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Protection measures for buried steel pipelines subjected to fault rupture

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ABSTRACT

Buried steel pipelines are critical lifelines that supply necessary energy resources for the economy and society. Pipelines are hazardous structures and any potential failure caused by fault rupture has to be eliminated. Various alternative protection measures are applied in practice or have been studied by researchers against the consequences of faulting on buried pipes. A comprehensive evaluation of the effectiveness of protection measures is presented in the paper for pipes subjected to normal and reverse fault rupture. The analysis is carried out numerically by employing the beam-on-Winkler-foundation model. The effectiveness of protection measures is compared to extract conclusions regarding their applicability. Results indicate that the most effective protection measure among the conventional ones examined is the trench backfilling with pumice, while steel grade upgrade and wall thickness increase provide little protection. Trench widening was found to be ineffective, while maximum strain reduction is achieved in the case of the introduction of flexible joints.

Keywords: buried pipeline, fault rupture, protection measures, numerical analysis

INTRODUCTION

Buried steel fuel transmission pipelines are critical parts of the energy infrastructure and connect oil and gas production sites, refineries, storage facilities, and customers traversing areas of various geological conditions. When seismic areas are crossed, the potential of fault rupture stands as the major threat to pipe integrity [O' Rourke and Liu (2012)]. The tectonic fault movement is an earthquake-induced action causing permanent ground displacements due to the differential movement of two soil blocks and can range from a few centimeters up to a few meters. Pipelines are elongated structures that are buried below the ground surface and in case of faulting are forced to follow the ground movement by experiencing large deformation and consequently high strain-state. The main failure modes that may occur are local buckling of the pipe wall and tensile fracture at weld locations between adjacent segments, depending on the relative orientation of the fault and the pipe, as well as the direction of faulting. Normal fault rupture causes pipe tension and bending, while reverse rupture causes pipe compression and bending. Safeguarding the integrity of pipelines remains a compelling task for pipeline operators, agencies and fuel companies.

The assessment of pipe mechanical behavior due to faulting has drawn the attention of researchers for over four decades. Analytical solutions, as those presented, for example by Karamitros et al. (2011), Trifonov and Cherniy (2012), Zhang et al. (2016) and Sarvanis et al. (2017), are useful tools for the rapid pipe assessment. However, numerical analysis approaches are necessary for the pipe design by employing either the beam-on-Winkler-foundation model (pipe modeling with beam-type elements and soil with springs), for example

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Joshi et al. (2011), Uckan et al. (2015), Liu et al. (2016) and Melissianos and Gantes (2017), or the continuous one (pipe modeling with shell elements and soil with 3D solid elements), for example Vazouras et al. (2015), Tifonov (2015), Banushi et al. (2018). The beam-type model is useful and reliable for practical applications and is, also, recommended by pertinent structural codes, for example ALA (2005) and Eurocode 8 – Part 4 (2006).

The design of buried pipelines subjected to seismic fault rupture is carried out in strain terms. Codes and standards provide expressions for the limitation of tensile and compressive strains in order to avoid failure caused by tensile rupture and local buckling, respectively. The operable strain limits suggested by ALA (2005) are adopted in the present study. The tensile (ε_t) and compressive (ε_c) strain limits are:

$$\varepsilon_t = 2\% \tag{1}$$

$$\varepsilon_c = 0.5(t/D') - 0.0025, \text{ with } D' = D/[1\text{-}3(D\text{-}D_{\min})/D] \tag{2}$$

where D is the pipe diameter, t is the pipe wall-thickness and $D_{\min}$ is the minimum pipe diameter due to possible ovalization.

The pipe mechanical behavior due to faulting has been extensively studied, while pipe protection measures have not been examined in depth. Pipe designers apply conventional measures, such as steel grade upgrade and wall thickness increase to improve pipe strength and stiffness, respectively, or trench backfilling with loose granular soil to decrease pipe-soil friction. However, the considerable repercussions of a potential pipe failure necessitate a comparative work on the effectiveness of these measures in terms of strain reduction. The objective of this study is to present an overview of such protection measures for pipes subjected to normal and reverse fault rupture, following the corresponding study for the case of strike-slip faulting presented by Gantes and Melissianos (2016).

PIPE PROTECTION AGAINST FAULTING

The general regulatory recommendation [ALA (2005), Eurocode 8 – Part 4 (2006)] is to avoid fault crossings by re-routing the pipeline. Nevertheless, physical obstacles, environmental restrictions, and regulatory limitations render this recommendation quite inapplicable, especially when it comes to seismic regions. An additional recommendation is the use of straight pipe segments in fault crossing, i.e. the avoidance of route change with sharp bends that may act as anchor points. In practice, apart from these guidelines, additional specific measures are necessary, which can be classified based on the protection "mechanism": (1) Friction Reduction Measures that aim at reducing the pipe-soil friction, (2) Pipe Strengthening Measures that aim at increasing pipe strength and stiffness and (3) Other Measures that cannot be categorized in one of the two previous groups.

Friction reduction measures

Pipe movement in the trench due to the fault offset leads to the generation of friction at the pipe-soil interface. There are measures that have been proposed and/or applied in practice that aim at reducing this friction:

- Pipe wrapping with geotextile [Gantes and Bouckovalas (2013)] for friction reduction and consequently increase of the anchor length. However, trench width dominates the effectiveness of this measure and it was experimentally found by Monroy-Concha (2013) that pipe wrapping with a double layer geotextile is effective only if the trench width is lower than two times the pipe diameter.
- Trench backfilling with loose granular soil, for example, with pumice, as suggested by Gantes and Bouckovalas (2013).
- Excavation of a wider trench, aiming at "allowing" pipe deformation to take place over a longer distance and therefore avoid strain concentration [Gantes and Bouckovalas (2013)].
- Installation of geocells and geogrids in the trench as backfilling "material", as proposed by Hedge and Sitharam (2015).

- Trench backfilling with tire-derived aggregate surrounded by sand, as proposed by Sim et al. (2012) and Ni et al. (2018).

Pipe strengthening measures

Pipe strengthening is a common protection measure that is adopted by designers. There are three options:
- Steel grade upgrade [Gantes and Bouckovalas (2013), Karamanos et al. (2014)].
- Wrapping the pipe with composite wraps [Mohtari and Alavi Nia (2015), Trifonov and Cherniy (2016)] to increase pipe strength.
- Wall thickness increase [Gantes and Bouckovalas (2013), Karamanos et al. (2014)] to improve pipe cross-section stiffness.

Other measures

The group of Other Measures includes those that cannot be classified in one of the two previous categories. These measures have been mainly proposed by researchers:
- Besstrashnov and Strom (2011) proposed the construction of a dog-leg structure that involves pipe route changing with a very high radius bend in order to allow pipe deformation to take place over a larger area.
- Hasegawa et al. (2014) proposed the creation of a predefined buckling pattern that consists of localized deformation of the pipe wall at specified locations aiming at controlling the pipe local deformation.
- Zhang et al. (2016) proposed a protective device that aims at reducing the potential of local buckling by applying external hydrostatic pressure.
- Melissianos et al. (2016) proposed the integration of bellow-type flexible joints between adjacent pipe parts in the fault vicinity. The aim is to concentrate strains at the joints by transforming the continuous structural system to segmented and consequently retaining pipe steel parts barely undeformed and hence unstrained.

Remarks on protection measures

The selection of a protection measure is based on achieving a balance between safety and economy. Indicatively, some of the issues that designers have to consider within a techno-economic framework are listed below:
- Cost of additional excavation in case of constructing a wider trench.
- Cost of purchase and installation of friction-reducing geotextile.
- Cost, availability, and transportation to the construction site of well-graded pumice, or geocells/geogrids, or tire-derived aggregate taking also into account that the fault crossing might be located at a remote or mountainous site.
- Production and purchase cost of customized flexible joints.
- Satisfaction of safety requirements dictated by regulatory authorities and the pipeline owner.

PIPELINE NUMERICAL MODELING

The pipeline-fault crossing is numerically modeled using the general purpose FEM software ADINA [ADINA R&D (2017)]. A beam-type model is developed, based on the suggestions of ALA (2005). The pipe is meshed into PIPE elements that are two-node Hermitian beam-type elements with additional degrees of freedom to account for the strains caused by in- and out-of-plane cross-section ovalization. Longitudinal mesh density of the pipe is equal to 0.25m, following a pertinent sensitivity analysis with respect to accuracy and computational cost. Modeling length is sufficiently high for the effects of imposed displacements to vanish. Therefore, boundary conditions at the pipeline ends have no effect.

The surrounding soil is modeled with non-linear (bilinear) translational springs in four directions, following the provisions of ALA (2005): (1) axial springs that model the pipe-soil friction, (2) transverse horizontal springs that model the soil resistance to pipe lateral movement in the trench, (3) vertical upward and (4) vertical downward springs that model the soil resistance to pipe vertical movement in the trench. Springs are two-node elements that “connect” a pipe node and a “ground” node. The latter is considered fixed in the fault footwall and movable on the fault hanging wall, where fault offset is applied as imposed displacement (Fig. 1). Soil spring properties are estimated according to ALA (2005) provisions. The effect of trench geometry (depth, width and walls incline) is taken into account by employing the correction coefficients proposed by Chaloulos et al. (2015) and Chaloulos et al. (2017) for the calculation of the transverse horizontal spring properties.

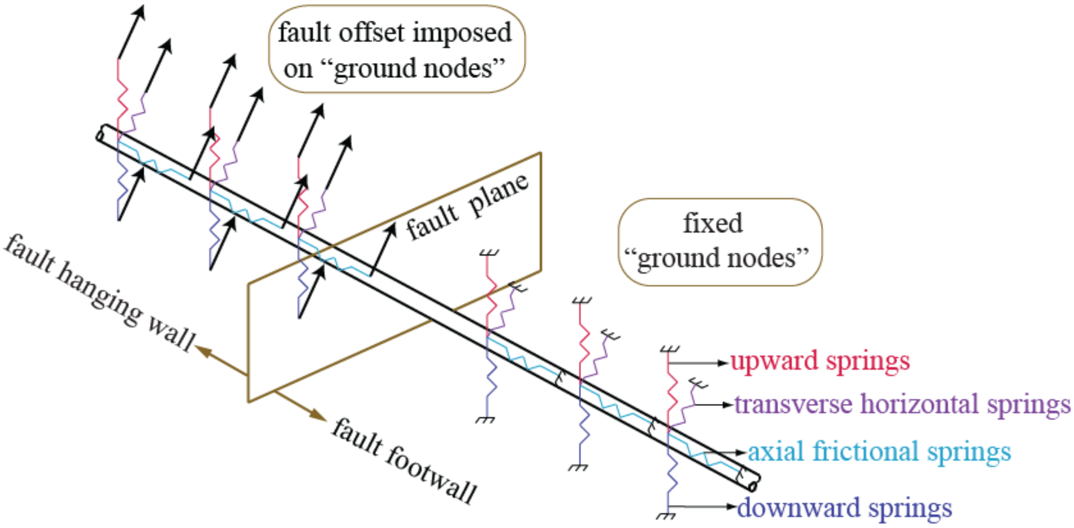


Figure 1. Pipeline-fault crossing numerical model [adapted from Gantes and Melissianos (2016)]

Pipelines are numerically analyzed by considering geometrical and material non-linearity and employing Newton-Raphson solution algorithms. To achieve convergence and reduced solution time, the automatic time stepping option is selected. If there is no convergence with the predefined time step, then the algorithm automatically sub-divides the time step until convergence is reached, while the time step might be increased to accelerate the solution [ADINA R&D (2017)]. The number of analysis steps is sufficiently high to comply with the assumption of the quasi-static application of the imposed displacement. Furthermore, the numerical considerations presented by Melissianos and Gantes (2017) and the suggestions of Kojic and Bathe (2004) are taken into account. The pipe integrity assessment is carried out via a safety checking of strains, i.e. $\varepsilon_{\mathrm{demand}} \leq \varepsilon_{\mathrm{capacity}}$, where strain demand ($\varepsilon_{\mathrm{demand}}$) is obtained/calculated at integration points of all cross-sections along the pipe and compared against strain capacity ($\varepsilon_{\mathrm{capacity}}$), namely the strain limitation expressions of ALA (2005), as presented in Eqs. (1) and (2).

CASE STUDY

Reference pipeline

A typical API5L-X65 pipeline is considered as the control case (reference/unprotected pipeline), featuring diameter D = 914mm and wall thickness t = 12.7mm. Pipeline steel is modeled as a bilinear material with properties: Young's modulus E = 210GPa, yield stress f_y = 448.5MPa, failure stress f_u = 531MPa and failure strain ε_u = 18%. The area of the pipeline-fault crossing is a medium density clay with internal friction angle 23°, cohesion 20kPa and unit weight 19kN/m^3. The trench cross-section is depicted in Fig. 2 and is backfilled with cohesionless medium density sand, having unit weight 18kN/m^3 and internal friction angle 36°.

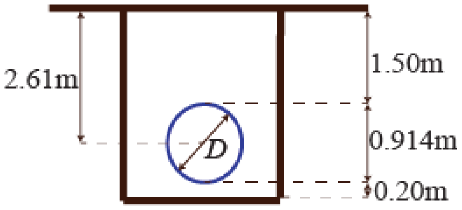


Figure 2. Trench cross-section of the case study

It is also assumed that the pipeline is corrosion- and defect-free, the internal pressure is ignored, restricting the investigation to unpressurized pipes, service loads and external non-seismic actions are not taken into account and finally, the aquifer is assumed to be located below the pipe burial level and thus buoyancy is neglected.

Pipe-fault crossing geometry

The pipe-fault crossing geometry is the key aspect that determines the pipe response to faulting and in particular the fault dip angle (ψ) and the pipe-fault crossing angle (β), as illustrated in Fig. 3. Both angles define whether the pipe will be subjected mainly to tension/compression or bending.

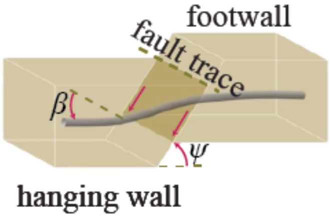


Figure 3. Pipeline-fault crossing geometry [adapted from Gantes and Melissianos (2016)]

Five characteristic combinations of angles are selected for the case study and are as follows: (a) $\psi = 60^o$ and $\beta = 70^o$, (b) $\psi = 60^o$ and $\beta = 90^o$, (c) $\psi = 75^o$ and $\beta = 70^o$, (d) $\psi = 75^o$ and $\beta = 90^o$, (e) $\psi = 90^o$ and $\beta = 90^o$. The following remarks are necessary regarding the selection of the combinations:

- Fault dip angle: The case of a vertical fault plane ($\psi = 90^o$) is rather theoretical but its examination is useful for comparison purposes and thus in nature, fault dip angle is usually $\psi < 90^o$. In general, as angle tends to $\psi = 90^o$, then the pipe is subjected mainly to bending, while for lower angle ψ, the pipe is subjected mainly to tension for normal fault and to compression for reverse faults.
- Pipe-fault crossing angle: Previous studies have shown that the optimal crossing angle is $\beta = 90^o$ [Paolucci et al. (2010), O’Rourke and Liu (2012), Ni and Mangalathu (2018)]. However, numerous limitations are encountered in the route selection procedure, for example, unstable soil, avoidance of sharp bends or populated areas or environmentally sensitive areas, and thus selecting the optimal angle is difficult. In general, as angle tends to $\beta = 90^o$, the pipe is subjected mainly to bending, while for lower angle β, the pipe is subjected mainly to tension for normal fault and to compression for reverse faults.

Protection measures

The examined measures of the case study are (1) steel grade upgrade (SG), (2) wall thickness increase (W), (3) trench backfilling with pumice (PUM), (4) trench widening (TR) and (5) introduction of flexible joints (FJ). The first four measures are conventional ones that have been used in practice, while the fifth, namely the introduction of flexible joints, is an innovative protection measure that has been proposed by Melissianos et al. (2016). Flexible joints are commercial products used in industrial piping for the absorption of thrust, thermal expansion, and machinery vibration, but have not been implemented in buried pipes under faulting. The numerical and experimental studies presented by Melissianos et al. (2016) and Melissianos et al. (2017), respectively, indicate that it is a promising solution towards safeguarding the pipe integrity. The examined measures are summarized and listed in Table 1.

The burial depth of the pipelines is within the range of $1.0D$ to $3.0D$ typically at fault crossings. This depth is mostly earth fill (upper soil layers) with heterogeneous properties. These upper layers may alter the fault offset direction from the underlying bedrock to the ground surface and therefore the soil rupture may not “appear” on the ground surface where it is expected to do so. This fact is referred to as fault trace uncertainty and its length along the pipeline may range up to a few hundred meters on each side of the fault trace. Hence, seismic protection measures have to be applied along this entire length. In the present study, the uncertainty length is assumed to be 250m on each side of the fault trace.

In more detail:

- Steel grade upgrade (SG): The pipeline steel is upgraded to API-5L X80 with Young’s modulus E = 201GPa, yield stress f_y = 530MPa, failure stress f_u = 621MPa, and failure strain ε_u = 18%.

- Wall thickness increase (W): The pipe wall thickness is increased from 12.70mm (reference pipeline) to 19.05mm, which are both commercially available thickness values for steel pipes with diameter D = 914mm.
- Pumice backfilling (PUM): Pumice is used as backfilling material, having unit weight 8kN/m^3, cohesion 0KPa, and internal friction angle 36°. Pumice backfilling is numerically modeled by recalculating soil spring properties. It is noted that downward spring properties are estimated based on the native soil properties and thus are not modified.
- Trench widening (TR): The reference pipeline is buried in a trench with a width equal to two times the pipe diameter. The trench is assumed to be widened to three times the pipe diameter, which is equal to 2.74m for the case study. Trench widening is numerically applied by modifying the lateral (horizontal transverse) soil spring properties according to the work of Chaloulos et al. (2017).
- Introduction of flexible joints (FJ): Hinged bellow-type flexible joints are introduced in the pipeline in the fault vicinity, following the topology configuration presented by Melissianos et al. (2016). Bellows are numerically modeled as generic joints [EJMA (2008), Peng and Peng (2009)], namely, they are represented by an elastic bi-rotational spring, while axial and lateral movement and torsion are restricted using numerical constraints. It is noted that the adopted modeling technique has been verified by Melissianos et al. (2017).

Table 1. Protection measures under investigation

Acronym	Measure	Brief description	Application
SG	Steel grade upgrade	Increase steel quality to improve pipe strength	Practice [Gantes and Bouckovalas (2013), Karamanos et al. (2014)]
W	Wall thickness increase	Increase pipe wall thickness to improve pipe stiffness	Practice [Gantes and Bouckovalas (2013), Karamanos et al. (2014)]
PUM	Pumice	Trench backfilling with pumice to reduce friction	Practice [Gantes and Bouckovalas (2013), Besstrashnov and Strom (2011)]
TR	Trench widening	Increase trench width for the pipe to deform freely	Practice [Gantes and Bouckovalas (2013), Besstrashnov and Strom (2011)]
FJ	Introduction of flexible joints	Introduction of flexible joints in the pipe to concentrate strains and retain the pipe segments undeformed	Research [Melissianos et al. (2016), Melissianos et al. (2017)]

RESULTS AND DISCUSSION

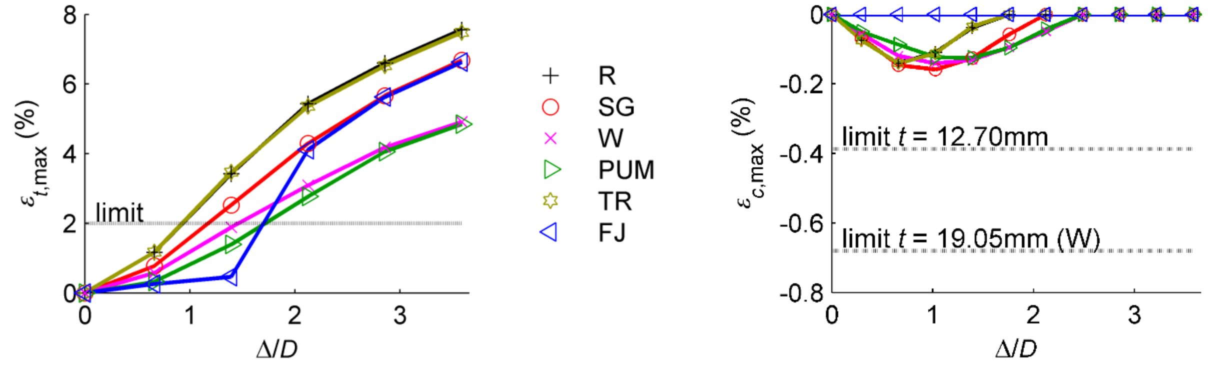
The effectiveness of each protection measure is examined through the evolution of the maximum tensile ($\varepsilon_{t,\max}$) and compressive ($\varepsilon_{c,\max}$) strains with respect to the normalized fault offset (Δ/D), presented in Figs. 4 and 5 for normal and reverse faults, respectively. Strains obtained from protected pipes are compared to those of the reference/unprotected pipe (R). The adopted operable strain limits after ALA (2005) are also presented in each diagram. The cases of normal and reverse fault rupture are examined separately in the next sections. It is noted that the protection measures are examined from a technical perspective, as there are no publicly available reliable data to carry out a comprehensive techno-economic analysis of the efficiency of protection measures.

Normal fault rupture

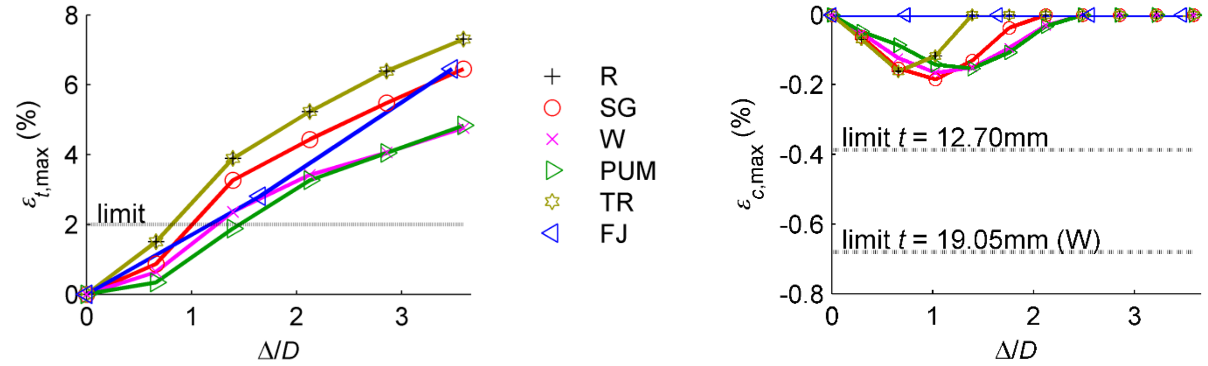
The evolution of tensile and compressive strains for the case of normal fault rupture for the five combinations of angles ψ and β is shown in Fig. 4. It is observed that for low fault offset the pipe experiences in all cases bending and consequently tension and compression are developed. Then, as the fault offset increases further, it leads to dominant tension and thus compressive strains vanish. Regarding the effectiveness of the protection measures, the following conclusions can be drawn:

- Steel grade upgrade (SG) provides relatively low protection compared to other measures. The effectiveness of wall thickness increase (W) is slightly lower than the trench backfilling with pumice (PUM).
- Trench backfilling with pumice (PUM) is an effective protection measure regardless of the fault angle and the crossing angle. Protection is provided against both tension and compression and the fault offset for pipe tensile rupture is roughly two times higher compared to the reference/unprotected pipe (R). Trench backfilling with pumice stands as the most effective conventional protection measure.
- Trench widening (TR) is expected to provide pipe protection in case there is a lateral pipe movement in the trench, namely for $\beta < 90^{\circ}$. It is concluded from Fig. 4 that for the specific case study, trench widening is ineffective.
- The effectiveness of the introduction of flexible joints (FJ) depends on the fault offset magnitude and the pipe-fault crossing geometry. This is attributed to the hinged layout of the joints that can only undergo biaxial rotation, while axial tensile strains due to the overall tension cannot be relieved. However, compression is eliminated in all cases. In case of $\psi < 90^{\circ}$ and $\beta < 90^{\circ}$ and for low fault offset magnitude (roughly $\Delta/D < 2$), flexible joints provide outstanding protection through the significant reduction of tensile strains as the pipe is subjected to bending. Then, as the fault offset increases and the pipe is subjected mainly to tension, a rapid increase in pipe tensile strains is observed and the protection is progressively eliminated. The ideal pipe-fault crossing geometry for the joints' maximum efficiency is the theoretical one with $\psi = 90^{\circ}$ and $\beta = 90^{\circ}$.
- The pipe-fault crossing geometry is found not to significantly affect the level of protection each conventional measure provides. On the other hand, the effectiveness of flexible joints, which act as "internal hinges" in the structural system, has been shown to depend on the crossing geometry.

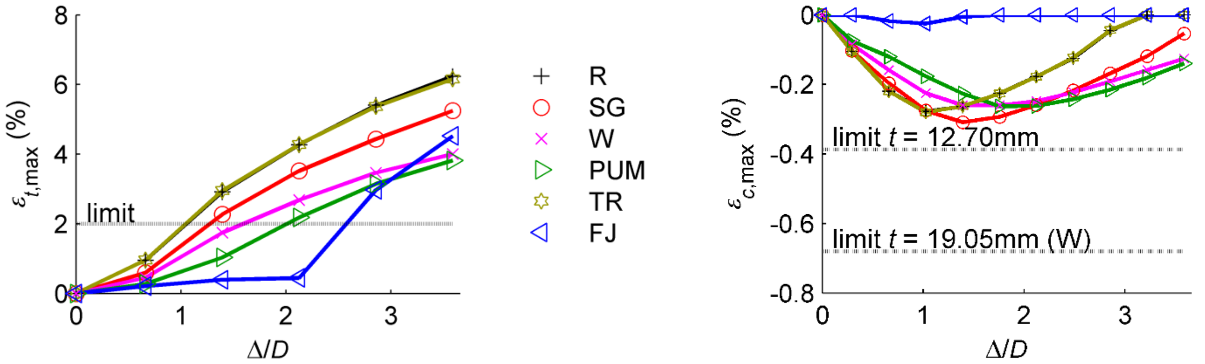
As a general comment, the case of pipe-fault crossing geometry with $\psi = 90^{\circ}$ is rather theoretical and a vertical fault plane can be hardly found in nature. In this case, the pipe, even though it is elongated due to fault movement, is expected to fail due to local buckling, as compressive strains exceed the code-based limit for lower fault displacement than the tensile strains. Similar results have been presented by Trifonov (2018).



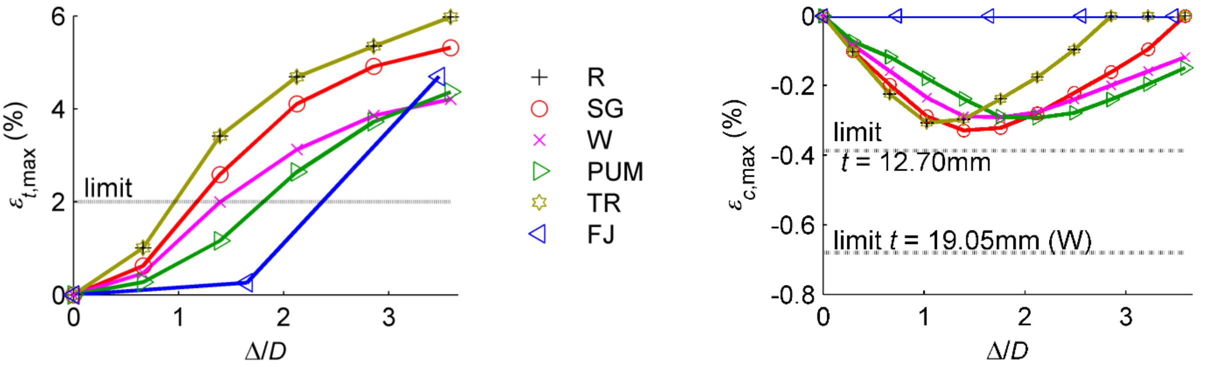
(a) fault dip angle $\psi = 60^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$



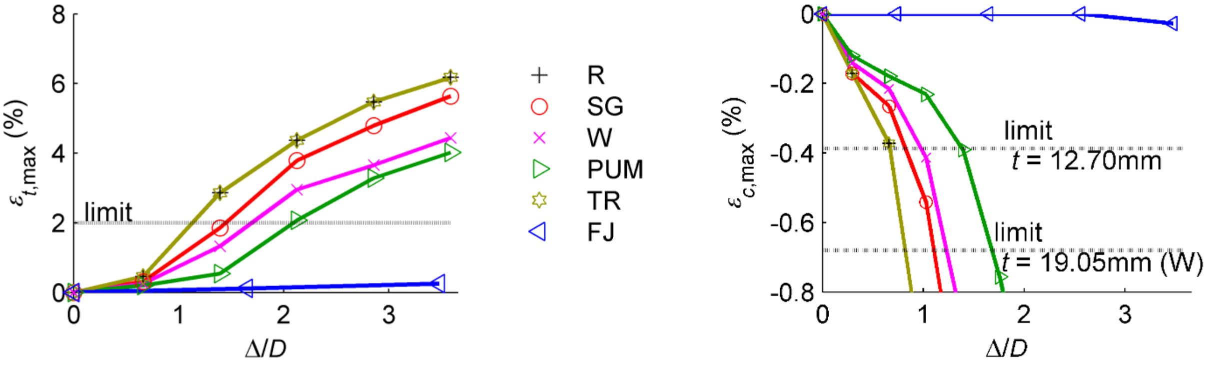
(b) fault dip angle $\psi = 60^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$



(c) fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$



(d) fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$

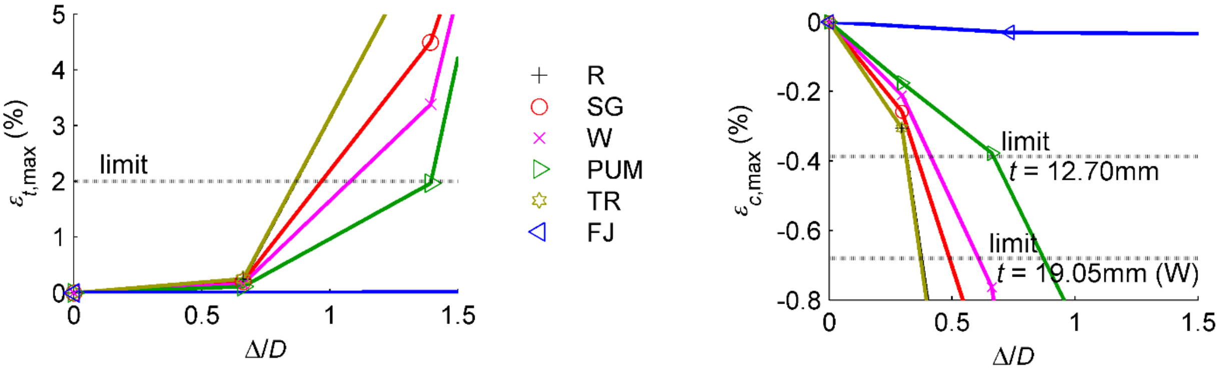


(e) fault dip angle $\psi = 90^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$

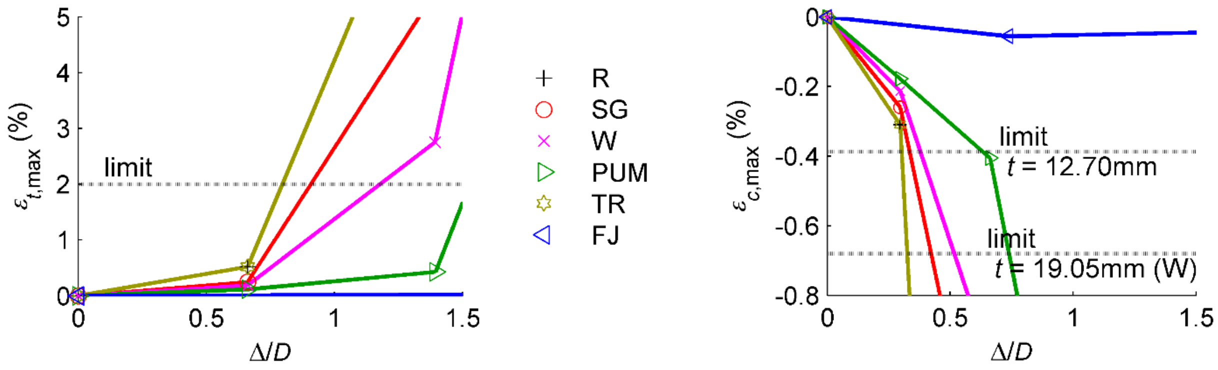
Figure 4. Tensile ($\varepsilon_{t,\max}$) and compressive ($\varepsilon_{c,\max}$) strain evolution with respect to fault offset magnitude for normal fault rupture

Reverse fault rupture

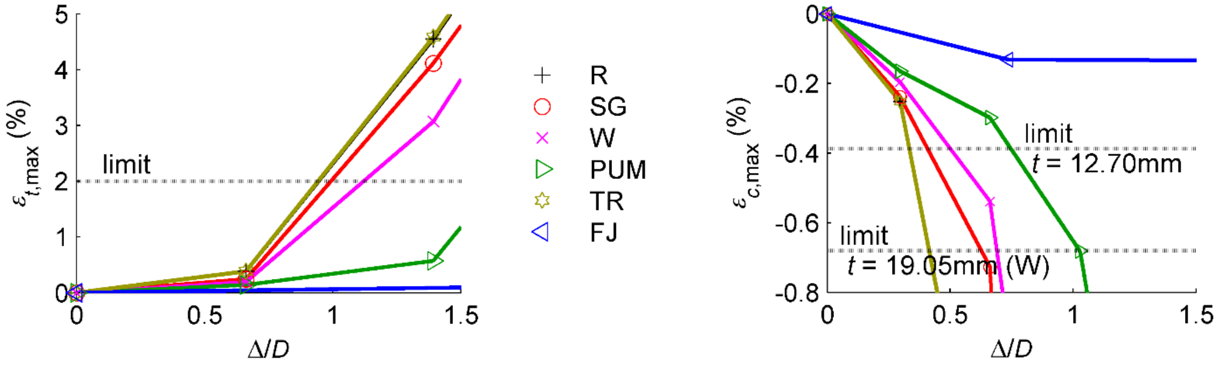
The evolution of tensile and compressive strains for the case of reverse fault rupture for the five combinations of angles ψ and β is shown in Fig. 5. Reverse fault rupture leads to significant pipe compression and thus the pertinent code-based strain limits are exceeded for very low fault offset magnitude. The primary observation in Fig. 5 is that, regardless of the fault crossing geometry, there is a certain “pattern” regarding the efficiency of the protection measures. In particular, trench widening (TR) is inefficient and the pertinent strain evolution curve is very close to the one of the reference/unprotected pipe (R). Then, the sequence of the efficiency of different protection measures, from the less to the most efficient, is steel grade upgrade (SG), wall thickness increase (W), trench backfilling with pumice (PUM) and the introduction of flexible joints (FJ). It is concluded that among the conventional measures, pumice backfilling (PUM) can provide sufficient pipe protection against tensile fracture and/or local buckling, given that the pertinent strain limit is reached for almost two times higher fault offset magnitude than for the other measures. As also indicated in the case of normal faulting, the introduction of flexible joints (FJ) stands out as the most efficient and promising protection measure for pipe protection. This is succeeded by the relative rotation of the adjacent pipe segments. However, it is noted that further analysis is necessary in order to confirm the pipe operability in case of excessive rotation of the joints.



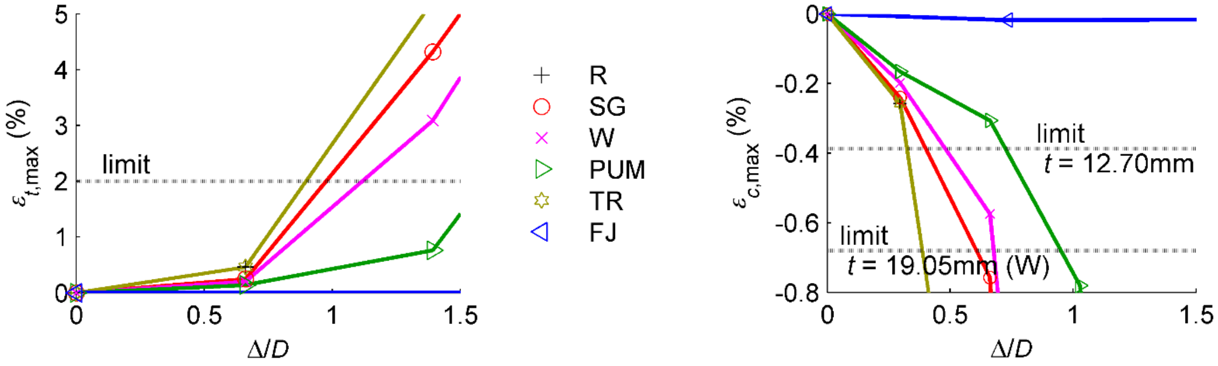
(a) fault dip angle $\psi = 60^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$



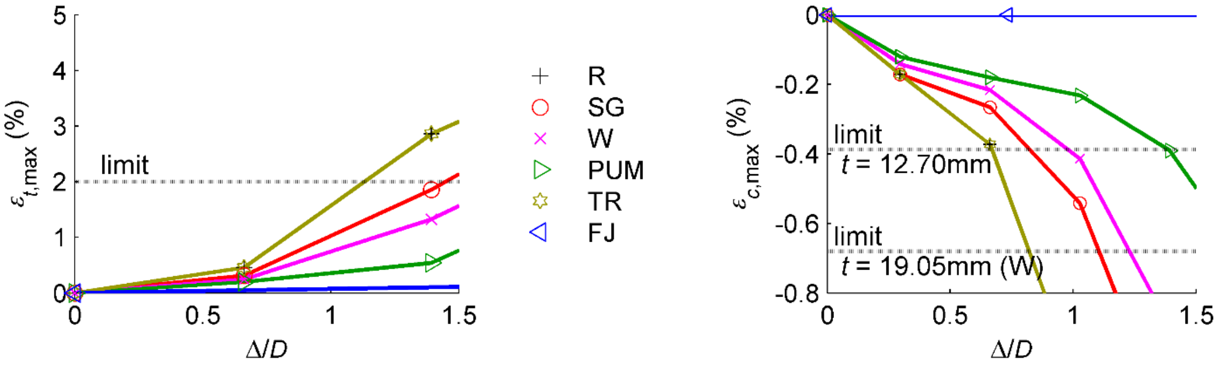
(b) fault dip angle $\psi = 60^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$



(c) fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$



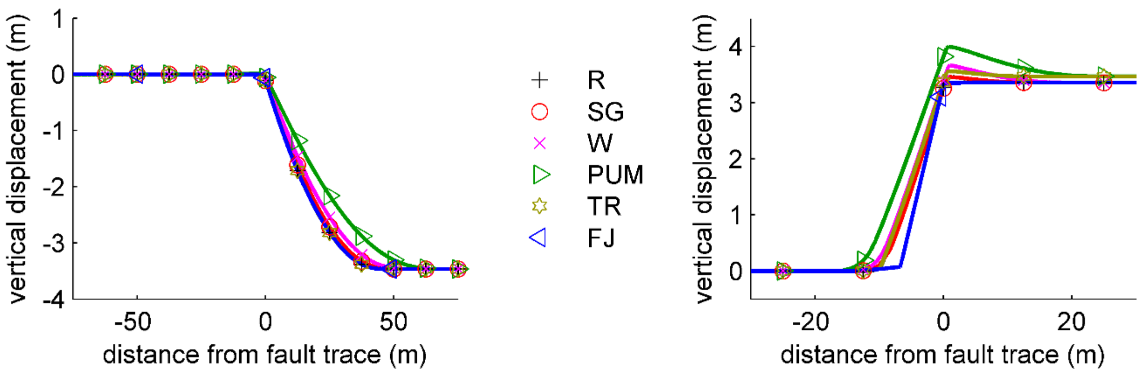
(d) fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$



(e) fault dip angle $\psi = 90^{\circ}$ and pipe-fault crossing angle $\beta = 90^{\circ}$

Figure 5. Tensile ($\varepsilon_{t,\max}$) and compressive ($\varepsilon_{c,\max}$) strain evolution with respect to fault offset magnitude for reverse fault rupture

The pipeline vertical deformation for fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$ is displayed in Fig. 6(a) in case of normal and in Fig. 6(b) in case of reverse fault rupture. The pipeline vertical deformation in case of normal fault rupture (Fig. 6(a)) indicates that protection measures do not modify the pipeline deformation pattern, apart from the case of trench backfilling with pumice (PUM) where the pipe deformation is smoother due to the reduced normal forces acting on the pipe caused by the decrease in the soil stiffness and strength. In the case of reverse fault rupture (Fig. 6(b)), the modification of pipe deformation scheme is more profound. Trench backfilling with pumice (PUM) leads to pipe smoother deformation, while noteworthy relative rotation of pipe adjacent segments is detected in the pipe with flexible joints (FJ), raising concerns regarding pipe operability that has to be considered in the analysis and in particular whether inspection pigs are able to pass through the rotated bellows. Finally, regarding the pipeline deformation in case of normal fault rupture that is displayed in Fig. 6(a), it is noted that the pipe deformed segment over the fault hanging wall is much longer than the corresponding one over the fault footwall. This difference is attributed to the different soil resistance to pipe upward and downward movement, given that the stiffness of upward springs is much lower than the one of the downward springs. Thus, soil resistance forces at the fault footwall reach the yielding value progressively with fault offset increase, while soil resistance forces at the fault hanging wall exceed the yielding value for very low fault offset and extend over the entire deformed pipe segment [Karamitros et al. (2011)]. Therefore, considering the different stiffness of upward and downward springs, the deformed pipe segment over the fault hanging wall is much longer than the one over the fault footwall. Finally, it is noted again that the case of a vertical fault plane $\psi = 90^{\circ}$ is rather theoretical and is presented here for comparison reasons. The behavior of a pipe under normal or reverse fault rupture in case of $\psi = 90^{\circ}$ is characterized by predominant pipe bending but differs because the stiffness of upward and downward springs that are "activated" in each case is very different.



(a) normal fault rupture (b) reverse fault rupture

Figure 6. Pipeline vertical deformation for fault dip angle $\psi = 75^{\circ}$ and pipe-fault crossing angle $\beta = 70^{\circ}$ in case of (a) normal fault and (b) reverse fault rupture

CONCLUSIONS

Even though there has been significant research effort on the assessment of pipe mechanical behavior due to seismic-induced permanent ground displacements, the relevant research on protection measures is viewed as limited. A review of the protection measures that are employed in practice or have been studied by researchers has been investigated. So far, the practical application of seismic countermeasures to pipes under faulting is mostly based on engineering judgment and experience. The present paper aims at contributing towards a more quantitative approach by numerically evaluating the effectiveness of five different protection measures, namely steel grade upgrade, wall thickness increase, trench backfilling with pumice, trench widening and the introduction of flexible joints. A typical large diameter buried steel pipe has been investigated as a case study that has been subjected to normal and reverse fault rupture under five indicative combinations of fault dip angle and pipe-fault crossing angle. A beam-type FE model has been developed and the numerical aspects for modeling each protection measure have been highlighted.

The main conclusions of the investigation are summarized as follows:

- Steel grade upgrade provides relatively low protection in terms of strain reduction and its effectiveness is limited. Wall thickness increase stands as a protection measure of moderate effectiveness.
- Trench widening is a protection measure that provides very low strain reduction and its application is not recommended.
- Trench backfilling with light-weighted pumice is an effective way to protect the pipe, provided that the used soil material is well-graded and the backfilling process is carried out according to good engineering practice.
- The integration of hinged bellow-type flexible joints stands out as a very promising solution for the protection of buried pipes against the consequences of faulting, provided that practical, legislation and manufacturing issues are solved prior to application. The joint rotation capability in conjunction with pipe operability has to be further considered.

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