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NUMERICAL EVALUATION OF THE STRIKE SLIP FAULT EFFECTS ON THE STEEL BURIED PIPELINES

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ABSTRACT

Pipelines are often referred as "lifelines" and this demonstrates that pipelines play an important role in human’s life. Based on the damage mechanism of buried pipelines, seismic effects can be either caused by transient strain and curvature in the ground due to traveling wave effects or caused by permanent ground deformations; such as fault deformation, landslide, and liquefaction-induced soil movements. Among them, the ground movements of active faults can have the most severe earthquake effects on buried pipelines. The traditional method of assessment of a buried pipeline subjected to seismic faulting is initially carried out using analytical methods. Due to the limitations of these techniques for large deformation soil movement associated with fault displacement, non-linear finite element (FE) methods are widely used to assess the pipeline integrity. The FE analysis typically idealises the pipeline using discrete structural beam-type elements and the pipeline-soil interaction as discrete non-linear springs, based on the concept of subgrade reactions proposed by Winkler. Recent research suggested that the use of the discrete Winkler element model leads to over-conservative results in comparison to the coupled continuum model. The principal reason for the conservatism is related to the poor modeling of realistic surrounding soil behaviour for large deformation events. In this paper the effects due to difference in ground motion from surface faulting has been studied using 3D finite element continuum model, winkler model and analytical method. The structural response of steel pipelines under strike-slip fault movement is examined numerically using the general purpose FE program ABAQUS. The nonlinear seismic response of buried pipeline under permanent ground deformation is analyzed using pseudo-static analysis method without considering the fracture of the soil. Some influential factors, such as fault-pipeline crossing angle, backfill type and burial depth are considered in the analysis in order to draw some regular conclusions.

1. INTRODUCTION

Earthquakes may constitute a threat for the structural integrity of buried pipelines. Post-earthquake investigations have demonstrated that the majority of seismic damages to continuous oil and gas steel pipelines were caused by permanent ground deformations such as fault movements, landslides, liquefaction-induced lateral spread, whereas only few pipelines were damaged by wave propagation. Permanent ground deformation is applied on the pipeline in a quasi-static manner, and it is not necessarily associated with high seismic intensity, but the pipeline may be seriously damaged. Such pipeline damages have been reported in numerous earthquakes, such as the 1971 San Fernando earthquake, and, more recently, the 1995 Kobe earthquake, the1999 Kocaeli earthquake and the 1999 Chi-Chi earthquake (Vazouras et al., 2010).

Evaluation of the response of buried steel pipelines at active fault crossings is among their top seismic design priorities. This is because the axial and bending strains induced to the pipeline by step-like permanent ground deformation may be come fairly large and lead to rupture, either due to tension or due to buckling. Apart from the detrimental effects that such a rupture can have to the operation of critical lifeline systems, an irrecoverable ecological disaster may also result from the leakage of environmentally hazardous material s such as natural gas, fuel or liquid waste. The currently available techniques of numerical analysis (e.g. large scale Finite Element models) allow a rigorous solution of this problem, minimizing the number of necessary approximations. Nevertheless, the non-linear behavior of the pipeline steel, the soil-pipeline interaction and the second order effects, induced by large displacements, make such analyses rather demanding, and provide ground for the use of simplified analytical methodologies, at least for preliminary design and verification purposes (Karamitros et al., 2007).

A simplified analytical methodology which is widely used today for strike-slip and normal faults, is the one originally proposed by Kennedy et al. (1977), and consequently adopted by the ASCE guidelines for the seismic design of pipelines (ASCE, 1984). Kennedy et al. extended the pioneering work of Newmark and Hall (1977), by taking into account soil-pipeline interaction in the transverse, as well as in the longitudinal directions. Most recently, Karamitros et al. (2007) extend the Kennedy model and incorporate some ideas from the Wang-Yeh model. Specifically, like Wang and Yeh, they use a beam-on-elastic foundation model for the “straight” pipe region.

The aim of present work is to examine and compare the mechanical response of continuous (welded) buried steel pipelines crossing active strike-slip seismic faults by three different methods including analytical method, Winkler model and 3D FEM continuum using ABAQUS software. (ABAQUS, 2012).

2. NUMERICAL MODELING

The structural response of steel pipelines under fault movement is examined numerically using advanced computational tools. General-purpose finite element program ABAQUS is employed to simulate the mechanical behaviour of the steel pipe, the surrounding soil medium and their interaction in a rigorous manner, considering the nonlinear geometry of the soil and the pipe (including the distortions of the pipeline cross-section), through a large-strain description of the pipe-line-soil system and the inelastic material behaviour for both the pipe and the soil.

2.1. CONTINUUM MODEL

For 3D FEM continuum model, an elongated prismatic model is considered, where the pipeline is embedded in the soil. The corresponding finite element mesh for the soil formation is depicted in Fig.1a and b, and for the steel pipe in Fig.1c. Four-node reduced-integration shell elements (type S4R) are employed for modeling the pipeline cylinder, whereas eight-node reduced-integration ‘‘brick’’ elements (C3D8R) are used to simulate the surrounding soil. The top surface represents the soil surface, and the burial depth is chosen equal to about 2 pipe diameters, which is in accordance with pipeline engineering practice. A short parametric study demonstrated that a 60-diameter length of the pipeline (in the x direction) is adequate for the purposes of the present analysis (Vazouras et al., 2010). Furthermore, prism dimensions in directions y and z equal to 10 and 5 times the pipe diameter, respectively, are also found to be adequate. The seismic fault plane is considered perpendicular to the pipeline axis at the pipeline middle section and divides the soil in two equal parts (Figure 1a). The analysis is conducted in two steps: gravity loading is applied first and, subsequently, fault movement is imposed. The vertical boundary nodes of the first block remain fixed in the horizontal direction (including the end nodes of the steel pipeline), whereas a uniform displacement due to fault movement is imposed in the external nodes of the second (moving) block in the horizontal y direction (including the end nodes of the pipeline).

2.2. WINKLER MODEL

The Winkler pipe model is modeled using ABAQUS 3D elastic-plastic beam elements (type B31) orientated along the longitudinal (x) axis. The pipeline length modeled is based on the effective unanchored length in the fault zone. This length is a function of the yield force and the longitudinal frictional restraint per unit length. The mesh is refined in the critical region within the vicinity of the fault with element lengths of 0.5m specified. The remainder of the pipeline was modeled with 1m long elements in the relatively undisturbed area (see Figure 2). The pipe-soil interaction was modeled following the methodology detailed in ASCE Design Guideline. The soil surrounding the pipeline was modeled as discrete elasto-plastic springs in the axial, lateral and vertical (up/down) directions. The ABAQUS SPRING2 element was used to model the non-linear springs. The SPRING2 element is between 2 nodes, acting in a fixed direction. The pipe-soil interaction force-displacement behaviour was defined using the formulation described in ASCE guideline (ASCE, 1984).

Plasticity is modeled using incremental theory with a von Mises yield surface, associated flow rule, and isotropic hardening. The material property is defined in terms of the true stress versus logarithmic strain as required by the ABAQUS program.

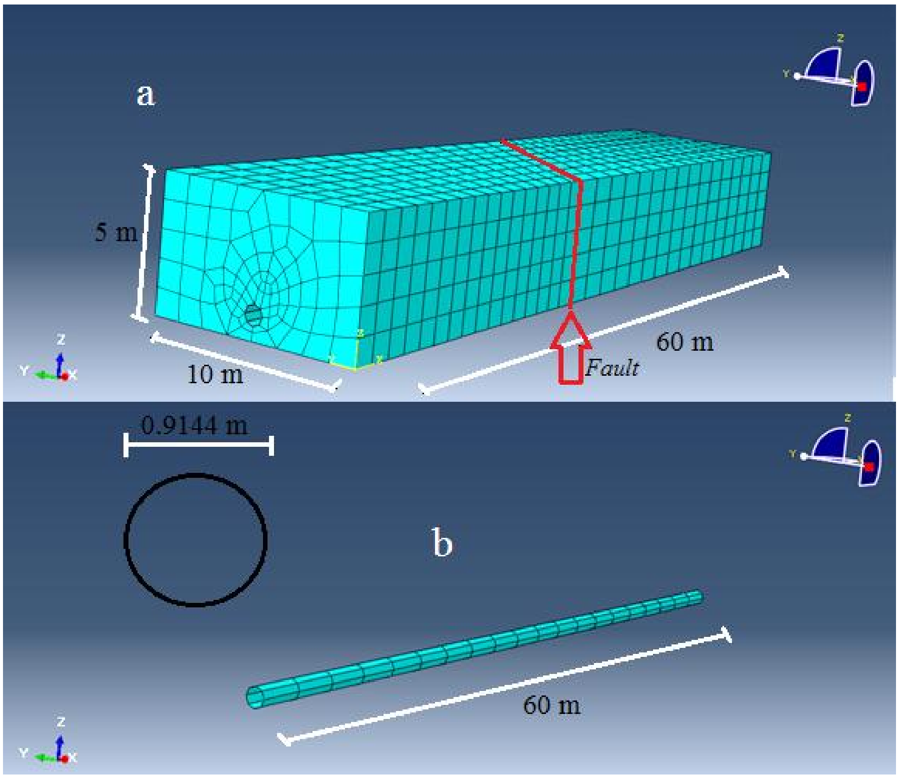


Figure 1. Finite element model of the (a) soil formation with tectonic fault and (b) steel pipeline

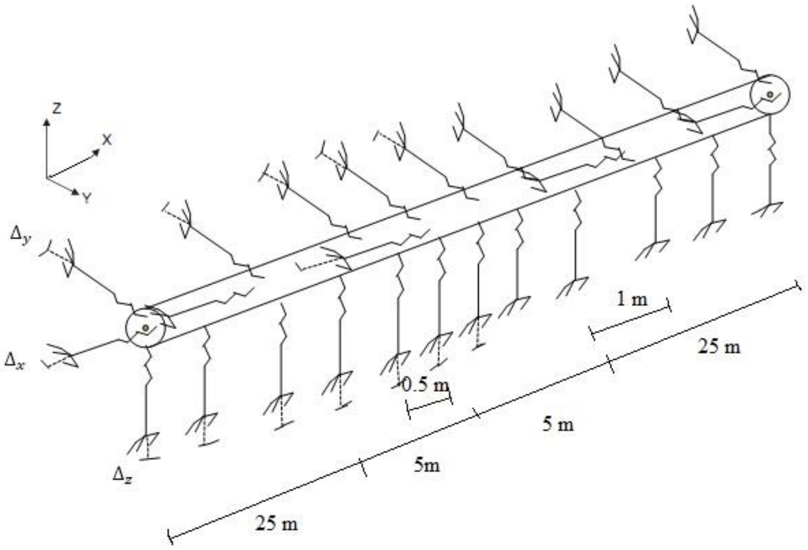


Figure 2. Geometry of proposed Winkler model for buried pipeline

2.3. SIMULATION OF FAULT MOTION

For both model the strike-slip fault is taken as an inclined plane, i.e. with null thickness of rupture zone, so that the intersection of the pipeline axis with the fault trace on the ground surface is reduced to a single point. The fault movement is defined in a Cartesian coordinate system, where the x-axis is collinear with the undeformed longitudinal axis of the pipeline, while the y axis is perpendicular to x in the horizontal plan. Subsequently, the fault movement is analyzed into two Cartesian components, Δx and Δy, interrelated through the angle formed by the x-axis and the fault trace (angle β in Figure 2). In its present form, the proposed method applies to crossing angles β≤90, resulting in pipeline elongation.

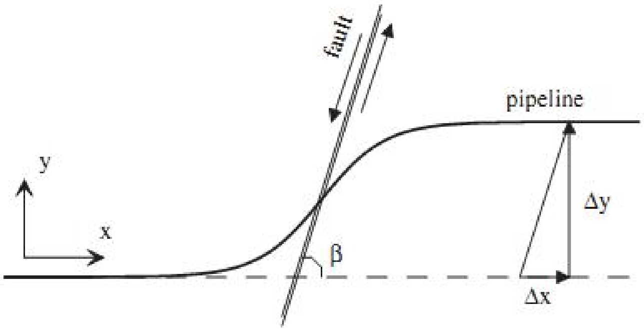


Figure 3. Definition of axes x and y and fault displacements Δx and Δy

$$\Delta_x = \Delta \cos(\beta) \tag{1}$$

$$\Delta_y = \Delta \sin(\beta) \tag{2}$$

Quasi-static conditions were simulated in the analysis by applying fault offset components to soil-spring ends in Winkler model and to moving block in continuum model through a smooth loading function of time (Smooth Step Function in ABAQUS) which avoids any sudden load changes, and by keeping a sufficiently long loading duration for the fault offset components.

2.4. MATERIAL PROPERTIES

Steel pipe material and the physical parameters of soil are shown in Tables 1 and 2 respectively. Soil–pipeline interaction is modeled rigorously through FEM which account for large strains and displacements, nonlinear material behavior and special conditions of contact and friction on the soil–pipe interface.

Table 1. Properties of AP15L-X 65 pipe

Yield stress (σ_1)	490 MPa
Failure stress (σ_2)	531 GPa
Failure strain (ε_2)	4.0%
Elastic Young's modulus (E_1)	210 GPa
Yield strain ($\varepsilon_1 = \sigma_1/E_1$)	0.233%
Plastic Young's modulus ($E_2 = (\sigma_2 - \sigma_1)/(\varepsilon_2 - \varepsilon_1$)	1.088 GPa
Diameter (D)	0.9144 m
Thickness (t)	0.0119 m
Length (L)	60 m

Table 2. Physical parameters of the soil

Type	Density ρ (Kg/m^3)	Elastic Young's modulus (MPa)	Friction angle Φ (^{o})	Poisson's ratio υ
Sand I	1850	8	30	0.3
Sand II	2100	50	40	0.3

For Winkler model, the properties of the soil-springs were calculated according to the ALA– ASCE guidelines, assuming that the pipeline top is buried under 1.30 m of medium-density sand with friction angle φ =36 ^{o} and unit weight ɣ =18 kN /m^2 . Table 3 shows considered soil-spring properties.

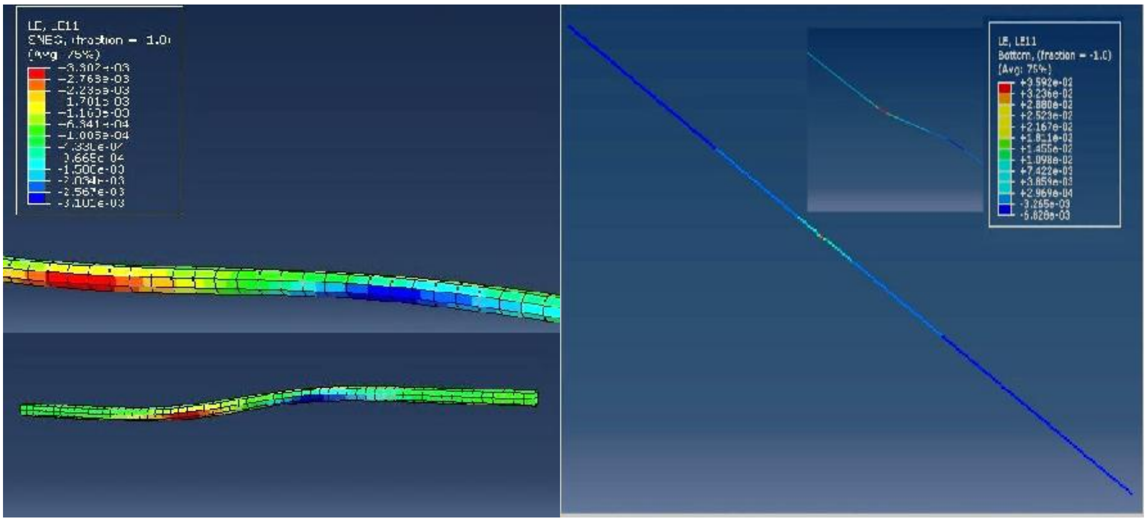
Table 3. Soil spring properties considered in the numerical analyses

Type of spring	Yield force (kN/m)	Yield displacement (mm)
Axial (friction) springs	40.5	3.0
Transverse horizontal springs	318.6	11.4
Vertical springs (upward movement)	52.0	2.2
Vertical springs (downward movement)	1360	100.0

3. RESULTS

With respect to the fact that the pipe mass is negligible compared to its stiffness, we can say that the inertia forces produced by pipe mass in the pipeline is negligible compared to the force which is proportional with stiffness of the soil-pipe system; therefore, the natural period of system is very small. Since the natural period of the system is very small compared with the time of movement resulting from the fault activity, utilization of a static analysis for investigating buried pipe behavior against large ground motions seems to be logical.

The factors influencing response of buried pipeline at strike-slip fault crossing include the fault offset (Δ), pipeline crossing angle (β), native and backfill soil type, burial depth (H), pipe diameter (D) and thickness (t) and pipe material. However, the designer has the choice to vary the factors β, the backfill soil type, H, D, t and pipe material so as to improve the pipeline's performance and optimize the design. Influence of these design parameters on the response of the buried steel pipe to strike-slip fault motion was studied using the previously described three different theoretical methods. These analyses were performed with a view to enable selection of design parameters that would enhance the pipeline's capacity to accommodate the strike-slip fault offset. Figure 4 shows a view of the distribution of axial strain in buried pipe in for Winkler and 3D FEM continuum model.

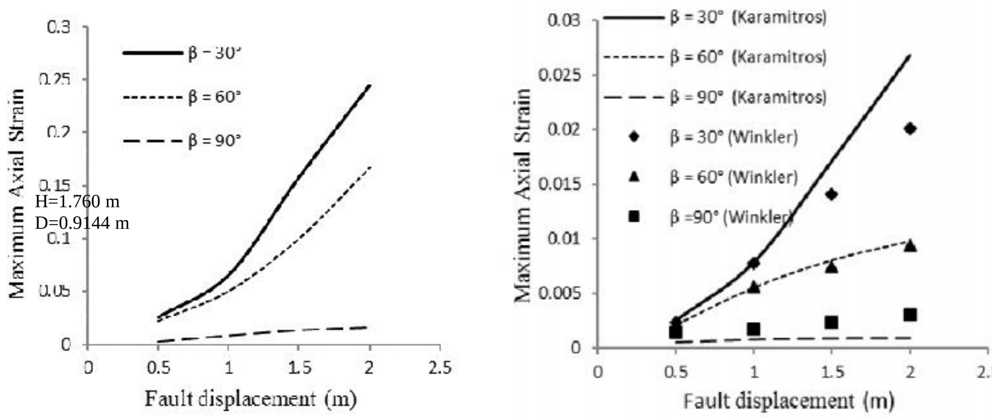


(a) (b)

Figure 4. Axial strain distribution in the deformed pipe, a) 3D FEM continuum model; b) Winkler model

3.1. INFLUENCE OF CROSSING ANGLE

Figure 0 shows the effect of crossing angle (β) using the three utilized methods on maximum axial strain in the pipeline at various strike-slip fault offset magnitudes. In all three methods, for each β of the pipeline, maximum axial strain increases as the value of Δ gradually increased up. Figure 5a and 5b show that, when the results are compared at a constant magnitude of Δ for various β angles, maximum axial strain decreases consistently as the crossing angle increased from 30–90. At each value of Δ, the smallest value of maximum axial strain was observed at β=90 °, and the largest at β=30 °. Also the Winkler and analytical methods predicts longitudinal strain less than those obtained from the continuum model.

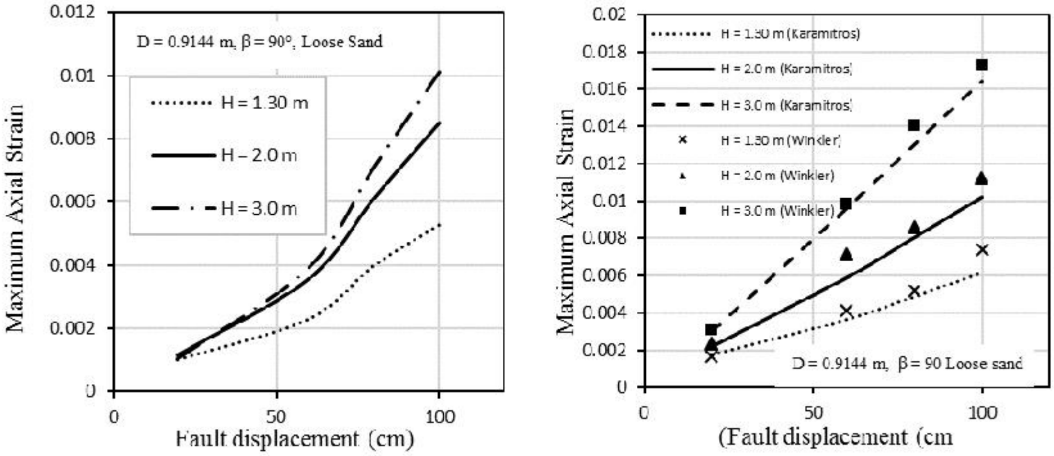


(a) (b)

Figure 5. Effect of the crossing angle (β) on the pipeline performance, a) 3D FEM continuum model; b) Winkler model and analytical method

3.2. INFLUENCE OF BURIAL DEPTH

Figure 6a shows plots of maximum axial strain against the applied Δ for three burial depths from 3D FEM simulation. maximum axial strain was observed to increase as the soil cover (H) increased from 1.30 to 3 m. Similar effect for the burial depth was observed when the same pipeline section was analyzed by Winkler and analytical karamitros methods (see Figure 6b). Results of the parametric study show that the increase in burial depth increased the values of limiting uplift soil force and limiting pipe–soil friction force acting on unit length of the pipeline, and consequently led to higher maximum axial strain for a constant magnitude of Δ. Thus, burial depth as shallow as possible is preferable in the fault crossing zone However, the live loads and environmental factors may also have an influence on the minimum soil cover.

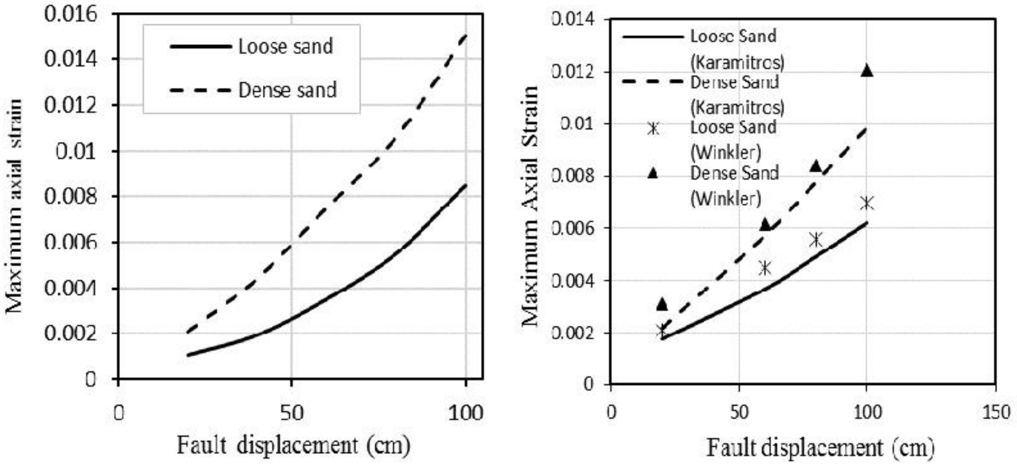


(a) (b)

Figure 6. Effect of burial depth on the maximum axial strain, a) 3D FEM continuum model; b) Winkler model and analytical method

3.3. INFLUENCE OF BACKFILL TYPE

Figure 7 shows the effect of backfill type on maximum axial strain in the pipeline at various strike-slip fault offset magnitudes. The same pipeline segment (with the same burial depth and pipe surface properties), as adopted in the previous section, was studied for two granular backfills: loose ($\varphi=30^{o}$) and dense ($\varphi=40^{o}$). Fault motion parameters (β) was chosen to be 90, and the pipeline was subjected to maximum fault offset of 120 cm in increments of 20 cm. For a constant magnitude of Δ, maximum axial strain value increased as the compactness of granular backfill increased. Note that, results obtained from Figure 7 suggest that the maximum compressive strain in the pipeline could be reduced by a fair amount by placing a very loose backfill in the fault crossing region and by avoiding its unnecessary over-compaction.



(a) (b)

Figure 7. Effect of the type of backfill on the maximum total compressive strain in the pipeline, a) 3D FEM continuum model; b) Winkler model and analytical method

4. DISCUSSION AND CONCLUSIONS

As shown in the pervious section, the comparison of three different Winkler, analytical and 3D FEM continuum model show how the choice of an analysis approach affects the outcome of the seismic fault assessment. The higher longitudinal strains calculated for the continuum model is largely driven by the boundary conditions and the simplified assumptions made for the Winkler and analytical model. The results presented for the comparison between the continuum,Winkler and analytical models have thus provided an impetus to make a critical review of the best approach for seismic fault analysis of buried pipelines.

During the early design phases of the project, in the event that the pipeline will be subject to seismic effects, there is a great advantage in using the Winkler model or analytical methods to get a better understanding of the potential impact of the earthquake loading on the pipeline. Thus the pipeline can be rerouted based on the outcome of the initial analysis. However, for an existing pipeline lying across a seismic fault line and requiring restabilisation, by rock placement, following an extreme environmental event, it is worthwhile undertaking an assessment of the pipeline structural integrity using the continuum model.

In conclusion, it is apparent that the use of the Winkler model and analytical methods for seismic fault line displacement analysis may not be sufficient for proper pipeline design and may lead to over-simplistic conclusions. Main conclusion of this study can be stated as follows. The capacity of the pipeline to safely accommodate the strike-slip fault offset can be further increased by choosing a loose granular backfill, adopting a shallower burial depth and increasing crossing angle between pipe and fault.

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