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# PERFORMANCE EVALUATION OF BURIED STEEL PIPES SUBJECT TO STRIKE SLIP FAULT OFFSETS

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**Abstract.** *Buried steel pipes are commonly used in oil and gas industry for transmitting hydrocarbon products. Fault crossing is considered as one of the most important extreme events. Buried steel pipes are more vulnerable to compressive strains as compared to tensile strains. In this study, a numerical study is carried out on a simplified numerical model to determine the seismic demand on steel pipes at fault crossings. The proposed model permits plastic hinge formation in the pipe due to incrementally applied fault movements, allow determining the critical length of the pipeline and measure strains developed on the tension and compression sides in the pipe. Based on the analyses carried out on the simple model and previous studies, two performance levels are defined for pipelines; namely, fully functional and partially functional.*

## 1 INTRODUCTION

Buried steel pipes are commonly used in oil and gas industry for transmitting hydrocarbon products from sources to end points. Critical hazard locations for such pipes are in spatially varying permanent ground deformation (PGD) zones (liquefaction and landslide) and fault-crossing locations. Among these, the fault crossing is considered as one of the most important extreme events since the axial strains in the pipe can reach to very high values due to combined effects of bending and axial deformations.

Past earthquakes (1999 Kocaeli earthquake, Turkey; 1999 Chi-Chi earthquake, Taiwan) revealed the fact that the strain demand on pipes crossing active faults may be quite extreme due to relative movement of the fault with respect to the pipe axis [1]. When a continuous pipe is subjected to permanent ground deformation due to fault rupture, the damage pattern depends on the type of the fault, material and geometric properties of the pipe. Pipes with high $D/t$ ratios are usually more vulnerable than the pipes with low $D/t$ ratios, where $D$ and $t$ are the diameter and thickness of the pipe, respectively [2, 3]. In Turkey, most of the pipe damage data is available for segmented pipes in PGD zones [4]. O'Rourke et al. [5] calculated the data points to develop the fragility curves for segmented pipes in Turkey using damage data from 1999 Kocaeli earthquake. Possibly, one of the best documented case study of buried continuous pipe response to fault offsets is the Thames Water Pipeline during the 1999 Izmit (Turkey) event [6, 7]. A welded steel, D= 2.2m water transmission pipe with (D/t = 122) crossing the Sapanca Segment of the North Anatolian Fault at an angle $\beta$ = 125 degrees in Kullar, southeastern Izmit, Kocaeli, Turkey (Figure 1) was subject to right lateral fault ruptured with an offset of 2.45 m in Kullar, Izmit. The fault offset caused two major wrinklings and one minor buckling at three different locations on the pipe.

The limit states for buried steel pipes are: a) the maximum tensile strain, b) local buckling due to axial compressive strain (critical buckling strain), c) distortion of pipeline cross section, and d) tearing of the pipe wall [2]. The amount of the strain depends on the type and orientation of the fault with respect to the pipe axis, geometric and material properties of the pipe (steel grade, pipe diameter and thickness), burial depth (deep or shallow), and the properties of the surrounding soil [2, 8].

Figure 1. A close-up view to the wrinkled pipe in Kullar, Izmit during the 1999 Kocaeli Earthquake

In this study, a numerical study is carried out on a simplified numerical model which takes into account the plastic hinge formations and nonlineat soil springs is constructed. The response of the nonlinear pipe-soil interaction system to incrementally applied fault displacements (perpendicular to the pipe axis) is calculated. Critical length of the pipeline, $L_{cr}$ (the distance between the first plastic hinges at both sides of the fault line), and strain demand on compression and tension sides of the pipes are selected as the major response parameters. Large displacement analyses are first verified on a benchmark problem and then applied to the model. The proposed model permits plastic hinge formation in the pipe due to incrementally applied fault movements, allow determining the critical length of the pipeline and measure strains developed on the tension and compression sides in the pipe. The model also considers the effect of bending minimum performance criteria for pipelines are proposed. Based on the analyses carried out on the simple model and previous studies, minimum performance criteria for pipelines are proposed. Two performance levels are defined for pipelines; namely, fully functional and partially functional.

## 2 STEEL PIPELINES AT FAULT CROSSINGS

Design of steel pipelines crossing a major fault line is based on the determination of axial strain. In general, two types of axial strains are involved in the pipe [3]:

a. Axial bending strains due to the transverse component of fault offset,
b. Net axial deformations of the pipe due to the axial (longitudinal) component of the fault offset.

The magnitude of the pipe strain, in general, depends on the orientation of the pipeline with respect to the pipe axis as well as the slip direction. A strike slip fault movement will induce an axial as well as transverse movement on steel pipes. Axial component will cause uniform axial strain in the forms of tension or compression. In the fault normal direction ($90^0$ to the pipeline axis), axial strain will be equal to zero, whereas axial strain (tension/compression) will gradually increase with increasing fault movement. As the fault movement increases, the tensile strains will develop due to stretching of the pipe in reversed direction. This will cause reduction in the compressive strains after the peak compressive strain has been reached [3]. The most significant deformation will happen in an effective length, *L,* of the *S* shaped segment of the pipeline (Figure 2). *L* is determined analytically and is based on the elastic behavior of the pipe. In this study, *L* is calculated numerically as the length of the pipe segment, $L_{cr}$, which is defined as the distance between the points where first significant yielding occurs in the pipe on both sides of the fault (Figure 2). Seismic design and analyses of steel pipes crossing fault lines are provided by ALA [9], Eurocode 8 [10] and ASCE [11] in detail. Seismic evaluation of these pipes should be based on performance-based design principles as proposed in this paper.

## 3 NUMERICAL ANALYSES

As a case study, seismic response of a steel pipe is investigated. The pipe is assumed to be perpendicular to the strike slip fault line in the horizontal plane. A structural model consisting of two segments (1st block and 2nd block) is constructed with a total length of 100.0 m; width of 10.0 m, and depth of 5.0 m (Figure 2). Incremental fault displacement is applied gradually to the 2nd block up to the total fault displacement of 3.0 m, while keeping the 1st block fixed.

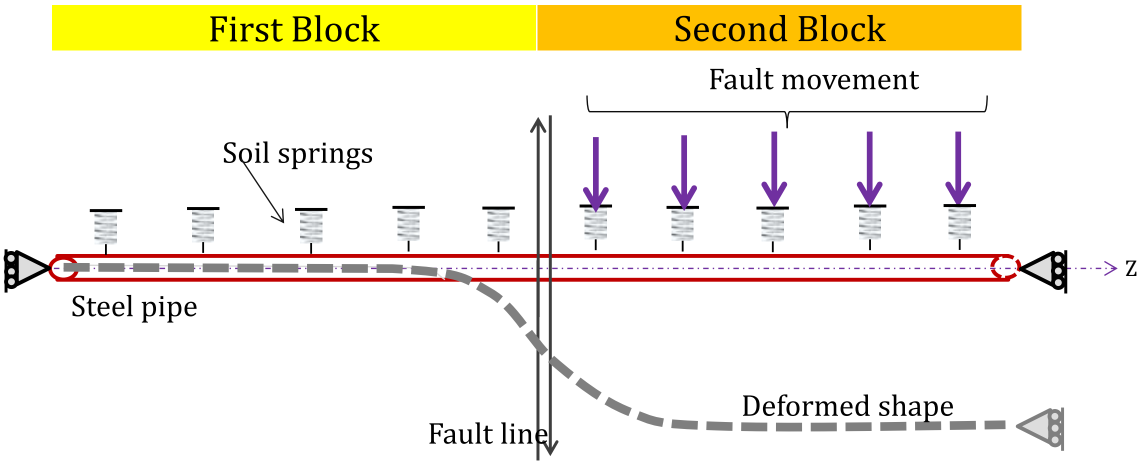


Figure 2. A plan view of the simple model representing pipe behavior under prescribed fault movement perpendicular to the pipe axis (Z axis)

A simplified model consisting of a nonlinear beam element to represent the pipe and linear/nonlinear soil springs attached to the pipe at discrete points is proposed to determine the seismic response of the pipe (Figure 2). Detailed information about the model can be found in [12]. The prescribed displacements are applied to the support nodes of the 2$^{nd}$ block (moving block) only. Nonlinear static analysis is performed to compute the deformations and strains in the pipe of the soil-pipe interaction system (Figure 2). SAP2000 V15 software [13] is used for the analyses. SAP2000 V15 [13] allows to consider large displacement and strain in the analyses. This is verified in a simple arc structure.

The steel pipe used in the study has a diameter (*D*) of 914.4 mm and thickness (*t*) of 12.7 mm (Figure 3). Steel grade is assumed as A992Grade50. To determine the plastic hinge formation, axial force (*P*)-moment (*M*) hinges are assigned along the pipe at 2.5 m intervals (Figure 4). Soil cohesion for soft clay is assumed to be 10 kPa at a depth of 3.0 m. The beam elements used in the analysis provide stresses and bending moments at nodal points. For further verification of the simplified model, a detailed 3-D finite element (FE) model of a similar pipeline with material and geometric nonlinearities has been constructed as well (Figure 5). Critical pipe length, $L_{cr}$, axial force and bending moments in the pipe, and strain demand in the pipe on the tension and compression sides are selected as response parameters.

The response of a buried pipeline due to fault offset consists of three phases. In Phase I (small offsets), both axial and bending strains are important, and both increase with fault offsets. Bending strains are large enough such that there is a non-zero net compressive strain. In Phase II (intermediate offsets), the axial strain is beyond yield, and bending stiffness (and hence bending strain) are decreasing and the net compressive strains approach zero. In Phase III (large offsets), the bending strain remains constant while axial strain increases with increasing fault offsets [6] .

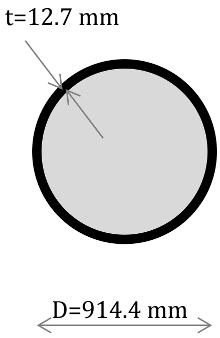


Figure 3. Steel pipe cross-section ($A_g$=36,000 mm$^2$)

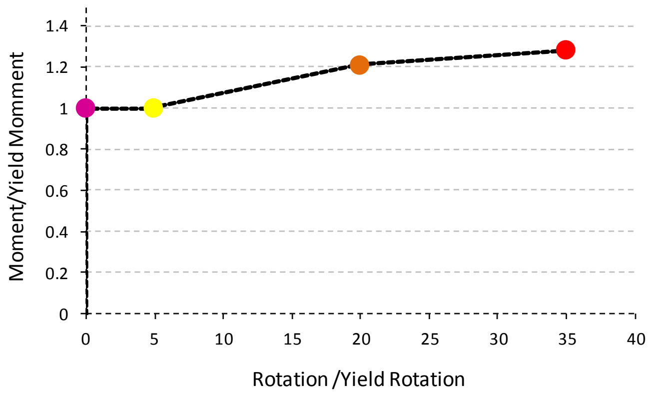


Figure 4. Moment hinge properties for the steel pipe

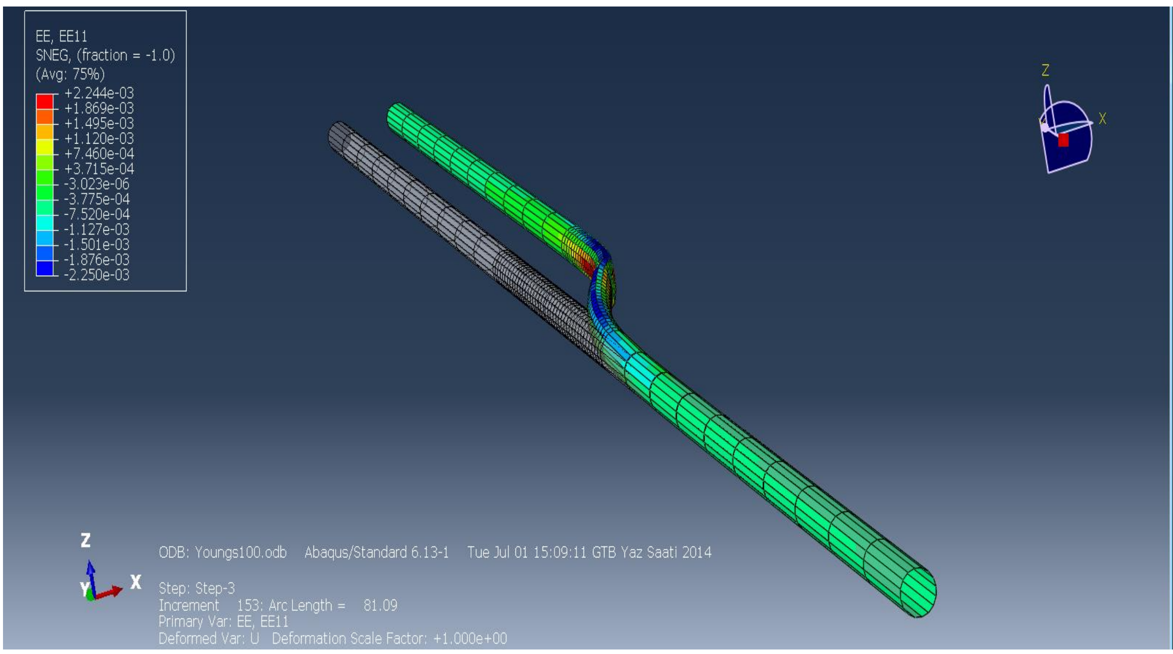


Figure 5. Stress analyses on 3-D FE model of a pipe [14]

## 4 DISCUSSION OF ANALYSES RESULTS

As a result of nonlinear static analyses, plastic hinge formation indicates $L_{cr}$ of 12.5 m for the pipe. $L_{cr}$ according to Vazouras et al. [3] is found to be 15.5 m for the pipe. Vazouras et al.' [3] expression is based on *D/t* ratio and soft clay as well as steel grade of X65, fault clearance of 33 cm and no internal pressure. Results can be considered as in reasonable agreement.

Fault movement is applied at small increments, *d*=0.2 m, 0.4 m, 0.6 m, 1.0 m, 1.50 m , 2.0 m, 2.5 m, and 3.0 m. The variation in the axial forces developed in the pipe is shown in Figure 6. The axial force is uniformly distributed throughout the pipeline and reaches to 10,900 kN for the pipe at *d*=3.0 m. The critical fault displacement ($d_{cr}$) corresponding to the first plastic hinge formation with low *D/t* ratio is found to be 1.28 m (Figure 7). As the fault movement increases, the plastic hinge formation spreads to the vicinities of the first plastic hinge formations at both sides of the pipe segment, $L_{cr}$. The variation of bending moment diagram for the pipe is plotted in Figure 8.

The pattern of the bending moment diagram remains the same along the pipe axis and is symmetrical with respect to the inflection point which is nearly in the middle of the $L_{cr}$. The peak bending moment is about 2,700 kNm at *d*=3.0 m at which the axial load is the maximum. It is about 4,750 kNm at $d_{cr}$=1.44 m which corresponds to the fault movement where the first plastic hinge is observed, at which the axial load is only 2,900 kN. Strains along $L_{cr}$ on the tension and compression sides of the pipe are also plotted in Figure 9. The maximum tensile strains are about 0.04 and 0.05 at $d_{cr}$=1.28 m and *d*=3.0 m, respectively. On the other hand, the maximum compressive strain is about 0.03 at $d_{cr}$=1.28 m and occurs at a distance for about 7.5 from the fault line. It tends to decrease as the fault moves further from $d_{cr}$.

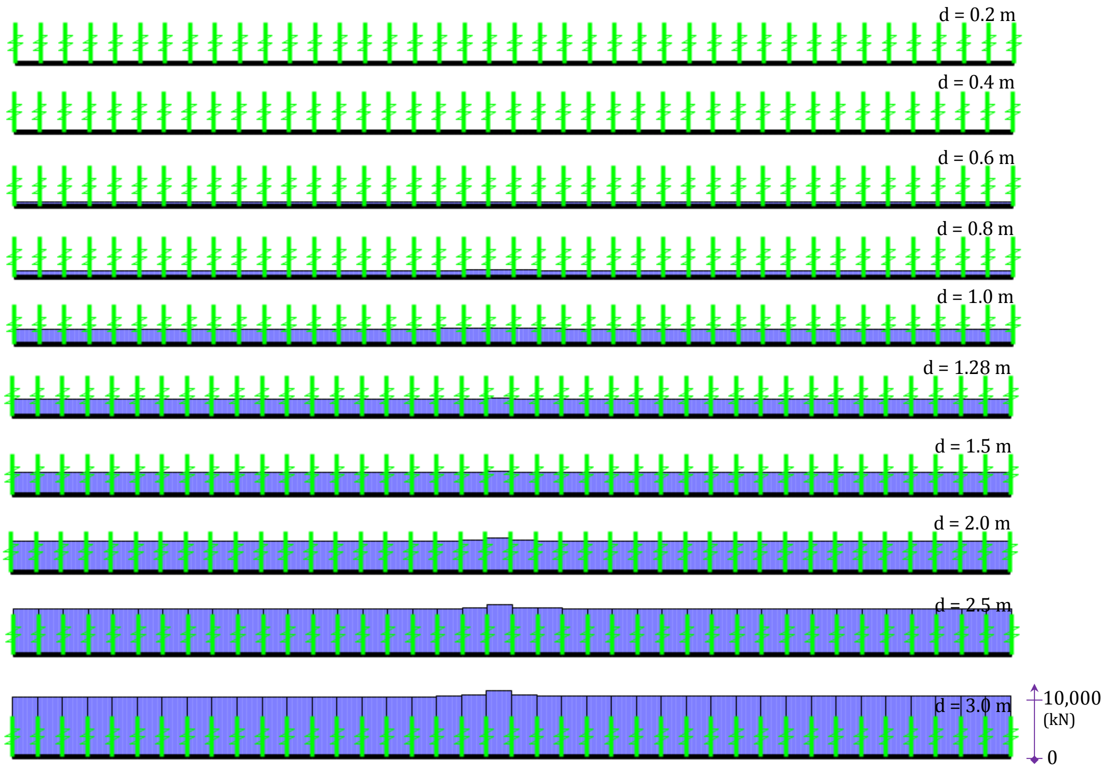


Figure 6. Axial forces developed in the pipe due to stretching at different fault movements

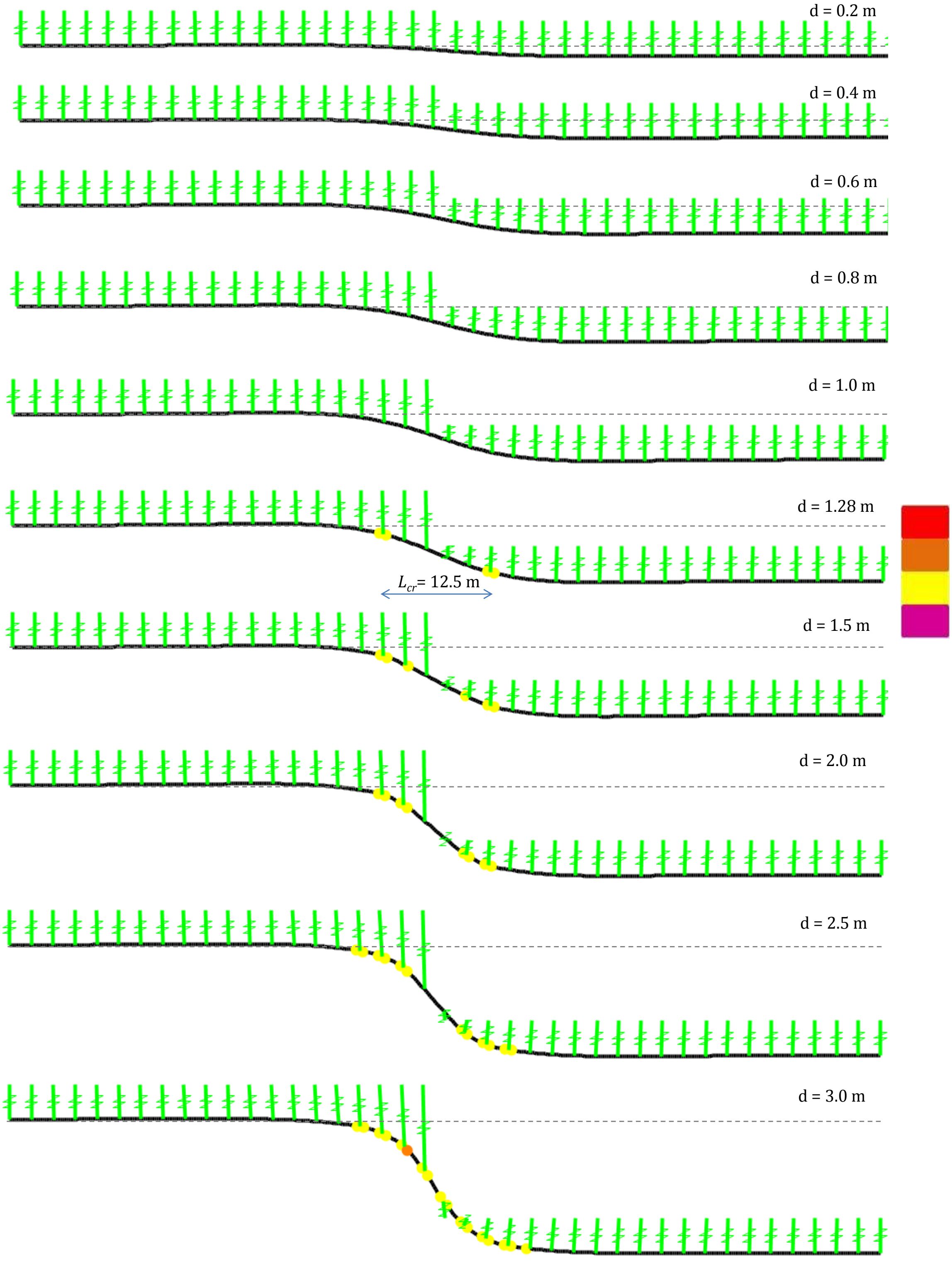


Figure 7. Deformed shape of the pipe at different fault movements (scale factor=5)

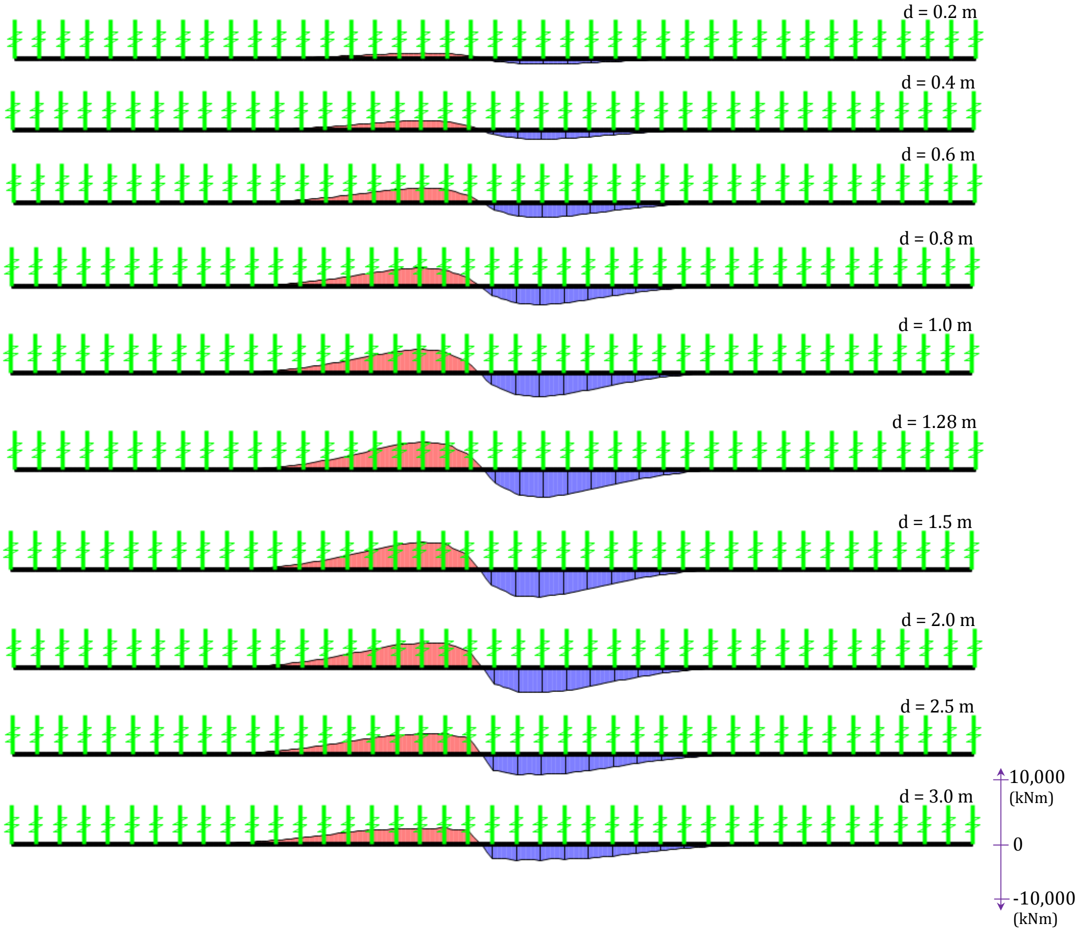


Figure 8. Bending moment diagram of the pipe at different fault movements

## 5 PERFORMANCE CRITERIA FOR PIPES

Depending on the ductility of the pipe, the pipeline can still be operational after the formations of plastic hinges. However, some micro-cracks or stress concentrations might have been occurred in the pipe during this stage [2]. Therefore, in the post earthquake phase, pressure fluctuations due to service loads may cause initiation of fatigue related fractures. Pipe rupture-/tearing of the pipe wall and loss of the pressure boundary, on the other hand, clearly constitute failure. Thus, performance criteria of the pipe in response to fault movement should be defined considering the critical length, the extent of the plastic hinge zone, geometric and material properties of the pipe and surrounding soil.

Two performance levels are defined for the pipelines; namely, fully functional (no permanent deformation such as wrinkling of the pipe wall) and partially functional (permanent deformation but no tearing/rupture of the pipe wall) (Table 1). Both limit states envision pressure integrity of the pipeline as a whole. Fully functional performance level is defined as the one where no significant damage occurs to the pipeline and the pipeline is fully operational after the earthquake. Partial functional performance level corresponds to the deformed shape of the pipeline where plastic deformations occur within the critical length and approximately 60% of the rupture capacity of the pipe has been reached. Suggested acceptability criteria corresponding to these two performance levels; fully functional and partially functional are 0.01% and 0.04% strain levels, respectively (Figure 10).

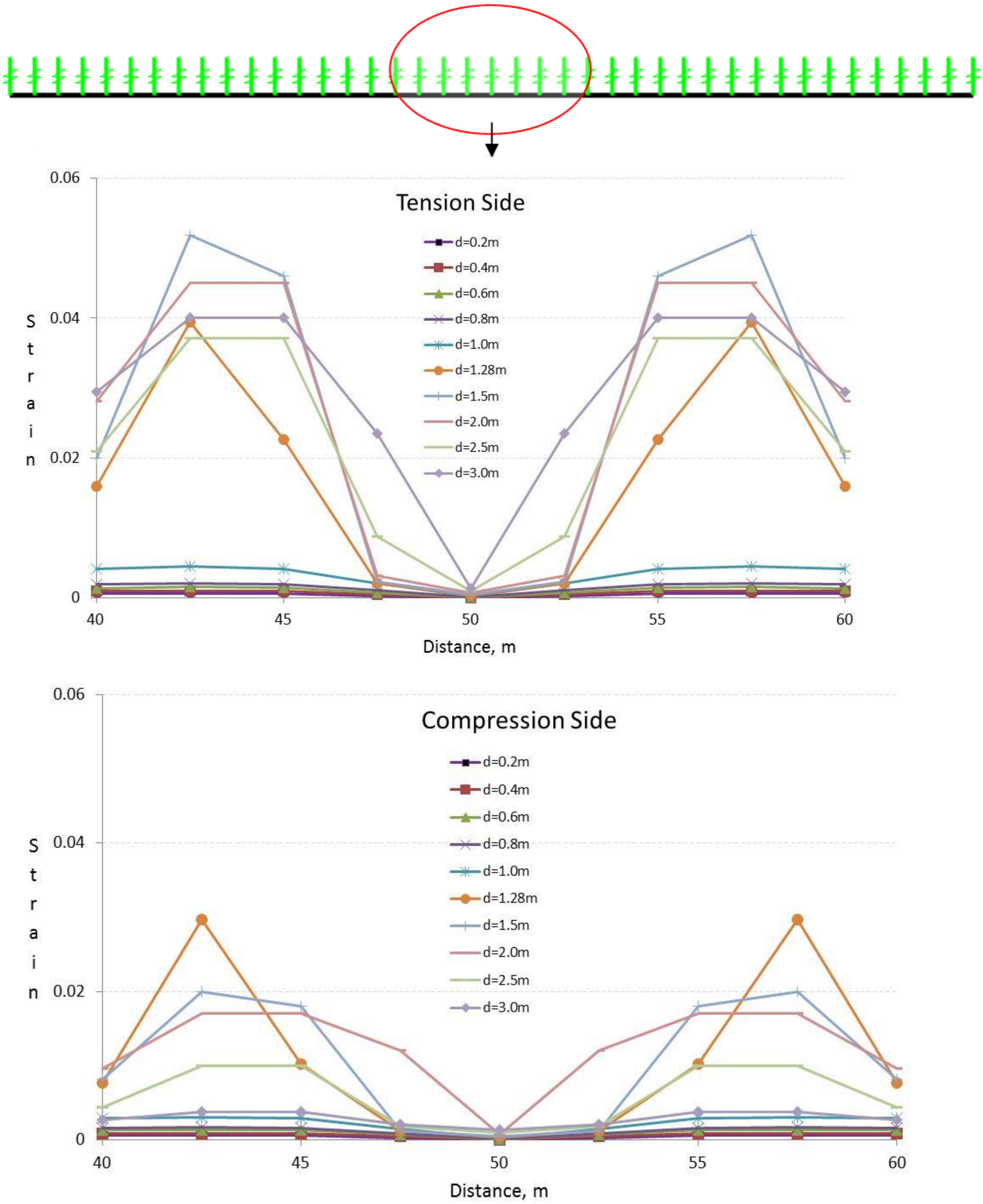


Figure 9. Strains along critical length of the pipe: a) on tension side; b) on compression side

Table 1. Minimum performance criteria for pipelines

| | **Earthquake Performance Level** | | |
|---|---|---|---|
| **Earthquake Design Level** | Probability of exceedance in 50 years | Fully functional (operational)* | Partially functional (operational)** |
| | Occasional (50%) | | |
| | Rare (10%) | | |
| | Very rare (2%) | | |

Note: yellow zones indicate minimum acceptance criteria, whereas red zones are not allowed.
*Fully functional: no significant damage has occurred to the pipeline system and the pipeline is fully operational after the earthquake.
**Partially functional and operational: Plastic deformations occurred within the critical length. 60% of the rupture capacity of the pipeline has been reached.

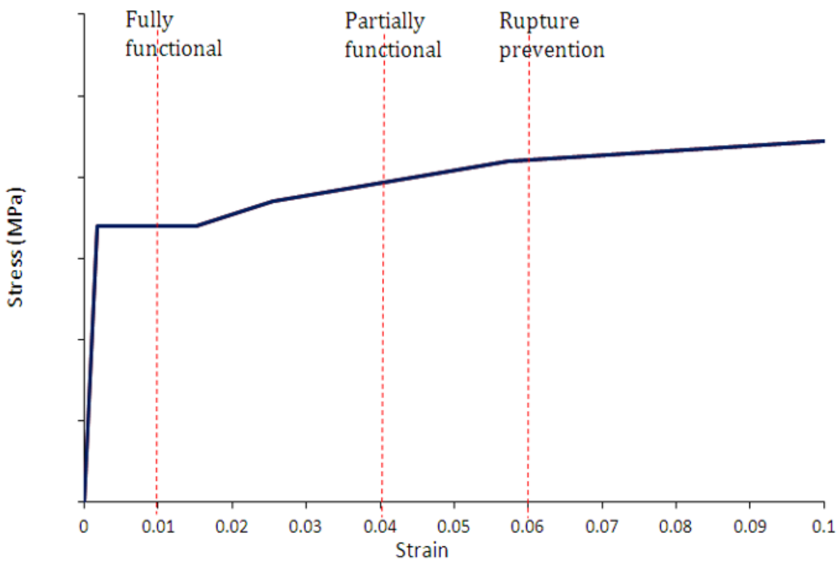


Figure 10. Suggested acceptibility criteria for buried pipelines corresponding to different performance levels

## 6 CONCLUSIONS

The present paper investigates the seismic response of buried steel pipes crossing strike-slip faults in the horizontal plane causing stress and deformation in the pipeline and proposes performance based design criteria for the pipes. A practical analysis model is presented for determining the critical design and response parameters. The proposed model is intended to be adopted for use in design and engineering practice. The buckling of the steel pipe is not considered in the proposed model. Large displacement and strain are included in the model to estimate the pipe response to PGD due to fault rupture. The distortion of the pipe cross section is ignored. The main outcomes of this study can be summarized as follows:

a. *D/t* ratio and steel grade affect the behavior of the pipe.

b. Axial load level in the pipe during the fault movement due to stretching is independent of the *D/t* ratio and increases almost linearly with respect to fault displacement.
c. The peak axial strain in the compression side of the pipe occurs nearly at a fault movement of twice the diameter of the pipe. This is consistent with the previous published research papers based on analytical formulations [2].

The results of this study are expected to enhance the available performance-based design methodologies for buried steel pipelines in engineering offices. Recommendations for further studies are given as follows:

a. Fragility expressions for buried pipelines at fault crossings should be developed by simplified methods.
b. The effects of stiffness of the steel pipes and the surrounding soil on the seismic response should be studied through a parametric study.

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