Full-Scale Laboratory Testing of Buried Pipelines Subjected to Permanent Ground Displacement Caused by Reverse Faulting

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SUMMARY:
Buried pipelines have become critical elements of the infrastructure of today's modern cities and usually traverse large geographical distances. Therefore, they could be subjected to different types of hazards caused by permanent ground displacement and/or wave propagation along their path. Permanent ground displacement (PGD) is caused by surface faulting, landslides, or liquefaction. Over the years, many researchers have attempted to study the behavior of buried pipelines crossing active faults. Recent studies at Cornell University and Rensselaer Polytechnic Institute focused on large-scale and centrifuge modeling techniques to study the behavior of buried high density poly-ethylene (HDPE) pipelines subjected to strike-slip faulting, respectively. In current work, the effect of reverse faulting on the behavior of a 4 inches buried steel pipeline is examined by performing full-scale laboratory testing. The test is performed for a dip angle of 61°. Using the tests results, a mathematical model is prepared to parametrically investigate the effects of different parameters such as the size of the horizontal and vertical offset of the reverse fault, the burial depth to the pipe diameter ratio, the crossing angle between the pipeline and the fault, etc., on the seismic behavior of the pipelines. The obtained results indicate a good agreement between the size and the distribution of the measured and numerically computed strains and also the deformation of the pipe.

Keywords: Buried Steel Pipe, Reverse Faulting, Full-Scale Test

1. INTRODUCTION

Nowadays, buried pipelines have become an integral part of the modern cities and play a vital role in supporting human lives. Unfortunately, these infrastructures are extremely vulnerable in seismically active zones. Thus, it is essential to study the behavior of buried pipelines under strong ground motions to identify the potential hazards and types of possible failures. Since, buried pipelines usually traverse large geographical distances, they could experience a variety of failures due to permanent ground displacement and/or wave propagation during an earthquake episode. Permanent ground displacements (PGD), in the form of surface faulting, landslides, seismic settlement and lateral spreading caused by soil liquefaction, can result in significant damages to the buried pipelines. For example in earthquakes such as 1906 San Francisco, 1972 Managua, 1976 Tang-shan, 1978 Miyagiken-Oki, 1983 Nihonkai-chubu, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Chi-Chi and the 1999 Kocaeli earthquakes, the pipeline systems, including water pipelines, have suffered heavy damages.

Faulting is considered to be the most common type of permanent ground displacement. Depending on the type of faulting and the relative orientation of the pipe and the fault, different behaviours can be expected from the pipeline. Fig.1 shows different types of faulting and the resulting induced deformation in the pipelines. If the movements are sufficiently large, the resulting stresses could cause different failures in the buried pipelines such as, rapture due to excessive tensile stress, buckling, wrinkling, and the breakage of the connection fixture.

Due to significance of their performance after an earthquake and the complicated behaviour of soil-pipe interaction and its effect on the behaviour of the pipeline crossing an active fault, many analytical, numerical and experimental researches have been conducted during the last few decades. Yoshizaki et al. (2003) carried out an experimental investigation on the effects of PGD on buried steel gas distribution pipelines with elbows during earthquakes, using large split-box at Cornell University, and calibrated the finite element models. The PGD represented the deformation of a strike-slip fault of right angle. This project was a joint program funded by Tokyo Gas Company, Ltd., MCEER, and NSF. Recent studies at Cornell University and Rensselaer Polytechnic Institute (NEESR-SG final report (2008) by Ha et al. (2008), Abdoun et al. (2009), Ha et al. (2010) and Xie et al. (2010)) have focused on large-scale and centrifuge testing as well as finite element techniques to study the effect of various parameters on the behavior of buried High Density Polyethylene (HDPE) pipelines subjected to strike-slip faulting, respectively.

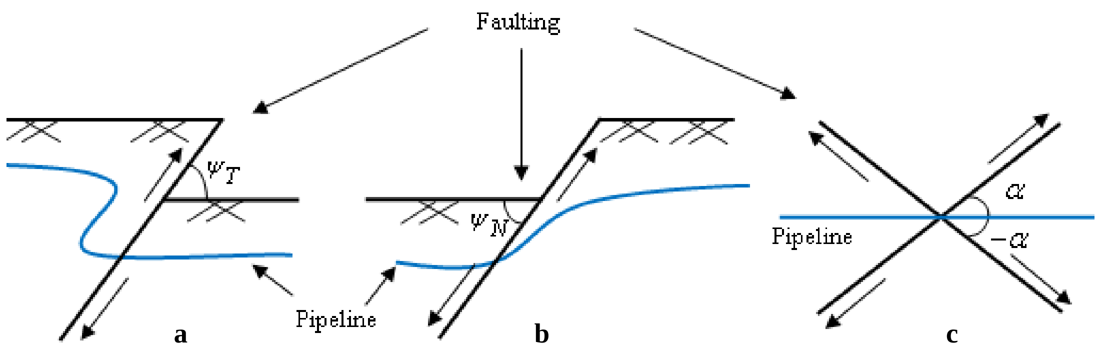


Figure1. Different fault types and their effect on pipelines: (a) thrust fault (cross-section) with angle, ψ_T, (b) normal fault (cross-section) with angle, ψ_N, (c) strike-slip fault (plan view) with angle, α.

Almost all of these studies have been conducted on strike-slip faulting to study the behaviour of buried pipelines using centrifuge testing, and only a few full-scale tests have been carried out. The behaviour of buried pipelines subjected to reverse faulting is very complicated due to the imposed deformation to the pipeline and no full-scale experimental data is available in this regard. To address this issue, a detailed joint research plan involving a number of full-scale modelling of the pipeline system has been planned at Sharif University of Technology with collaboration of Tehran province Gas Company, to study the behavior of buried gas distribution pipelines crossing reverse faults. In this paper the effect of reverse faulting on the behaviour of a 4 inches buried steel gas pipeline is examined by performing full-scale laboratory testing in a quasi-static manner using a displacement-based approach. Also a mathematical model is prepared and verified using the test results to parametrically investigate the effect of different parameters such as the size of the horizontal and vertical offset of the fault, the ratio of burial depth to the pipe diameter, the angle between the pipeline and the fault, etc. on the seismic response of the pipelines subjected.

2. EXPERIMENTAL PROGRAM

2.1. Experiment Setup

The full-scale laboratory testing allows for field conditions to be closely accounted for. However, it should be noted that simplifying some of the field conditions for laboratory testing is inevitable. The ground deformation caused by reverse faulting is very complicated and spatially distributed deformation is expected for ground deformation. However by concentrating the deformation along planes of soil failure, it is possible to set an upper bound on their effects on pipelines.

A large split-box test basin were designed and constructed at Building and Housing Research Center, for investigating the effect of various parameters on the behavior of buried gas distribution pipelines subjected to reverse faulting (Fig. 2). The split-box has been designed to test 8 m-long steel and high-density polyethylene. The approximate dimensions of the test-basin are 8.5×1.7×2m (length×width×height) with a dip angle equal to 61°. The fault plane located at the middle of the box, dividing the box into two fixed and the moving parts. The moving part can be displaced along the dip angle up to 90 cm, whilst only 60 cm uplift was employed in the tests. The floor of the test basin is bolted to 8 laterally restrained columns, each 1 m high, which are attached to the laboratory strong-floor. It should be pointed out that the configuration of the test basin can be reasonably modified in order to meet alternative test configurations.

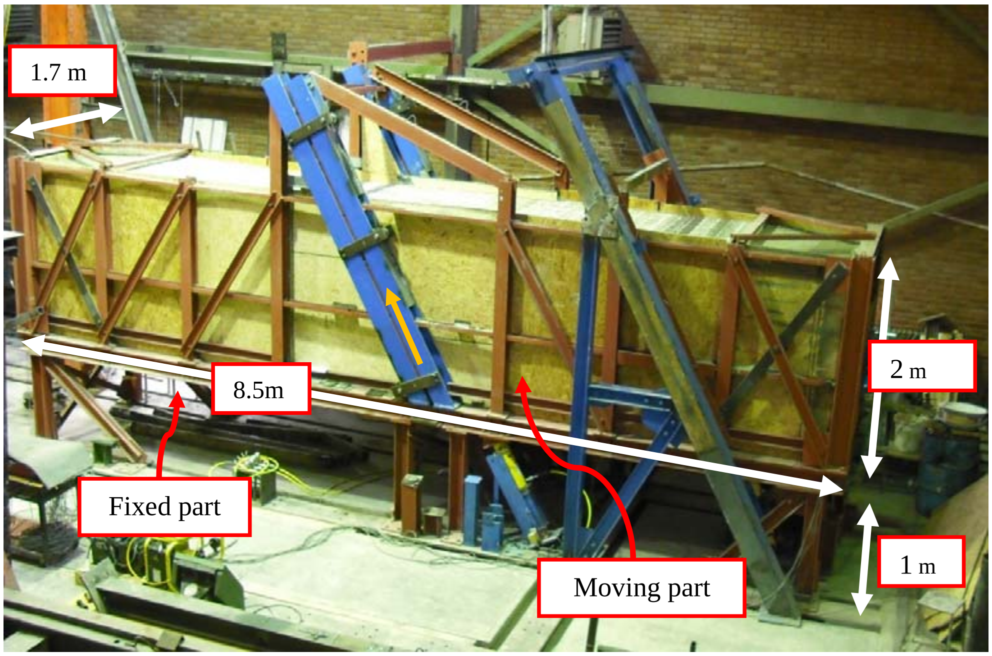


Figure 2. Sharif University split-box test basin at Building and Housing Research Center Laboratory

The truss-like configuration of the box and the floor framing is composed of W-shape steel sections with 18 mm oriented strand board (OSB) panels as sheathing and steel plate as decking. C-shape steel sections were considered for the bracing of the basin and support of OSB panels. Each part of the split-box was weighing approximately 25 metric tons when filled with sand. Four rails (two at the fault-interface and two on the external frames), were used to lift the moving part using three hydraulic jacks with compressive load capacities of 490 kN each. High level force tolerating ball bearings were used inside the rails to ease the slippage of the two parts under applied loading. The external frames are considered to guarantee the stability of the moving part. The three hydraulic jacks were placed under the test basin, in the space provided by the 1m columns and were configured as apices of a triangle, aligned with the fault line.

2.2. Test Material

The soil used for the experiment is a well graded sand (SW) commonly used as backfill in Iran, with a water content of about 5%. The material properties of the sand in this study are summarized in Table 2.1. The 4 inches steel pipeline used in the experiments is made of API-5L Grade B, with a specified minimum yield stress of 241 MPa and a minimum ultimate tensile strength of 414 MPa. It was used in the tests with external coating to resemble the typical field conditions. The pipe is made of API-5L Grade B, with a specified minimum yield stress of 241 MPa and a minimum ultimate tensile strength of 414 MPa. The outside diameter D, and the shell thickness t, of the pipe are 114.3 mm and 4.4 mm, respectively. The resulting diameter to wall thickness ratio, D/t, is 26.

Table 2.1. Material properties for sand backfill

Soil Property	Value
γ_d , dry unit weight (kN/m^3)	17.9
G_s, specific gravity	2.56
ϕ , friction angle (degree)	33.5
D_{50}, average particle size (mm)	1.1
C_u, coefficient of uniformity	6.69
C_c, coefficient of curvature	1.01

2.3. Instrumentation

In order to study the behavior of the buried pipe, the pipeline is instrumented with 50 strain gauges and 6 linear variable differential transformers (LVDTs). The strain gauges are able to measure strains as high as 20% and are distributed in 20 stations so that they measure strain in the longitudinal direction. Hereby the axial and bending strains can be measured with great accuracy. Since the faulting deformation is considered to be abrupt, it is rational to use more strain gauges within the vicinity of the faulting zone. The displacement caused by faulting was also measured by 3 independent displacement transducers.

2.4. Experiment Procedure

The burial depth of 4 inches pipe is around 1 m, just like their typical burial depth in field installations. Approximately 20 m^3 of soil is required for performing the test. The soil is placed in nine 200 mm lifts and is then compacted using a vibratory plate tamper. The rest of the experiments follows a displacement-control procedure, where the moving part of the test basin is lifted using the three actuators to a displacement of 600 mm. Table 2.2 summarizes the properties of this experiment.

Table 2.2. Properties of the experiment

D (mm)	t (mm)	D/t	H(m)	H/D	Fault dip angle (°)	Displacement (mm)
114.3	4.4	26	1	8.8	61	600

3. FINITE ELEMENT MODEL

In order to develop simple models to investigate the effect of various parameters on the seismic behaviour of pipelines subjected to reverse faulting, first a more detailed mathematical model has to be prepared and verified using the experiment results. Therefore, a 3-D continuum finite element model is constructed to model the soil-pipeline system and the effect of reverse faulting on the pipe behavior, utilizing the finite element program ABAQUS (2008). The model is able to simulate the mechanical behavior of the steel pipe, the surrounding soil and their interaction through a contact algorithm, considering the geometrical and material nonlinearity of both the pipe and the soil.

The same pipe diameter and burial depth are used for numerical analysis as described in the experiments. Having performed sensitivity analyses, the length of the pipeline was considered to be 8 m, which is more than adequate for the present analysis. Similarly, the width and height of the soil medium are considered as 1.7m and 2m, which are also consistent with the dimensions of the split-box test basin and the studies conducted by Vazouras et al. (2010). The simulation of pipe buckling and post-buckling behavior is of significance. Therefore, the pipeline is modeled using four-node reduced integration shell elements (type S4R), whereas eight-node reduced-integration brick elements (C3D8R) have been employed to model the surrounding soil as shown in Fig.3. The shell elements are based on a large deformation formulation with three displacement degrees of freedom per node defined by linear shape functions. The finite element mesh for the pipe is uniform, with 16 shell elements around the circumference of the pipe, resulting in a total of 6400 elements for the pipeline. The mesh for the soil was selected after a number of convergence studies were performed to identify an appropriate mesh for the analysis. A total of 15000 solid continuum elements were required to model the soil.

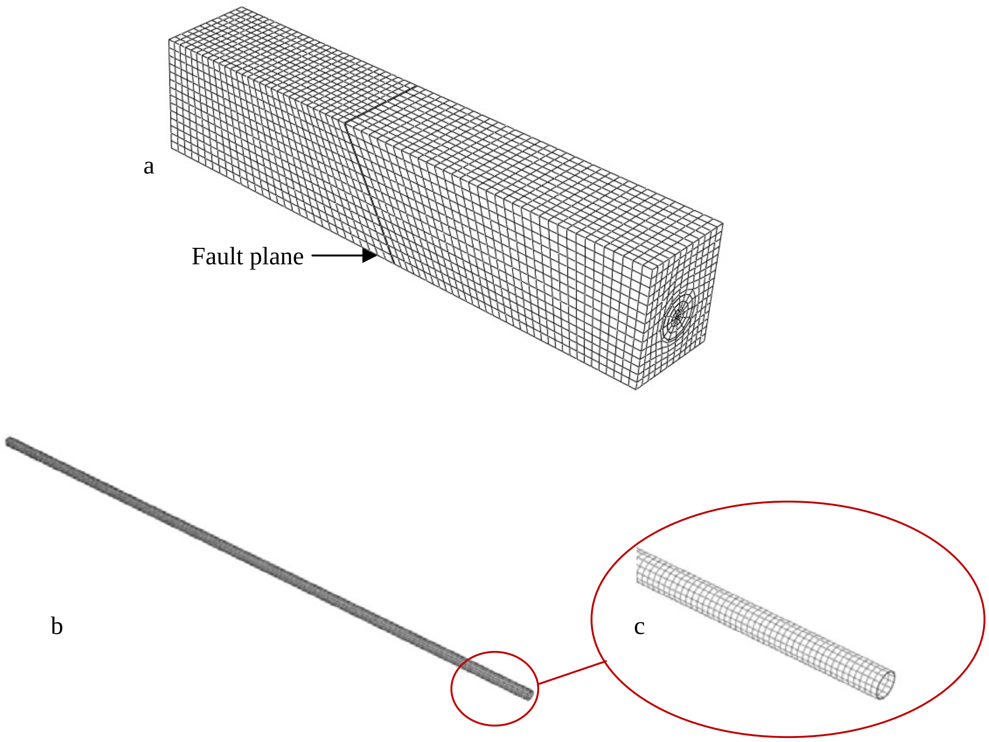


Figure 3. Finite element model of the (a) soil, (b) pipe and (c) magnification of the steel pipe

An elastic-plastic material behaviour with von Mises plasticity model and isotropic hardening rule is assumed for the steel pipeline. For the soil behavior an elastic-perfectly plastic Mohr-Coulomb model is used, in which the soil mass density, friction angle, dilation angle, Poisson's ratio and cohesiveness are considered consistent with the soil used in the experiment. The soil-pipeline interface takes into account the interface friction using a Coulomb friction criterion and also allows slippage and separation between the soil medium and the pipe. The friction coefficient, μ, was calculated based on the reduced interface friction angle between the soil and the pipe, equal to $2/3\,\varphi$ according to Yimsiri et al. (2003). Thus, for the experimental soil μ was set to 0.41. Before applying the reverse faulting motion, a gravity loading is considered first to account for the initial stress state in the soil. For imposing the reverse faulting motion, consistent boundary conditions need to be applied. The surrounding and bottom faces of the footwall are restrained in all directions, simulating a fixed block and the end of the pipe buried in the static soil medium is restrained in the longitudinal direction. The sides of the footwall side are also restrained in the lateral directions. The hanging wall is displaced along the faulting plane with an angle of 61 with respect to the horizontal plane up to the maximum fault offset, in this case 600 mm. In addition, the end of the pipe is displaced by the same amount in the same plane by imposing displacements at all nodes of the end of the pipe in the moving soil medium.

4. RESULTS

4.1. Observations

Fig. 4 shows the split-box test basin after imposing the 600 mm faulting displacement on the soil-pipe system. The ground surface before the test and after 300 mm and 600 mm displacement are shown in Fig. 5. Significant cracking of the soil was observed at the fault plane between the movable and fix parts after the test. The location of local buckling and maximum strain in the pipeline is also shown in Fig. 5, where significance upheaval is observed and the failure planes of soil and cracking reach the soil surface. It should be pointed out that no change on the soil outer surface is observed at the fix box.

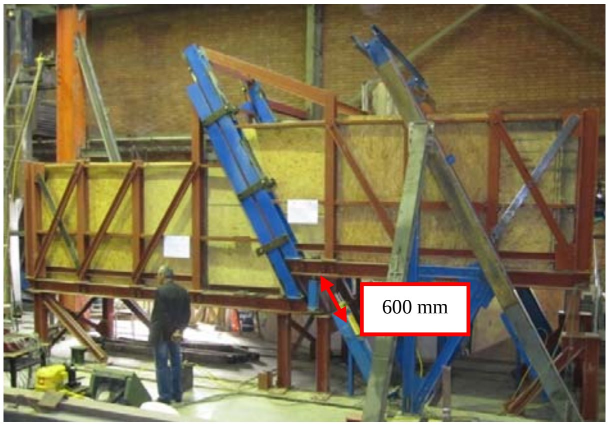


Figure 4. Split-box test basin after 600 mm faulting displacement

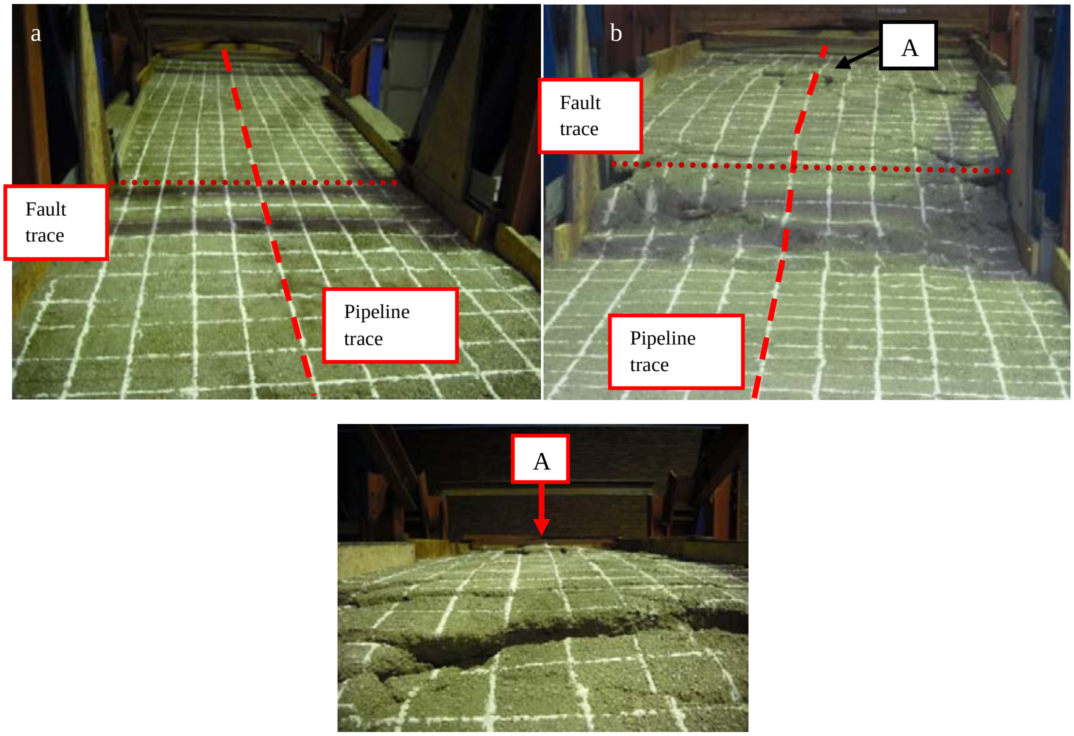


Figure 5. (a) Surface condition before the test, (b) surface observation at 300 mm faulting, (c) upheaval and crack at the surface after 600 mm faulting (A: position of local buckling and maximum strain in the pipe)

A view of the test compartment after removing the soil is shown in Fig. 6, demonstrating the deformed shape of the pipeline. As shown in Fig. 6, the pipe has buckled after the faulting. The unsymmetrical buckling has occurred with respect to the fault plane at two locations. The distance between the two buckling locations is approximately 1.60 m. Severe ovaling is observed at the two buckling locations due to the large wrinkling at these sections.

Figure 6. Deformed pipe after faulting

The pipe external coating and strain gauges were removed to observe the buckling locations in detail. Fig. 7 and Fig. 8 show the pipe section at buckling locations in the fixed and moving boxes respectively. As shown in Fig. 7 and Fig. 8, there were no signs of rupture near these locations, but significance yielding and plastic deformations were observed at the buckled section in the moving box, which definitely leads to rupture if subjected to higher faulting offsets. Also the location of buckling is consistent with the soil failure wedge formation shown in Fig. 5. At the compression side of the pipe sections at the two buckling locations, 2 strain gauges were installed in order to obtain accurate results. These are at the pipe crown and invert for the buckling locations in the fixed and moving boxes, respectively.

4.2. FEM vs. Experimental results

Fig. 9 shows the measured and predicted longitudinal crown and invert strains along the pipeline for different levels of ground displacement. There is a good agreement between the numerical simulations and the experimental results. The deformed pipeline shape obtained from numerical simulation and

Figure 7. Wrinkling of the steel pipe section in the fix box: (a) plan view, (b) side view

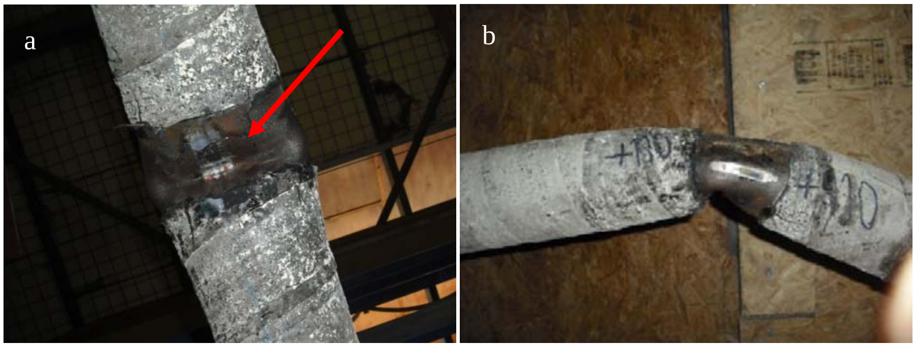
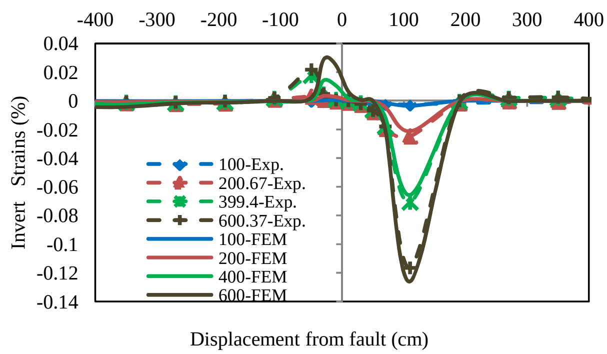
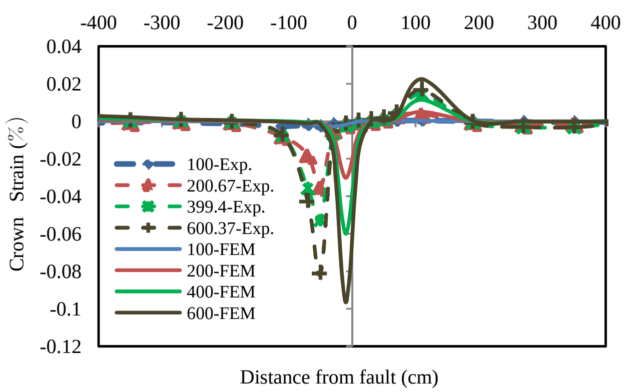


Figure 8. Wrinkling of the steel pipe section in the moving box: (a) plan view (from below), (b) side view



(a)



(b)

Figure 9. Longitudinal strain for (a) crown and invert of pipelines

buckling of the pipe at those locations are shown in Fig.10. In general, except for the place of local buckling in the fixed box, there is good agreement for both the size and distribution of measured and numerical strains and deformation and the view of the deformed pipeline in Fig. 6. A common way to represent the degree of distortion of the pipe's cross section is by using a factor of ovality, defined by Eqn. 4.1, where f_o, D_{max} and D_{min} are the ovalization factor, maximum and minimum diameters of the pipe cross section after buckling, respectively.

$$f_o = \frac{D_{\max} - D_{\min}}{D_{\max} + D_{\min}} \tag{4.1}$$

The maximum and minimum diameter and the ovalization factor from experiment and numerical simulation for the buckled section in the moving box are given in Table 4.1, that show good agreement between the measured and simulated values.

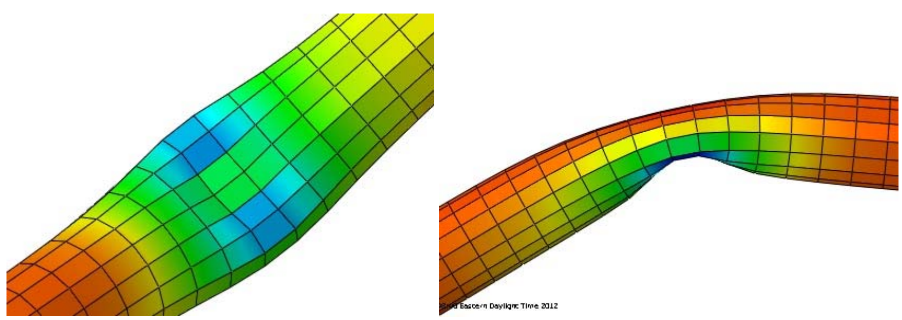
Table 4.1. measurements for ovalization of cross section

Experiment			Numerical simulation		
D_{max} (mm)	D_{min} (mm)	f_o	D_{max} (mm)	D_{min} (mm)	f_o
155.02	59.40	0.45	160.71	56.84	0.48

The strain associated with the onset of buckling in an un-pressurized cylindrical is given in Eqn. 4.2, where R and t are the radius and shell thickness of the pipe cross section, respectively. For the pipe used in this experiment this limit is equal to 1.35%. The measured strains and the predicted strains from the numerical simulations at locations of local buckling are well above the strain level associated with the onset of pipe local buckling, resulting in the local buckling of the pipe at those locations.

$$\varepsilon_c = 0.175 \cdot \frac{t}{R} \tag{4.2}$$

(a)



(b) (c)

Figure 10. Deformed shape based on numerical simulations for (a) the whole pipe, (b) buckled section in the footwall, (c) buckled section in the hanging wall.

5. CONCLUSION

This paper describes a full-scale experiment on a 4 inches API-5L grade B steel pipe to investigate the effect of reverse faulting on buried steel gas distribution pipelines. The pipeline was buried with burial depth of 1 m and was subjected to 600 mm of ground displacement simulating reverse faulting. As expected, local buckling along the pipe was observed at two locations, in the fixed and the moving parts of the test boxes. Also at these locations severe yielding and plastic deformation was observed. A 3-D continuum finite element model was prepared to simulate the soil-pipeline system in order to validate and calibrate these models with the experiment results for future application. Longitudinal strains along the pipeline, deformed shape and cross-section distortion by means of ovalization factor were compared. The results of the simulation show that there is good agreement between the experiment and the numerical simulation, making it useful for further numerical studies. Also the longitudinal strains were compared with the strain associated with the onset of local buckling and it was observed that they exceed this limit, resulting in the local buckling of the pipe at two locations.

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