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Numerical evaluation of the effectiveness of flexible joints in buried pipelines subjected to strike-slip fault rupture

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ABSTRACT

Buried steel pipelines transport large amounts of fuel over long distances and inevitably cross active tectonic seismic faults when seismic areas are traversed. Eventual fault activation leads to large imposed displacements on the pipeline, which may then fail due to local wall buckling or tensile weld fracture, having grave financial, social and environmental consequences. In this paper, flexible joints are evaluated as an innovative mitigating measure against the consequences of faulting on pipelines. Joints are introduced in the pipeline in the fault vicinity, aiming at absorbing the developing deformation through relative rotation between adjacent pipeline parts, which then remain relatively unstressed. The effectiveness of flexible joints is numerically evaluated through advanced 3D nonlinear finite element modeling. Extensive parametric analysis is carried out to determine the effect of pipeline – fault crossing angle, fault offset magnitude, joint angular capacity, burial depth and diameter over thickness ratio on the joint efficiency. The uncertainty regarding the fault trace is also addressed.

1. Introduction

Onshore buried steel pipelines with girth-welded joints are used in the energy industry to transport large amounts of fuel over long distances. Permanent ground displacements (PGD), such as those due to fault rupture, ground settlement or sloping ground failure, have been identified as the dominant causes of catastrophic pipeline failure due to earthquake-induced actions after past major earthquake events [1] (e.g. the 1995 Kobe [2], the 1999 Kocaeli [3] and the 1999 Chi-Chi [4] earthquakes). A potential failure of pipelines (e.g. fuel leakage, explosion) can have significant environmental and financial consequences. Fault offset is the result of earth plates' relative movement and its consequences on pipeline performance can be severe. The principal failure modes in this case are directly related to the extensive deformation of pipelines due to faulting causing local buckling/wrinkling due to compressive strains or tensile weld fracture due to tensile strains.

Analytical or numerical approaches have been applied to assess the pipe stress-state due to faulting. Newmark and Hall [5] analytically calculated the pipeline wall stress-state, considering the pipeline as a long cable undergoing small displacements that intercepts a planar fault. Kennedy et al. [6,7] extended previous work [5] by incorporating lateral soil interaction and pipe – soil friction nonlinearity. Wang and Yeh [8] integrated the pipe bending stiffness in the established analytical models. The pipe model of elastic beam was adopted by Vougioukas et al. [9] to account for the vertical and horizontal fault movements. Wang and Wang [10] modeled the pipe as a beam on elastic foundation, while Takada et al. [11] proposed a more accurate model by relating the cross-sectional deformation and the pipe bending angle to calculate the maximum strain. Recently, Karamitros et al. [12,13] improved the previous analytical approaches by combining the model of a beam on elastic foundation and the elastic beam theory to estimate the maximum strains due to strike-slip and normal faulting. Trifonov and Cherniy [14,15] presented a semi-analytical methodology for pipeline stress – strain analysis by considering the contribution of transverse displacements to the axial elongation.

The analytical approach remains a helpful tool during the preliminary design stage of a pipeline project. The pipeline – soil interaction complexity, however, requires the implementation of

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advanced numerical models that are capable of considering all pertinent parameters, such as geometrical and material nonlinearity, cross-section ovalization and complex soil properties. The finite element method was initially introduced [16] to evaluate the developing strains and nowadays two categories of numerical models are available:

- The first is the so-called beam-type model, where the pipeline is meshed with beam-type finite elements that can model the axial, shear and bending deformation and can provide stresses and strains at cross-section integration points along the pipe. The surrounding soil is modeled using a series of nonlinear translational springs in four directions (axial, transverse horizontal, transverse vertical upward and downward), based on the Winkler soil approach. However, trench dimensions and native soil properties cannot be directly encountered in the analysis. Additionally, the use of beam-type finite elements does not allow the direct estimation of local buckling, cross-section ovalization and detailed stress-strain distributions around the circumference of the pipe. Thus, checks on failure modes are carried out by comparing the maximum developing tensile and compressive strains obtained from the integration points to the corresponding strain limits provided by pertinent standards. The beam-type model is extensively used by researchers to verify the pipeline safety at active fault crossings. Joshi et al. [17] employed this model to investigate the pipe behavior due to reverse faulting. Uckan et al. [18] presented a simplified beam-type model as a useful tool to calculate the pipe critical length and established a methodology to formulate pipe fragility curves. This model is also adopted by worldwide Standards and Regulations such as Eurocode 8 [19], ALA [20] and ASCE [21] as a reliable and computationally efficient modeling approach.
- The second approach is the so-called continuum model, where the pipeline is discretized into shell finite elements and the surrounding soil into 3D solid elements. The pipe – soil interaction is modeled with contact elements. This approach severely increases modeling complexity, nonlinearity and computational effort in terms of solution time requirements, boundary conditions, resulting degrees of freedom, convergence difficulties, fault rupture modeling and particularly the introduction of contact elements. The initial attempts to employ the continuum model by considering pipe – soil contact issues were presented in [22,23]. Recently, Vazouras et al. [24–26] presented a rigorous finite element model for pipeline – strike-slip fault crossing by considering soil parameters, pipe – fault crossing angle and pipeline mechanical characteristics to come up with a simplified expression for critical buckling strain. This model was then adopted in [27,28] to consider the effects of trench dimensions, native soil properties and fault motion simulation. As an alternative, nonlinear translation springs can be used for soil modeling instead of 3D-solid elements to avoid the numerical difficulties related to the use of contact elements between the pipeline and the soil [12,13,29,30].

Avoiding pipeline failure is the major priority in pipeline design against faulting. A set of different seismic countermeasures is thus employed in engineering and constructional practice to minimize the developing strains on pipe walls, mainly by reducing pipe – soil reaction forces. The adopted measures are:

- Pipeline embedment in a shallow, sloped-wall trench with loose backfill to reduce soil resistance and allow the pipeline deformation to take place over a longer length. Development of large strains and permanent deformations is allowed, as long as pipe failure is prevented [30,31].
- Pipe wall thickness increase or steel grade upgrade to reduce developing strains and pipe curvature by increasing pipe stiffness [30,31].
- Avoidance of sharp bends that increase constraints to axial displacements and may impose additional forces on the pipeline [19,20,30].
- Pipeline wrapping with friction-reducing geotextile to reduce pipe – soil friction and increase the anchor length, thus reducing the developing longitudinal strains [30].
- Pipeline wrapping with composite FRP wraps to increase strength and the critical fault movement that causes failure [32].
- Pipeline placement within buried concrete culverts. Culverts are sacrificed during the fault movement to retain the pipeline unstressed. The lack of backfilling drastically reduces friction-induced strains on the pipeline.
- Use of geocells and geogrids in the trench above the pipeline to reduce pipe deformation [33].
- Backfill pipe trench with tire-derived aggregate surrounded by sand to reduce pipe bending moments [34].

Various parameters, such as the fault offset magnitude and constructional issues, can limit the efficiency of these measures. Monroy [35] for example, suggests that wrapping the pipeline with a double layer geotextile is effective only if the distance between pipeline and trench wall is less than half the pipeline diameter.

Research presented in the present paper focuses on the use of innovative materials or commercial devices/products that could be integrated in the pipeline in the fault vicinity in order to reduce the developing strains. Segmented pipelines have been used in the piping industry for decades, but mainly for water or sewage transmission under low pressure. The joints used in these pipelines (slip and spigot-bell joints) do no ensure the continuity of the structure in terms of axial, shear and/or rotational deformations, depending on the type of joint, and thus extensive research has been carried out on investigating the integrity of segmented pipelines under permanent ground displacements based on the joints' properties [36–44], investigating among others the potential of joint pull-out failure. The mitigation measure proposed in the present study follows the suggestions of Bekki et al. [45] in introducing flexible joints between the adjacent pipeline parts in the fault crossing area. The principal objective is to concentrate strains at the joints and retain the steel parts almost undeformed [46,47]. This concept introduces a different design approach for reducing the risk of local buckling or tensile failure, by transforming the pipeline structural system from continuous to segmented, so as to concentrate strains at the joints, instead of reducing the soil friction.

Flexible joints are widely used in the piping industry, for example to absorb thermal expansion, thrust and machinery vibration or as joints between the adjacent parts of segmented pipelines. A major advantage is that flexible joints are commercial products, thus they can be either readily available or customized with respect to diameter, internal pressure and allowable deformations. Among the available flexible joints, namely slip joints, spigot-bell joints and bellows, it was concluded that the appropriate type for buried pipe applications that operate in high pressure is the hinged metallic bellow (Fig. 1), which is capable of undergoing angular deformation only, as lateral and axial movements are restrained. The selection is based on the following criteria: (i) availability in the market and production upon request, (ii) contribution to developing longitudinal strain reduction, (iii) ease of construction in the field, (iv) compliance with pipe flow, (v) operability of pipeline after fault rupture and (vi) full structural cooperation between the pipe and the flexible joint, i.e. avoidance of joint pull-out failure. Focus on the latter is important due to the