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Designing Offshore Pipelines Facing the Geohazard of Active Seismic Faults

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***Abstract*—**The current study focuses on the seismic design of offshore pipelines against active faults. After an extensive literature review of the provisions of the seismic norms worldwide and of the available analytical methods, the study simulates numerically (through finite-element modeling and strain-based criteria) the distress of offshore pipelines subjected to PGDs induced by active normal and reverse seismic faults at the seabed. Factors, such as the geometrical properties of the fault, the mechanical properties of the ruptured soil formations, and the pipeline characteristics, are examined. After some interesting conclusions regarding the seismic vulnerability of offshore pipelines, potential cost-effective mitigation measures are proposed taking into account constructability issues.

***Keywords*—**Active faults, Seismic design, offshore pipelines.

I. Introduction

THE extensive use of pipelines for transportation of hydrocarbons has been extremely significant during the last decades. Nowadays, the need to transport hydrocarbons among countries, as well as the exploitation of hydrocarbons reserves in deep seas and oceans, have made the use of offshore pipelines more appealing. Therefore, the design, construction and operation of offshore pipelines are currently very substantial. Under this perspective, it is evident that many more offshore pipelines are expected to be constructed in the near future, with some already announced to be in the process of design or construction.

The wide areas that offshore pipelines are usually crossing, depending on the prevailing geomorphological and geological conditions, may present a variety of geo-hazards that impose substantial permanent ground deformations (PGDs) to the pipeline and potentially threaten its integrity. PGDs include surface faulting, settlements or lateral spreading due to soil liquefaction phenomena and land sliding. Despite the fact that PGD hazards exist in small regions within the pipeline network, they may impose large deformations to the pipe and therefore affect the whole network with detrimental consequences. Thus, the quantitative assessment of the geo-hazard of surface faulting and the evaluation of the associated risk for the pipeline are undoubtedly very important issues of the pipeline design. In case of a geo-hazard area, there exist three options to proceed. The first option is to avoid the problematic area through rerouting, which is usually regarded as an unfavorable solution due to its high cost and the great loss of time, both extremely important for such projects. The second is to apply (if possible) mitigation/protection measures in order to eliminate the geo-hazard itself, an option difficult to apply in great depth. Finally, the last appealing option is to allow the pipeline crossing through the geo-hazard area, provided that the pipeline will have been verified against the expected PGDs.

The current study focuses on the seismic design of offshore pipelines against active normal and reverse seismic faults. It is worthy to mention that although worldwide there is a great experience in offshore geo-technics and pipeline design, the experience in seismic design of offshore pipelines is rather limited due to the fact that most of the pipelines have been constructed in non-seismic regions (e.g. North Sea, West Australia, Gulf of Mexico, etc.). Thus, the seismic design of offshore pipelines against active faults requires special attention and further research.

After an extensive literature review of the provisions of the seismic norms worldwide, it has been observed that there is a lack of sufficient guidelines regarding offshore pipelines crossing active seismic faults. In particular, concerning offshore pipelines, ISO 19901 [1], as well as the standard of API [2], do not include specific guidelines or any design provisions for offshore pipelines crossings faults. It is simply mentioned that fault crossings should be avoided. In the offshore standard DNV [3] it is only mentioned that in areas where there is evidence of increased geological activity or significant historic events that may impact the integrity of the pipeline, additional geo-hazard studies should be performed. On the contrary, there are plenty of guidelines and design provisions concerning onshore buried pipelines crossing active faults, such as EC8 [4], IITK-GSDMA [5] and ALA [6]. According to modern norms, the evaluation of pipeline response to faulting requires numerical analyses that account for non-linear soil and pipeline behaviour.

In many cases in the past, extensive damages to pipelines due to surface faulting have been observed during previous earthquakes, demonstrating the vulnerability of onshore pipelines to PGDs. Examples of documented pipeline damage, regardless its use and material, include: the 1905 San Francisco, 1933 Long Beach, 1952 Kern Country, 1964 Alaska, 1964 Niigata, 1971 San Fernando, 1979 Imperial Valley, 1987 Ecuador, 1989 Loma Prieta, 1990 Manjil Earthquake, 1991 Costa Rica, 1994 Northridge, 1995 Kobe, 1999 Chi-Chi, 1999 Izmit (Kocaeli), 2010 Chile, 2010-2011 Christchurch and 2011 Japan.

Regarding offshore pipelines crossing active faults, one of

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the most interesting case studies is the case of the Japan-Sakhalin Gas Pipeline, which connects the Russian Sakhalin islands with the Tokyo area through the Japan Sea, crossing the Hokkaido Island (Japan) and the Pacific Ocean, as shown in Fig. 1, [7], [8]. This pipeline is 1100 km long, of which about 1000 km is offshore and the rest onshore. The steel pipes of 65 to 70 cm diameter are resting on the seabed or buried in the ground, in the active seismic zone along the Pacific Ocean, and are able to deliver about 800 million cubic feet natural gas per day [7].

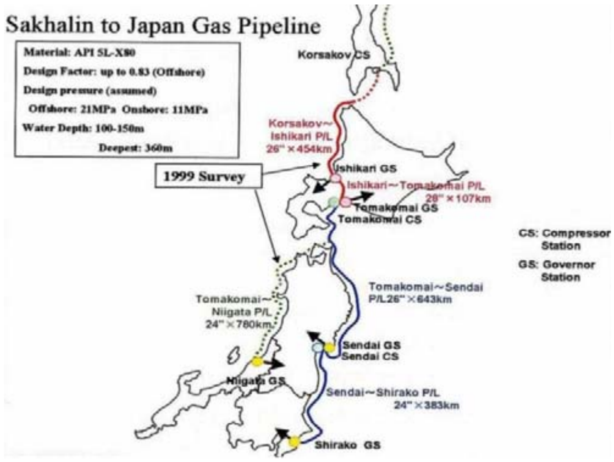

Fig. 1 Japan-Sakhalin Gas Pipeline (after Hamada [8])

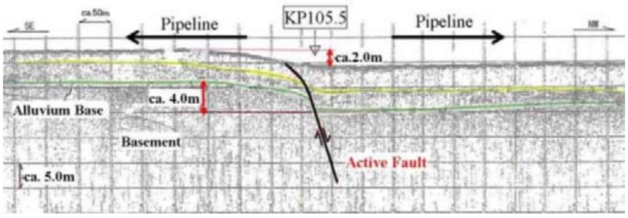

Fig. 2 Intersection of the Japan-Sakhalin Gas pipeline with an active normal fault offshore of Chiba prefecture to the east of Tokyo (after [8])

After the initial routing of the pipeline, which aimed in the avoidance of any active faults, another more detailed route survey revealed that the designed pipeline route intersects with three active faults. The pipeline crosses an active normal fault (Fig. 2) off Chiba prefecture, where an approximately 2 meter vertical seabed displacement was detected and the average displacement rate has been estimated 22cm/1000 years. The only information from the route survey is about the vertical fault movement, while information about movement in the horizontal direction is not available (Fig. 2)

The current study simulates numerically (through finite-element modeling and strain-based criteria) the distress of offshore pipelines subjected to PGDs induced by active normal and reverse seismic faults at the seabed. Factors, such as the geometrical properties of the fault, the mechanical properties of the ruptured soil formations, and the pipeline characteristics, are examined. Before the performance of the parametric study, a validation of the numerical model had been performed in the case of a normal fault through the comparison of the numerical results of the current study with the analytical predictions of [14].

After some interesting conclusions regarding the seismic vulnerability of offshore pipelines, potential cost-effective mitigation measures are proposed taking into account constructability issues.

II. Literature Review of Analytical Approaches

The issue of pipelines crossing active faults has been approached using analytical, numerical, as well as experimental methods. Only the analytical solutions are reviewed herein.

Newmark and Hall [9] were the first to study the problem of the effect of a fault movement on a pipeline. Their study focused on a pipeline subject to tensile strain induced by the rupture of a right lateral strike-slip fault intersecting the pipeline at an angle $\beta \leq 90^o$. In their model the pipe is assumed to be firmly attached to the surrounding soil at two anchor points, which develop substantial resistance to the axial movement of the pipe. The bending stiffness of the pipe as well as the lateral pipe-soil interaction are neglected. The elongation of the pipe is considered to be composed of both an axial and a lateral component of the fault movement. At the area near the fault, where there are no constraints, the only forces that cause the axial resistance of the pipeline are the friction forces. Failure in the Newmark and Hall approach is assumed to occur when the average strain exceeds the limit of 4%. Despite the fact that this approach provided insight on the mechanics of this problem, the tolerable fault movement for pipelines is overestimated, since the average strain is used as a failure criterion and the lateral interaction at the pipe-soil interface is neglected. This model was further modified by [10] by taking into account the soil-pipeline interaction in the transverse, incorporating the lateral pressure offered by the soil. They also considered the decrease of the pipe's bending stiffness under the influence of large axial strains. It is assumed that the pipeline is a flexible cable deformed into a single constant curve approaching asymptotically to the undistorted portion of the pipeline. Unlike the Newmark-Hall [9] model, bending and corresponding arc-length effects occur relatively close to the fault, while the axial friction forces extend well beyond the fault region. They focused on cases where the fault rupture provokes severe elongation of the pipeline, so as tension is the prevailing mode of deformation, and analyzed the relationship between the axial tensile force, the bending moment and the corresponding axial and bending strains. Subsequently, [11] further modified this model by dividing the pipe into three regions depending on the curvature of the pipeline. More precisely, their model consists of a beam on an elastic foundation (BEF) that stands for the "straight" portion of the pipeline beyond the constant curvature region, and of the constant curvature region which is subdivided into elastic strain and inelastic strain regions. In their methodology, they neglect the influence of pipe axial stress on pipe bending stiffness and come with the conclusion that the pipe fails at the start of the BEF region.

Karamitros et al. [12] extended the Kennedy model and introduced number of refinements in the method proposed by [11]. Specifically, they adopted the pipeline segmentation proposed by [11], retained the beam on an elastic foundation for the “straight” portion of the pipeline, with the difference that the segments corresponding to the high-curvature zone of the pipeline were analyzed with the aid of the elastic-beam theory, in order to locate the most unfavorable combination of axial and bending strains. They also introduced material nonlinearity by assuming a bilinear stress-strain relationship for the pipeline steel. Their methodology is suitable for both small and large offsets but is strictly applicable to strike-slip faults, since a symmetric pipeline deformation about the intersection point of the pipeline axis with the fault trace is assumed.

The model proposed by [12] for strike-slip fault crossings was extended to normal fault crossings by [13]. More specifically, they rejected the symmetry condition about the intersection point, proposed by [12], allowing the analysis of different types of fault kinematics. In addition, within the four-segmented pipeline modelling, the two segments in high curvature zones on both sides of the fault were analyzed as beams under both bending and tension so that the axial force is directly included in the equations of motion. Finally, they took under consideration the contribution of transverse displacements in order to estimate more accurately the axial elongation of the pipeline. Although the model proposed by Trifonov and Cherniy, extended the field of application of the method to both strike-slip and normal faults, lacked of simplicity to their algorithms, causing complexity. Subsequently, [14] modified their initial model [12], extending their methodology to normal fault crossings, maintaining the simplicity of the equations used for the analysis. They examine the case of right (90^o) intersection angle between the pipeline axis and the fault trace and prove that the case of the intersection with an oblique fault can be decomposed into the separate problems of a strike-slip fault and a normal fault intersection, respectively. The intersection of the pipe with the fault trace is treated as a single point, as the fault is assumed to be an inclined plane without thickness of the rupture zone. The pipeline is discretized into three segments, the two of which are the straight segments of the pipeline away from the fault trace and are analyzed as beams on an elastic foundation. The drawback of this method is that the effects of local buckling are not taken under consideration and thus this method cannot be applied to cases where the strain extends beyond the strain limits defined by design codes.

The work of Trifonov and Cherniy [13] has been extended by [15] in an attempt to refine the analytical model for inelastic material behavior of the steel pipeline. In their methodology, the plane stress conditions in the pipeline subjected to axial force, bending moment and internal pressure are treated systematically within the elasto-plastic framework.

III. Numerical Modeling

In order to examine the most influencing factors to the distress of pipelines subjected to fault rupture(s), a numerical parametric study was conducted using the commercial finite element analysis code ABAQUS. This parametric study was performed after the validation of the numerical model with the mechanical and geometrical properties of the pipeline that had been examined in [14].

A. Description of the Finite Element Model

The model that was considered is a typical offshore high-pressure natural gas pipeline with an external diameter of 0.9144 m (36 in) and a wall thickness of 0.027 m (1.063 in). The total length of the model is 1000 m intersecting a fault in the middle of its length at 90^o. The pipe is discretized into 1000 equal size pipe elements, each of 1.0 m length.

The pipeline model is made of steel API-X65 type, with a bilinear elasto-plastic stress-strain behavior, as presented in Fig. 3, with the properties of the material listed in Table I.

TABLE I
API5L-X65 Steel Properties

Yield stress (σ_1)	490 MPa
Failure stress (σ_2)	531 MPa
Yield strain (ε_1)	0.233 %
Failure strain (ε_2)	4 %
Elastic Young’s modulus (E_1)	210 GPa
Plastic Young’s modulus (E_2)	1.088 GPa

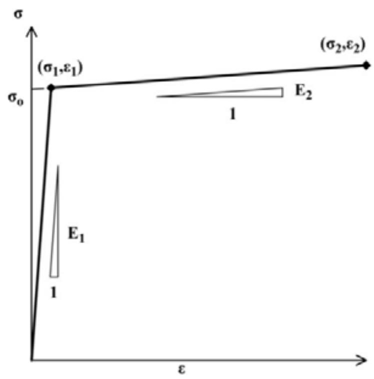

Fig. 3 Bilinear stress-strain relationship assumed for the pipeline steel

In order to simulate the pipe-soil interaction, each node of the designed pipeline was connected with soil springs in the axial, the transverse horizontal and the transverse vertical direction (Fig. 4). The properties of the soil springs, presented in Table II, were derived from the ALA guidelines [6], assuming that the pipeline top is at medium density sand with friction angle φ=36^o and unit weight γ=18 kN/m^3. The fault displacement was applied to the pipeline statically, by displacing the free ends of the corresponding soil springs.

Note that for constructability issues offshore pipelines are mainly located above seabed, while at the landfall areas offshore pipelines may be buried along a certain extent. It is evident that in the case of an above-seabed pipeline, some of the aforementioned soil springs may be neglected depending on the circumstances.

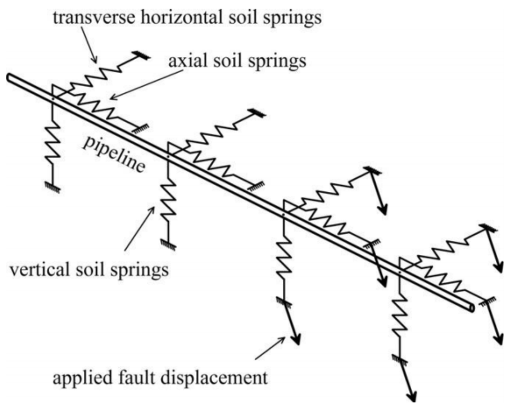

Fig. 4 Schematic presentation of the 3D model used to conduct the finite element analysis

B. Validation of the Numerical Method

As mentioned before, for the validation of the numerical simulation that is being performed in the current study, the analytical method of Karamitros et al. [14] has been used. The pipeline that has been used for the validation has the same external diameter (0.9144m) with the examined pipeline, but different wall thickness (0.0119m instead of 0.027m). The steel properties and the properties of the surrounding soil are identical with the ones described in the previous section (i.e. section A).

A range of analyses were conducted, for three different angles of the fault plane ψ=55^o, 70^o, 85^o. In each case, the fault displacement ranges from 0.1D to 2.0D, applied incrementally with a step size of 0.1D.

TABLE II
SOIL SPRING PROPERTIES

Spring type	Yield force (kN/m)	Yield displacement (mm)
Axial (friction)	40.5	3.0
Transverse horizontal	318.6	11.4
Vertical (upward displacement)	52.0	2.2
Vertical (downward displacement)	1360.0	100.0

The comparison shown in Fig. 5 is made over the peak values of axial strain ε_a, bending strain ε_b and total strain ε_{max}= ε_a+ ε_b. A good agreement may be testified for all components of pipeline strain in the two first cases (ψ=55^o, 70^o). In the case of the nearly vertical fault plane (ψ=85^o) there is a good agreement with the analytical solutions for fault displacements up to 1.6D, while for greater fault displacements there is an obvious difference between the numerical and analytical results to all strains. Note that similar discrepancies between analytical and numerical results had been observed by [14] as well.

The greater values of strain appear in the case of the smaller fault angle (ψ=55^o) where for a maximum displacement of 2.0D the axial strain reaches 2% against 1.1% in the case of ψ=70^o and 1.2% in the case of ψ=85^o, respectively. Such a difference is also obvious in the case of maximum strains, with greater values for fault displacements over 1.0D than the other cases. Only in the case of the nearly vertical fault plane, in fault displacements over 1.5D the values of bending strain and maximum strain reach near the values of the first case (ψ=55^o) of 1.8% and 3%, respectively.

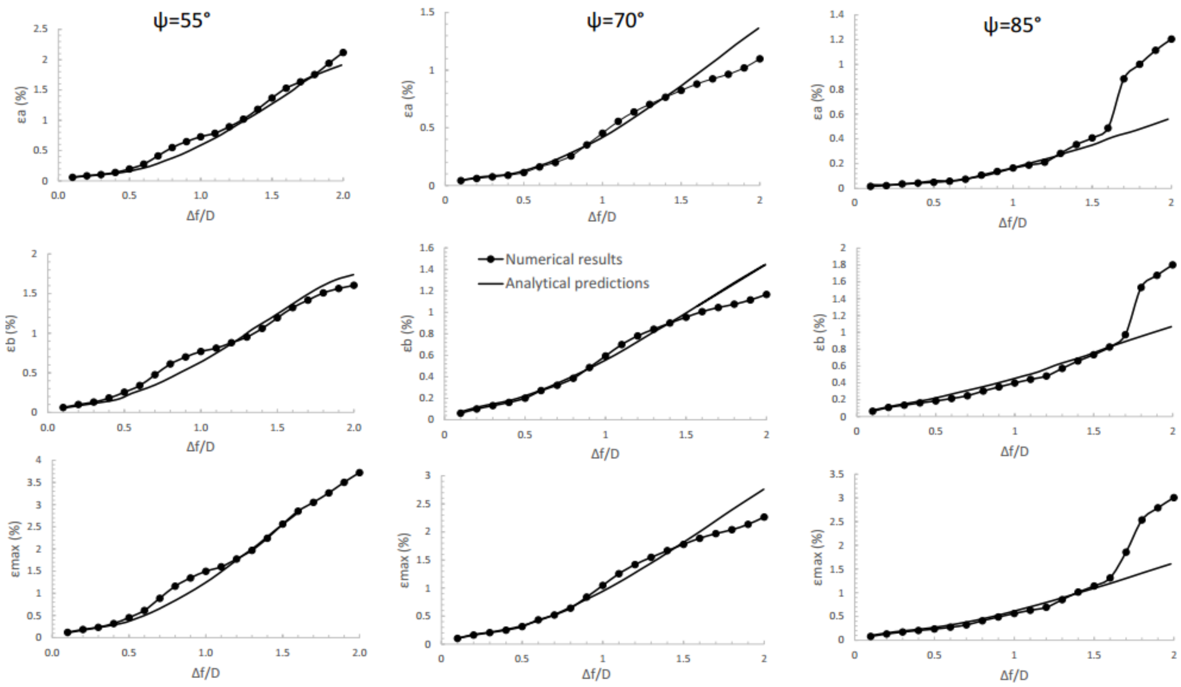

Fig. 5 Numerical results of the current study versus the analytical predictions from [14]

C. Parametric Study

As mentioned before, a parametric study was conducted in order to obtain the pipeline response under various conditions.

First of all the impact of the fault offset was examined at an intersection with a normal fault. The angle of the fault was considered as $\psi=70^o$ relative to the horizontal plane. The fault displacements considered were Δf = 0.5D, 1.0D, 1.5D, 2.0D, with D being the external diameter of the pipe.

Fig. 6 presents the axial displacement, the axial force and the axial strain of the pipe, as well as the soil friction forces, along the length of the pipeline for the considered fault displacements. The axial displacement of the pipe is distributed over a large component of the pipeline, depending on the size of the fault offset. As it was expected, for larger fault offsets, a wider area of the pipeline is affected. Tensile forces are developed, with a maximum value at the intersection point of the pipeline with the trace of the fault decreasing linearly away from the fault due to the friction forces developed. The peak value of the soil friction force reaches 40 kN for all the considered fault displacements.

The axial strains also present a linear behavior with a significantly larger peak value at the intersection point of the pipeline with the fault trace, decreasing linearly with the distance away from this point. The maximum axial strain for a fault offset Δf = 2.0D reaches 0.36%, substantially greater than the axial strain for a fault offset Δf=1.5D which reaches almost 0.20%. Furthermore, comparing this value with the corresponding case in Fig. 5 of section B, it becomes evident that the increase of the pipe wall thickness (from 0.0119 m to 0.027 m) causes a significant reduction in axial strains under the same circumstances, from 1.1% to 0.36% respectively, for a fault offset of 2.0D.

Fig. 7 shows the vertical displacements, shear forces, bending moments, bending strains and spring forces for upward and downward pipeline displacement corresponding to the soil resistance, focusing on the central area of the pipeline near the fault trace. The length of the pipeline subjected to vertical displacement appears to be considerably smaller than the corresponding length subjected to axial displacement. Vertical displacement occurs mainly over the hanging wall of the fault and presents greater values for larger fault offsets, up to 1.8 m for an offset of Δf=2.0D. This is attributed to the resistance forces of the soil, which present significantly larger values on the footwall of the fault and as a result the segment of the pipeline on the hanging wall of the fault accommodates most of the vertical component of the fault movement.

Concerning the shear forces and bending moments, they present similar peak values, despite the variation of the fault offset, except of the smallest fault displacement.

Subsequently, the same model of the pipeline was analyzed in an intersection with a reverse fault with characteristics identical to the characteristics of the previously examined normal fault (Figs. 8 and 9). In the case of the intersection with a reverse fault, the pipeline is subjected to axial tensile forces of the same order as in the case of the normal fault reaching a maximum axial strain of 0.35% for a fault displacement of 2.0D. The most significant difference between the cases of the normal and reverse fault is the value of bending strain, as in the case of the reverse fault, bending strains present smaller peak values for all fault offsets than the corresponding strains of the normal fault case. More precisely, the peak value of the bending strain for a fault offset of 2.0D is 1.2% for the intersection with a normal fault, while it is 0.5% in the case of intersection with a reverse fault.

Another parameter examined, is the impact of the internal pressure of the pipeline, due to the gas transmitted through the pipe, as well as the impact of the external pressure when the pipeline is underwater, depending on the depth of the establishment. The assumed pressures used for the analyses are presented in Table III and the results in Figs. 10 and 11.

The variation of axial displacements, axial forces, soil friction forces and axial strains along the length of the pipeline are presented in Fig. 10. The cases in which the pipeline is under larger axial displacement, axial tensile forces and axial strains are under zero pressures and under both internal and external pressures in a relatively small depth of 500 m. The increase of the water depth results to a decrease in the axial forces, subjecting the pipe to compression for a great depth of 2000 m.

When the pipeline is subjected to large external pressures, the vertical displacement of the pipe, as well as the bending strains, reduce substantially (Fig. 11).

Finally, a series of analyses were conducted to ascertain the effect of the characteristics of the surrounding soil of the pipeline. The properties of the vertical upward and downward soil springs were adjusted, assuming that the pipeline is buried under clay, with friction angle $\varphi=30^o$ and dry unit weight $\gamma=18$ kN/m^3, and very hard rock with friction angle $\varphi=36^o$, cohesion c=80 kPa and dry unit weight $\gamma=22$ kN/m^3. The properties of the soil springs were derived from the ALA guidelines [6], as listed in Table IV. The axial and horizontal springs were kept the same as described in section A.

In the case of rock, the pipeline presents an abrupt axial displacement and a great axial force at the intersection with the fault. The axial strain reaches values of almost 2.5%.

According to the results presented in Figs. 12-14, softer soils result in a more even distribution of the vertical displacements to the pipeline, whilst rock forces the pipeline to a very abrupt motion causing large forces and strains at the point of the intersection with the fault trace, significantly larger than the cases of softer soils, clay and sand. With clay as bedrock, the pipeline is subjected to smaller bending strains, while with rock, bending strains reach 3%.

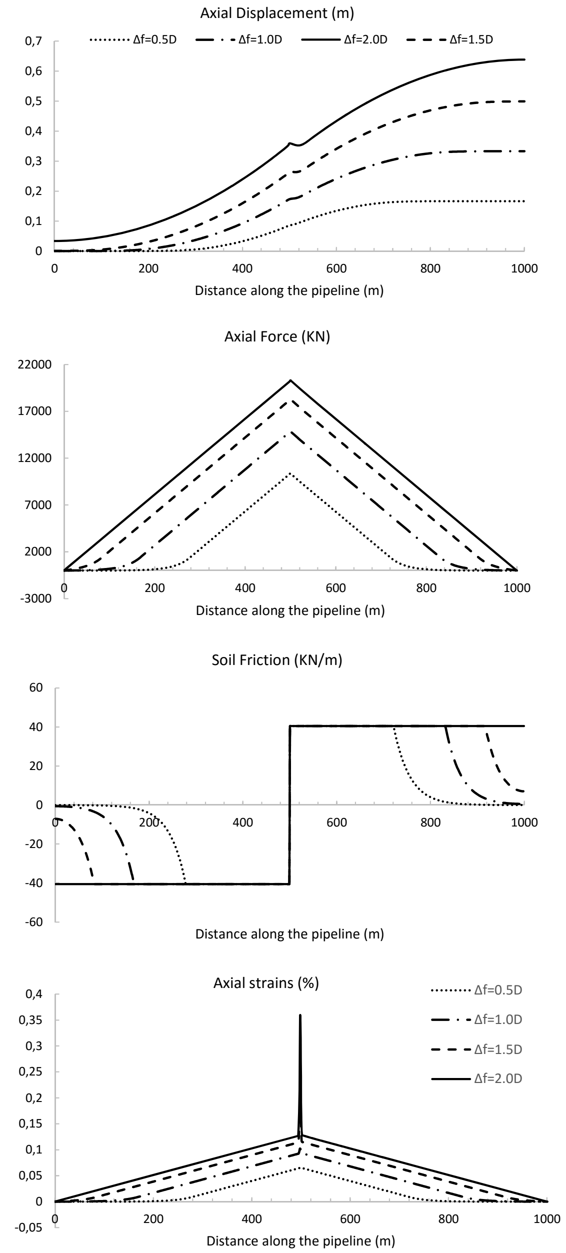

Fig. 6 Axial displacement, axial force, soil friction forces and axial strain along the length of the pipeline for the considered fault displacements; intersection with a normal fault

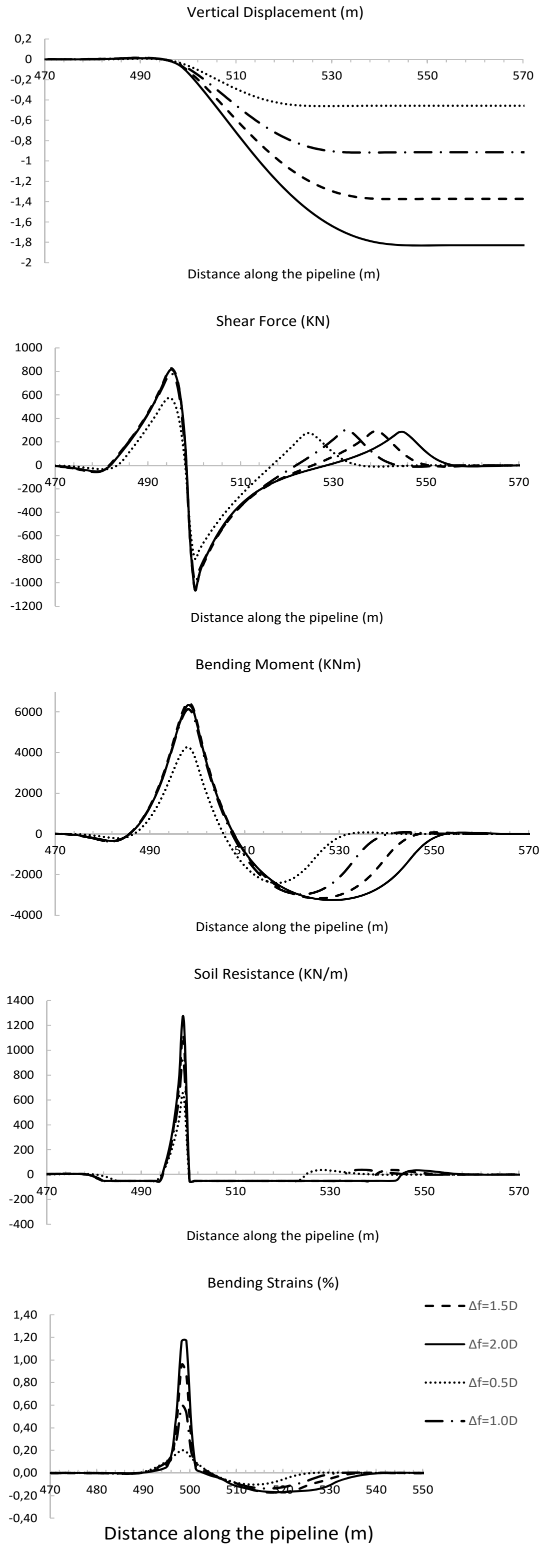

Fig. 7 Vertical displacements, shear forces, bending moments, soil resistance forces for upward and downward displacement and bending strains along the length of the pipeline, in the area near the fault trace; intersection with a normal fault

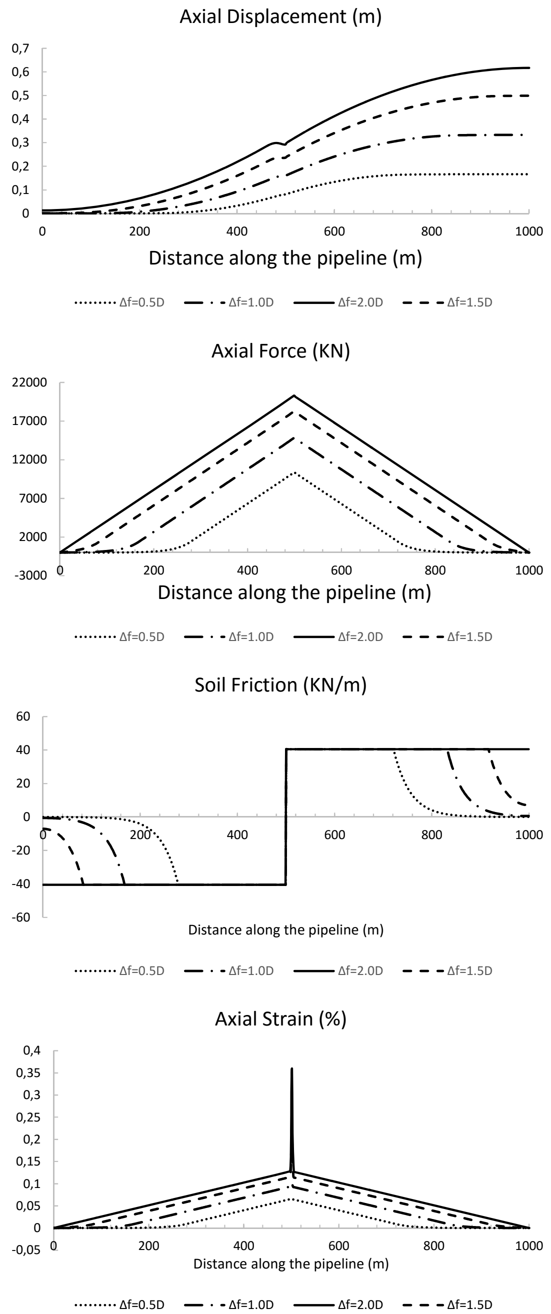

Fig. 8 Axial displacement, axial force, soil friction forces and axial strain along the length of the pipeline for the considered fault displacements; intersection with a reverse fault

TABLE III
PRESSURE STATES ASSUMED FOR THE ANALYSES

Pressure state	$P_{internal}$ (kPa)	$P_{external}$ (kPa)
1. Zero pressure	-	-
2. Internal pressure	11,000	-
3. Depth 500 m	11,000	4,904
4. Depth 1000 m	11,000	9,807
5. Depth 2000 m	11,000	19,614

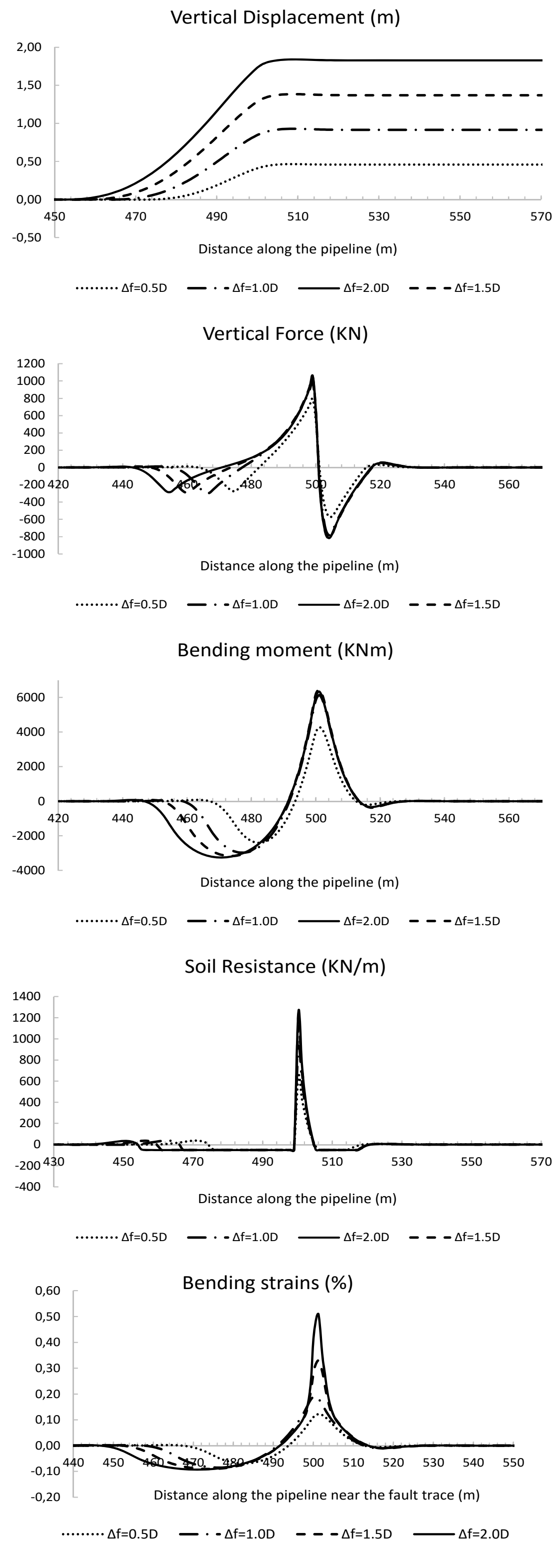

Fig. 9 Vertical displacements, shear forces, bending moments, soil resistance forces for upward and downward displacement and bending strains along the length of the pipeline, in the area near the fault trace; intersection with a reverse fault

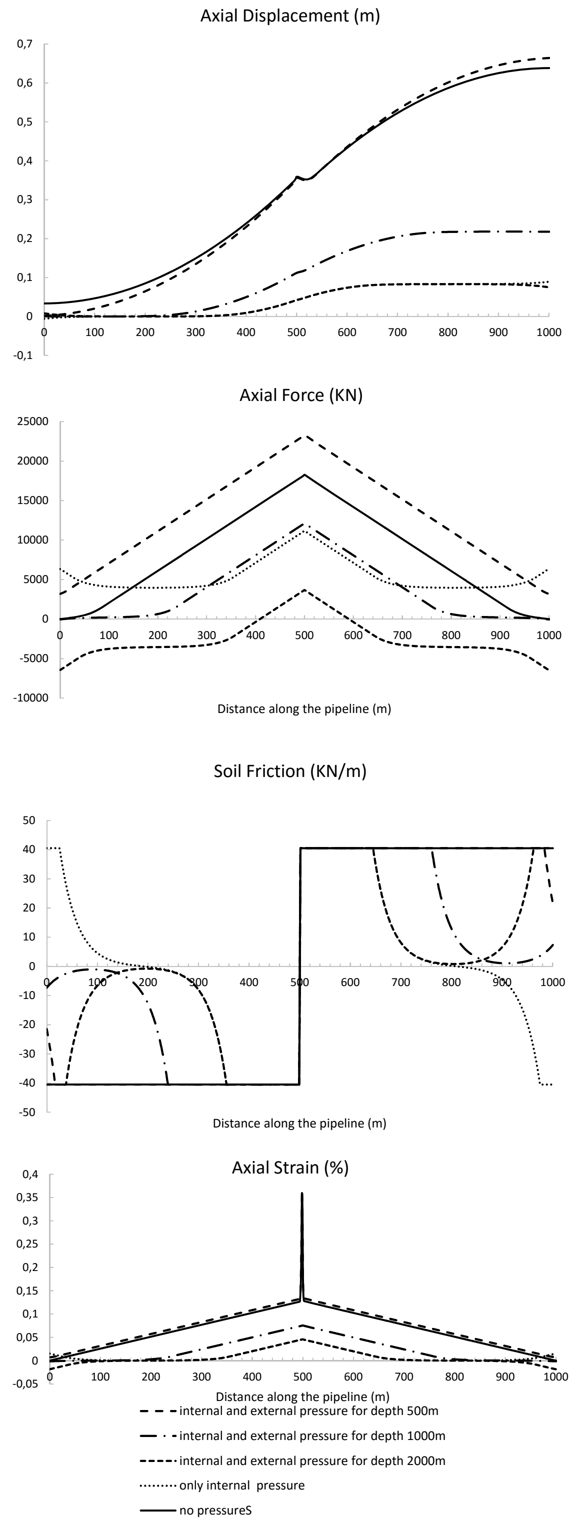

Fig. 10 Axial displacement, axial forces, soil friction forces and axial strains along the length of the pipeline for the considered pressure states; intersection with a normal fault

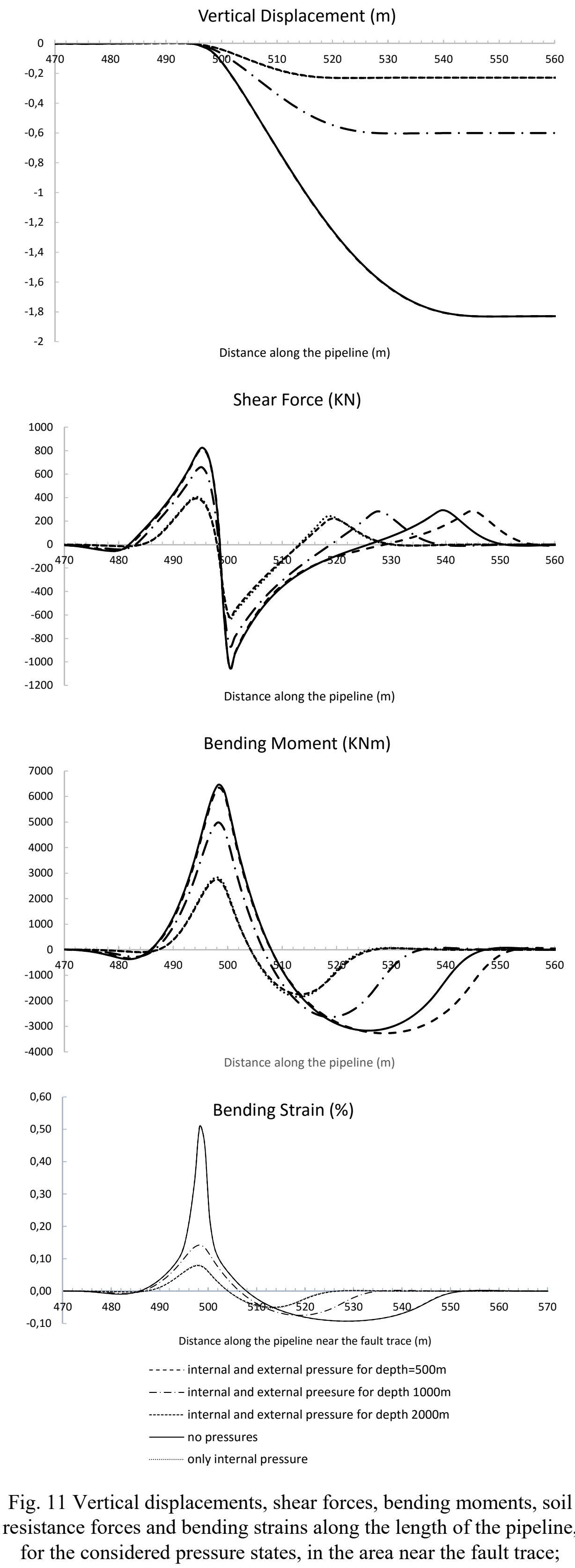

Fig. 11 Vertical displacements, shear forces, bending moments, soil resistance forces and bending strains along the length of the pipeline, for the considered pressure states, in the area near the fault trace; intersection with a normal fault

TABLE IV
SOIL SPRINGS PROPERTIES

Soil	Spring type	Yield force (kN/m)	Yield displacement (mm)
Medium density sand	Vertical (upward displacement)	52.0	2.2
	Vertical (downward displacement)	1360.0	100.0
Clay	Vertical (upward displacement)	38.95	35.14
	Vertical (downward displacement)	763.52	91.44
Rock	Vertical (upward displacement)	336.73	17.57
	Vertical (downward displacement)	5751.25	182.88

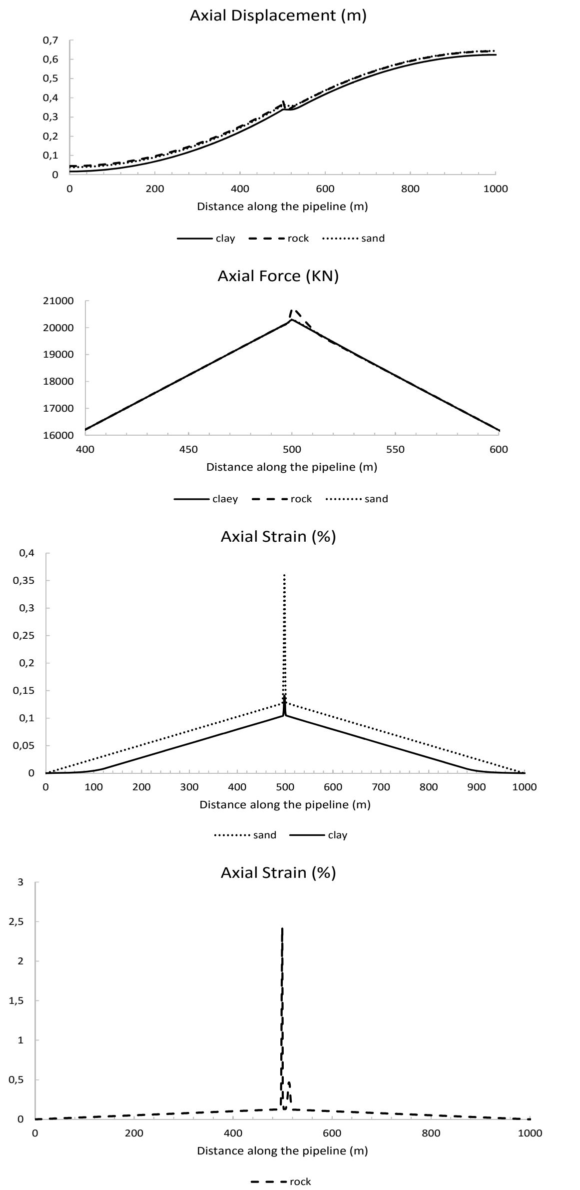

Fig. 12 Axial displacement, axial forces, soil friction forces and axial strains along the length of the pipeline for the considered soil conditions; intersection with a normal fault

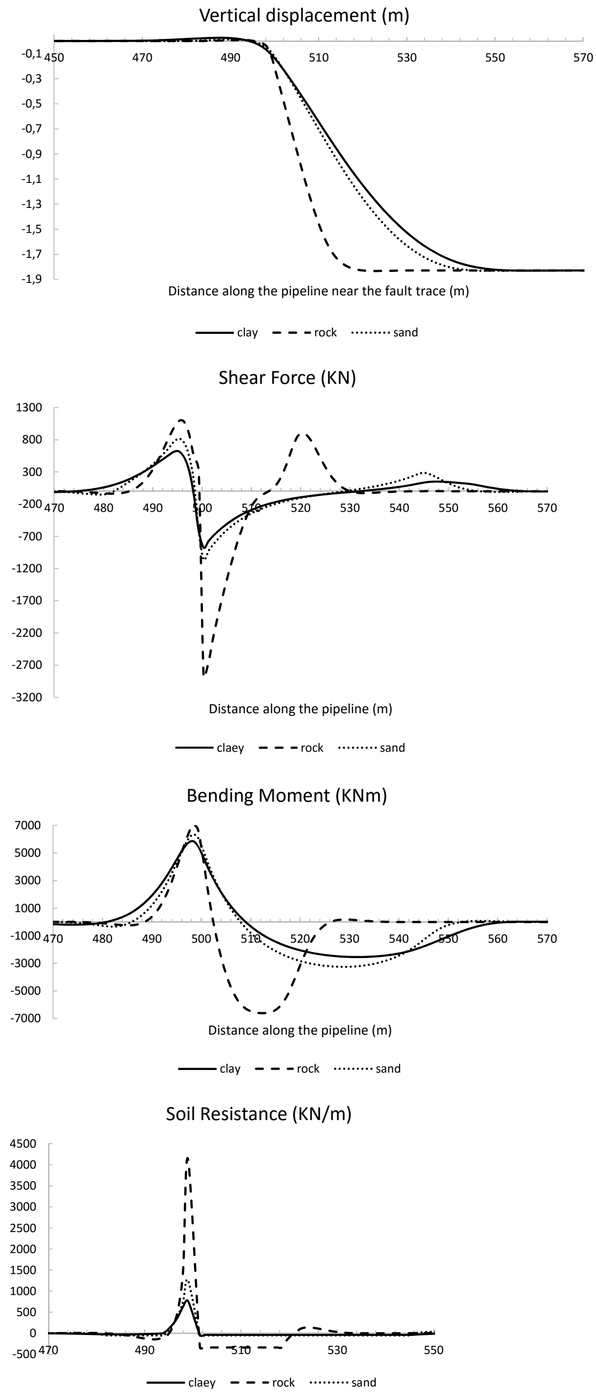

Fig. 13 Vertical displacements, shear forces, bending moments and soil resistance forces for the considered soil conditions, in the area near the fault trace; intersection with a normal fault

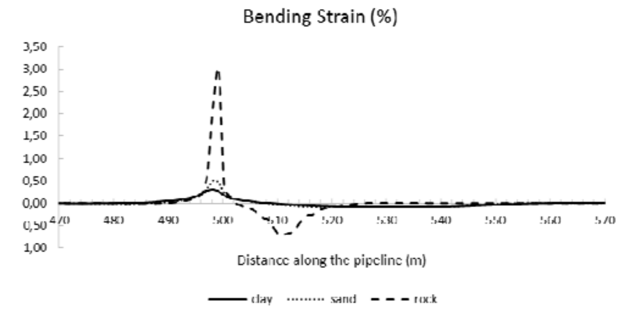

Fig. 14 Bending strains of the pipeline for the assumed soil conditions

IV. Potential Mitigation Measures

The design of mitigation measures is a very important issue. It is evident that the adopted measures should be verified by detailed geotechnical investigation and simulations on a case-by-case basis. Depending on the special characteristics of the fault, the selection of any mitigation or protection measure should take into consideration various parameters, such as environmental impact, constructability, accessibility, cost, etc. In the case of crossing a potentially active fault, an increase in pipe wall thickness could be adopted. This measure will increase the capacity of the pipeline to withstand fault movement at a given level of maximum strain as proved by the parametric analysis performed in the current study. On each side of the fault, relatively thick-walled pipe segments should be used. If a slight relocation of the pipeline is possible, then the segment of the pipeline crossing the fault should be oriented in such a way as to place the pipeline in tension (and not in compression, which may additionally cause buckling effects).

V. Conclusions

The current paper refers to the issue of offshore pipelines intersecting active seismic faults, and the risks that may arise. Through a parametric numerical analysis the most influencing factors for the integrity of the pipeline are explored, demonstrating the vulnerability of pipelines to fault crossings.

In areas where the route of the pipeline intersects with an active fault, the relocation of the pipeline to avoid the critical area would be an option. However, since the pipeline relocation may be impractical or even impossible for various reasons, mitigation and/or protection measures should be adopted aiming to eliminate or reduce the imposed pipeline distress to acceptable levels.

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