Pipeline – Fault Crossing: Structural Considerations on the Use of Flexible Joints for Mitigating a Potential Failure

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ABSTRACT:
Buried steel pipeline pipelines are considered as hazardous structures and their potential failure due to seismic fault activation constitutes a research topic of significant interest. Various mitigating measures have been applied to eliminate the consequences of fault activation, mostly aiming at reducing the interaction between pipeline and surrounding soil. In the present study a novel approach is investigated, consisting of introducing flexible joints between adjacent pipeline parts, aiming at concentrating strains at these joints and allowing steel parts to remain essentially undeformed. Advanced numerical simulation is employed to highlight the effectiveness of the proposed approach in terms of reduction of bending moments, strains and stresses in the steel parts of the pipeline. The beneficial effect of joints are illustrated for the cases of normal and strike-slip faulting.

1. INTRODUCTION

The industrial development over the last decades has caused increased energy demand for oil and oil products. Pipelines have been proven to be the most reliable, safe and economic way of transporting hydrocarbonates over long distances between oil fields and oil consumers, thus playing a major role in the energy supply chain. Moreover, pipelines are also considered as structures of very high risk, given that any potential failure may lead to fuel leakage, even explosion, and may have devastating consequences on the environment, nearby populated areas as well as economic losses. It is also noted that, as pipelines extend to hundreds of kilometers, crossing seismic areas is not unlikely. Such areas usually incorporate active tectonic faults, leading to several pipeline – fault crossings. In such cases, fault activation imposes large permanent ground displacements on the pipeline, which the latter has to follow by developing extensive deformation. The dominant failure modes are local buckling due to high compressive strains, tensile fracture due to high tensile strains, especially at the girth weld zones, and upheaval buckling due to compressive axial forces, mainly in case of reverse fault type. Thus, it is not surprising that investigation of past earthquake events has outlined faulting as the dominant cause of pipeline failure, compared to other natural hazards (O’Rourke and Liu, 1999).

Onshore buried steel pipeline damage due to faulting has been extensively investigated by numerous researchers. Newmark and Hall (1975) were the first to present an analytical model for assessing the integrity of a buried pipeline crossing a ruptured fault. Their model was based on the assumption that the fault is represented by a single planar surface between two rigid bodies that exhibit relative motion. They, also, introduced a so called anchor point along the pipeline, beyond which the pipeline is not affected by soil movement. Kennedy et al. (1977) extended the analytical model by incorporating the lateral soil interaction to evaluate the maximum axial strain, while Kennedy and Kincaid (1983) considered the nonlinearity of pipeline – soil friction in the analysis. This approach was adopted by Wang and Yeh (1985) to estimate pipeline bending stiffness.

Vougioukas et at. (1979) numerically analyzed buried pipes as elastic beams taking into account both horizontal and vertical movement of the fault. Later, Ariman and Le (1991) introduced the finite element method to evaluate pipeline strain. Takada et al. (2001) proposed a simplified method to estimate maximum axial strain by taking into account the deformation of the pipeline cross-section and relating the pipe bending angle to the maximum axial strain. Karamitros et al. (2007, 2011) improved the existing analytical methodologies for both strike-slip and normal faulting by combining the model of beam on elastic foundation and the elastic beam theory to calculate maximum strains, while considering also material and geometric non-linearities. Additionally, Trifonov and Cherniy (2010) presented a semi-analytical approach for pipeline stress analysis. From the point of view of advanced numerical simulation with continuum finite element models, Vazouras et al. (2010, 2012) presented numerical models for pipeline – strike-slip fault crossings by considering all nonlinearities of the problem as well as the contact interaction between the pipe and the surrounding soil. They also investigated the effect of diameter over thickness ratio for X65 and X80 pipelines and concluded that local buckling is the dominant failure mode for compressed pipes, while tensile failure and cross-sectional flattening are the dominant failure modes for pipes under tension. Recently, Trifonov (2014) extended the continuum models of Vazouras et al. (2010, 2012) by considering trench dimensions and paying special attention on modeling fault discontinuity.

Mitigating the consequences of faulting on buried pipelines is a top priority research topic for both the academia and the industry. Nowadays, several mitigating measures are adopted in practice, even though their efficiency has not always been thoroughly investigated. The usual design approach for pipeline fault crossings is to embed the pipeline in a shallow, sloped-wall trench with loose backfill, in order to reduce soil resistance and allow the pipeline to deform over a longer length, permitting the development of large strains and permanent deformations, providing pipe rupture is prevented. That is to say, the risk of damage requiring repair is generally acceptable, as long as the integrity of the pressure boundary is maintained. Moreover, buried crossings are generally preferred, because they avoid technical issues associated with a long run of unrestrained pipe and limits exposure to third-party damage (Nyman et al. 2003). In case of strike-slip fault type, the pipeline may be placed on the ground inside concrete culverts without backfilling. In this case the idea is to sacrifice culverts and allow the pipeline to remain undeformed. Another approach is the application of geotextiles, which are wrapped around the pipeline in order to reduce the developing pipeline – soil friction (Gantes and Bouckovalas, 2013). However, the effectiveness of this approach has not been fully quantified and according to Monroy (2013) wrapping the pipeline with a double layer geotextile is effective only if the pipeline to trench wall distance is less than half the pipeline diameter.

Recently, research is directed towards integrating expansion joints between adjacent pipeline parts in the vicinity of fault crossing, in order to concentrate strains at the joints and retain the steel pipe virtually undeformed (Bekki et al., 2002). This design approach aims at reducing the risk of failure due to local buckling or tensile fracture, and will be investigated further in the present article

2. REVIEW OF BURIED PIPELINE NUMERICAL MODELING

Analysis and design of buried pipelines for earthquake resistance is directly linked to soil behavior, which is highly nonlinear, while pipe – soil contact conditions increase further the complexity of the problem. Thus, the implementation of advanced numerical modeling techniques is imperative. Two types of models are commonly adopted for such analyses: (i) the beam-type model where the pipeline is discretized with beam – type finite elements, while the soil with nonlinear translational springs and (ii) the continuum model where the pipeline is modeled with shell finite elements and the surrounding soil with 3D-solid finite elements.

Figure 1 shows the geometry of the pipeline – fault crossing site in plan and section view, for the case that the pipe is subjected to normal faulting. The global coordinate system (1,2,3) refers to the spatial fault movement, while (x,y,z) is the local coordinate system of the pipeline. Then, β and ψ are the pipeline crossing angle and fault dip angle respectively, LF is the fault length and L_p is the crossing site distance from fault left edge. The magnitude of the soil mass movement is denoted by Δ, having spatial components Δ_1, Δ_2 and Δ_3, given in Equation 1. The imposed ground displacements on the pipeline in its local coordinate system, namely Δ_x, Δ_y and Δ_z, are obtained via Equation 2.

$$\Delta = \sqrt{\Delta_1^2 + \Delta_2^2 + \Delta_3^2} \text{ with } \Delta_3 = \Delta_2 \tan(\psi) \tag{1}$$

$$\begin{aligned} \Delta_x &= \Delta_1 \sin(\beta) + \frac{\Delta_3}{\tan(\psi)} \cos(\beta) \\ \Delta_y &= \Delta_1 \cos(\beta) - \frac{\Delta_3}{\tan(\psi)} \sin(\beta) \\ \Delta_z &= \pm \Delta_3 \end{aligned} \tag{2}$$

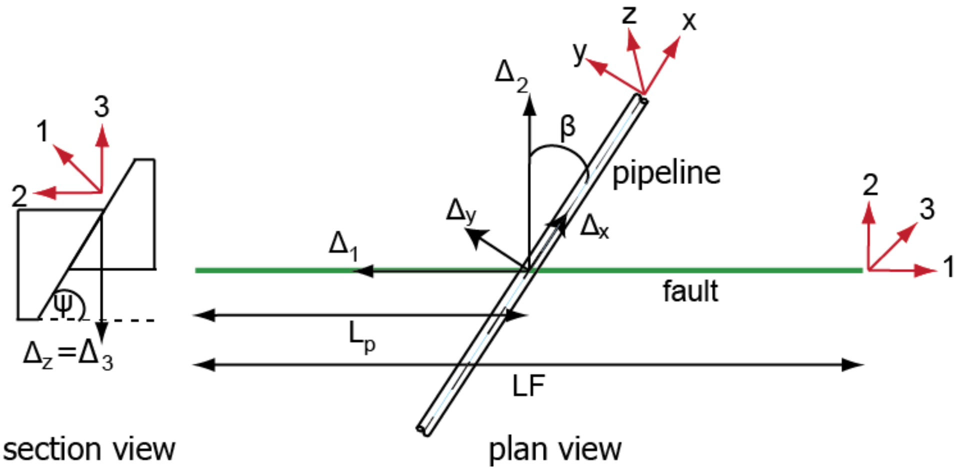


Figure 1: Geometry of the pipeline – fault crossing

Beam-type models are adopted by modern structural Codes and Standards (e.g. ALA, EC3, EC8 and API5L) as reliable and computationally efficient. According to this modeling technique, the pipeline is meshed with beam-type finite elements that can simulate its bending and axial deformation and potential global buckling, and can also provide stresses and strains on cross-sections along the pipeline. The soil is represented by a series of mutually independent translational non-linear springs in three directions, axial, transverse horizontal and transverse vertical. Pipeline steel and soil nonlinear properties as well as geometrical nonlinearities are readily taken into account. The main advantage of beam-type models is their simplicity and computational efficiency, combined with their ability to capture, directly or indirectly the main effects and failure mechanisms, while their main weakness is that local buckling cannot be assessed in a direct manner.

Both tensile fracture and local buckling risk are then evaluated by comparing maximum values of resulting strains to upper bounds prescribed by pertinent codes. ALA (2001) provisions suggest the tensile limit $\varepsilon_{t,c}$ of Equation 3 and the compressive limit $\varepsilon_{c,c}$ of Equation 4 for longitudinal strains resulting from ground movement due to earthquake.

$$\varepsilon_{t,c} = 2\% \tag{3}$$

$$\varepsilon_{c,c} = 0.50\left(\frac{t}{D'}\right) - 0.0025 + 3000\left(\frac{pD}{2Et}\right)^2, \text{ with } D' = \frac{D}{1-3\left(D-D_{min}\right)/D} \tag{4}$$

where t is the pipeline wall thickness, D the pipeline external diameter, D_{min} the pipeline internal diameter, p the internal pressure and E the pipeline steel Young’s modulus. Cross-section ovalization as well as internal pressure can be considered by using so-called pipe elements, which are a variation of Timoshenko beam elements featuring these two additional capabilities.

Continuum models are employed to overcome the shortcomings of beam-type models. In these models, the pipeline is meshed with shell elements. Soil, then, can be represented either by soil springs, which was widely used in the past (Liu et al., 2008, Karamitros et al., 2007, 2011), or 3D-solid finite elements (Vazouras et al., 2010, 2012). However, the use of springs that connect “ground” nodes with shell element nodes s lead to the introduction of local forces on shell elements that, especially in case of coarse mesh, do not represent well the physical problem, as they alter the distribution of stresses and strains on the pipeline wall. On the other hand, three-dimensional soil representation significantly increases both computational effort and problem nonlinearity, given the need for contact elements in modeling pipeline – soil interaction, which can cause convergence problems. Thus, their applicability in practice is limited.

In the present study the aim is to highlight the effectiveness of flexible joints as innovative mitigating measures against the consequences of fault activation on buried steel pipelines. For that purpose, beam-type models are adopted on the basis of their reliability, computational efficiency and compatibility with flexible joints’ modeling. It is noted that the compressive strain limit of Equation 2 includes a term for internal pressure, which acts as a relief against external soil pressure. In the present study, it is assumed a less favorable situation and internal pressure equals zero with the corresponding final term of Equation 2 being neglected.

3. DETAILS OF BEAM-TYPE FINITE ELEMENT MODEL

3.1 Pipeline modeling

In the present study, buried pipeline numerical modeling is carried out using the commercial software ADINA (2008). A straight pipeline segment with length L=1000m is considered for the analysis, as good engineering practice as well as pertinent codes suggest to avoid bends in fault crossings, as additional forces may be imposed on the pipeline due to route change. The fault is considered to be planar and intersects the pipeline in its middle-span. The cross-section is of diameter D=0.914m and thickness t=0.0127m, representing a typical section for high-pressure large diameter gas transmission pipelines. The pipeline is meshed with PIPE elements. As the pipe is subjected to large imposed displacements, yielding is expected to occur around the fault crossing zone. Thus, material nonlinearity is considered through a plastic-bilinear material law. Steel is of type API5L-X65 and considered as elastic with isotropic hardening, with properties listed in Table 1. Geometric nonlinearity is also considered in the analysis to account for second order effects, as fault activation is commonly related to offset in the order of meters.

Table 1: API5L-X65 steel properties

Young’s modulus (GPa)	210.0
yield stress (MPa)	448.5
ultimate stress (MPa)	510.0
ultimate strain (%)	4.0

3.2 Soil modeling

The soil surrounding the buried pipeline is simulated using discrete springs, according to ALA (2001) provisions. As illustrated in Figure 2, every pipeline node is connected to the ground via four different elastic – perfectly plastic translational springs, with “ground” nodes considered fixed on the fault footwall and subjected to imposed displacements on the hanging wall. Soil springs are simulated in ADINA (2008) using SPRING uniaxial elements exhibiting stiffness only in the local axial direction. The pipeline is assumed to be coated with coal tar having a friction coefficient to the soil equal to f=0.90 and to be embedded in granular loose sand with cohesion c=0, unit weight γ=18kN/m^3 and internal friction angle φ=36^o, in 1.30m depth from its top line. Soil springs’ force – displacement curves adopted in the analyses are depicted in Figure 3.

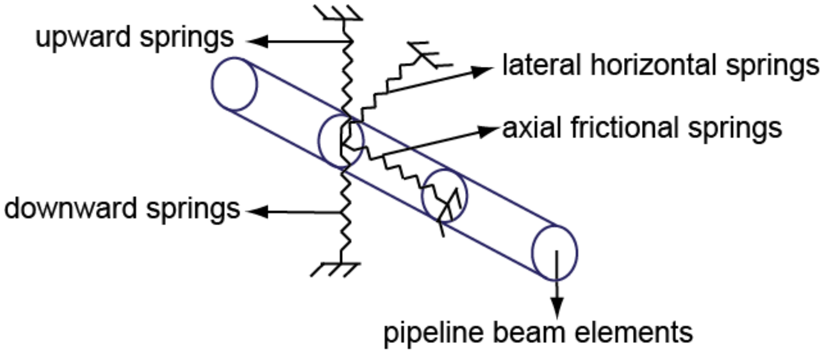


Figure 2: Beam-type finite model

Axial soil springs model the pipeline – soil friction and their properties are related to backfill soil properties and pipeline coating material. Friction forces are estimated using geotechnical approaches that are used to simulate force transfer on axially loaded interfaces of piles. For sand and cohesionless soil types, friction forces are calculated through integration of shear stresses along the pipeline – soil interface. Given the roughness of the pipe surface, friction angle δ equals 50 to 100% of soil friction angle φ. Then, maximum soil resistance is achieved for relatively small displacement within 2.5mm to 5.0mm for dense to loose sand (Sanghal, 1980). In the present study it is assumed that soil resistance is achieved at 3.0mm.

Transverse horizontal (lateral) springs model the soil resistance to any horizontal transverse movement of the pipeline in the trench. Thus, pipeline – soil interaction mechanisms are similar to those of vertical anchor plates or horizontal moving foundations by activating passive earth pressure. For cohesionless soil, the transverse force is expressed though a hyperbolic equation proposed by Trautmann and O'Rourke (1983). Given that the force – deformation relationship is assumed elastic – perfectly plastic, the nonlinear equation is bilinearized by multiplying the relative soil displacement with a factor of 0.26.

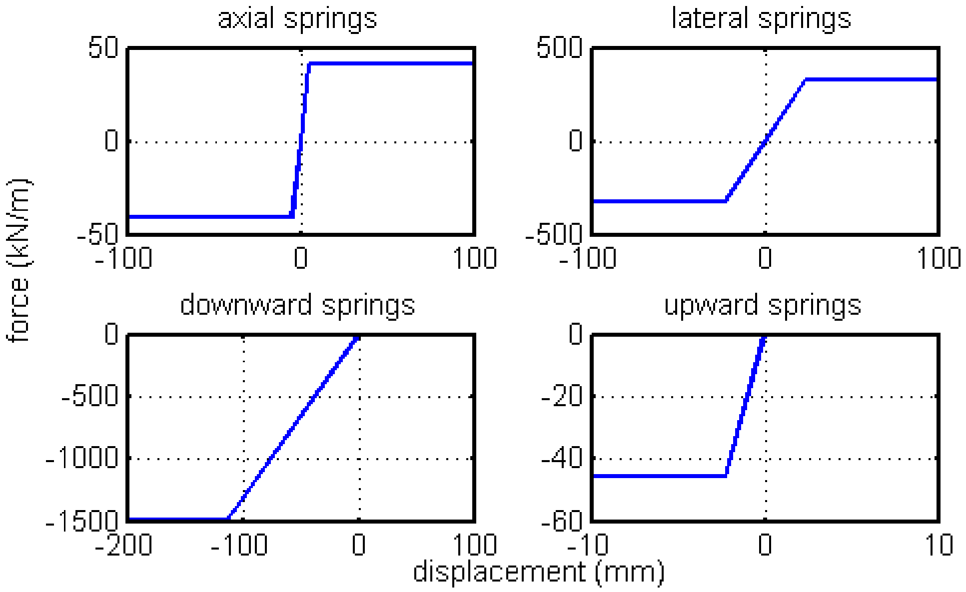


Figure 3: Soil spring force – displacement curves

Vertical upward and downward springs model the vertical movement of the pipeline in the trench, but their properties differ significantly, as backfill soil above the pipeline has very low stiffness in order to reduce friction, while native soil below the pipeline has much higher stiffness. Upward movement perpendicular to the pipeline axis results to vertical forces at the pipe – soil interface, whose maximum corresponds to the weight of an inverted triangle prism of soil above the pipeline top. Downward movement perpendicular to the pipeline axis results to vertical forces at the pipe – soil interface, which correspond to the vertical bearing capacity of a footing (O'Rourke and Liu, 2012). Both for upward and downward springs the nonlinear equation is bilinearized and the soil yield displacement is estimated in the analysis as 13% of the maximum provided by ALA (2001).

3.3 Fault offset modeling

Although earthquakes are typical natural dynamic phenomena caused by the relative movement of tectonic plates, fault activation is usually considered in the analysis as a quasi-static process. Thus, fault displacement in numerical analyses is applied as imposed displacements of "ground" nodes of soil springs at a sufficiently slow rate that allows to neglect the effects of the dynamic nature of the problem. In the present study, the nonlinearity of the problem is handled by implementing the nonlinear solution algorithm Newton-Raphson. The algorithm solves the nonlinear problem by separating it to numerous linear problems. The latter is achieved by imposing displacement in steps through a linear time function. The selected number of steps is sufficiently high in order to achieve convergence and to apply displacement smoothly, in order to follow closely the evolution of the response.

Fault motion is simulated by applying simultaneously fault offset components Δ_1, Δ_2 and Δ_3 according to Figure 1 to "ground" nodes of axial, lateral and vertical springs of the fault hanging wall. In the present study, fault offset is assumed for simplicity reasons to take place only in the vertical plane along the pipeline for normal faulting ($\Delta_1=0$) and in the vertical plane perpendicular to the pipeline for strike-slip fault ($\Delta_2=\Delta_3=0$). For every fault type the dominant fault component is assumed equal to 1.50m. In Table 2 the fault offsets considered in the analyses are summarized. As the pipeline – fault crossing angle equals $\beta=90^o$, the applied displacements on the pipeline are calculated via Equation 2 and are listed in Table 2.

Table 2: Fault offsets and pipeline applied displacements

	fault hanging wall			pipeline		
fault type	Δ_1 (m)	Δ_2 (m)	Δ_3 (m)	Δ_x (m)	Δ_y (m)	Δ_z (m)
Normal	-	0.55	1.50	0.55	-	1.50
Strike-slip	1.50	-	-	-	1.50	-

4. INTRODUCTION OF FLEXIBLE JOINTS

The response of the buried pipeline due to faulting is directly related to the fault type, the fault dip angle and the pipeline – fault intersection angle. It is generally accepted that steel members perform better in tension than in compression, as the latter is associated with buckling phenomena. Therefore, buried pipelines subjected to direct tension can better accommodate large fault offsets compared to the case of direct compression. However, imposed large displacements generally lead to pipeline bending, tension or compression and shear, thus the combined effect of all pertinent actions must be considered for pipeline verification. For that purpose, the pipeline design against fault offset is carried out in strain terms. Namely, strain limits for determining the fault displacement capacity of the pipelines are based on allowing yielding and distortion of the pipe wall while maintaining pressure boundary integrity (Nyman et al. 2003). Thus, mitigating measures aim at reducing the severity of the developing stress state, usually by minimizing pipe – soil friction in order to reduce developing strains. The new proposed mitigating measure, namely integrating flexible joints in continuous pipeline around the fault zone, introduces a whole different design approach. Instead of trying to reduce the friction, the pipeline structural system is transformed from continuous to segmented by using flexible joints that act as internal hinges, aiming at concentrating strains at the joints and retain steel pipe parts virtually undeformed.

Flexible joints are commercial mechanical products, usually referred as expansion joints or bellows, used in the piping industry to absorb thermal expansion and thrust. The two main types of joints are the single joint with axial, lateral and angular deformation capability and the hinge joint with angular deformation only, while lateral and axial movements are constrained. A schematic presentation of a hinged joint is illustrated in Figure 4. As flexible joints are commercial products, bellow manufacturer can produce them upon costumer's requirements, regarding diameter, internal pressure and allowable rotation in order to fit the specifications of the pipeline project. Among the two joint types, for applications on pipeline – fault crossing the hinged joint is selected for two main reasons: (i) axial and lateral stiffness of single joints are too small to withstand large movements due to faulting and (ii) transmission pipelines operate under high pressure that in case of buried pipelines may deform the joint in normal operation, while hinge joints absorb internal pressure within the joint.

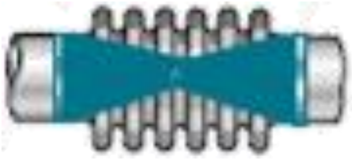


Figure 4: Schematic drawing of hinged flexible joint

There are two approaches for flexible joint numerical simulation (Peng and Peng, 2009): (i) bellow modeling as a generic flexible joint represented by a rotational spring at the center point without modeling the bellow length and (ii) bellow modeling as a general beam finite element with a stiffness matrix constructed from the spring rates provided by the manufacturer. In the present study, the first simulation approach is adopted by modeling hinged bellows as elastic rotational springs with stiffness 0.0088kNm/deg, while relative axial and lateral movements at the two ends of the bellow are restrained through constraint equations. Moreover, as bellows are vulnerable to torsion, rotation about the longitudinal axis is also restricted through constraints.

5. NUMERICAL RESULTS

As mentioned above, the numerical modeling and analysis is performed with the commercial finite element software ADINA (2008). The total length of the pipeline is discretized per 0.50m, after a mesh density sensitivity analysis was carried out to establish the appropriate mesh size, resulting to 2000 pipe elements. The surrounding soil is represented by 2001 axial frictional springs, 2001 lateral springs, 2001 vertical upward and 2001 vertical downward springs. Thus, the finite model herein consists of 10005 nodes and 18018 degrees of freedom.

The effectiveness of flexible joints is investigated for the cases of normal and strike-slip faulting. In each case, firstly, a continuous pipeline, abbreviated as CP, is investigated and then the positions of flexible joints are selected based on the location of maximum bending moment of CP. Three flexible joints are integrated into the pipeline, now abbreviated as PFJ, one on the fault, one in the footwall part and the third in the hanging wall part of the fault. The beneficial effect of bellows is illustrated by comparing the stress state of CP vs. PFJ in terms of axial force, bending moment and developing longitudinal stresses and strains. Soil force distribution along the pipeline is also presented to demonstrate the spread of soil plastification due to pipeline movement.

5.1 Normal fault offset

The pipe deformation due to normal fault offset is schematically illustrated in Figure 5, resulting mainly to pipeline tension and bending.

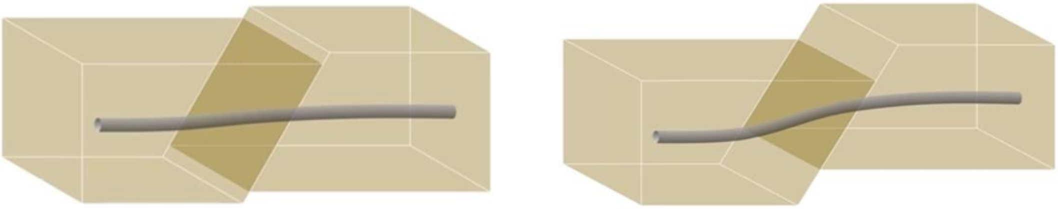


Figure 5: Schematic deformation of a continuous pipeline due to normal faulting

The deformation of continuous pipeline and pipeline with flexible joints due to normal faulting is illustrated in Figure 6. CP deformation is a smooth curved line, while PFJ deformation resembles a polyline with straight segments around the fault. The axial force distribution in Figure 7 indicates a minor increase of tension and a major decrease in bending moment of PFJ due to the introduction of flexible joints. The joints act as flexible internal hinges, virtually eliminating the bending moment at their locations. Based on the expected fault offset, a more detailed analysis is necessary in order to determine the adequate number and optimum positions of joints in order to achieve a sufficient decrease in bending moments.

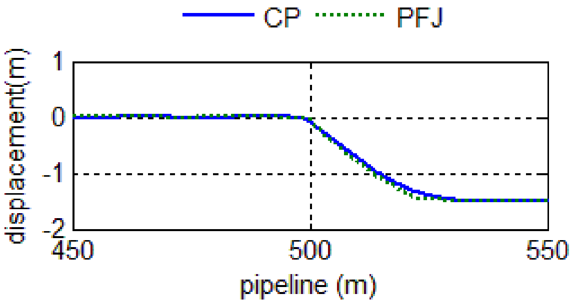


Figure 6: Deformation of continuous pipeline and pipeline with flexible joints

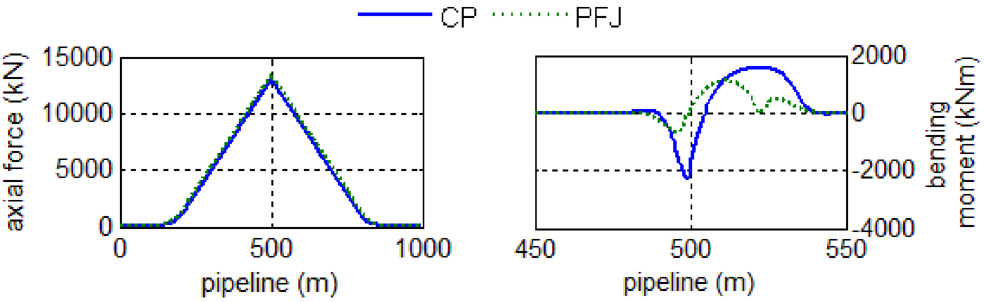


Figure 7: Axial force and bending moment of continuous pipeline and pipeline with flexible joints

The longitudinal stress distribution along the pipeline in Figure 8 indicates steel yielding for CP near the fault, while stresses of PFJ marginally reach yielding. On the contrary, the longitudinal strain distribution along the pipeline in Figure 9 indicates the drastical decrease of strains for PFJ compared to CP. Strains are concentrated at the flexible joints and at the same time lower strains are developed on the pipe steel parts, thus reducing the risk of failure due to buckling phenomena or tensile fracture. Strain concentration at the joints is due to the reduction of the pipeline’s global stiffness, as joints act as flexible internal hinges. Nevertheless, stresses remain rather high, which is not of great concern as the structural integrity can rely on the post-yielding strength of steel. It is also noted that the much sharper reduction of strains than stresses is due to the fact that in CP steel yielding does not allow stresses to grow proportionally to the very high developing strains.

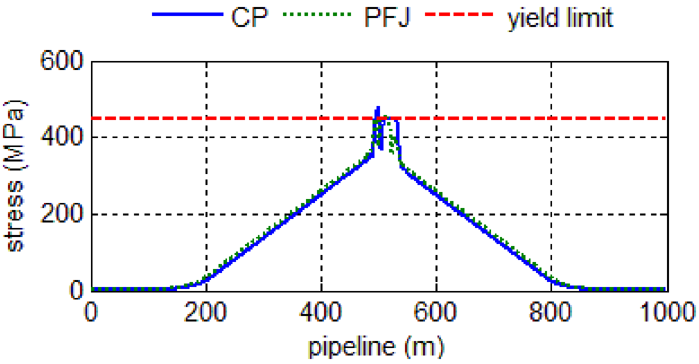


Figure 8: Longitudinal stress distribution of continuous pipeline and pipeline with flexible joints

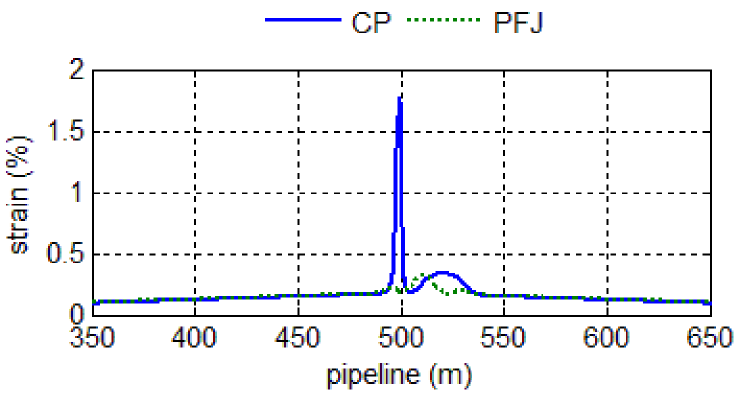


Figure 9: Longitudinal strain distribution of continuous pipeline and pipeline with flexible joints

Regarding soil behavior, the distribution of soil friction force (Figure 10) and vertical soil spring force (Figure 11) along the pipeline demonstrate that the introduction of joints does not modify significantly the length of soil plastification, as soil force development is due to pipeline relative movement in the trench, which is similar in both cases. For upward soil force a minor decrease is identified in case of PFJ.

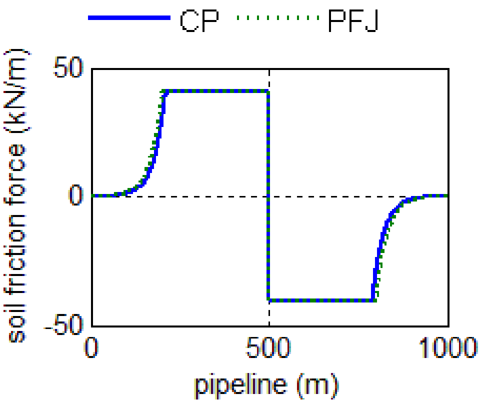


Figure 10: Frictional soil spring force

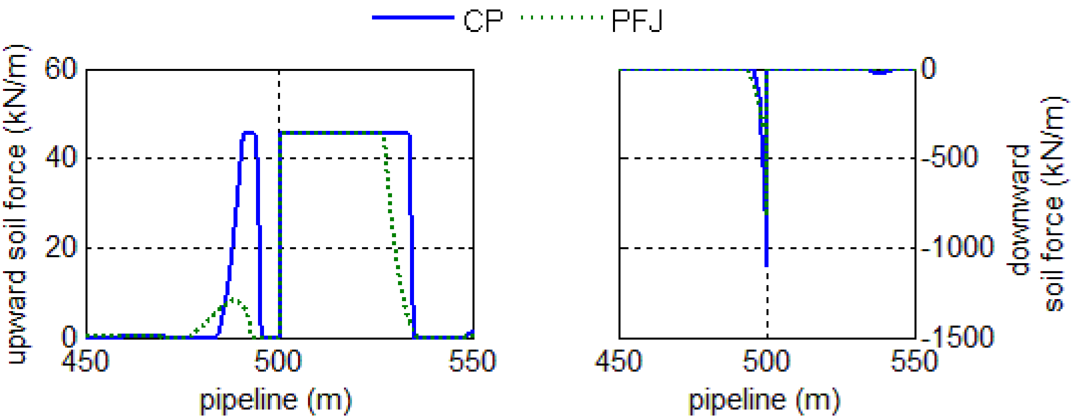


Figure 11: Vertical upward and downward spring forces

5.2 Strike-slip fault offset

The pipe deformation due to strike-slip fault offset is schematically illustrated in Figure 12 and results mainly in pipeline tension/compression and bending.

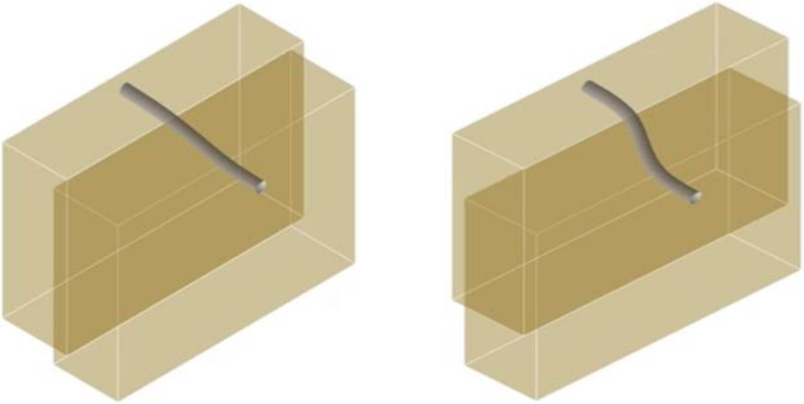


Figure 12: Schematic deformation of a continuous pipeline due to strike-slip faulting

The deformation of the continuous pipeline and the pipeline with flexible joints due to strike-slip fault type activation is depicted in Figure 13, indicating the transformation of the continuous system to an articulated one, due to joints acting as flexible internal hinges. Regarding the resulting forces on the pipeline, the tension distribution of PFJ in Figure 14 shows a 23% increase compared to CP. At the same time, the bending moment distribution in Figure 14 shows a 70% decrease, as the joints diminish bending at their locations. It is noted, also, that the pipeline deformation as well as the force distribution are characterized by symmetry around the fault, as lateral soil springs are activated having the same properties in tension and compression.

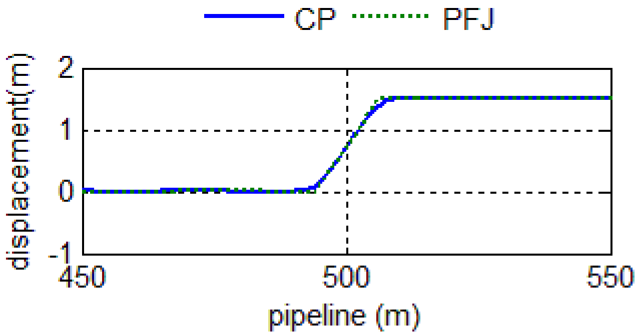


Figure 13: Deformation of continuous and pipeline with flexible joints

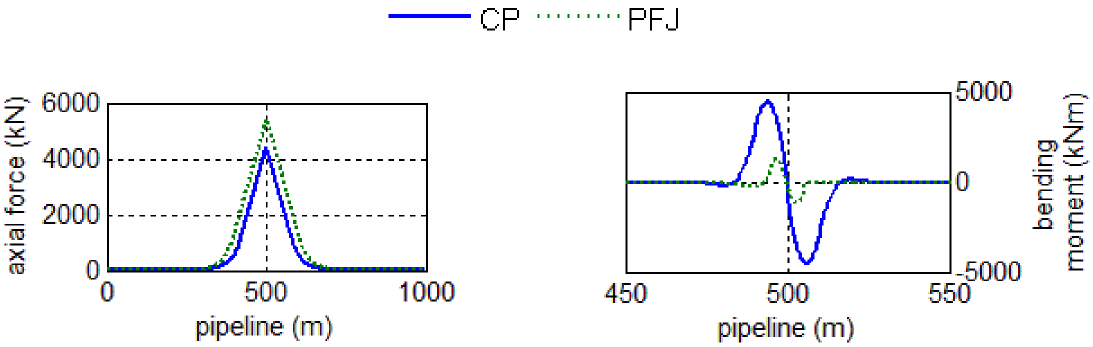
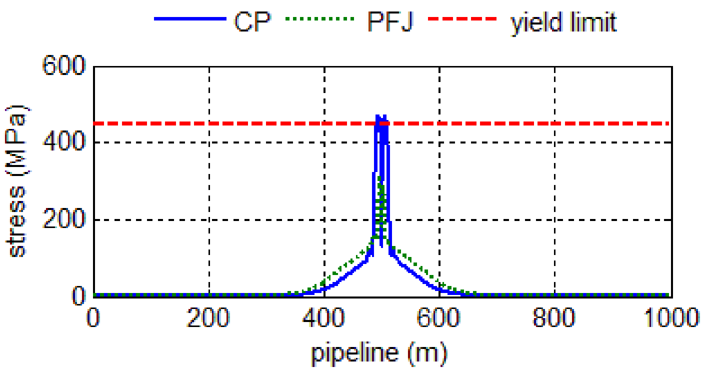


Figure 14: Axial force and bending moment of continuous and pipeline with flexible joints

The longitudinal stress distribution along τηε pipeline in Figure 15 shows steel yielding for CP in the close vicinity of the fault, while stresses for PFJ are well in the elastic range of the material. This significant difference in the stress state ensures the avoidance of plastic deformations for PFJ, while permanent deformations are expected on CP.



The longitudinal strain distribution along the pipeline in Figure 16 demonstrates the effectiveness of the joints, as the reduction is by a factor of 7. Given that the design of buried pipelines for earthquake resistance is strain-based, strain decrease ensures the avoidance of the dominant failure modes, i.e. local buckling and tensile fracture of girth welds.

Figure 15: Longitudinal stress distribution of continuous and pipeline with flexible joints

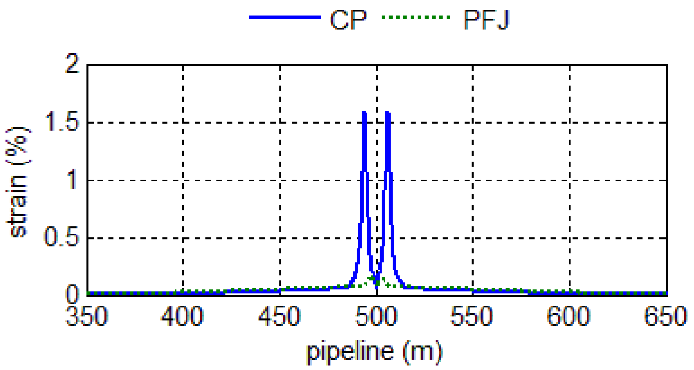


Figure 16: Longitudinal strain distribution of continuous and pipeline with flexible joints

The magnitude of pipeline movement in the trench is associated with soil response. As illustrated in Figure 13, the deformation of CP and PFJ do not differ substantially to rationalize different soil behavior for the two cases. Thus, the distribution of soil friction force and soil lateral force in Figure 17 demonstrate a minor increase in the former and a minor decrease in the latter, which is related, also, to the symmetrical mechanical response of the pipeline around the fault.

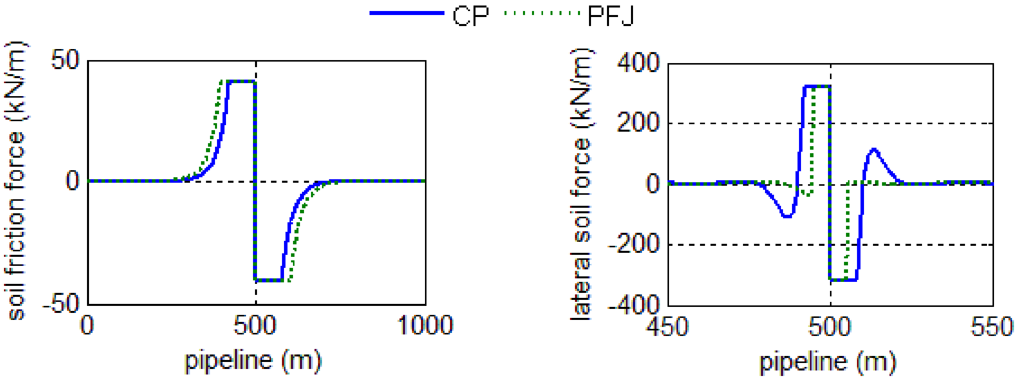


Figure 17: Friction and lateral soil spring forces

6. CONCLUSIONS

The response of continuous buried steel pipelines subjected to normal and strike-slip faulting has been compared to the one of the same pipelines with flexible joints using beam-type finite element models. The pipeline is assumed straight, crossing the fault line perpendicularly, while pipeline deformation is assumed to take place in a vertical plane in case of normal fault and in a horizontal plane in case of strike-slip fault. The pipeline under consideration is a typical large-diameter transmission steel pipeline of steel type API5L-X65.

On the basis of the obtained numerical results, the effectiveness of introduction of flexible joints between pipe adjacent parts, as an innovative mitigating measure against pipe failure, is investigated. The proposed mitigating approach aims at concentrating strains at the joints and retain steel parts virtually undeformed by modifying the structural system from continuous to segmented, given that joints act as flexible internal hinges. This approach differs from the commonly used measures, which aim at reducing the pipe – soil friction. The position of joints along the pipeline was selected based on the location of maximum developing bending moment of the continuous pipeline. The numerical results demonstrate the effectiveness of joints in terms of reducing bending moment, even though a slight increase of axial force is observed, due to the modification of the global stiffness and associated stress redistribution. It is also shown that decrease of longitudinal strains is considerable, especially in case of strike-slip fault type, while decrease of longitudinal stresses is moderate. Regarding soil behavior, it no remarkable change was observed, as the length of soil plastification depends on the pipeline movement within the trench. In conclusion, the results of the present study are encouraging regarding the efficiency of flexible joints as mitigating measures in pipelines crossing active seismic faults.

7. ACKNOWLEDGMENTS

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8. REFERENCES

ADINA R & D Inc. (2006), “Theory and Modeling Guide. Volume I: ADINA, Report ARD 08-7”. ADINA R & D Inc., Watertown – Boston, USA.

ALA American Lifelines Alliance (2001), “Guideline for the Design of Buried Steel Pipe – July 2001 (with addenda through February 2005)”. American Society of Civil Engineers, USA.

Ariman, T. and Lee B. J. (1991), “Tension/Bending behavior of buried pipelines under large ground deformation in active faults”. U.S. Conference on Lifeline Earthquake Engineering, Technical Council on Lifeline Earthquake Engineering, ASCE, New York, Vol. 4, pp. 226-233.

Bekki, H., Kobayashi K., Tanaka Y. and Asada T. (2002), “Dynamic behavior of buried pipe with flexible joints in liquefied ground”, Journal of Japan Sewage Association, Vol. 39, pp. 201-208.

Gantes, C. J. and Bouckovalas, G. D. (2013), “Seismic verification of high pressure natural gas pipeline Komotini – Alexandropoulis – Kipi in areas of active fault crossings”. Structural Engineering International, Vol. 2, pp. 204-208.

Joshi, S., Prashant, A., Deb, A. and Jain, S. K. (2011), “Analysis of buried pipelines subjected to reverse fault motion”. Soil Dynamics and Earthquake Engineering, Vol. 31, pp. 930-940.

Karamitros, D. K., Bouckovalas, G. D. and Kouretzis, G. D. (2007), “Stress analysis of buried steel pipelines at strike-slip fault crossings”. Soil Dynamics and Earthquake Engineering, Vol. 27, pp. 200-211.

Karamitros, D. K., Bouckovalas, G. D., Kouretzis, G. D. and Gkesouli, V. (2011), “An analytical method for strength verification of buried steel pipelines at normal fault crossings”. Soil Dynamics and Earthquake Engineering, Vol. 31, pp. 1452-1464.

Kennedy, R. P. and Kincaid R. H. (1983), “Fault crossing design for buried gas oil pipeline”. ASME, Proceeding of the PVP Conference 1983, Vol. 77, pp. 1-9.

Kennedy, R. P., Chow, A. W. and Williamson, R. A. (1977), “Fault movement effects of buried oil pipeline”. ASCE Journal of Transportation Engineering, Vol. 103, pp. 617-33.

Liu, M., Wang, Y-Y. and Yu, Z. (2008), “Response of pipelines under fault crossing”. Proceedings of the International Offshore and Polar Engineering Conference, Vancouver, BC, Canada.

Monroy-Concha, M. (2013), “Soil restraints on steel buried pipelines crossing active seismic faults”, Ph.D. The University of British Columbia, Canada.

Newmark, N. M. and Hall, W. J. (1975), “Pipeline design to resist large fault displacement”. Proceedings of U.S. National Conference on Earthquake Engineering, pp. 416-25.

O’ Rourke, M. J. and Liu X. (1999), “Response of buried pipelines subjected to earthquake effects. Monograph No. 3”. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, USA.

O’Rourke, M. J. and Liu, X. (2012), “Seismic design of buried and offshore pipelines. Monograph No. 4”. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, USA.

Peng, L. C. and Peng, A. (2009), “Pipe stress engineering”, ASME Press, New York, USA.

Sanghal, A. C. (1980), “Strength characteristics of buried jointed pipelines”. Report to the Engineering Foundation and ASCE, Grant No. RC-A-77-6A, USA.

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

Trautmann, C. H. and O’Rourke, T. D. (1983), “Behavior of pipe in dry sand under lateral and uplift loading”. Geotechnical Engineering Report 83-7, Cornell University, USA.

Trifonov, O. V. (2014), “Numerical stress-strain analysis of buried steel pipelines crossing active strike-slip faults with an emphasis on fault modeling aspects”. ASCE Journal of Pipeline Systems Engineering and Practice, in press (available online).

Trifonov, O. V. and 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, Vol. 30, pp. 1298-1308.

Vazouras P., Karamanos S. A. and Dakoulas P. (2010), “Finite element analysis of buried steel pipelines under strike-slip fault displacements”. Soil Dynamics and Earthquake Engineering, Vol. 30(11), pp. 1361-1376.

Vazouras P., Karamanos S. A. and Dakoulas P. (2012), “Mechanical behavior of buried steel pipes crossing active strike-slip faults”. Soil Dynamics and Earthquake Engineering, Vol. 41, pp. 164-180.

Vougioukas, E. A., Theodossis, C. and Carydis P. G. (1979), “Seismic analysis of buried pipelines subjected to vertical fault movement”. ASCE Journal of Technical Councils, Vol. 105(TCI), pp. 432-441.

Wang L. R. L. and Yeh Y. A. (1985), “A refined seismic analysis and design of buried pipelines subjected to vertical fault movement”. Earthquake Engineering and Structural Dynamics, Vol. 13, pp. 75-96.

Yun, H. D. and Kyriakides, S. (1990), “On the beam and shell modes of buckling of buried steel pipelines”. Soil Dynamics and Earthquake Engineering, Vol. 9, pp. 179-193.