EVALUATION OF MODELING APPROACHES FOR BURIED PIPELINE SUBJECTED TO STRIKE–SLIP FAULT MOVEMENTS

F. Talebi(1), J. Kiyono(2)

(1) *PhD student, Graduate School of Engineering, Kyoto University, talebi.farzad.57z@st.kyoto-u.ac.jp*
(2) *Professor, Graduate School of Engineering, Kyoto University, kiyono.junji.5x@kyoto-u.ac.jp*

Abstract

The development of pipeline systems for the transport of gas, oil, and water is vital for human societies. Therefore, pipelines have been constructed around the world, even in high seismic risk zones such as fault zones, which are prone to permanent ground displacements owing to fault rupture, sloping ground failure, or transient ground displacements. These ground displacements cause enormous axial and bending forces and strains, which expose the pipeline to a high risk of rupture. Because of the fault displacements that are produced during the strong ground motion at the pipeline and fault intersection, the occurrence of many damages has been reported by various case studies. This study mainly has focused on the analysis approaches of the buried pipeline subjected to the strike-slip fault movement during strong ground deformation. There have been 2 main modeling approaches for the problem of buried pipeline subjected to the fault movement. In the first approach, soil-pipe interaction has been modeled by soil spring elements and their characteristics which is the most popular in design codes and in the second approach soil-pipe interaction is modeled by 3D solid soil elements and its contact characteristics with the pipeline which is more complex in the aspect of analyzing and mainly is used for research purposes. This study desired to evaluate the performance of the buried steel pipeline by both spring and solid elements and compare the force-displacement and stress-strain field responses of the buried pipeline for these finite element method-based modeling approaches. Since the problem of buried pipeline subjected to fault movement is a large deformation problem, pipeline material nonlinearity, soil-pipe interaction nonlinearity, and geometrical nonlinearity effects have been applied to the finite-element based analysis.

It has been found that in 3D-solid model, due to confinement effect of fault movement on soil around fault zone, soil stiffness increases locally around fault zone. And high curvature zone for pipeline modeled with 3D-solid approach is shorter than beam approach, because of local stiffening of soil at 3D-solid model. Stress and strain responses of buried pipeline before occurrence of local buckling in 3D-Solid model, are higher than beam model. And after occurrence of local buckling in 3D-solid model, pipeline axial strain on in beam model drastically increases, which can represent pipeline is damaged. Evidently, in 3D-solid model damages to pipeline can be observed and moreover it has found that in case of beam model strain responses of pipeline can be a good criterion about damage evaluation of the pipeline.

Keywords: strike-slip fault, 3D finite-element-method, buried pipeline, nonlinear soil-pipe interaction, soil springs, FEM.

1. Introduction

Pipeline network has been spread all over the world to provide the vital needs of human societies (e.g. for transmission of gas, water, oil, wastewater, and chemical products). Therefore, there are a lot of pipelines crossing the seismic hazardous areas such as fault zones [1].

Many damages to the buried pipelines have been reported during earthquakes [2-12] and more recently 2017 Sarpole-Zahab earthquake [13]. During an earthquake, buried pipelines are damaged owing to permanent ground deformation (PGD) as fault movements at fault intersection and very limited pipelines are damaged due to wave propagations [14, 15].

Damage to pipelines not only vastly influences the human societies after earthquake because of the stopping of energy and water networks, but also results in environmental hazards that may be owing to the leakage of ecologically dangerous materials (e.g., chemicals, natural gas, fuel, or liquid waste). Therefore, evaluation of the buried pipeline at earthquake fault crossing is a key problem in engineering design [1,16].

Nowadays, by improvement of processors and finite element method (FEM), FEM-based analysis is applicable solutions for the problem of the buried pipeline crossing active fault. FEM has been recently used for verification of analytical solutions and evaluation of the buried pipeline performance for assessment of criteria such as local buckling, ovalization and tensile damages [17-29]. There exist several FEM-based pieces of research, with different modeling approaches. In 2015, Vazouras et al. modeled a hybrid (shell and solid elements beside equivalent springs) pipeline buried in solid soil, by adding the analytically extracted equivalent axial springs of soil and pipeline, they shortened the size of needed FEM model with the same accuracy of the full FEM model [27]. Liu et al., modeled buried pipeline at reverse fault crossing using FE commercial code ABAQUS which pipe was modeled as shell elements and soil-pipe interaction was modeled as non-linear soil springs. They modeled pipe as shell elements and soil-pipe interaction was modeled as non-linear soil springs. besides, they had an investigation on buckling of buried pipeline influenced by yield strength and strain hardening parameters [30]. Demirci et al. studied the behavior of a continuous buried pipeline subjected to reverse fault motion by a new experimental centrifuge modeling of pipeline crossing reverse fault. Which used 3D FEM analyses besides for more details. A review of the FEM-based researches in the literature shows that for modeling of pipe various modeling approaches including beam, shell, hybrid (beam+shell), new hybrid (spring+shell) and soil continuum-shell model are used to evaluate pipeline performance against earthquake fault movement.

Simulation of the buried pipeline and surrounding soil respectively by shell elements and solid elements for a 3D FEM-based analysis is the most detailed approach for modeling the pipeline at fault crossing problem. which can produce the most realistic performance of buried pipeline including the local buckling, ovalization, and tensile damages. Because of the modeling complexity, this method mostly is used for research purposes which in this study we call it 3D-solid modeling approach. It is common to use the beam element for modeling of pipe and spring elements for modeling of soil-pipe interactions for design and even research purposes which is simpler than the 3D-sold modeling approach and in this study, we call it beam modeling approach. Both over mentioned FEM models include the geometrical nonlinearity effects and material nonlinearity effects.

In this study, it is intended to have a FEM-based investigation on the performance of buried pipeline at strike-slip fault crossing through 3D-solid and beam modeling approaches. Firstly, force-displacement curvatures of equivariant soil springs in axial, transverse and vertical directions are extracted through the FEM-based 3D-solid model soil box. Secondly, response of buried pipeline modeled by 3D-soild approach is compared versus beam approach to evaluate the capability range of the FEM modeling approaches to understand the performance of pipeline for through both modeling approaches and compare the damage related parameters.

2. AXIAL AND TRANSVERSE SOIL SPRINGS

To study the axial and transverse soil pipe interaction two 3D FEM models have been created. The first model is an axial pipe pull-out test of the pipeline for extracting the of the axial soil-pipe interaction force-displacement curve. And the Second model is a transverse pipe sliding test to extract the transverse soil-pipe interaction force-displacement curve.

Both of the analysis results are obtained for an X65 steel 36" pipeline with an outer diameter of D=0.914m, thickness t=0.0095mYoug's Modulus of E=21Tpa, Poisson's ratio of $\nu = 0.3$ and density of 7850 kg/m^3. the young's module for pipe material has been assumed 100 times stiffer than X65 steel to decease the pipeline deformation effect on soil-pipe interaction evaluation. The pipeline is assumed to be buried in undrained clay. The soil has density of 2000 kg/m^3, Young's Modulus of $E_s = 25\ MPa$, Poisson's ratio of $\nu_s = 0.5$, cohesion of $c = 50\ kPa$, friction angle of $\phi = 0°$. Same with real cases, it has assumed that the buried pipeline has sounded by a thin layer of sand. Thus, frictional soil-pipe interaction has been anticipated. The soil box is modeled in multi-purpose finite element program ABAQUS [31] in dimensions of 20 m × 10 m × 5 m.

Soil material is defined as elastic-perfectly plastic Mohr-coulomb constitutive model. Pipe elements are 4-node shell S4R element type and soil elements are 8-node linear brick, reduced integration with hourglass control C3D8R element type. Geometrical nonlinearity effect has been taken in to account for all the analyses by Nlgeom method, which is conducted by finite element program of ABAQUS.

2.1 3D FEM analyses results

2.1.1 Axial pull-out test analyses

To evaluate the axial soil pipe interaction, three 3D FEM cases for axial pull-out tests has been created. Validity of the FEM analysis results has been highly verified versus Vazouras et al. (2015) [27] Pull-out test results as illustrated in Fig. 1. Axial force-displacement curve of unit length of pipeline for the pull-out test results in three cases with friction coefficients of 0.2, 0.3 and 0.4 is demonstrated in Fig.2, which illustrates the axial soil-pipe interaction curves as elastic perfectly plastic curves for all the cases. Therefore, the pipeline has started to slide after passing the yielding displacement of each case.

2.1.2 Transverse sliding test analyses

After verification of the soil-pipe contact results for axial soil-pipe interaction, FEM model is extended to the transverse sliding test for reproduction of the transverse soil-pipe interaction curve.

From Fig. 3, the transverse soil-pipe interaction curves for cases with friction coefficients of 0.2, 0.3 and 0.4 in elastic range are almost same and have almost equal stiffness. And The variation of transverse soil-pipe

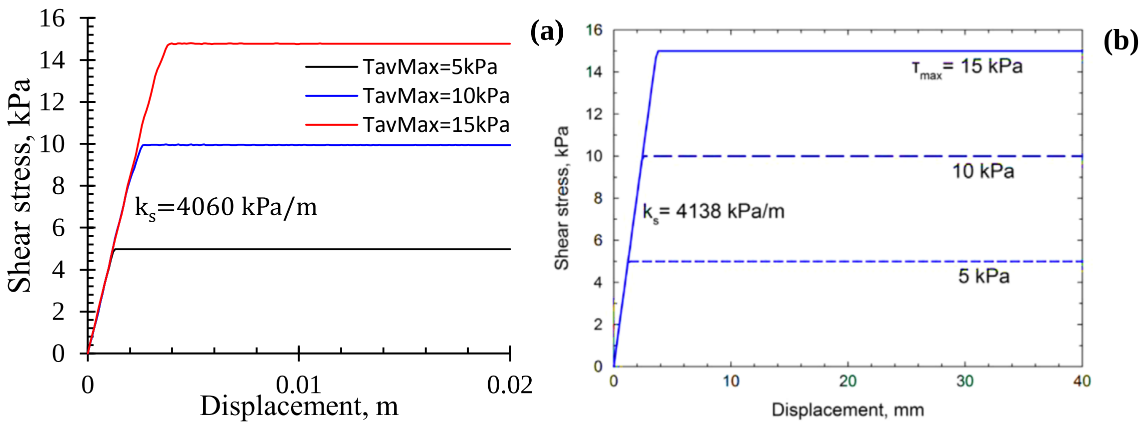

Fig. 1 – stress–strain relationship at the pipe–soil interface for friction coefficients of 0.2, 0.3 and 0.4: (a) this study. (b) Vazouras et al. (2015) [27].

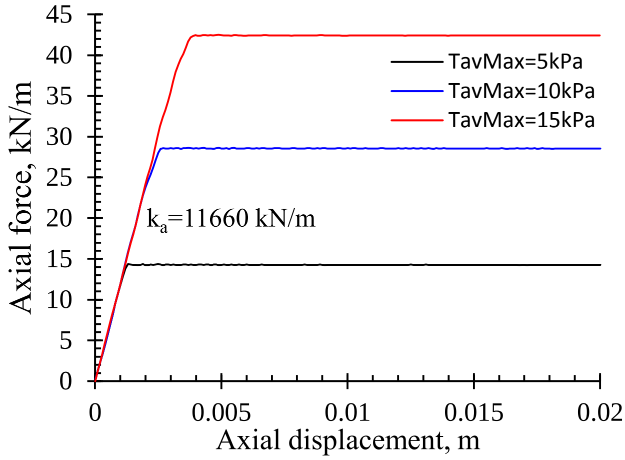

Fig. 2 – Axial soil pipe interaction force-displacement relationship at the pipe–soil interface for friction coefficients of 0.2, 0.3 and 0.4.

interaction curves for mentioned cases is not so much. By little difference, the case with 0.4 friction coefficient case has the highest transverse force and 0.2 case has the lowest. However, transverse soil-pipe interaction curves for all the cases are almost same.

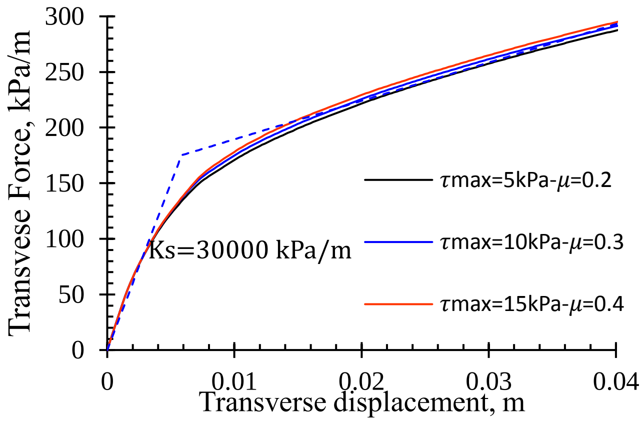

Fig. 3 – Transverse soil-pipe interactions force displacement relationship for friction coefficients of 0.2, 0.3 and 0.4.

3. MODELING OF PIPELINE AT STREK-SLIP FAULT CROSSING

To study on the FEM modeling approaches effect for problem of buried pipeline at crossing with strike-slip fault, same case has been modeled by 3D-solid and beam modeling approaches. Both of the analysis results are obtained for an X65 steel 36” pipeline with outer diameter of D=0.914m, thickness t=0.0095mYoug’s Modulus of E=210Gpa, Poisson’s ratio of $\nu = 0.3$ and density of 7850 kg/m^3. Pipeline’s steel material plastic properties are modeled based on table 1. The pipeline is assumed to be buried in undrained clay. The soil has density of 2000 kg/m^3, Young’s Modulus of $E_s = 25$ MPa, Poisson’s ratio of $\nu_s = 0.5$, cohesion of $c =$ 50 kPa, friction angle of $\phi = 0°$. Same with real cases, it has assumed that the buried pipeline has sounded by a thin layer of sand. Thus, frictional soil-pipe interaction has been anticipated. In this model Buried pipeline is subjected to a 60° strike-slip fault movement.

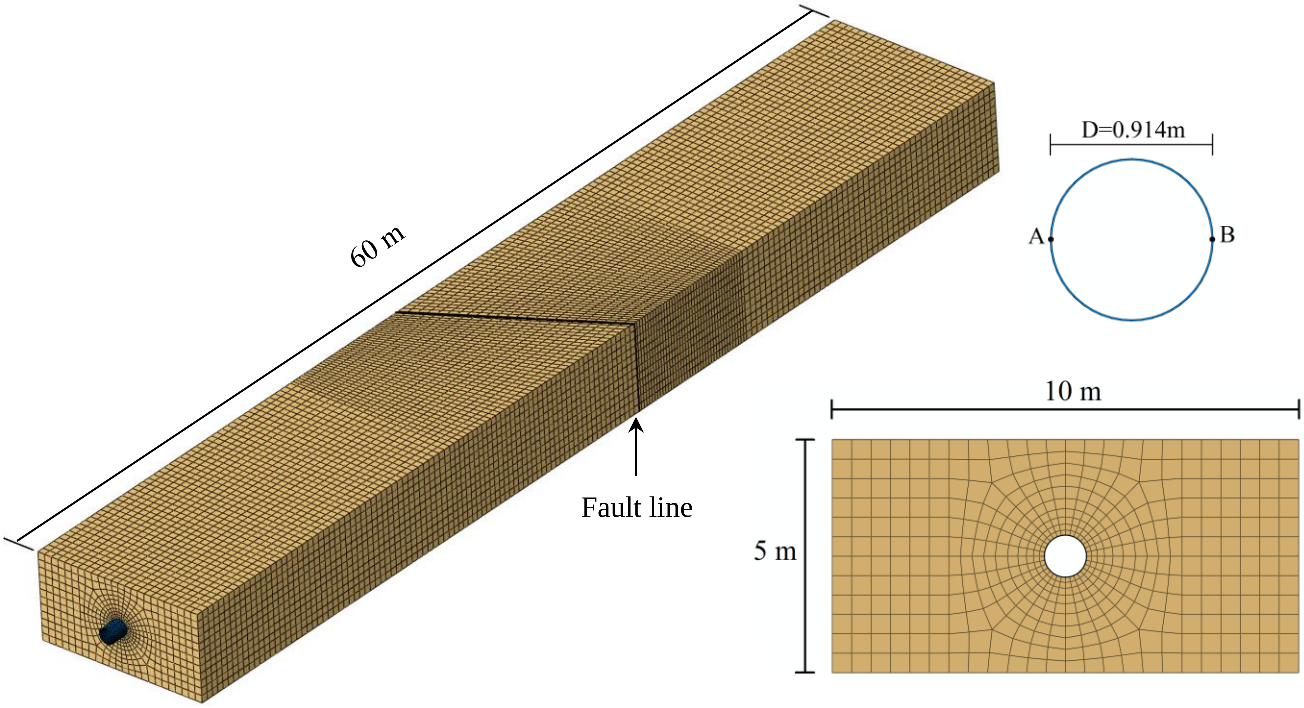

Fig. 4 – 3D-soild model for buried steel pipeline subjected to 60º strike-slip fault movement. Points A and B are springlines of the pipe.

For the 3D-solid model, soil box is modeled in multi-purpose finite element program ABAQUS in dimensions of 60 m × 10 m × 5 m as illustrated in Fig. 4. Soil material is defined as elastic-perfectly plastic Mohr-coulomb constitutive model. Pipe elements are 4-node shell S4R element type and soil elements are 8-node linear brick, reduced integration with hourglass control C3D8R element type. Friction coefficient of 0.3 is assumed for contact modeling, which is equivalent with the demonstrated soil to TavMax= 10kpa soil at previous section. the Geometrical nonlinearity effect has been taken in to account for all the analyses by Nlgeom method, which is conducted by finite element program of ABAQUS. The fault movements and boundary conditions all are applied to the soil box's faces.

Table 1 –API5L-X65 steel material of pipeline

Young modulus (E)	210 GPa
Yielding stress (σ_y)	490 MPa
Yielding strain (ε_y)	0.233%
Failure stress (σ_f)	531MPa
Failure strain (ε_f)	4.0%

For beam model, all the properties are same as the 3D-solid model. A 60 m pipeline made of API5L-X65 steel material is modeled through Abaqus (Fig. 5). For pipe elements in beam model B31 elements, for rigid bodies RB3D2 elements and for soil CONN3D2 elements are used. Soil-pipe interaction in beam model is modeled through, equivalent nonlinear soil springs in axial, transverse (horizontal) and vertical directions extracted from FEM simulations of section 2 for case of 0.3 friction coefficient and TavMax = 10kPa, which are shown in Fig. 6. The fault displacement components are applied to the ends of the rigid elements at the end of the soil spring elements and the pipeline is free to move on axial direction in both ends. The geometrical nonlinearity effect also same as the 3D-soild model has been taken in to account for all the analyses by the Nlgeom method.

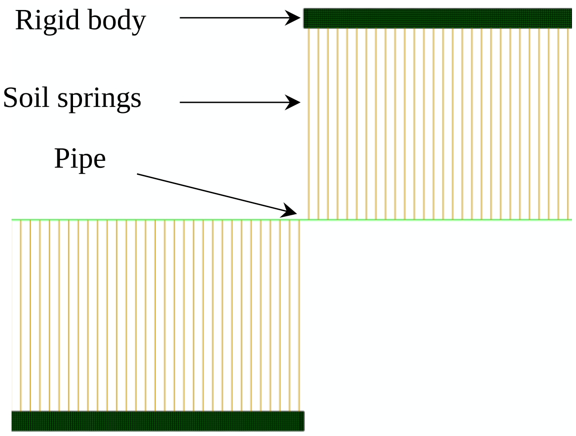

Fig. 5 – A part of beam model for buried steel pipeline subjected to 60º strike-slip fault movement with length of 60 m.

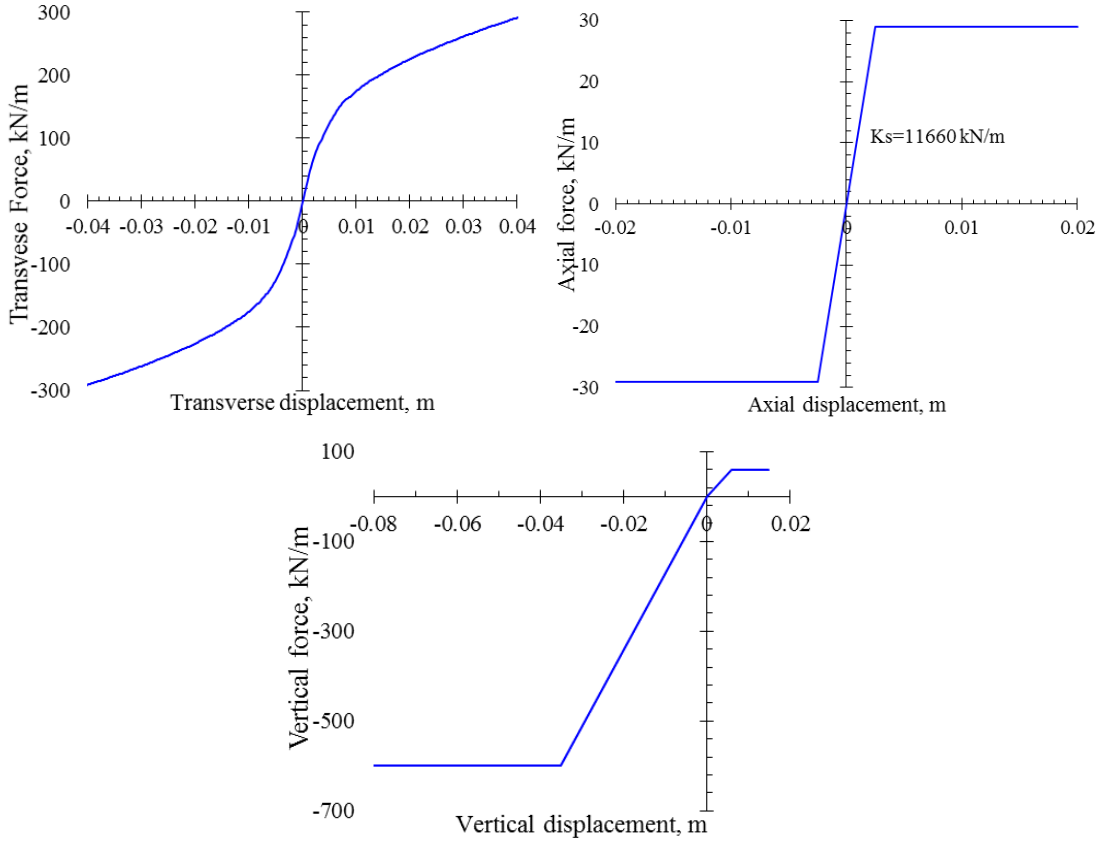

Fig. 6 – Equivalent nonlinear soil springs for beam model.

4. RESULTS AND DISCUSSION

Performance of buried pipeline at 60º strike-slip fault crossing has been evaluated through FEM based beam and 3D-solid models' analysis. Fig. 7 shows the mises stress outputs of 3D-solid buried pipeline deformation and it's buckling for each of fault movement cases. Regarding Fig. 8, transverse displacement behavior of buried pipeline for 3D- solid and beam models are in good agreement. However, around fault zone, there is a gap between 3Dsolid and beam model and high curvature zone for the 3D-solid model is shorter and it shows that in the 3D-solid model, soil stiffness at fault crossing zone has got locally increased. The reason for this

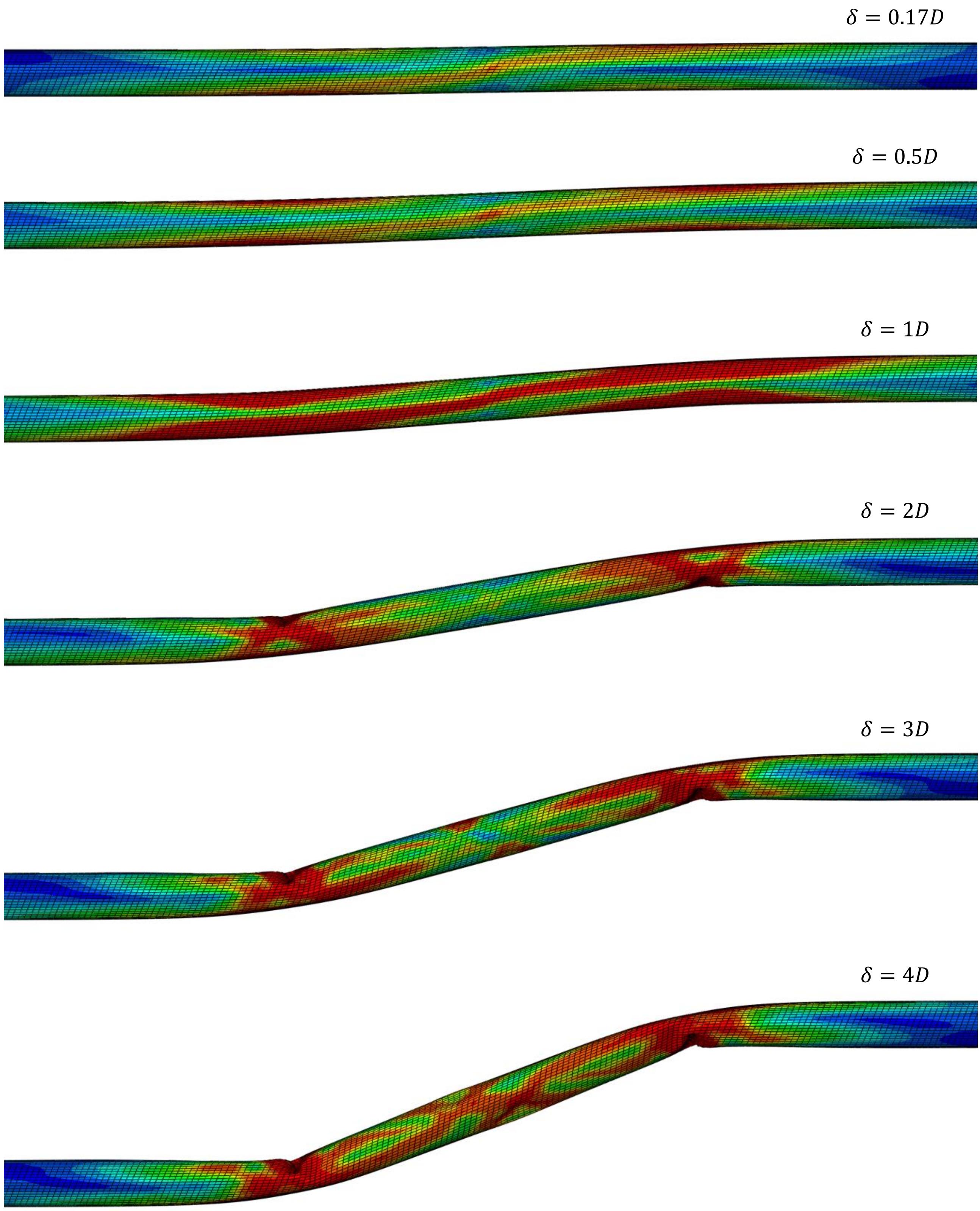

Fig. 7 – Mises stress and buckling status of buried pipeline at 60° strike-slip fault crossing with 0.17D, 0.5D, 1D, 2D, 3D and 4D fault movements.

local stiffening of soil is the confinement of soil which appeared due to the Faultline movement at fault crossing zone.

Additionally, because of buckling of the pipeline at 3D-solid model, transverse displacement of pipeline at further parts than fault line is less than beam model results.

Stress and strain outputs are shown for left and right springlines (A and B points at Fig. 4) for the pipeline at one side of fault due to symmetry of the problem. The left springline side is in tensile and the right springline side is in compression owing to the bending of pipeline. As shown in Figs 9–12, the distance between maximum tensile/compression stress and strain of buried pipeline and Faultline for the case of 3D-solid model is shorter than beam model. This is again because of the shortening of the high curvature zone due to the local stiffening of soil at 3D-solid model.

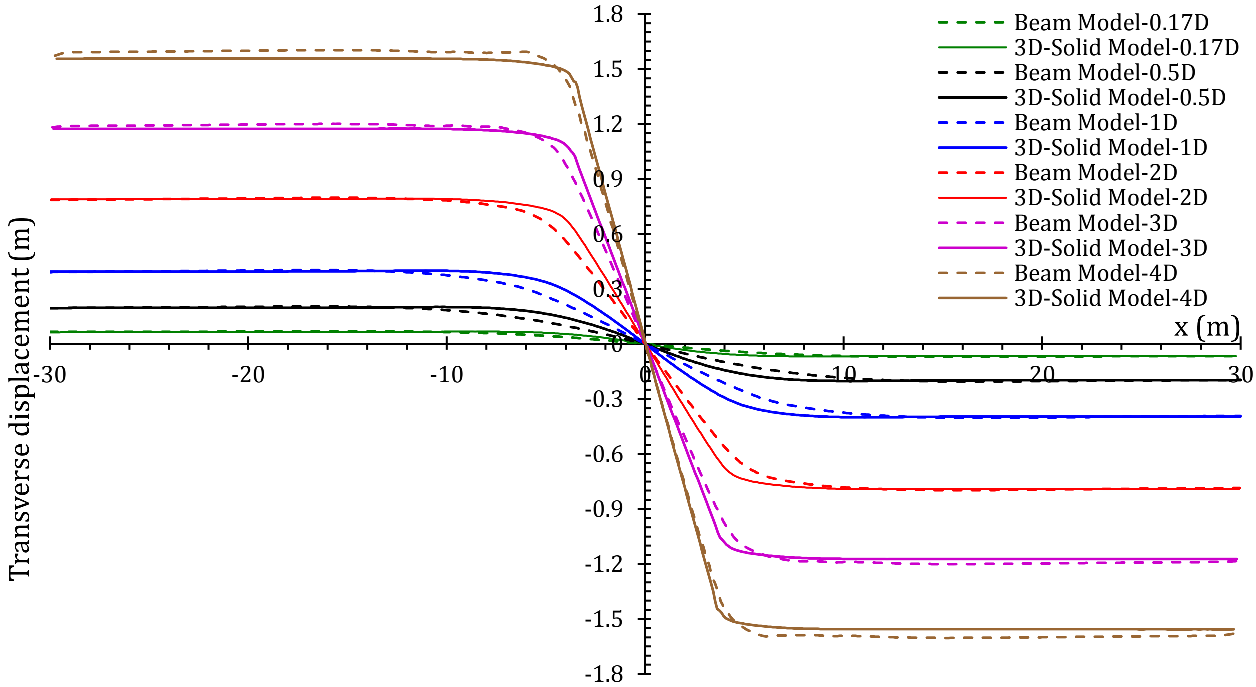

Fig. 8 – Transverse displacement of pipeline 3D-solid model vs Beam model at strike-slip fault crossing on neutral axis of pipe section.

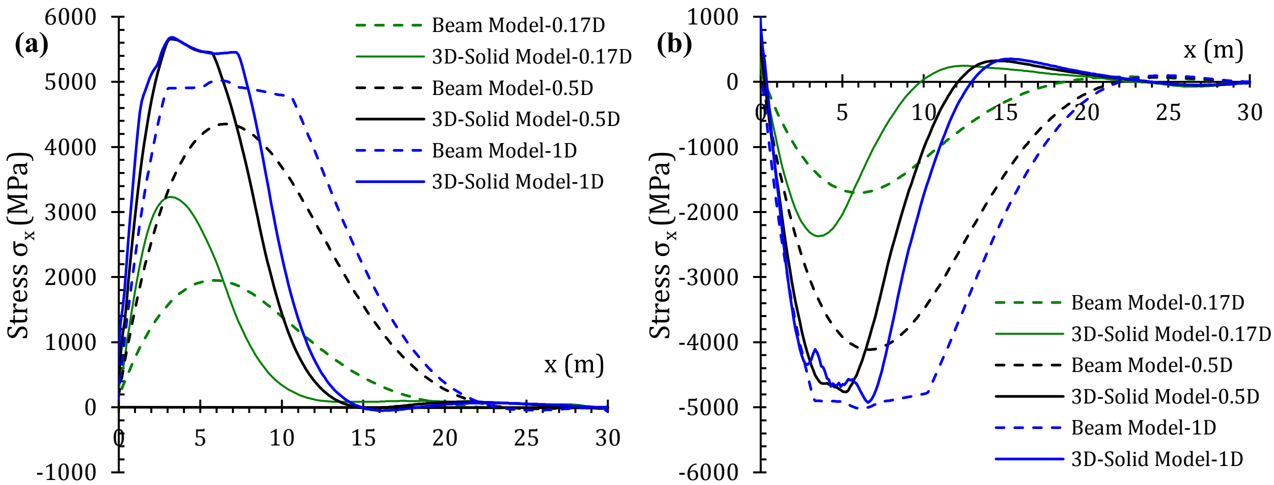

Fig. 9 – Maximum axial stresses of buried pipeline subjected to 60° strike-slip fault 0.17D to 1D movement, 3D-solid model vs Beam model: (a) Left springline (b) Right springline.

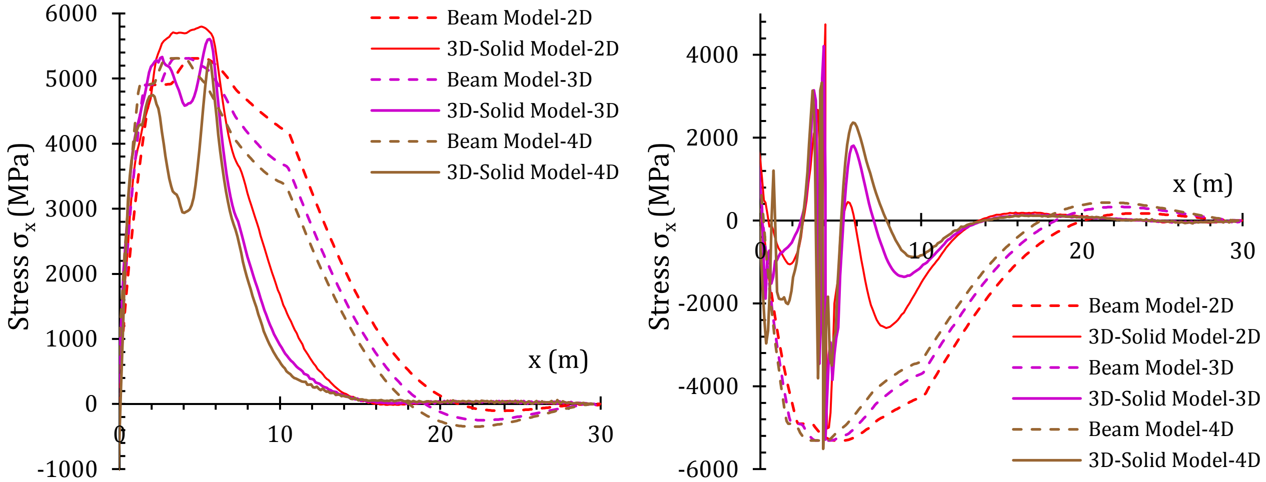

Fig. 10 – Maximum axial stresses of buried pipeline subjected to 60° strike-slip fault 2D to 4D movement, 3D-solid model vs Beam model: (a) Left springline (b) Right springline.

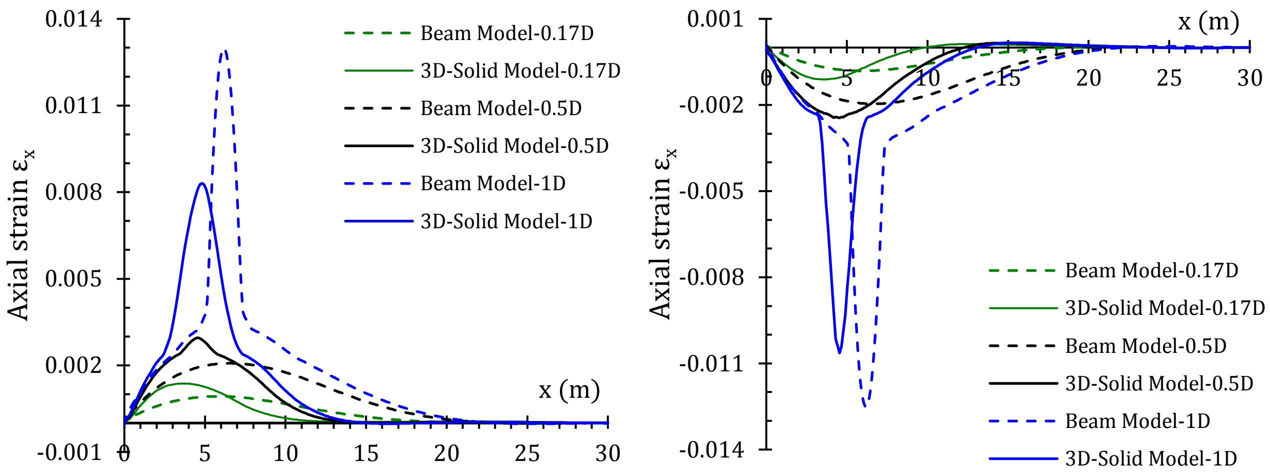

Fig. 11 – Maximum axial strain of buried pipeline subjected to 60° strike-slip fault 0.17D to 1D movement, 3D-solid model vs Beam model: (a) Left springline (b) Right springline.

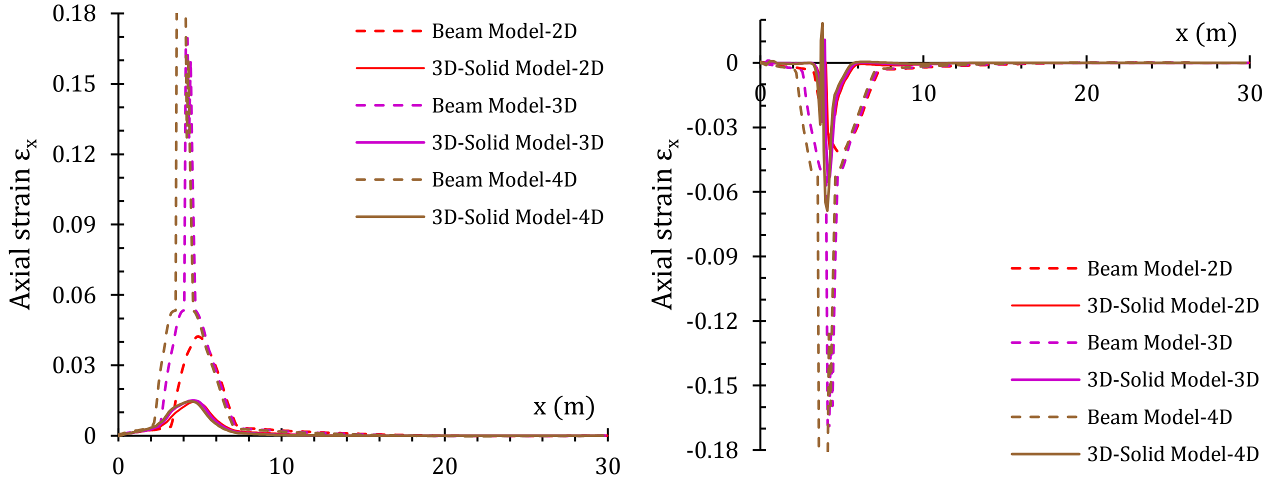

Fig. 12 – Maximum axial strain of buried pipeline subjected to 60° strike-slip fault 2D to 4D movement, 3D-solid model vs Beam model: (a) Left springline (b) Right springline.

Because of local stiffening of soil material around the fault zone at the 3D-solid model, pipeline experiences higher stresses at elastic zone and maximum stress of pipeline reach yielding stress earlier than beam model. After yielding of the pipeline at local buckling zones cases with deformation over 2D, because of buckling of pipeline, stress response of pipeline is decreasing at local buckling zones and are chaotic. Strain and stress responses of buried pipeline before appearing of local buckling in the 3D-solid model, are similar to the beam model. However, in 3D-solid model after buckling, stress and strain responses are lower than beam model and tensile strain response in cases over 2D fault movement (with local buckling) do not change by increasing of fault movement; though the compression strains are increasing and are very chaotic (because of local buckling).

Indeed, in beam models, in cases over 2D fault movement, strain responses are significantly high and can represent a damaged pipeline possibility correspondingly.

5. CONCLUSIONS

In this study, 6 cases of buried pipeline subjected to 60º strike-slip fault have been evaluated through beam and 3D-solid modeling approaches. Finally, it has been found that:

1- In the 3D-solid model, due to the confinement effect of fault movement on soil around fault zone, soil stiffness increases locally around fault zone.

2- High curvature zone for pipeline modeled with 3D-solid approach is shorter than beam approach, because of local stiffening of soil at 3D-solid model.

3- Stress and strain responses of buried pipeline before occurrence of local buckling in 3D-Solid model, are higher than beam model.

4- After occurrence of local buckling in the 3D-solid model, pipeline strain on springline in beam model drastically increases, which can represent pipeline is damaged.

5- In The 3D-solid model damages to pipeline can be observed and in case of beam model strain responses of pipeline can be a good criterion about damage evaluation of the pipeline.

6- Creating of the 3D-solid model is much complex than the beam model and it is easy to make mistake in modeling for an amateur analyst, besides modeling and analyzing take much more time and cost. However, it can reproduce much detailed results and cover all phenomenon.

6. REFERENCES

[1] O’Rourke, M. J., Liu, X. (1999). “Response of buried pipelines subject to earthquake effects,” Monograph Series, Multidisciplinary Center for Earthquake Engineering Research (MCEER).

[2] O’Rourke, T. D., Lane, P. A. (1989). “Liquefaction hazards and their effects on buried pipelines,” Technical report NCEER-89-0007, National Center for Earthquake Engineering Research, Buffalo, NY, USA.

[3] O’Rourke, T. D., Palmer, M.C. (1996). “Earthquake performance of gas transmission pipelines,” Earthquake Spectra 20(3), 493–527.

[4] Earthquake Engineering Research Institute (1999). “Kocaeli, Turkey Earthquake of August 17,” EERI Special Earthquake Report.

[5] Uzarski, J., Arnold, C. (2001). “Chi-Chi, Taiwan, earthquake of September 21, 1999 reconnaissance Report,” Earthquake Spectra 17 (Suppl. A).

[6] Jennings, P. C., (1971). “Engineering features of the San Fernando earthquake February 9, 1971,” California Institute of Technology Report, EERL, 71–02.

[7] MaCaffrey, M. A., O’Rourke, T. D. (1983). “Buried pipeline response to reverse faulting during the 1971 San Fernando Earthquake,” ASME, PVP 77, 151–9.

[8] Desmond, T. P., Power, M. S., Taylor, C. L., Lau, R. W. (1995). "Behavior of large-diameter pipeline at fault crossings," ASCE, TCLEE (6), 296–303.

[9] Nakata, T., Hasuda, K. (1995). "Active fault I 1995 Hyogoken Nanbu earthquake," Kagaku 65, 127–42.

[10] Takada, S., Nakayama M., Ueno J., Tajima C. (1999). "Report on Taiwan Earthquake," RCUSS, Earthquake Laboratory of Kobe University, 2–9.

[11] Kazama, M., Noda, T. (2012). "Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage)," Journal of Soils and Foundations 52(5), 780–792.

[12] Wham, B. P, Dashti, S., Franke, K., Kayen, R., Oettle, N. K. (2017). "Water supply damage caused by the 2016 Kumamoto Earthquake," Journal of Lowland Technology International 19(3), 165-174.

[13] Miyajima, M., Fallahi, A., Ikemoto, T., Samaei, M., Karimzadeh, S., Setiawan, H., Talebi, F., Karashi J. (2018). "Site Investigation of the Sarpole-Zahab Earthquake, Mw 7.3 in SW Iran of November 12, 2017," JSCE Journal of Disaster FactSheets.

[14] Ariman, T., Muleski, G. E. (1981). "A review of the response of buried pipelines under seismic excitations." Earthquake Engineering and Structural Dynamics 9, 133–51.

[15] Liang, J., Sun, S. [2000] "Site effects on seismic behavior of pipelines: a review," ASME Journal of Pressure Vessel Technology 122(4), 469–75.

[16] Manolis, G. D., Beskos, D. E. (1997). "Underground and lifeline structures," in Computer analysis and design of earthquake resistant structures: a handbook, ed. Beskos, D. E and Anagnostopoulos, S.A. (CMP, Southampton, United Kingdom), 775–837.

[17] Karamitros, D., Bouckovalas, G., Kouretzis, G. (2007). "Stress analysis of buried steel pipelines at strike-slip fault crossings," Soil Dynamics and Earthquake Engineering 27, 200–11.

[18] Trifonov, O. V., Cherniy, V. P. (2010). "A semi-analytical approach to a nonlinear stress–strain analysis of buried steel pipelines crossing active faults," Soil Dynamics and Earthquake Engineering 30(11), 1298–308.

[19] Karamitros, D. K., Bouckovalas, G. D., Kouretzis G. P., Gkesouli V. (2011). "An analytical method for strength verification of buried steel pipelines at normal fault crossings," Soil Dynamics and Earthquake Engineering (13), 1452-1464.

[20] Trifonov, O. V., Cherniy V. P. (2012). "Elastoplastic stress-strain analysis of buried steel pipelines subjected to fault displacements with account for service loads," Soil Dyn Earthq Eng 33,54–62.

[21] Lim, M. L., Kim, M. K., Kim, T. W., Jang, J. W. (2001). "The behavior analysis of buried pipeline considering longitudinal permanent ground deformation," In pipeline 2001: advances in pipelines engineering & construction (San Diego, California), vol. 3, 107. ASCE. https://doi.org/10.1061/40574(2001)3

[22] O'Rourke, M. J., Vikram, G., Abdoun, T. (2003). "Centrifuge modeling of buried pipelines," In: Proceedings of the Sixth U.S. conference and workshop on lifeline earthquake engineering, August 10–13, 2003, Long Beach, CA. pp. 757–768.

[23] Sakanoue, T., Yoshizaki, K. (2004). "A study on eartquake-resistant design for buried pipeline using lightweight backfill," In: Proceedings of the 13th world conference on earthquake engineering, Vancouver, B.C., Canada, August 1-6, Paper No.2389.

[24] Takada, S., Hassani, N., Fukuda, K. (2001). "A new proposal for simplified design of buried steel pipes crossing active faults," Earthq Eng Struct Dyn ;30:1243–57.

[25] Vazouras, P., Karamanos, S. A., Dakoulas, P. (2010). "Finite element analysis of buried steel pipelines under strike-slip fault displacement," Soil Dyn Earthq Eng ;30:1361–76.

[26] Vazouras, P., Karamanos, S. A., Dakoulas, P. (2012). "Mechanical behavior of buried steel pipes crossing active strike-slip fault," S, Soil Dyn Earthq Eng;41:164–80.

[27] Vazouras, P., Dakoulas, P., Karamanos, S. A. (2015). "Pipe–soil interaction and pipeline performance under strike–slip fault movements," Soil Dyn Earthq Eng ;72:48–65.

[28] Zhang, L., Zhao, X., Yan, X., Yang, X. (2016). "A new finite element model of buried steel pipelines crossing strike-

slip faults considering equivalent boundary springs," Eng Struct;123:30–44.

[29] Demirci, H. E., Bhattacharya, S., Karamitros, D., Alexander, N. (2018) "Experimental and numerical modelling of buried pipelines crossing reverse faults," Soil Dyn Earthq Eng ;114:198–214.

[30] Liu, X., Zhang, H., Li, M., Xia, M., Zheng, W., Wu, K., Han, Y. (2016). "Effects of steel properties on the local buckling response of high strength pipelines subjected to reverse faulting," J Nat Gas Sci Eng ;33:378–87.

[31] ABAQUS/CAE 2017. Dassault Systems Simulia Corp, documentation of 2017 release.

