Numerical Analysis of Buried Steel Pipelines

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ABSTRACT

Various alternative numerical analysis methods that are used to simulate the response of buried steel pipelines subjected to large imposed displacements triggered by seismic fault activation are presented. Due to the grave financial, social and environmental consequences of a potential pipeline leakage, damage or failure is a problem deserving special attention. Advanced nonlinear numerical simulations are the only way to handlewith sufficient accuracy the complexity of the physical problem associated with the surrounding soil and the relevant pipeline-soil interaction.During preliminary design,however, reliable numerical models are required that demandminimum computational effort.

In this paper alternative simulations of the problem making use ofbeam-type finite elements are presented and compared in terms of accuracy and computational cost. Comparisons are carried out regarding the types of finite elements, whether geometric nonlinearity is included or not.

1 INTRODUCTION

During the design procedure of a new pipeline various limitations are encountered, e.g. avoidance of populated or environmentally sensitive areas. Therefore, pipeline crossing of active tectonic faults is often inevitable. As a buried pipeline is forced to follow soil movement, its integrity is heavily influenced by potential fault activations. This has been proven from numerous past earthquake events to be the dominant cause of pipeline failure, compared to landslides, liquefaction-induced lateral spread, seismic wave propagation etc.

Newmark and Hall [1] were the pioneers of pertinent research efforts by introducing an analytical model for assessing the integrity of a buried pipeline crossing a ruptured fault. Their work was based on the assumption of a single and adequately defined fault plane by considering soil masses on both fault sides being rigid bodies. Also, they introduced a so called anchor point situated at a certain distance from the fault, beyond which the pipeline and the surrounding soil have no relative displacement. Kennedy et al. [2] evolved the ideas of Newmark and Hall by taking into account the lateral soil interaction to evaluate the maximum axial strain. Ariman and Le [3] introduced the use of the finite element method in pipeline response analysis to evaluate pipeline strain. Takada et al. [4] proposed a simplified method to evaluate the maximum axial strain considering the deformation of the pipe cross-section by relating pipe bending angle and the maximum axial strain. Karamitros et al. [5-6] improved analytical methodologies for strike-slip and normal faults by combining the theory of beam-on-elastic-foundation and the elastic-beam theory to calculate the bending moments.They also took into account material and geometric non-linearities to calculate pipeline stresses and maximum strain. Trifonov et al. [7] improved the pipeline stress analysis using a semi-analytical approach.

2 PIPELINE DESIGN AND MODELING

2.1 General Design Considerations

The top priority in pipeline earthquake design is the avoidanceof any potential damage that could lead to loss of containment and then to oil spills, environmental damage and human injuries. Fault activation causeslarge permanent ground deformationimposed on the pipeline in a quasi-static manner.Although pipeline steel is a ductile material, high level strain concentration in certain areas is of great concern. High compressive strains can lead to local buckling of the pipeline wall and resultin a potential fracture and leak. On the other hand, high tensile strains endanger the integrity of girth welds, even if serious defects are absent and coatings and cathodic protection are properly installed. Investigation of previous earthquake damages showed that girth welds seem to be the weakest locations and prone to stress and strain concentration. Finally, excessive strains tend to significantly ovalize the cross-section and aggravate the above potential problems. So, the primary consideration during buried pipeline design is the determination of strain capacity.

2.2 Pipeline modeling

The objective of pipeline numerical analysis in the preliminary design stage is the general assessment of pipeline response in case of fault activation.It is then necessary to use simple, no time consuming but reliable simulation tools. Beam-type finite elements are the proper choice for this procedure as their capability to calculate stresses and strains at selected positions along the pipeline length and on pipeline cross-section allow engineers to quickly assess pipeline response.

Nevertheless, in subsequentdesign stages, when pipeline serviceability is also important and local buckling risk has to be examined, the use of shell-type finite elements seems to be inevitable for the exact prediction of the developing cross-section distortions and potential wall local buckling.

However, shell-type finite elements increase dramatically the complexity of the model and the computational effort. Thus, a combination of the above mentioned simulation options can give the desired results. Gantes and Bouckovalas [8] used a hybrid numerical model consisting of a pipeline part around the fault modeled as a cylindrical shell to assess local buckling and cross-section ovalization risk. The remaining part of the pipeline, where stresses and strains are relatively small and local buckling risk is low, is modeled as a beam using beam-type finite elements.

2.3 Soil modeling

There are two options to simulate soil-pipeline interaction effects using modern numerical methods. The first is using translational nonlinear springs in three directions (Figure 1). Springs in the longitudinal pipeline axis direction simulatepipeline-soil friction, transverse horizontal springssimulate transverse horizontal pipeline movement within the trench, and couples of springs in the vertical direction simulate pipeline vertical upward and downward movement, as the soil above and below the pipeline has essentially different characteristics. Above the pipeline the backfill soil is usually selected with specific characteristics in order to allow the pipeline to smoothly undergo displacements within the trench without significant pipeline-soil friction. Below the pipeline the native soil has varying characteristics depending on the local soil conditions of the crossing area. Additionally, soil springs are compatible to beam-type finite elements when used for pipeline modeling. This simulation option is adopted by all modern pipeline Codes, Standards and Regulations, such as Eurocode 8, ASCE-ALA Guidelines, API 5L, ASME B31 Code etc.

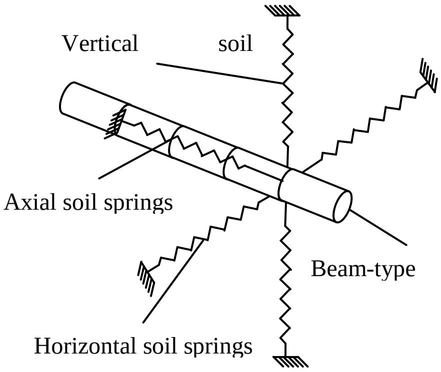

Figure 1Model used for analyses with the Finite Element Method

The second option is the soil simulation using “solid” or “brick” elements [9]. This simulation demands the use of shell-type elements for pipeline simulation and at the same time it necessitates the simulation of a large soil area around the pipeline. Additionally, a couple of numerical considerations rise for the interface simulation between soil and pipeline. This advanced simulation technique significantly increases the complexity of the problem and the required computational effort. It may, however, be meaningfulwhen issues of local buckling, welding strength assessments etc. are under investigation.

3 CASE STUDY

3.1 Pipelineinvestigated

Pipeline numerical modeling is performed with the commercial code ADINA™ [10]. For this purpose a typical high-pressure natural gas pipeline is considered, featuring an external diameter of 0.9144m (36in), a wall thickness of 0.0119m (0.469in), and a total length of 1000m. The steel is of the API5L-X65 type and considered bilinear (elastic-plastic) with the properties listed in Table 1.

The fault is considered to be normal with angle $\psi = 70^o$, the fault plane to be planar and the pipeline intersection angle is equal to $\beta = 60^o$. The fault movement is applied statically on the hanging wall of the fault, as a permanent displacement of the free end of the corresponding soil springs. The analysis proceeds incrementally to a final fault displacement $\Delta f = 2D$, with D being the pipeline’s external diameter.

Table 1API5L-X65 Steel Properties Considered in the Numerical Analyses

Yield stress (σ_1)	490MPa
Failure stress (σ_2)	531MPa
Failure strain (ε_2)	4.0%
Elastic Young’s modulus (E_1)	210GPa
Yield strain ($\varepsilon_1 = \sigma_1 / E_1$)	0.233%
Plastic Young’s modulus ($E_2 = (\sigma_2 - \sigma_1) / (\varepsilon_2 - \varepsilon_1)$)	1.088GPa

Pipeline numerical simulation is carried out using BEAM type elements and PIPE type elements. Pipeline is discretized with 0.50m long finite elements. Thus, the finite element model used herein consists of a total number of 10,006 nodes and 10,004 elements and has 24,006 degrees of freedom.

Moreover, a mesh density sensitivity analysis was carried out by the authors to investigate the proper length of finite elements. Models discretized with 0.20m, 0.50m, 1.00m and 2.00m long finite elements were created. Results demonstrated that between the finite element length of 0.20m and 0.50m differences were found to be negligible. On the other hand, differences between models discretized with 0.50m, 1.00m and 2.00m long elements respectively were found to be significant. Hence, the length of 0.50m for discretization was adopted for the analyses.

3.2 Soil Modeling

For our case study it is assumed that the pipeline top is buried under 1.30 m of medium-density sand with friction angle $\varphi = 36^o$ and unit weight $\gamma = 18\ kN/m^2$. Soil-springs are modeled as elastic-perfectly plastic SPRING elements with property nonlinearityonly. Soil-springs properties are calculated according to the ASCE-ALA [11] guidelines and listed in Table2.

Table 2Soil Spring Properties Considered in the Numerical Analyses

	Yield force (kN/m)	Yield displacement (mm)	Ultimate displacement (mm)
Axial (friction) springs	40.72	3.0	5.0
Transverse horizontal springs	320.22	12.0	89.0
Vertical springs (upward movement)	45.47	2.3	18.0
Vertical springs (downward movement)	1494.61	12.0	91.0

4 NUMERICAL RESULTS

4.1 Geometrical non-linearity

Firstly, results for maximum longitudinal stress and strain are compared,derivedfrom numerical models considering geometric nonlinearity or not. The analysis is performed using BEAM elements that allow the option of large displacements/geometric nonlinearity during the analysis. However, at the same time strains remain small. The analyses' results are illustrated in Figure 2 for the evolution of axial stress along pipeline length and Figure 3 for the evolution of axial stain along pipeline length around the fault zone.

From Figures 2 and 3 is concluded that the geometric nonlinearity leads to larger stresses and strains. Moreover, axial strains, derived from geometrically nonlinear model, seem to have a smoother evolution around the fault zone than axial strains derived from geometrically linear model. Geometric nonlinearity is considered to be a better and more precise simulation of the physical problem since pipeline undergoes displacements of a few meters. Ignorance of geometric nonlinearity or large displacements in the numerical analysis can lead to important underestimation of stresses and strains and then to errors in the design procedure.

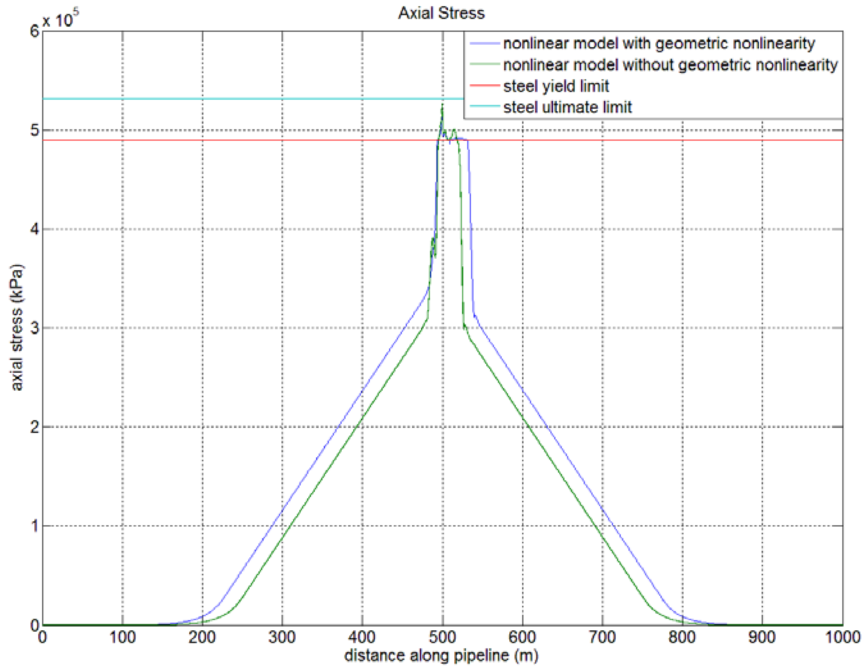

Figure 2Axial stress

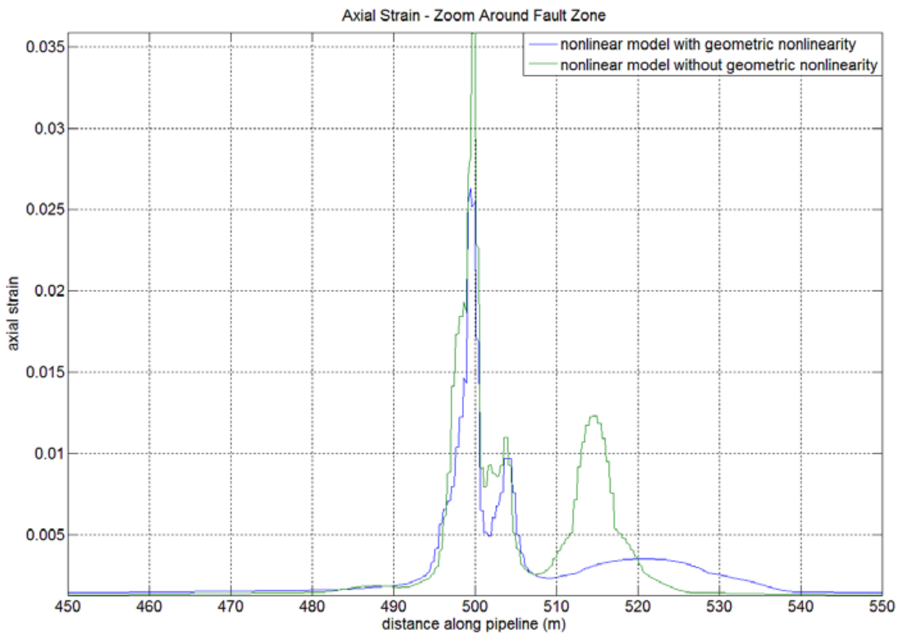

Figure 3 Axial strains around the fault zone

4.2 Cross-section Ovalization

The next comparison is carried outbetween numerical models using PIPE elements taking into account or not cross-section ovalization. PIPE elements in ADINA^{TM} [10] are beam-type elements with some characteristics of shell-type elements. They are capableof undergoing large displacements and mainly take cross-section ovalization into account.The analyses' results are illustrated in Figure 4 for the evolution of axial stress along pipeline length and Figure 5 for the evolution of axial stain along pipeline length around the fault zone.

Figures 4 and 5 indicate that cross-section ovalization does not differentiate significantly the results in terms of stresses and strains. Nevertheless, the importance of cross-section integrity, as it is presented in previous section, cannot be neglected, even though in the preliminary design stage the use of beam-type finite elements cannot fully estimate cross-section ovalization.

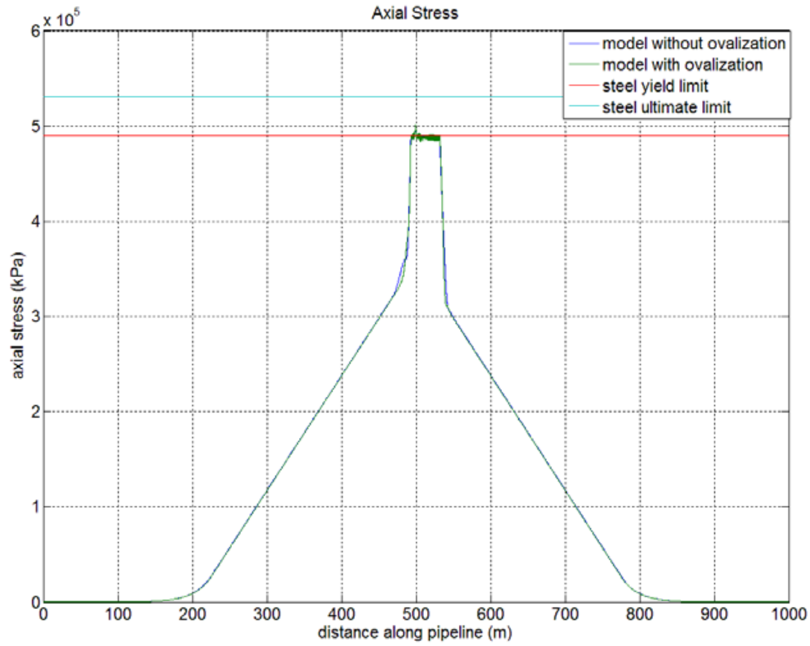

Figure 4Axial stress

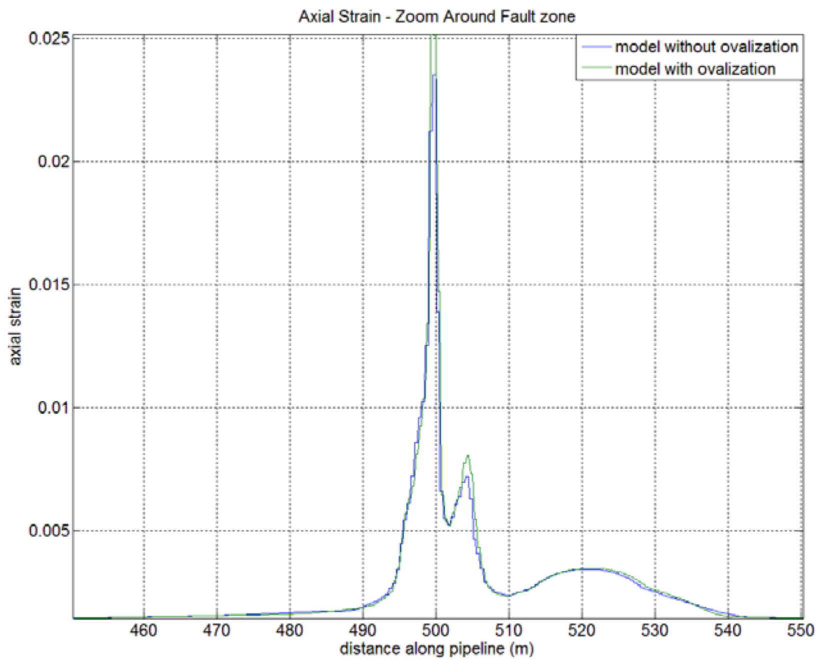

Figure 5Axial strain around the fault zone

4.3 Comparison of beam vs. pipe element models

The third comparison is conducted between numerical models using BEAM and PIPE elements. PIPE elements are compared to BEAM elements in order to investigate any differences that can lead designers to utilize one or the other type of beam-type finite element.The analyses' results are depicted in Figure 6 for the evolution of axial stress along pipeline length and Figure 7 for the evolution of axial stain along pipeline length around the fault zone. Figures 6 and 7 present no remarkable difference in results concerning stresses and strains. Figure 7 indicates same variation in axial strains about 5 m after the fault. Despite the fact that there are no substantial differences between these two types of finite elements, the design engineer has to choose the proper one based on his/her experience and the targeted results.

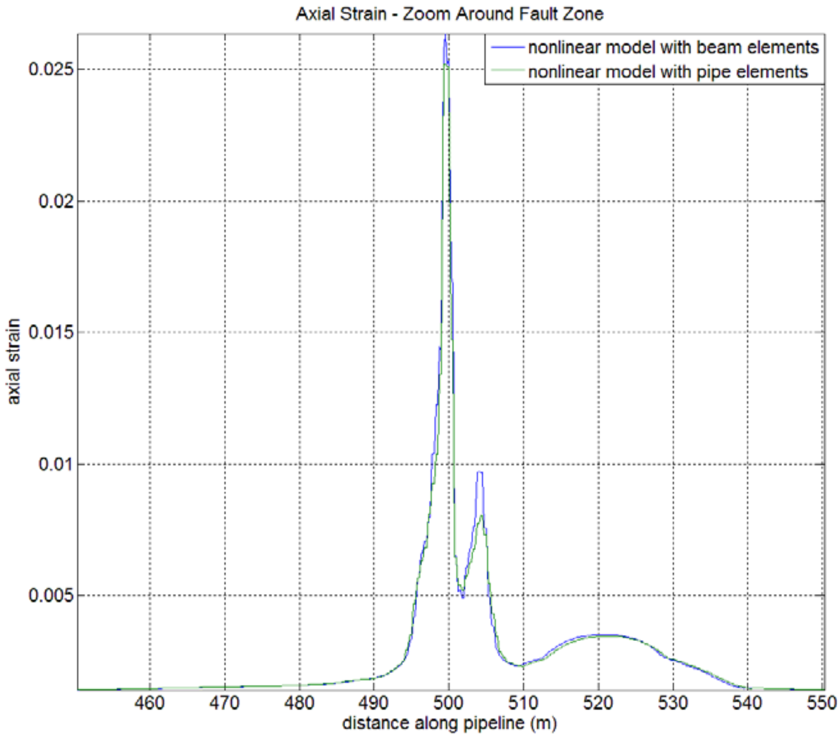

Figure 6Axial stress

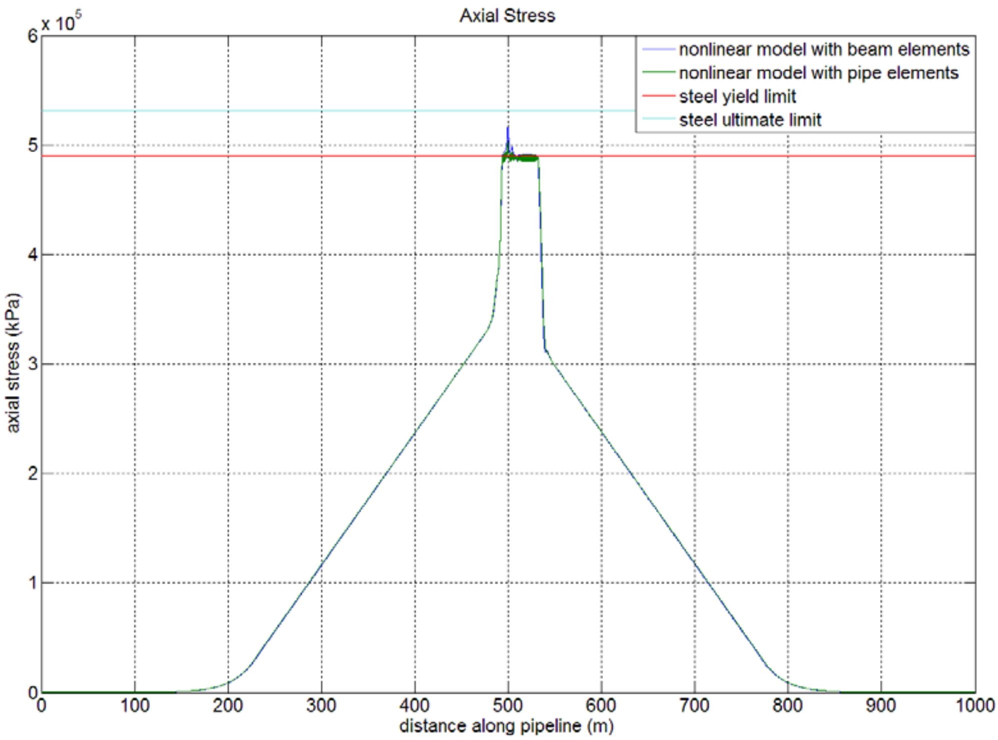

Figure 7Axial stress and strain around the fault zone

5 SUMMARY AND CONCLUSIONS

The response of buried steel pipelines crossing an active normal fault is investigatedusing various capabilities of finite element simulation tools. The pipeline is assumed horizontal, an idealized case, which allows for the investigation of alternative simulation options concerning the numerical analysis options.The cases investigated include models considering geometric nonlinearity of the problem or not and cross-section ovalization.Finally a comparison between two types of beam-type finite elements is carried out.

Acknowledging that design engineers can in practice use various numerical methods and relevant software packages to assess pipeline response, the presented investigation leads to some useful and general findings. Geometric nonlinearity is an important parameter of the problem and has always to be considered in the analysis. Ovalization consequences, even though they are crucial for pipeline integrity because they are often associated with local buckling effects, cannot be properly evaluated using beam-type finite elements. Finally, the use of finite elements of different type relies on the engineering judgment of the designer.

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