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Pipe–soil interaction and pipeline performance under strike–slip fault movements

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ABSTRACT

The performance of pipelines subjected to permanent strike–slip fault movement is investigated by combining detailed numerical simulations and closed-form solutions. First a closed-form solution for the force–displacement relationship of a buried pipeline subjected to tension is presented for pipelines of finite and infinite lengths. Subsequently the solution is used in the form of nonlinear springs at the two ends of the pipeline in a refined finite element model, allowing an efficient nonlinear analysis of the pipe–soil system at large strike–slip fault movements. The analysis accounts for large strains, inelastic material behavior of the pipeline and the surrounding soil, as well as contact and friction conditions on the soil–pipe interface. The numerical models consider infinite and finite length of the pipeline corresponding to various angles β between the pipeline axis and the normal to the fault plane. Using the proposed closed-form nonlinear force–displacement relationship for buried pipelines of finite and infinite length, axial strains are in excellent agreement with results obtained from detailed finite element models that employ beam elements and distributed springs along the pipeline length. Appropriate performance criteria of the steel pipeline are adopted and monitored throughout the analysis. It is shown that the end conditions of the pipeline have a significant influence on pipeline performance. For a strike–slip fault normal to the pipeline axis, local buckling occurs at relatively small fault displacements. As the angle between the fault normal and the pipeline axis increases, local buckling can be avoided due to longitudinal stretching, but the pipeline may fail due to excessive axial tensile strains or cross sectional flattening. Finally a simplified analytical model introduced elsewhere, is enhanced to account for end effects and illustrates the formation of local buckling for relative small values of crossing angle.

1. Introduction

1.1. Background

Most of the observed damages in oil and gas pipelines during earthquakes are caused by permanent ground movement related to near-surface fault rupture, landslides, settlements, and liquefaction-induced lateral spreading. Large ground movements related to such phenomena may induce severe plastic deformation or rupture in the pipeline, and pose significant danger to the population, industrial facilities and the environment.

In the present paper, ground-induced actions on buried pipelines crossing strike slip faults are considered (Fig. 1). To ensure pipeline safety against a large permanent strike–slip fault movement, the corresponding deformational and stress state of the pipeline should be evaluated. Newmark and Hall [1] were the first to investigate the pipeline response under fault displacement and calculate stresses and strains within its walls, using a simplified analytical model of a long cable. Kennedy et al. [2,3] extended the work in [1], considering non-uniform friction at the pipe–soil interface, whereas Wang and Yeh [4] accounted for pipeline bending stiffness. Vougioukas et al. [5] considered both horizontal and vertical movement of faults and analyzed buried pipes as elastic beams. McCaffrey and O'Rourke [6] and Desmod [7] studied the development of strains in buried pipes crossing faults with reference to the performance of gas and water pipes during the San Fernando earthquake. Wang and Wang [8] considered the pipe as a beam on elastic foundation, whereas Takada et al. [9] evaluated the critical strain of fault-crossing steel pipes using the relation between pipe longitudinal deformation with cross-sectional deformation.

Recently, the structural response of buried steel pipelines subjected to ground-induced deformations has received

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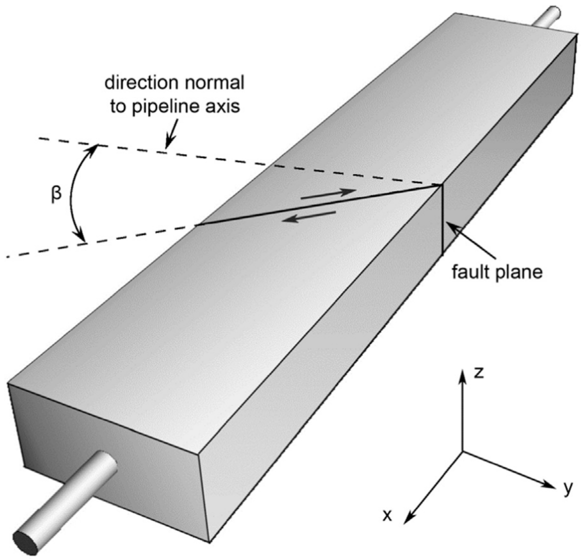

Fig. 1. Schematic representation of buried pipeline subjected to oblique strike–slip fault movement.

significant attention. It has been recognized that, apart from the pipeline characteristics and soil conditions, the complex soil–pipe interaction in the near fault region may have a strong influence on pipeline response [10]. Kokavessis and Anagnostidis [11], using a finite element methodology and contact elements to describe soil–pipe interaction, analyzed buried pipes under permanent ground-induced actions. Karamitros et al. [12], presented an analytical methodology, using a combination of beam-on-elastic-foundation and beam theory, to compute the pipeline axial force, bending moment and maximum strain. Liu et al. [13] presented a shell finite element simulation of pipelines crossing active faults (i.e. a combination of shell elements and springs) and predicted axial strain along the pipeline. Shitamoto et al. [14] examined the compressive strain limit of X80 pipelines to resist ground-induced actions. Using a solid-element model of a pipe, they compared the strain corresponding to the maximum moment to the strain induced by soil liquefaction. The seismic analysis of buried pipelines under both transient and permanent ground movements by Arifin et al. [15], using beam elements for the pipeline and nonlinear springs for the surrounding soil, resulted in useful recommendations for mitigating seismic effects. Odina and Tan [16] investigated buried pipeline response under seismic fault displacement, using a beam element model with elastic–plastic springs for the soil effects. Extended the work in [16,17] examining the effects of Lüder's plateau of the stress–strain material curve on the pipeline response. A similar numerical methodology to those in [15–17] has been presented by Gu and Zhang [18], aiming at determining the optimum crossing angle for the pipeline. More recently, a semi-analytical investigation of buried pipelines behavior under seismic faults has been presented by Trifonov and Cherniy [19,20] in an attempt to refine the analytical model for inelastic material behavior of the steel pipeline. Daiyan et al. [21] simulated the soil around a non-deformable pipe with elastic–plastic 3D solid finite elements to investigate the soil–pipe interaction and load transfer mechanisms.

Apart from the numerical studies, experimental research on the effects of strike–slip faults on buried polyethylene pipelines have been reported by Ha et al. [22,23] and Abdoun et al. [24]. Based on centrifuge modeling, this research examined the influence of the type of faulting, the angle of strike–slip faults on the pipeline mechanical behavior, as well as the effects of embedment depth and pipe diameter. Apart from centrifuge tests, nine full-scale strike slip tests were conducted in Cornell University for HDPE and steel pipelines in the course of NEES-SG project [25]. All pipes were 12.2 m long and embedded in sand. In these tests HDPE pipes of 400 mm and 250 mm-diameter were selected, whereas for steel pipes a 150 mm-diameter was used. The HDPE pipelines were 24 mm thick, whereas the steel pipe had a wall thickness of 3 mm (D/t=50). Strain gauges and robotic laser measurements were employed for instrumenting the pipes. The steel pipe, was wrapped with tactile force sensors to measure contact pressure with soil. The angle between the fault trace and the pipeline axis was set to 65° for all experiments. Eight specimens were tested in tension strike–slip conditions (including the steel pipe) with one of them pressurized at 500 kPa and one pipe was subjected to compression conditions. A good agreement between centrifuge and large scale tests for HDPE pipes was reported.

In a recent paper [26], the present authors reported an integrated approach for buried steel pipelines crossing strike–slip faults at right angle (90°) with respect to the fault plane, through a finite element modeling of the soil–pipeline system. The analysis accounted rigorously for the inelastic behavior of the surrounding soil, the pipe–soil interaction (including frictional contact and gap opening), the development of large inelastic strains in the pipeline, the distortion of the cross-section, the formation of local buckling, and the presence of internal pressure. Considering the same numerical methodology, their work was extended in [27], for buried steel pipelines crossing the vertical fault plane at various angles, and examining pipeline response with respect to appropriate performance criteria, expressed in terms of local strain or cross sectional deformation. Pipes of steel grades X65 and X80 were considered, for values of diameter-to-thickness ratio ranging from 57 to 144, in cohesive and non-cohesive soils, and for different levels of internal pressure. Numerical results were presented depicting the fault displacement corresponding to specific performance criteria with respect to the crossing angle, for typical values of diameter-to-thickness ratio and for various soil conditions.

1.2. Research objective

The numerical models employed in [26,27] have assumed fixed conditions at the two ends of the pipeline. Nevertheless, in order to represent the actual conditions at the two ends, the boundary conditions may not be fixed. Pipeline continuity provides flexibility at both ends of the pipeline, which results in a reduction of pipeline stretching and the corresponding tensile strains, possibly leading to earlier formation of local buckling or different cross-sectional distortional pattern. The objective of the present paper is to develop a refined numerical model, extend the work presented in [26,27] and accounting for appropriate end effects, to investigate the mechanical behavior of underground steel pipelines crossing oblique strike–slip faults subjected to permanent ground movement. Towards this purpose, the rigorous numerical methodology developed in the previous publications is combined with a new closed-form mathematical solution of equivalent nonlinear springs at the model ends, representing finite or infinitely long pipeline segments, allowing for efficient and accurate simulation of pipeline behavior.

To determine the flexibility of the end sections, closed-form solutions are developed for a straight buried pipeline segment subjected to pure tension. The solutions are presented in Sections 2 and 3 for infinite and finite length of the pipeline segment, respectively assuming that the pipeline segment behaves elastically and sliding occurs along the pipe–soil interface after the interface strength is reached.

In Section 4, a parametric study is conducted considering finite and infinite pipeline length. In Section 5 comparisons of different models are performed enhancing the models presented in