Buried Pipeline Response Analysis to Reverse-Slip Fault Displacements

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SUMMARY:
Different fault displacement patterns like strike-slip, normal-slip, reverse-slip and oblique-slip may occur. Most of the efforts in the analysis of pipelines subjected to fault motion have been mainly focused on strike-slip and normal-slip faults, but only a few limited studies are related to reverse-slip faults' pattern. Present paper investigates the structural response of buried pipelines crossing reverse-slip faults under various fault displacement quantities in different soil conditions and faulting plane angles. Finite element models of the pipeline are established considering internal pressure and soil-pipe interaction. Typical steel material for oil and gas pipeline applications, API-5L-X65, and three different "diameter to thickness" ratios are assumed for material and geometrical properties of the pipeline. Large strains and displacements, buckling and nonlinear material behaviour are considered in these analyses. Four different soil conditions categorized as cohesive and non-cohesive types as well as three different intersection angles between the faulting plane and the pipeline are investigated in the analysis. Finally, plastic strain locations along the pipeline, critical fault displacements due to the local buckling or rupture of the pipe wall are obtained by numerical analyses for different cases. Some useful guidelines based on the obtained results are presented to improve the response of the pipelines crossing reverse-slip faults.

Keywords: Buried pipeline, Reverse-slip fault, Soil-pipe interaction, Finite element, Local buckling

1. INTRODUCTION

Buried pipelines are generally used to transport water, gas and oil. They are called as lifelines because they carry essential materials to support human life. Due to the importance of lifelines survivability, it is very important to study the threats to them so that to mitigate damages. Among various kinds of natural hazards, earthquakes are the most serious threats for lifelines serviceability. They can damage lifelines through faulting, permanent ground deformation (PGD) and deformations due to seismic waves propagation. Faulting can affect pipelines in various ways and cause severe damages depending on faulting movement direction [1].

For the purpose of explanations, Principal types of the faulting movement include strike-slip, normal-slip and reverse slip. Various faults are most commonly classified based on the direction of relative slip. Portion of the ground which remains stationary during the slipping is referred to as foot wall; and the other portion that slips over the foot wall is referred to as hanging wall. In strike-slip fault, the predominant motion is horizontal which deforms a continuous pipe primarily in tension or compression depending on the pipe-fault intersection angle. In the normal and reverse faults the predominant ground displacement is vertical. When the overhanging side of the fault moves downwards, the fault is normal and primarily causes tension and bending in horizontal pipe. When the overhanging side of the fault moves upwards, the fault is reverse and primarily causes compression and bending in horizontal pipe. An oblique fault is a combination of strike-slip and normal or reverse fault [2,3,4].

Response analyses of buried pipelines have been investigated by different methods in the past. Many closed form solutions to the pipe-soil interaction problem based on "beam on elastic foundation" have been proposed. Some of these studies were accomplished by using analytical methods. Since the response of the pipe to faulting depends on several factors, to facilitate the analysis process, some simplified assumptions have been used by analytical methods which consequently led to low accuracy of the estimated responses. Some other researchers have also studied these effects via numerical methods. In these studies, some parameters such as soil-pipe interaction which considerably influence the responses have not taken into account [3].

In 1975, Newmark and Hall developed simplified analysis methods for the fault crossing problem. They considered a model in which a pipeline intersects a right-lateral strike-slip fault at an angle such that the pipe is primarily subjected to tensile strain. In 1977 Kennedy et al. extended the work by Newmark and Hall, by considering the effects of lateral interaction at the pipe-soil interface in their analysis and the influence of large axial strains on the bending stiffness of the pipe. Subsequent to the Kennedy et al. work, Wang and Yeh in 1985 suggested modifications to the closed-form analytical model by employing the theory of "beams on elastic foundations" to represent the pipeline-soil system. In 2007 Karamitros et al. maintained assumptions in existing analytical methodologies, but introduced refinements to achieve a wider range of application [5]. Takada et al. in 2001, studied elasto-plastic shell model buckling of a pipe subjected to normal and reverse fault movement using shell finite element method. They found that pipes are much more vulnerable to reverse fault movement, and seismic design of shell model can be approximated by beam model for normal fault movement, but not for reverse fault movement [4]. More recently, Joshi et al. [6], attempted to analyse the response of buried pipelines subjected to reverse fault motion by developing a simple finite element model using 3D beam elements in which surrounding soil of the pipeline was modelled using nonlinear springs which support the pipeline at discrete points. Precise simulation of the local buckling, large section deformations and the effect of internal pipe pressure were ignored due to the use of beam elements.

In this paper, the structural behaviour of buried pipelines crossing reverse-slip faults is investigated via numerical analyses. Non-linearity of material properties and soil-pipe interaction are considered in the finite element simulation procedures. These analyses include three different geometrical properties of the pipeline (the diameter to thickness ratios), four different soil conditions and three intersection angles between the fault plane and the pipeline. The effects of different parameters on the response of the buried pipeline crossing reverse-slip faults are evaluated.

1. NUMERICAL MODELING

To evaluate the response of buried pipelines under different reverse-slip fault displacement conditions, steel pipelines with material property of API-5L-X65 including three diameter to thickness ratios (*D/t= 64, 77* and *96*) are assumed and modelled using finite element software ABAQUS/CAE (Ver. 6.9) [7]. The models are used to simulate the steel pipe, the surrounding soil medium and their interaction, considering the nonlinear geometry of the soil and the pipe (including the distortions of the pipeline cross-section). These are done through a large-strain description of the pipeline–soil system and the inelastic material behavior for both the pipe and the soil [8]. Problems including the non-linearity of geometry and material sometimes involve buckling or collapse behavior, where the load–displacement response takes on the negative stiffness and negative eigenvalues. At this time, the structure must release strain energy to remain in equilibrium [9]. The non-linear stabilization algorithm is employed to solve the limit load-bearing problem of the pipeline due to faulting. The finite element model of the pipeline including the stress-strain bilinear relationship of the API-5L-X65 steel is illustrated in Fig.1.1. The geometrical and mechanical characteristics of the pipeline are presented in Tab.1.1.

Geometrical properties of the studied pipelines are selected based on available and under-design experiences. In order to obtain the critical conditions of buried pipelines, the internal pressure of the pipes is considered equal to $0.4P_{max}$ which is arranged in different numbers according to manufacturing specifications [10]. On the other hand, bilinear Stress-strain relationship for the steel material API-5L-X65 is considered in numerical analyses [11].

Table 1.1. Geometrical and Stress-Strain Characteristics of Pipelines

Geometrical characteristics					Mechanical characteristics					
D/t	Length (m)	Diameter (m)	Thickness (mm)	Pressure (Mpa)	$\sigma_1=\sigma_y$ (Mpa)	$\sigma_2=\sigma_f$ (Mpa)	E_1 (Gpa)	E_2 (Gpa)	Strain limit	
									Elastic	Failure
64	60	0.6	6.35	6.72	490	531	210	1.088	0.0023	0.04
77	60	0.6	7.92	8.38						
96	60	0.6	9.52	10.08						

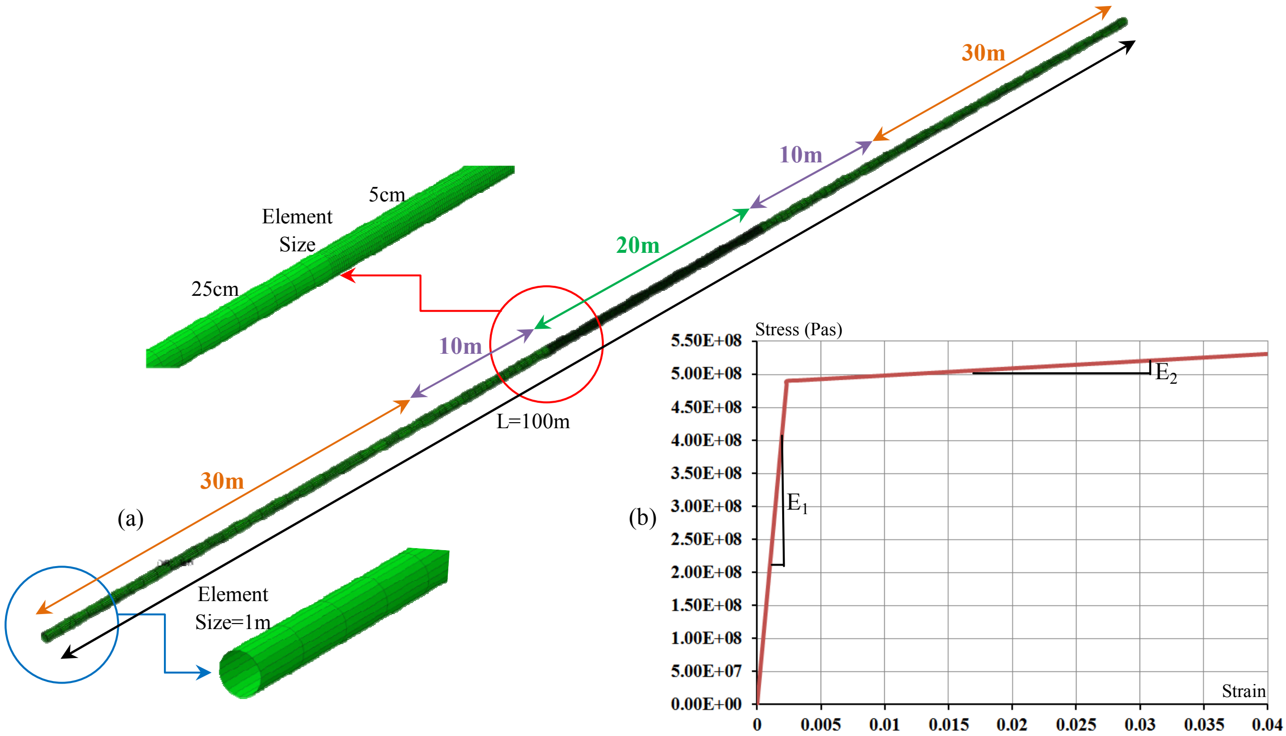

Figure 1.1. (a) 3D Finite Element Model of the Pipeline. (b) Material Properties of API-5L-X65 Steel.

Four-node reduced-integration “Shell” elements (S4R) are employed for modelling of the pipe, whereas eight-node reduced-integration ‘‘Brick’’ elements (C3D8R) are used to simulate the surrounding soil [2]. The pipeline is assumed to be embedded in two types of cohesive soils and two types of non-cohesive soils. The soil is modelled using the Mohr-Columb model with von-Mises yield criterion and required the following constitutive parameters: density (γ), friction angle (φ^o), dilation angle (Ψ^o), cohesion (c), Young’s modulus (E) and Poisson’s ratio (v). The applied numerical values are presented in Tab.1.2 [8].

Table 1.2. Surrounding Soil Properties

Soil Type		γ (kN/m^3)	φ°	Ψ°	c (Kpa)	E (Mpa)	v
Cohesive	CSO=Soft Clay	18	0	0	50	25	0.35
	CST=Stiff Clay	18	0	0	200	100	0.35
Non-Cohesive	GLO=Loose Granular	18	30	10	5	8	0.30
	GDE=Dense Granular	18	39	10	5	50	0.30

The vast primary analyses are implemented including different geometrical dimensions of the soil model and subsequently different lengths of the pipeline to obtain more accurate results and less computational time. The optimum dimensions of the soil-pipeline model are obtained according to the Fig.1.2. It is worthy of mentioning that, each calculation lasts for about 5-12 hours depending on the model specifications on a computer with four processors (the main frequency of each processor is 2.53 GHz) and 6GB memory. At the next step, optimum size of elements along pipe axis is derived by

“Adaptive Meshing” feature of the ABAQUS software. Finally, a regular pattern of map meshing is applied in various pipes buried in different soil conditions. As it is shown in Fig.1.1, sizes of the elements are increased as they are located farther with respect to the fault plane (mid-length of pipeline). So, the first 30 meters of the pipeline from the ends are meshed with elements in 1m length, the next 10 meters with elements in 25 centimetres length and finally the next 10 meters of the pipe which are located at vicinity of the fault plane are discretized by elements with the length of 5 centimetres. This pattern of map meshing allows the pipelines to remain stable during the analyses and identical results to be derived. Fig.1.2 indicates the optimum dimensions of the soil model with various intersection angles of the fault plane and pipeline axis including geometrical dimensions, finite element meshing, and burial depth of the pipe. The intersection angle is investigated in three variants of 30^o, 45^o and 60^o as presented in Fig.1.2.

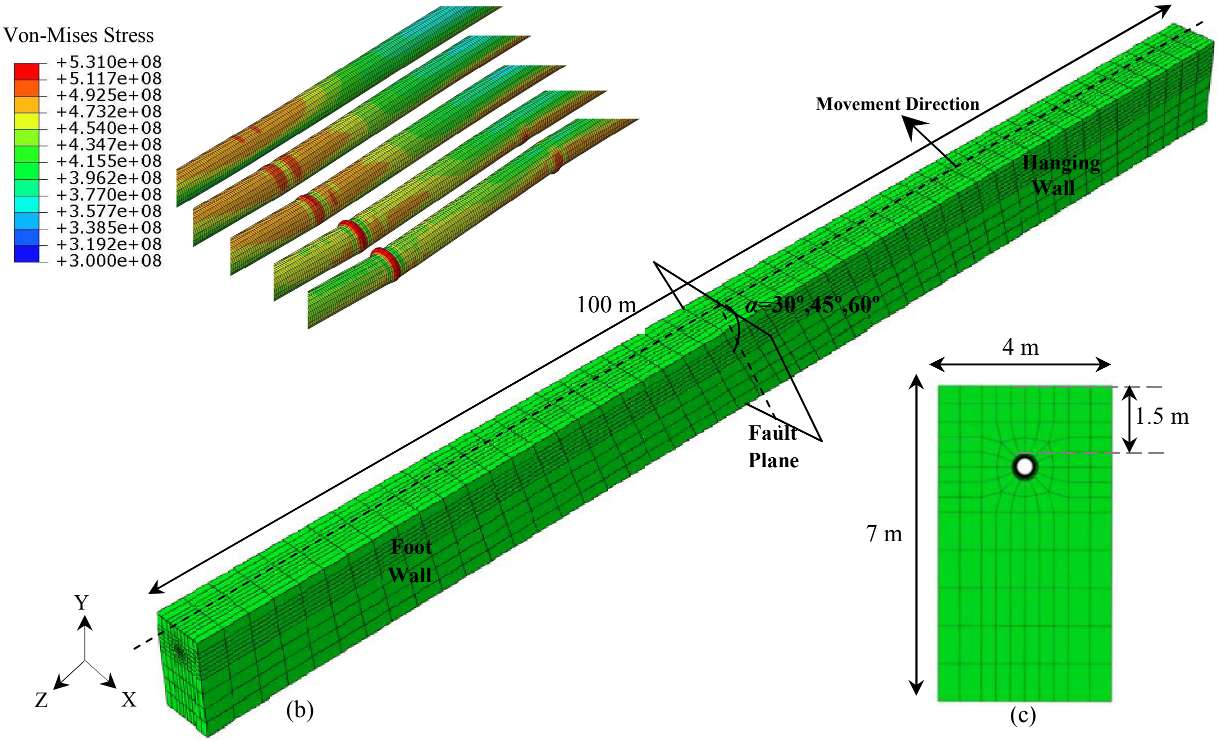

Figure 1.2. (a) An Example of Local Buckling of Pipeline Due to Energy Release at Wrinkling Zones (b) Various Intersection Angles of the Fault Plane and Pipe Axis (c) Cross Section and Meshing of Soil Model

The contact surface approach implemented in ABAQUS/Standard that allows for the separation and sliding of finite amplitude and arbitrary relative rotation of the contact surfaces, is used to simulate the pipe-soil interface. The contact is assumed frictional with Coulomb friction. The shear stress between the surfaces in contact is limited by a maximum value “$\tau_{max}=\mu p$” where p is the normal effective contact pressure, and μ is the friction coefficient. A value of “$tan(0.6\varphi)$” [12] is considered for μ, where φ is soil friction angle.

The analyses are conducted in three steps: first, gravity loading is applied in which the self-weight of both pipeline and soil are considered by adding gravity acceleration of 9.81 N/m^2 in ($-y$) direction. Next, the internal pressure of the pipeline, according to Tab.1.1, is applied to the internal surface of pipeline model. Finally, the fault displacement is applied statically using the nonlinear stabilization method at the boundary surfaces of hanging wall (including the end nodes of the pipeline). Results from the numerical simulations using ABAQUS are presented herein in the form of von-Mises stresses for comparison with failure stresses because the yield principle of von-Mises was adopted during creating models and assigning material properties involving pipeline and soil model.

2. NUMERICAL RESULTS

In this section the effects of different parameters such as wall thickness, fault-pipe intersection angle and surrounding soil condition, are investigated on the response of buried pipelines.

1.2. Influence of Wall Thickness on Peak Failure Displacement of Pipeline

The effects of different wall thickness as (*D/t=96, 77* and *64*) on the response of buried pipelines are investigated. The pipelines include similar properties of burial depth equal to 1.5 meters (as shown in Fig.1.2), the fault-pipe intersection angle of 45º and different surrounding soil conditions as clarified in Tab.1.2. The results reveal that increasing pipe wall thickness imposes the pipeline to remain more sustainable under various faulting patterns and correspondingly increases the failure displacement of the pipeline. Accordingly, identifying the embedment conditions and surrounding soils would be essential to propose the required method of retrofitting or rehabilitation. According to the results illustrated in Fig.2.1 and Tab.2.1, the more increase in wall thickness of pipeline buried in stiff cohesive soil (with high elastic modulus property), the more increase in failure displacement capability of the pipeline, whereas the more increase in wall thickness of pipeline buried in dense granular soil, the less increase in failure displacement of the pipeline. Consequently, increasing the wall thickness of pipes has the most effect on the pipes buried in loose granular soils (e.g. GLO) and the least effect on the pipes buried in soft cohesive soils (e.g. CSO).

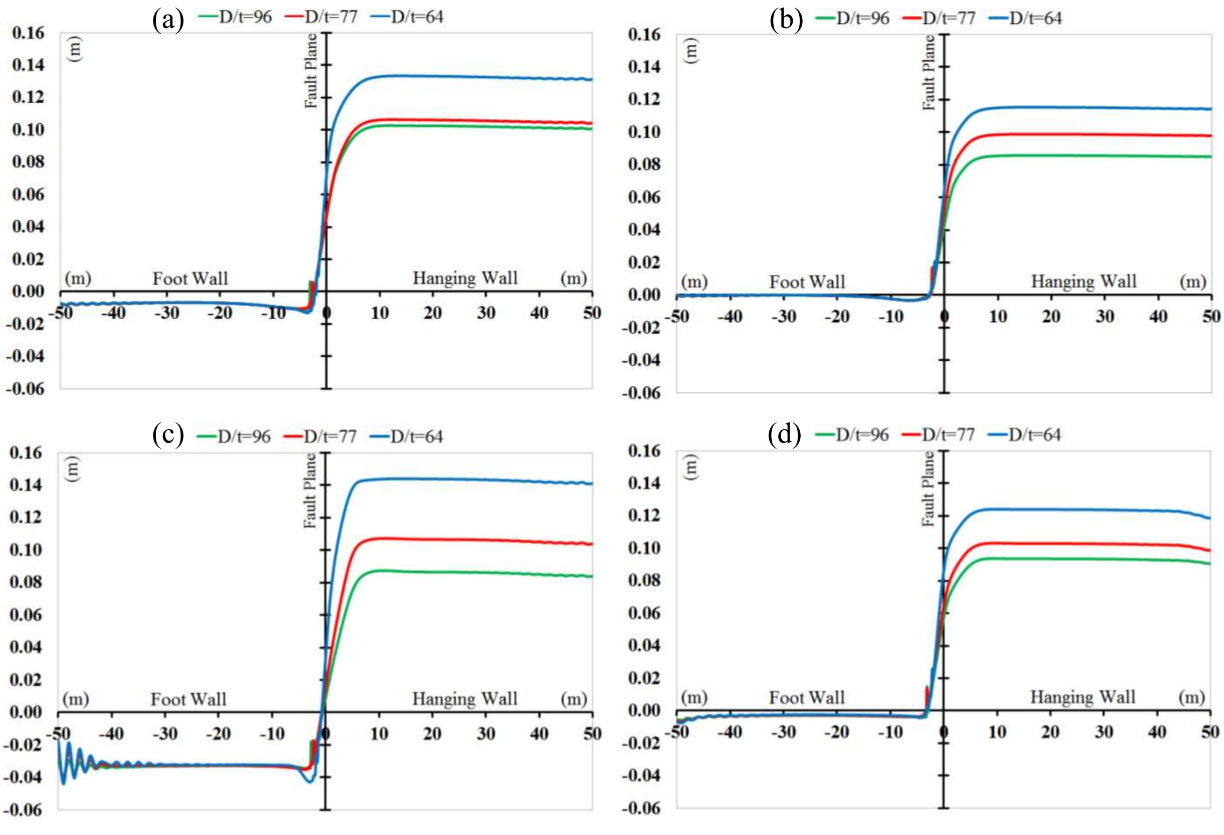

Figure 2.1. Influence of Pipe Wall Thickness on Failure Displacement of Pipelines in (*y*) Direction, Buried in: (a) Soil CSO (b) Soil CST (c) Soil GLO (d) Soil GDE (*α=45º*, Crown Edge of Pipelines)

Table 2.1. Influence of Wall Thickness on Peak Failure Displacement of Pipeline (*α=45º*)

Soil	Displacement of failed element in (*y*) direction (cm)			Changes of failure displacement of failed element at crown edge of pipeline in (*y*) direction	
	D/t=96	*D/t=77*	*D/t=64*	Increasing the pipe wall thickness from *D/t=96* to *D/t=77*	Increasing the pipe wall thickness from *D/t=96* to *D/t=64*
CSO	10.2	10.6	13.3	%3.60 - Increase	%29.92 -Increase
CST	8.5	9.8	11.5	%15.24-Increase	%34.53-Increase
GLO	8.6	10.6	14.3	%18.79-Increase	%65.91-Increase
GDE	9.3	10.2	12.3	%10.06-Increase	%32.48-Increase
Avg.	---	---	---	%11.92-Increase	%40.71-Increase

Overall, based on different selected soil conditions and intersection fault-pipe angle ($\alpha=45^o$), an average increase of %11.92 in failure displacement of pipe with respect to %20 decrease in *D/t* ratio, and also average increase of %40.71 in failure displacement with respect to %33 decrease in *D/t* ratio of the pipe, concludes that increasing in wall thickness of the pipe is a proper method of retrofitting.

2.2. Influence of Wall Thickness on Stress Response of Pipeline

The results shown in Fig.2.2 and Tab.2.2 indicate that increasing the wall thickness helps the pipeline to remain more stable and unfailing during the fault movements. Therefore, due to the increase of failure displacement of pipeline, further increase in fault plane movement results in growing the longitudinal compressive forces and bending moments along the pipeline. At failure time, stress of elements located at crown edge of the pipeline increases as diameter to thickness ratios decreases from *96* to *77* and *64*. In general, an average increase of stress about %3.71 with respect to %20 increases in *D/t* ratio and also %8.90 with respect to %33 increase in *D/t* ratio of the pipeline, provides a meaningful outlook on designing and retrofitting method selection for pipelines crossing reverse-slip faults. Furthermore, increasing the wall thickness incites extensive longitudinal and circumferential distribution of peak yield stresses in elements at the vicinity of the fault plane. Thus, in the pipes with thick walls or low *D/t* ratios, broader zone of the pipeline becomes plastic and should be retrofitted.

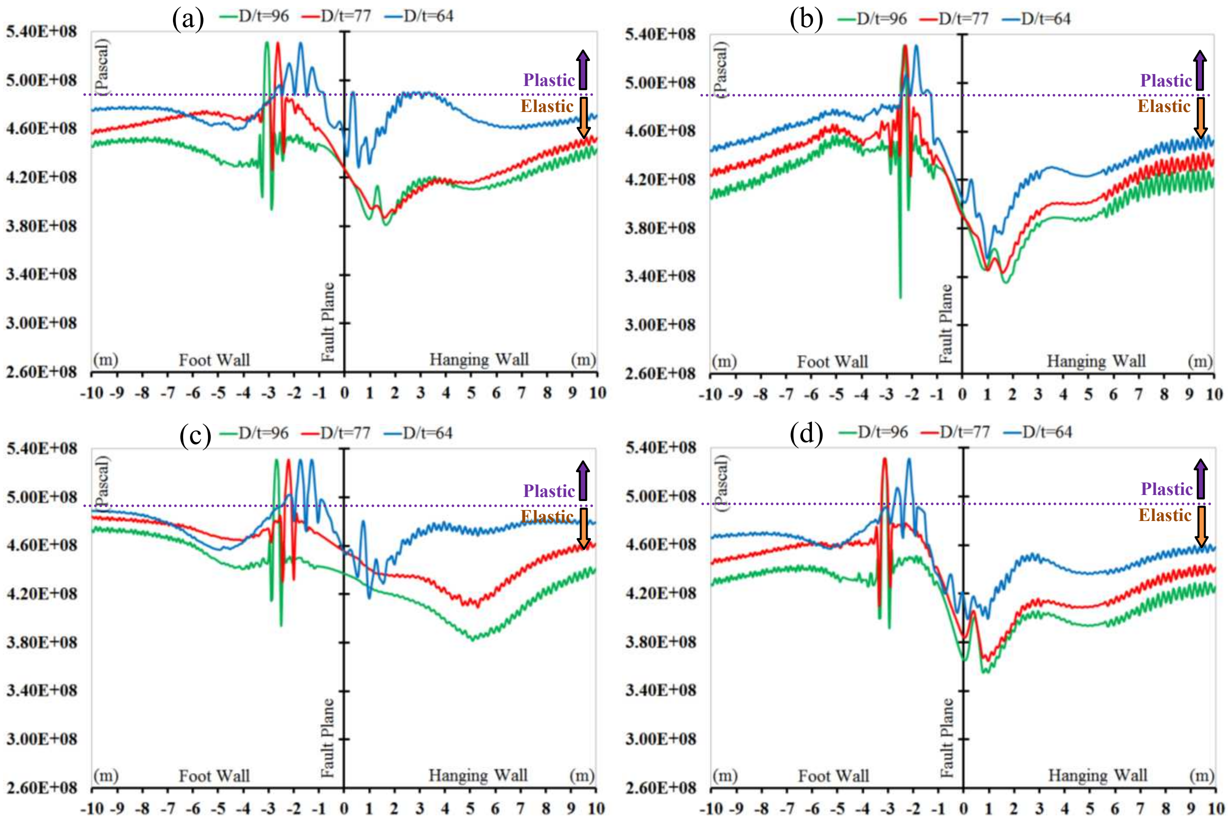

Figure 2.2. Influence of the Pipe Wall Thickness on Stress Response of Pipelines, Buried in: (a) Soil CSO (b) Soil CST (c) Soil GLO (d) Soil GDE ($\alpha=45^o$, Crown Edge of Pipelines)

Table 2.2. Influence of Wall Thickness on Stress Response of Pipeline ($\alpha=45^o$)

Soil	Average changes of stress distribution at crown edge of pipeline	
	Increasing the pipe wall thickness from *D/t=96* to *D/t=77*	Increasing the pipe wall thickness from *D/t=96* to *D/t=64*
CSO	%3.03-Increase	%9.58 -Increase
CST	%3.29-Increase	%8.53-Increase
GLO	%4.49-Increase	%8.58-Increase
GDE	%4.03-Increase	%8.92-Increase
Avg.	%3.71-Increase	%8.90-Increase

2.3. Influence of Wall Thickness on Total Displacement of Fault Plane and Buckled Locations of the Pipeline

As the fault movement increases, a wavy pattern of stresses initiates at compression zones and under a critical fault displacement, wrinkle zones at foot wall and hanging wall become dominant and the local buckling occurs. However, the first failed element of all pipelines crossing reverse-slip fault (with different soil conditions and intersection angle of 45^o) is located on foot wall at crown edge of the pipeline. On the other hand, as the thickness of the pipelines buried in soft or loose soils increases, failure of pipe elements initiates at both sides of the fault plane (e.g. pipes with $D/t=64$ buried in GLO or CSO soil types). As shown in Fig.2.2 and Fig.2.3.a, increasing the wall thickness of the pipeline, induces closer positioning of the failed elements with respect to the fault plane.

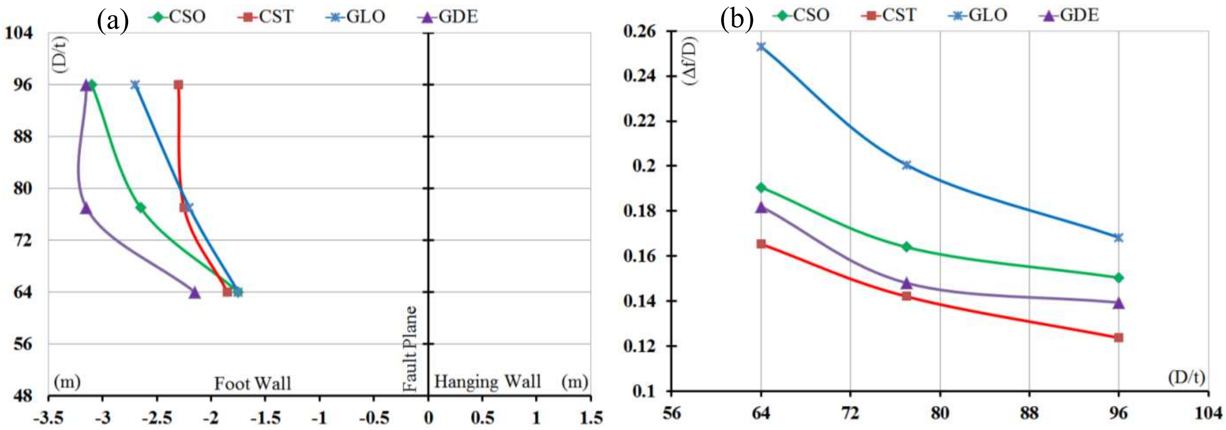

Figure 2.3. Influence of the Pipe Wall Thickness on (a) Failure Position of Elements Located at Crown Edge of Pipeline (b) Failure Fault Plane displacement to Diameter Ratio ($\Delta f/D$) With Respect to D/t. ($\alpha=45^o$)

As shown in Fig.2.3.b, the maximum failure displacements of fault planes occur in the pipelines buried in loose non-cohesive soils (GLO), whereas the minimum occur in the pipelines buried in stiff cohesive soils (CST). On the other hand, as the wall thickness of the pipeline decreases, the failure fault displacement ratio decreases.

2.4. Influence of Fault-Pipe Intersection Angle on Peak Failure Displacement of Pipeline

According to Fig.2.4 and Tab.2.3: (a) for ($\alpha>45^o$), increasing of the intersection angle causes increasing of the failure displacement of the pipelines in various soil conditions; (b) for ($\alpha<45^o$), increasing of the intersection angle induces different consequences which increases the failure displacement of the pipes buried in soils with lower elastic modulus (CSO and GLO), and decreases the failure displacement of the pipes buried in soils with higher elastic modulus (CST and GDE). Overall, to improve the safety of the pipeline system, laying the pipe with intersection angle close to the vertical position would be an appropriate method.

Table 2.3. Influence of Fault-Pipe intersection Angle on Peak Failure Displacement of Pipeline ($D/t=96$)

Soil	Displacement of failed element in (y) direction at pipes with: (cm)			Changes of failure displacement of failed element at crown edge of pipeline in (y) direction	
	$\alpha=30^o$	$\alpha=45^o$	$\alpha=60^o$	Increasing the intersection angle from $\alpha=45^o$ to $\alpha=60^o$	Decreasing the intersection angle from $\alpha=45^o$ to $\alpha=30^o$
CSO	11.0	10.2	12.9	%26.43-Increase	%7.46-Increase
CST	6.4	8.5	10.0	%8.58-Increase	%24.48-Decrease
GLO	11.1	8.6	13.3	%54.17-Increase	%28.39-Increase
GDE	5.7	9.3	14.1	%51.18-Increase	%38.26-Decrease

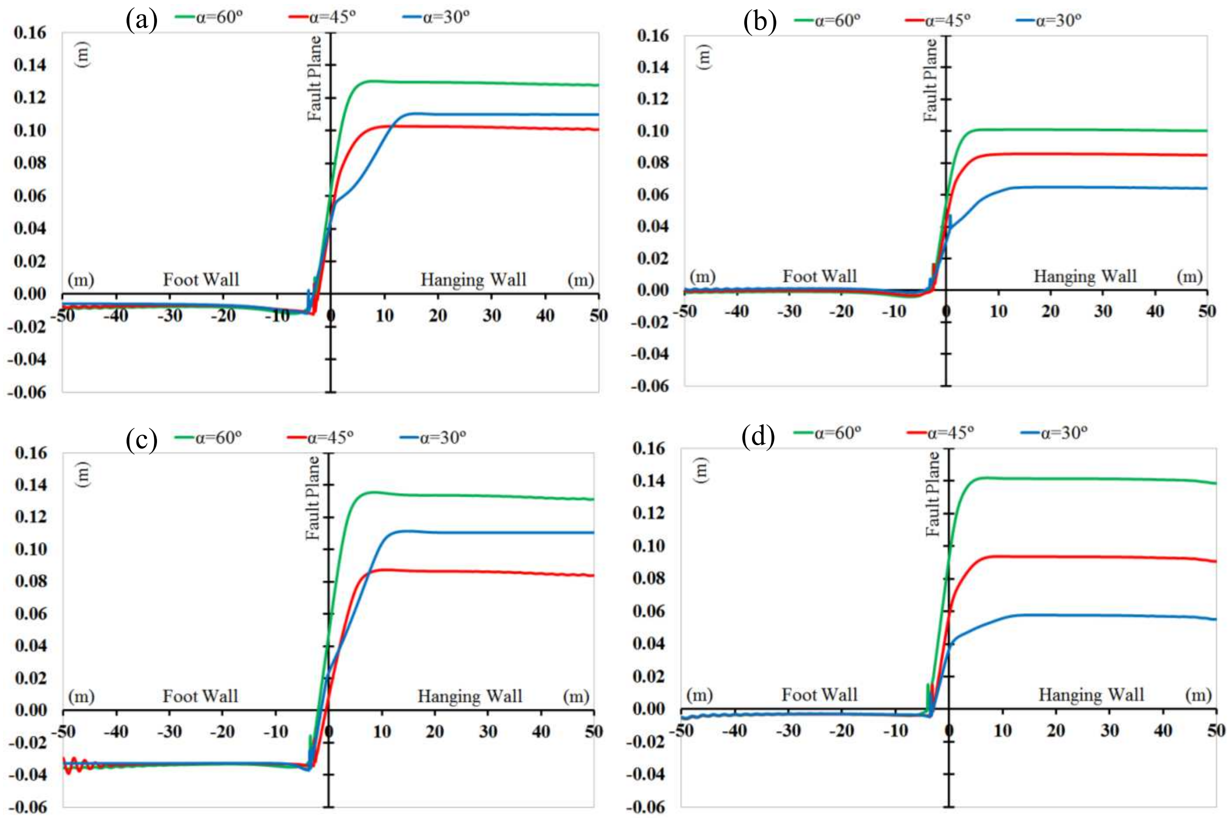

Figure 2.4. Influence of Fault-Pipe Intersection Angle on Peak Failure Displacement of Pipelines Buried in: (a) Soil CSO (b) Soil CST (c) Soil GLO (d) Soil GDE (*D/t=96*, Crown Edge of the Pipelines)

2.5. Influence of Fault-Pipe Intersection Angle on Stress Response of Pipeline

Influences of change in intersection angle of the pipe-fault are investigated in the form of ($\alpha=45^o$ to $\alpha=60^o$) and ($\alpha=45^o$ to $\alpha=30^o$). As shown in Fig.2.5, increasing the crossing angle of the fault-pipe decreases the distributed stresses in elements which are located at both hanging wall and foot wall of fault and along the crown edge of the pipeline. The main reason can be found in counteraction of external concentrated compression stresses (in elements of invert edge reclined to bedding soil) with circumferential tensile stresses (due to internal pressure). On the other hand, decreasing the cross angle of the fault-pipe increases distributed stresses in the elements of the pipe. This is due to the directional propagation of boundary reactions toward the compression (wrinkled) zones, which results from lower shear (frictional) stresses along the pipeline (Caused by pipe-soil interaction).

The results in Tab.2.4 indicate that increasing of the fault-pipe intersection angle has the maximum effect on reduction of the stresses (at failure time) in the pipes buried in soft cohesive soils, whereas decreasing of the fault-pipe intersection angle has a considerable effect on increasing of the stresses in the pipes buried in stiff cohesive soils (the same at the failure time). An Increase of 15º in the intersection angle of the fault-pipe results in about %7.84 average decrease of stresses, while a decrease of 15º in the intersection angle results in about %8.56 average increase of stresses.

Table 2.4. Influence of Fault-Pipe Intersection Angle on Stress Response of Pipeline at Failure Time (*D/t=96*)

Soil	Average changes of stress distribution at crown edge of pipeline	
	Increasing the intersection angle from $\alpha=45^o$ to $\alpha=60^o$	Decreasing the intersection angle from $\alpha=45^o$ to $\alpha=30^o$
CSO	%9.51-Decrease	%8.38 -Increase
CST	%9.01- Decrease	%12.02-Increase
GLO	%7.08- Decrease	%6.36-Increase
GDE	%5.78- Decrease	%7.48-Increase
Avg.	%7.84- Decrease	%8.56-Increase

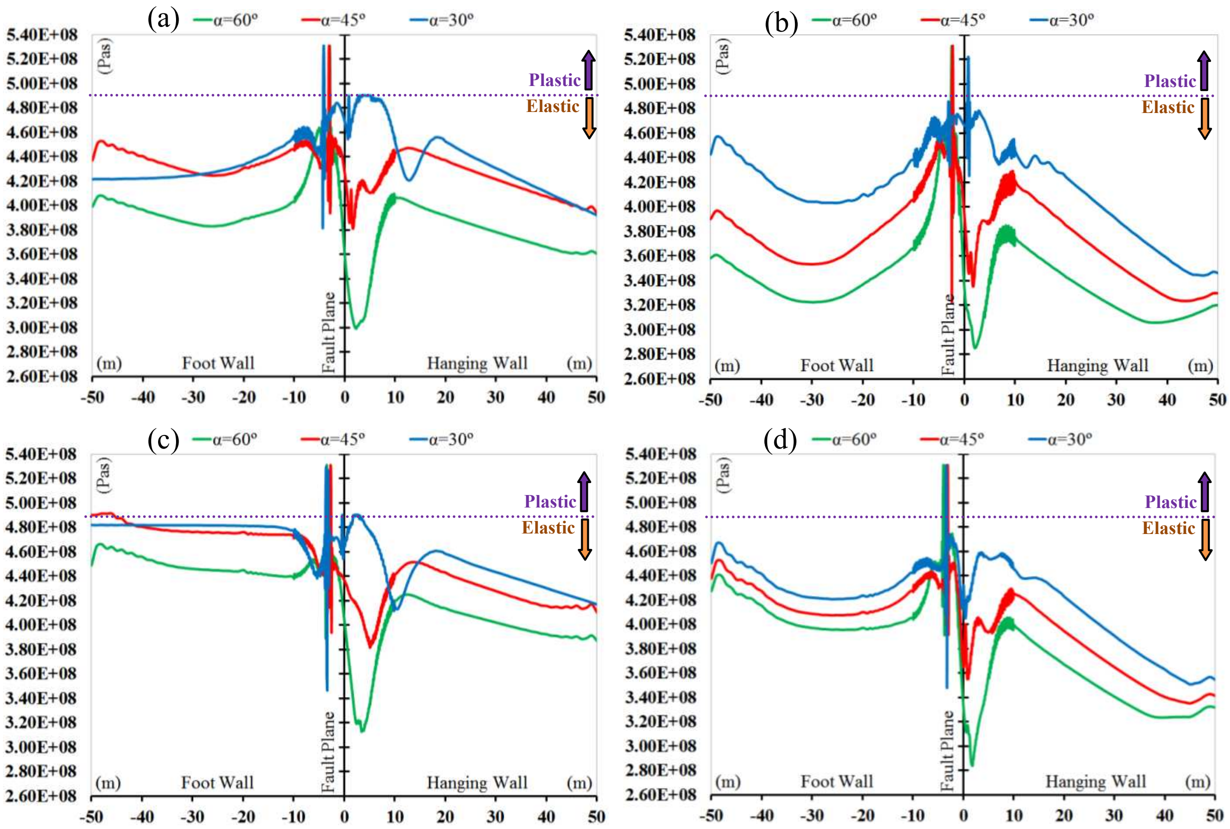

Figure 2.5. Influence of Fault-Pipe Intersection Angle on Stress Response of Pipelines Buried in: (a) Soil CSO (b) Soil CST (c) Soil GLO (d) Soil GDE (*D/t=96*, Crown Edge of Pipeline)

2.6. Influence of Surrounding Soil Conditions on Peak Failure Displacement of Pipeline

The effects of various surrounding soil conditions of the pipelines are categorized in different crossing angles, wherein clarified in Tab.2.5. Numerical results indicate that, generally, decreasing the elastic modulus of surrounding cohesive soils (softening the cohesive soil, e.g. changing from CST to CSO) increases the capability of the pipeline to withstand greater fault ruptures, whereas the similar changes in granular soils (loosening the granular soil, e.g. changing from GDE to GLO) would be useful in pipes crossing the fault plane with lower intersection angles. Overall, modification of the environmental trench soil conditions of the pipeline (by lessening the stiffness of cohesive soils or lowering the friction angle of non-cohesive soils) will improve the failure displacements of the pipeline (especially at lower crossing fault-pipe angles).

Table 2.5. Influence of Surrounding Soil Conditions on Peak Failure Displacement of Pipeline

Intersection angle	Soil type				Changes of failure displacement of failed element at crown edge of pipeline in (y) direction	
	CSO	CST	GLO	GDE	Softening cohesive soil (changing CST to CSO)	Loosening non-cohesive soil (changing GDE to GLO)
$\alpha=30^o$	11.0	6.4	11.1	5.7	%70.33-Increase	%93.60-Increase
$\alpha=45^o$	10.2	8.5	8.6	9.3	%19.69-Increase	%7.80-Decrease
$\alpha=60^o$	12.9	10.0	13.3	14.1	%28.10-Increase	%5.40-Decrease

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3. SUMMARY AND CONCLUSIONS

In this paper the structural response of buried pipelines crossing reverse-slip faults are investigated by 3D finite element analyses. The study includes pipes with typical steel material API-5L-X65 considering internal pressure, soil-pipe interaction, nonlinear effects of large deformations and displacements, buckling and nonlinearity of materials. The following conclusions are obtained based on this study:

1. Increasing of the pipe wall thickness helps the pipeline to remain more sustainable under various faulting conditions and correspondingly increases the failure displacement of the pipeline. Increasing of the wall thickness has the most effect on the pipes buried in loose granular soils and the least effect on the pipes buried in soft cohesive soils.
2. Increasing of the pipe wall thickness incites extensive longitudinal and circumferential distribution of peak yield stresses in elements at the vicinity of the fault plane due to the increase of failure displacement of the pipeline, thus the pipes with thick walls have broader plastic zones.
3. The maximum displacements of the fault planes (at failure time) occur in the pipelines buried in loose granular soils, whereas the minimum are for the pipelines buried in stiff cohesive soils.
4. In general, to improve the response of the pipeline crossing faults, intersection angle of the pipeline axis with the fault plane close to the vertical would be an appropriate method.
5. Increasing of the cross angle of fault-pipe decreases the distributed stresses in elements which are located at both sides of fault plane and along the crown edge of the pipeline (and vice versa).
6. Increasing of the fault-pipe intersection angle has the maximum effect on the reduction of the stresses (at failure time) in the pipes buried in soft cohesive soils, whereas decreasing of the fault-pipe intersection angle has a considerable effect on increasing of the stresses in the pipes buried in stiff cohesive soils (the same at the failure time).
7. Decreasing of the elastic modulus of surrounding cohesive soils increases the capability of the pipeline to withstand greater fault displacements (regardless of the intersection angle), Whereas the similar changes in granular soils would be useful just in pipes crossing the fault plane with lower intersection angles.

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