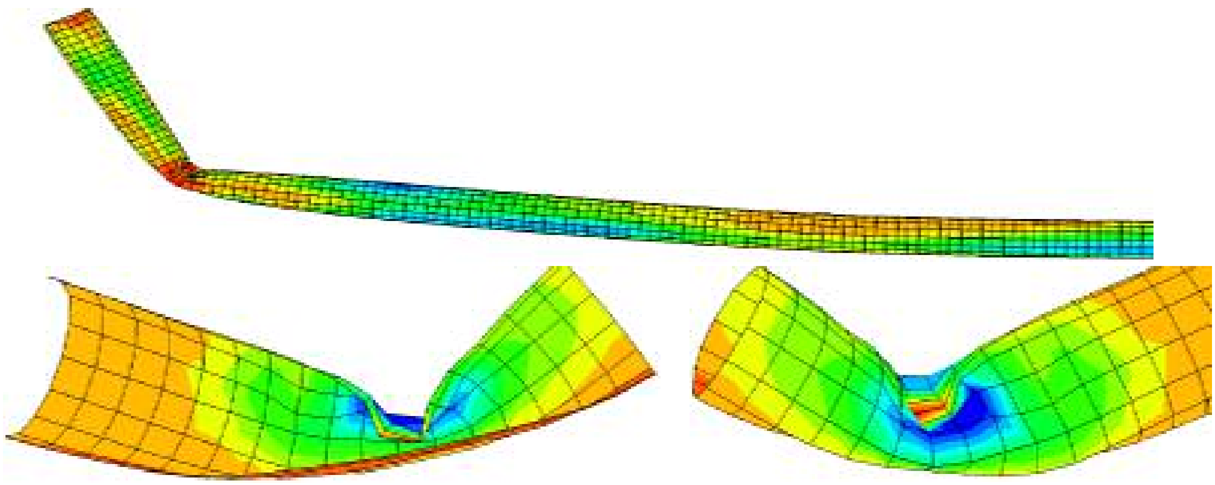

Figure 5. Local deformations of the pipe subject to fault movement

5. CONCLUSIONS

The new hybrid method for assessment of damages to buried pipelines under large three dimensional displacements, developed by the authors (2008), employed to study the nonlinear behavior of HDPE buried pipelines subject to permanent ground deformations. In this method, using the superposition principle, only the near-field soil around the pipe is modeled to take into account the nonlinear behavior of soil. Also the pipeline segment near fault should be modeled with plastic shell elements in order to consider the effect of local buckling and large section deformation. The effect of some important parameters such as crossing fault angle and fault displacement on the earthquake-resistance of HDPE buried pipelines was investigated. Finite element analyses were conducted to evaluate the local buckling in the pipe and non-linear soil-pipe interaction. It was concluded that by increasing the fault movement incrementally, local buckling could be occurred. Therefore, the response of buried HDPE pipelines to the oblique-slip fault movements is highly influenced by the fault movement. The crossing angle may also change the distribution of the axial strain along the pipe and around the pipe's section. The main buckling point is near the fault offset on the side with more rigid soil.

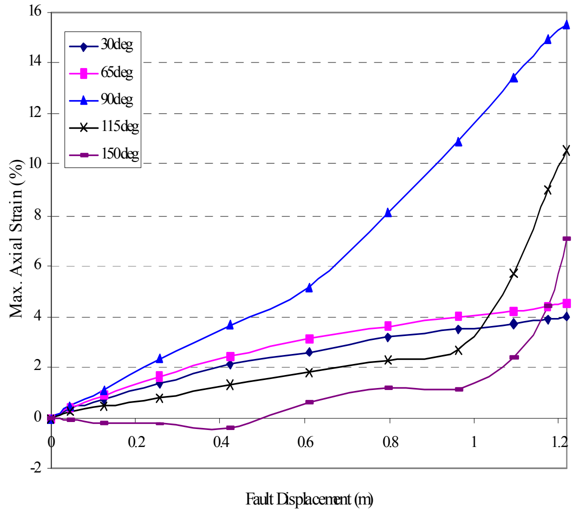

Figure 6. Variation of maximum axial strain with fault displacement

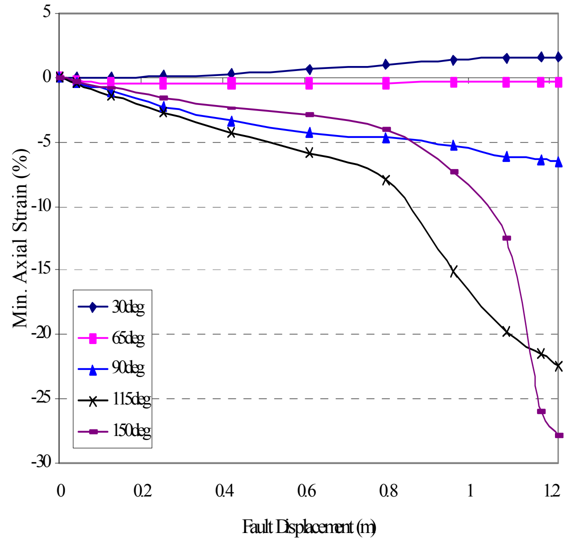

Figure 7. Variation of minimum axial strain with fault displacement

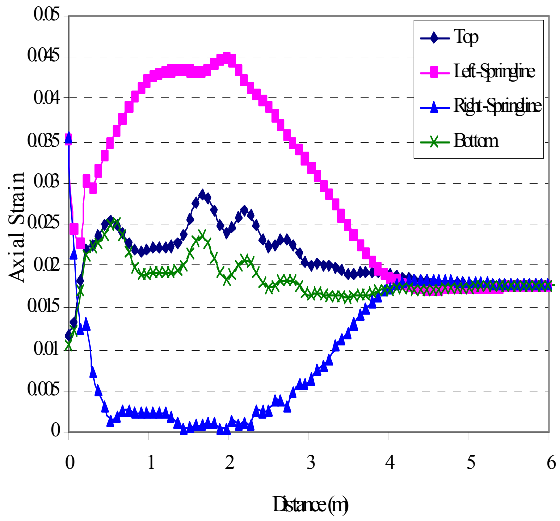

Figure 8. Variations of axial strains along the pipe for crossing angle 65^0

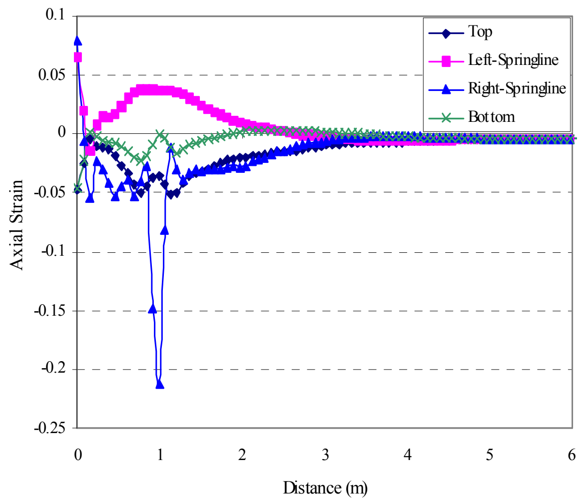

Figure 9. Variations of axial strains along the pipe for crossing angle 110^0

REFERENCES

American Lifelines Alliance – ASCE (2001). *Guidelines for the Design of Buried Steel Pipes*.

Ariman, T. and Lee B. J. (1992). Tension/bending behavior of buried pipelines subjected to fault movements in earthquake. *Proceeding 10th World Conference on Earthquake Engineering*, Madrid, 5423-5426.

Halabian, A.M., Hokmabadi, T., Hashemolhosseini, S.H. (2008), A new hybrid model for rigorous analysis of buried pipelines subjected to general fault movements accounting for material and geometric non-linearities. *Submitted to Journal of Soil Dynamics and Earthquake Engineering.*

Kennedy, R. P., Chow, A. W. and Williamson, R. A. (1977). Fault movement effects on buried oil pipeline. *Transportation Engineering Journal*, ASCE **103:5**, 617-633.

Liu, A. W., Takada, S. and Hu. Y. (2004). A shell model with an equivalent boundary for buried pipelines under the fault movement. *Proceeding of 13th World Conference on Earthquake Engineering*, Vancouver, No. 613.

Newmark, N. M. and Hall, W. J. (1975). Pipeline design to resist large fault displacement. *Proceeding of U. S. National Conference on Earthquake Engineering*, 2416-2425.

Takada, S., Hassani, N. and Fukuda, K. (2001). A new proposal for simplified design of buried steel pipes crossing active faults. *Earthquake Engineering and Structural Dynamics* **30**, 1243-1257.

Wang L., R., L., and Yeh Y. (1985). A refined seismic analysis and design of buried pipeline for fault movement. *Earthquake Engineering and Structural Dynamics* **13**, 75-96.