Pipeline Performance Under Longitudinal Permanent Ground Deformation

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ABSTRACT:
Performance of buried pipelines during earthquakes is affected by many factors related to geotechnical properties of the surrounding soil and physical properties of pipe itself and its coating. For example, axial soil friction is an important parameter for assessing pipeline response to relative ground displacements. This study focuses on evaluation of relatively large diameter pipeline performance under soil movement parallel to the longitudinal axes of the pipelines. DIANA finite element program was used to model permanent ground deformation and in the analysis of pipelines. Analysis results of four continuous pipelines, two of which failed and two of them were not damaged, are presented. The pipelines and soil information was taken from the Balboa Blvd. in the city of Los Angeles, U.S.A., and the 1994 Northridge earthquake case study.

Keywords:Damage, DIANA, FEM, Pipelines, Seismic

1. INTRODUCTION

Recent earthquakes showed that pipeline damage is relatively heavy especially in the areas where permanent ground deformations existed. Evaluation of behavior of pipelines in those areas is particularly important to understand their response to earthquake loadings. Performance of buried pipelines during earthquakes is affected by many factors related to geotechnical properties of the surrounding soil and physical properties of pipe itself and its coating. One such parameter is axial soil friction which is an important parameter for assessing pipeline response to relative ground displacements.

Honegger (1999) did field measurement of axial soil friction forces on two buried pipelines, one of which (Old Line 120) was located at Balboa Blvd. Soil friction measurements were made by applying an axial load to one end of an isolated section of the pipe. Axial load was applied by means of a hydraulic jack. The results of the tests illustrate that the maximum soil friction force for the initial test and reload test was 32 kPa for both initial and reload tests. He found out that the adhesion factor values for axial soil friction forces in clay soils recommended by ASCE (1984) are too high and represent an unnecessary level of conservatism and adhesion factors from Tomlinson (1957) are more appropriate. Honegger test results were used herein for the finite element method (FEM) analysis of Old Line 120 in Balboa Blvd. and compared with results from FEM analysis by using the previous soil –pipe friction parameters. In this study, DIANA finite element program was used to model PGD and in the analysis of pipelines. In addition to Old Line 120, analysis results of three other selected pipelines from the large diameter pipeline case study from the 1994 Northridge earthquake are also presented. In essence, FEM analysis results for two failed and two good performing pipelines are presented. The pipelines and soil information was taken from the Balboa Blvd. and the 1994 Northridge earthquake case study. This important case study and the relevant analytical results were presented and discussed by several researchers before (e.g., Toprak, 1998; O'Rourke and O'Rourke, 1995; and O'Rourke and Toprak, 1995).

2. SITE CHARACTERISTICS AND PIPELINES AROUND BALBOA BLVD.

Permanent ground deformation at Balboa Blvd. was part of a larger pattern of ground displacements produced by the 1994 Northridge earthquake along a 5-km long linear belt within suburban Granada Hills and Mission Hills in the northern San Fernando Valley. Hecker, et al. (1995a) mapped and described the ground deformation in this area. They report that ground deformation across the Granada Hills-Mission Hills belt most likely involved shallow seated displacements caused by one or more of the following phenomena: slope failure, lurching of surficial deposits, compaction of loose sediment, and liquefaction. Based on the survey of curbs, sidewalks, and concrete drainage gutters. Hecker, et al. (1995b) reported an extension of 540 mm at Balboa Blvd. across the tension zone (measured between Lorillard St. and Halsey St.). Similarly, they reported a compression of 420 mm and 270 mm along east and west sides of Balboa Blvd., respectively, across the compression zone measured between Halsey St. and Rinaldi St.

Sano (1998) presented PGD displacements in the Balboa Blvd. area evaluated from surveys performed by the Los Angeles Bureau of Engineering (LABE) and air photos taken before and after the earthquake. Holzer, et al. (1996) conducted detailed geotechnical investigation to clarify the failure mechanism in this area. They reported that aggregate compressional and extensional displacements across the northern and southern margins, respectively, of the failure zone were about 500 mm. Table 1 summarizes measurements related to PGD that occurred in the Balboa Blvd. area (Toprak, 1998). As can be seen in Table 1, ground displacements from different sources are in close agreement and suggest extension along Balboa Blvd. from Lorillard to Halsey Streets of 45-54 cm. In this work, a 50 cm of extension at Balboa Blvd. is adopted which is approximately the mid value of the displacement range given in Table 1. Unlike displacements in the extension zone, reported ground movements in the compression zone, between Halsey St. and Rinaldi St., vary considerably. For example, Hecker et al. (1995b) report displacements in the range of 27 and 42 cm, whereas Holzer et al. (1996) report displacements of 50 cm. Displacements reported by Sano (1998) are about 37 cm. This variation of PGD is related to the characteristics of compressive ground deformation. For example, it is harder to assess the magnitude of compression from surface effects than to determine movements at tension cracks. Tension cracks form at relatively low levels of tensile ground strain, whereas substantially larger compressive strains must accumulate before ground rupture is observed.

Table 1. Summary of Measured Extensions Between Lorillard and Halsey Streets

	Extension Measurements Along North-South Streets				
Source	Paso Robles (cm)	West Alley (cm)	Balboa Blvd. (cm)	East Alley (cm)	McLennon Ave (cm)
Ground Survey Along Streets LABE (1995)	32	39	45	45	30
Air Photo Measurements Sano (1998)			45		40
Street Centerline Surveys Holzer et al. (1996)			50		
Cumulative Crack Width Measurements Hecker, et al. (1995b)	38-40		54		

O'Rourke and Toprak (1997) presents the largest databases ever assembled in U.S. of spatially distributed transient and permanent ground displacements in conjunction with damage to water supply and distribution lifelines. The 1994 Northridge earthquake caused the most extensive damage to a US water supply system since the 1906 San Francisco earthquake. O'Rourke and Palmer (1994) have described the response of buried pipelines in Balboa Blvd. area. Information from their study has been combined with additional observations and measurements at site as provided by O'Rourke and Toprak (1995) and Toprak (1998). Figure 1 is a map of the pipelines near Balboa Blvd. in the PGD zones. There were two 762 mm-diameter gas transmission lines and a 406 mm-diameter petroleum pipeline that were not damaged. Two water trunk lines operated by the Los Angeles Department of Water and Power (LADWP), the 1,245 mm-diameter Granada and the 1,727 mm-diameter Rinaldi Trunk Lines, failed in tension and compression in the tensile and compressive zones of ground deformation, respectively. Gas pipeline damage on Balboa Blvd. occurred in Old Line 120, a 559 mm-diameter steel pipeline constructed in 1930. The line had been scheduled for replacement, and a new 610 mm-diameter pipeline (New Line 120) had been constructed parallel to the older one along McLennon Ave. New Line 120 had not been opened for gas flow at the time of the earthquake. Even though it crossed similar zones of tensile and compressive ground deformation, it was not damaged.

3. FEM ANALYSIS OF PIPELINES

In this study, a finite element program, DIANA (TNO DIANA, 2007) was used for the analysis. The same pipe and soil properties presented in Toprak (1998), O'Rourke and O'Rourke (1995) and O'Rourke and Toprak (1995) are used herein for all pipelines. Figure 2 shows stress-strain relationships for the pipes and Ramberg-Osgood parameters for the representation of the relationships. In addition, Honegger (1999) field test results for axial soil friction are used for the Old Line 120. Pipelines were modelled as beam elements. Soil-pipe interaction was modelled by using elastic-perfectly plastic springs.

Figure 3 shows the results for the New Line 120. This pipeline has a nominal diameter of 610 mm with a wall thickness of 6.4 mm. The external coating of the pipe is fusion bonded epoxy and burial depth is 1.5 m. The yield stress of the pipe material is 415 MPa. The pipeline has almost 90^0 bends at 100 m away from the tensile zone and 40 m away from the compression zone. These points are modeled as supports in FE model because the pipe movement is constrained by the bents (Figure 3a). FEM results show that pipeline displacement as high as 155 mm occurred as a result of 500 mm displacement of 275 m soil block (Figure 3b). Maximum pipe strains of 0.124 % and 0.143 % were calculated at tensile and compression zones, respectively (Figure 3c). The maximum tensile and compressive stresses in the pipeline are 248 MPa and 286 MPa, respectively (Figure 3d). The strains and stresses experienced by the pipeline during the earthquake loading are much lower than the yield values and in accordance with the observed behaviour.

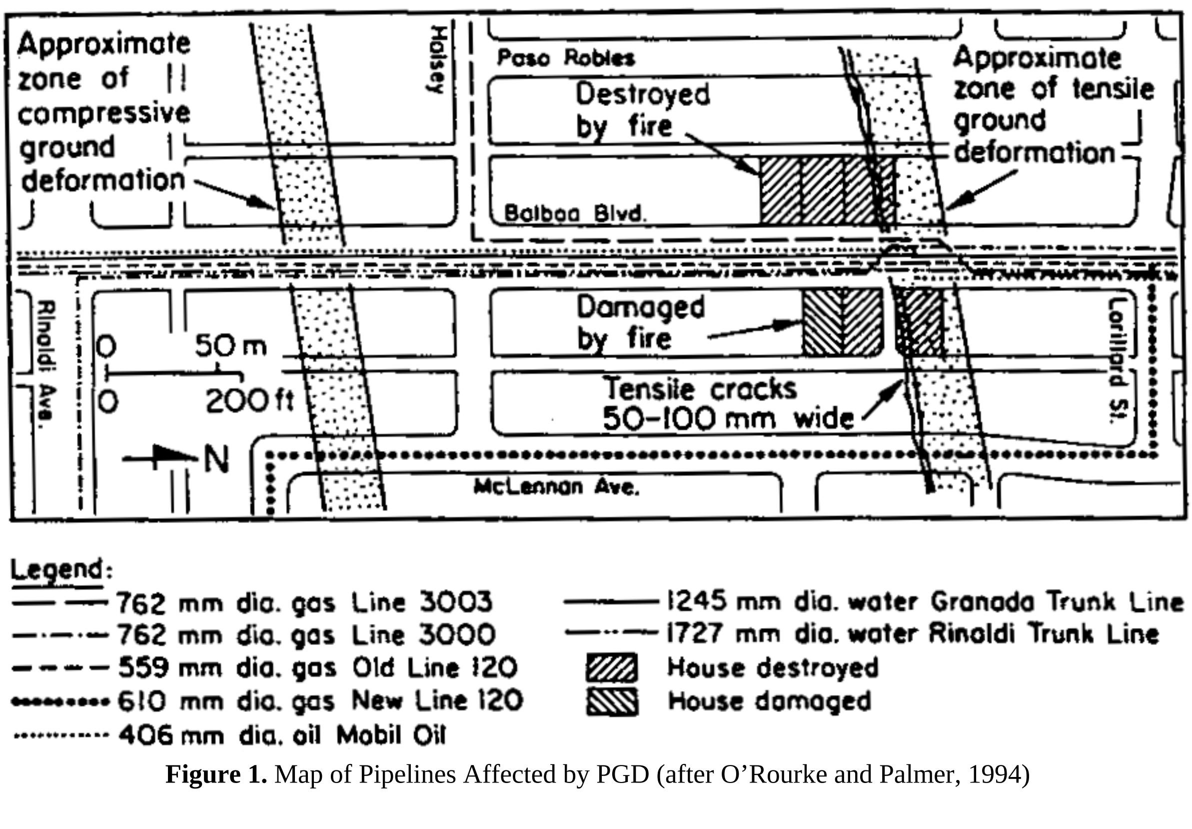


Figure 1. Map of Pipelines Affected by PGD (after O'Rourke and Palmer, 1994)

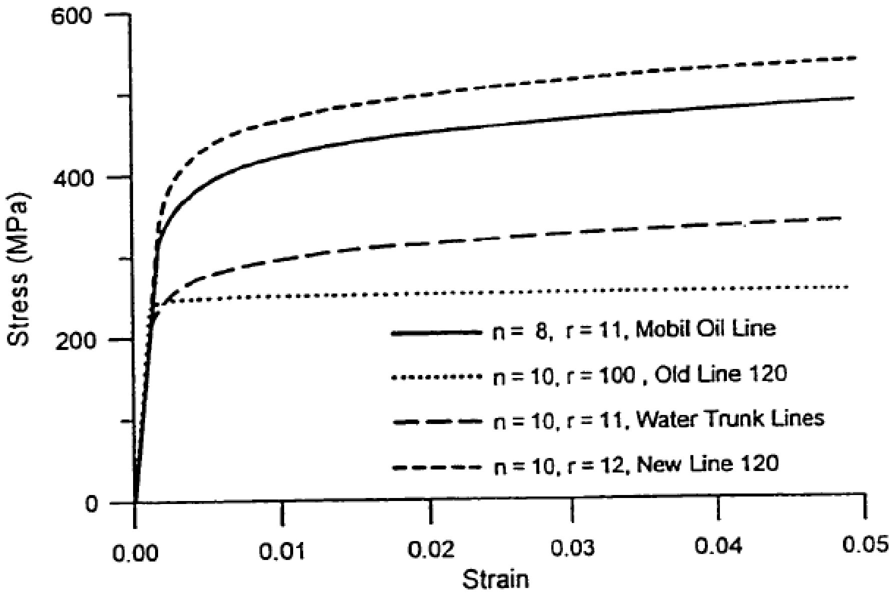
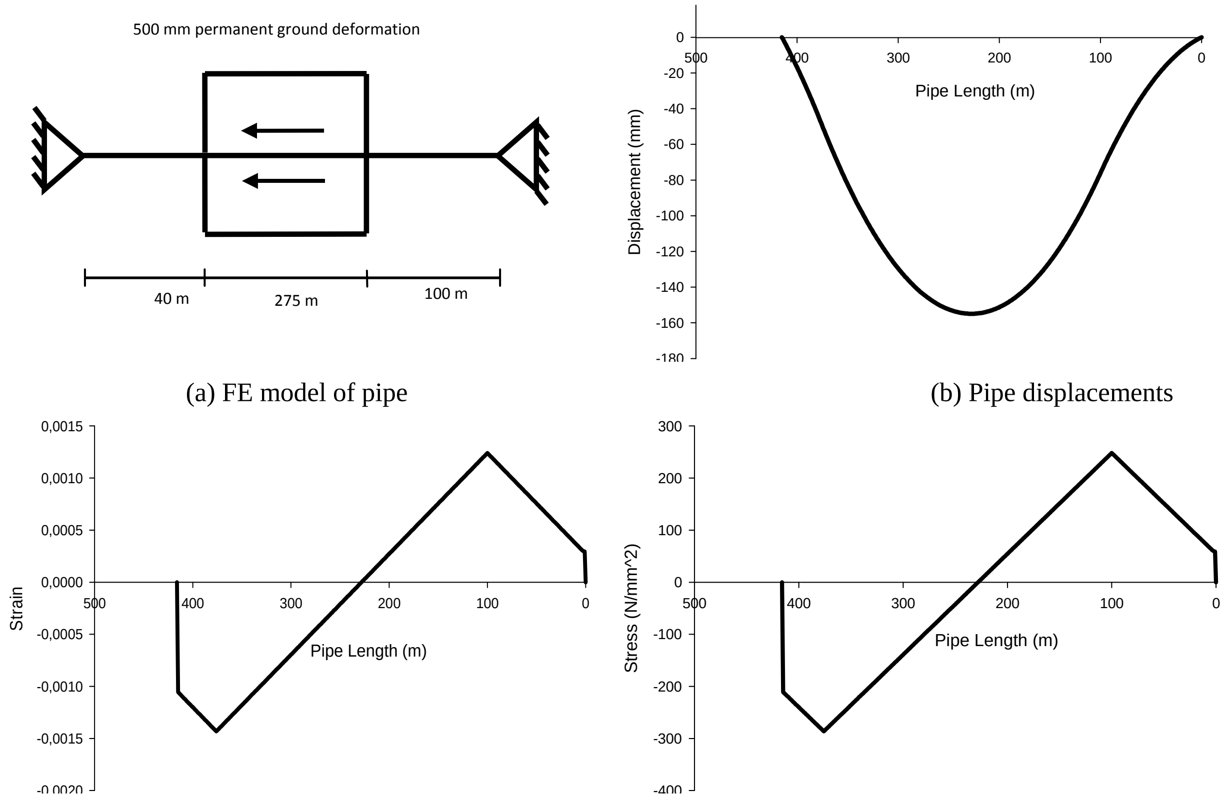


Figure 2. Stress-strain relationship for pipe steel (after Toprak, 1998)



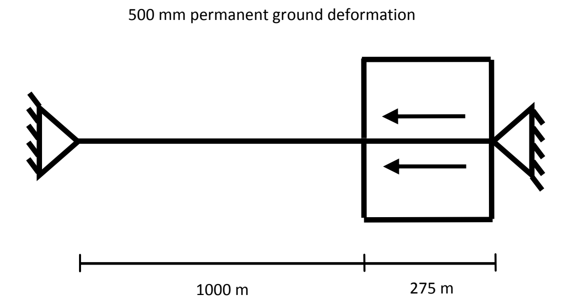
(a) FE model of pipe (b) Pipe displacements

(c) Strains in the pipeline (d) Stresses in the pipeline

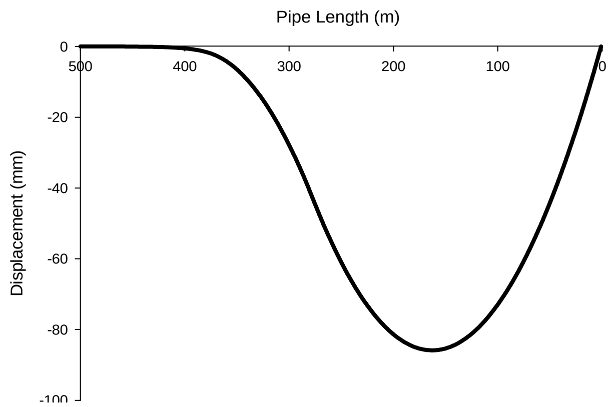
Figure 3. The FEM results for the New Line 120 (after Toprak, et al., 2010)

Figure 4 shows the results for the Mobil Oil Line. This pipeline has a nominal diameter of 406 mm with a wall thickness of 9.5 mm. The external coating of the pipe is polyethylene (PE) and burial depth is 1.5 m. The yield stress of the pipe material is 360 MPa. The pipeline has almost 90^0 bends at tensile zone. This point is modelled as support in FEM model because the pipe movement is constrained by the bent (Figure 4a). Because pipe extends beyond the compressive zone as a straight line, the support was placed far away. Figure 4b shows that the pipe displacement approaches zero about 400 m away from the right support. FEM results show that pipeline displacement as high as 86 mm occurred as a result of 500 mm displacement of 275 m soil block. Maximum pipe strains of 0.105 % and 0.075 % were calculated at tensile and compression zones, respectively (Figure 4c). The maximum tensile and compressive stresses in the pipeline are 212 MPa and 149 MPa, respectively (Figure 4d). Like the New Line 120, the strains and stresses experienced by the pipeline during the earthquake loading are much lower than the yield values and in accordance with the observed behaviour.

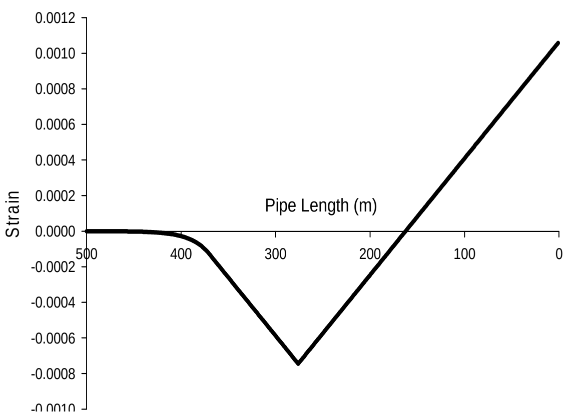
Figure 5 shows the results for the Old Line 120. This pipeline has a nominal diameter of 559 mm with a wall thickness of 7.1 mm. The external coating of the pipe is coal tar epoxy and burial depth is 1.5 m. The yield stress of the pipe material is 242 MPa. Because pipe extended beyond the compressive and tensile zones as a straight line, the supports were placed about far away (Figure 5a). FEM results show that pipeline displacement became equivalent to the 500 mm displacement of 275 m soil block (Figure 5b). Maximum pipe strains of 20 % were calculated at both tensile and compression zones (Figure 5c). The maximum tensile and compressive stresses in the pipeline exceeded yield values (Figure 5d). The FEM results agree with the observed pipe failures in the compression and tension zones. Figure 6 shows the results for the Old Line 120 using Honegger (1999) axial friction values for cohesive soil. This case resulted in higher strains (about 30 %) in the pipe.



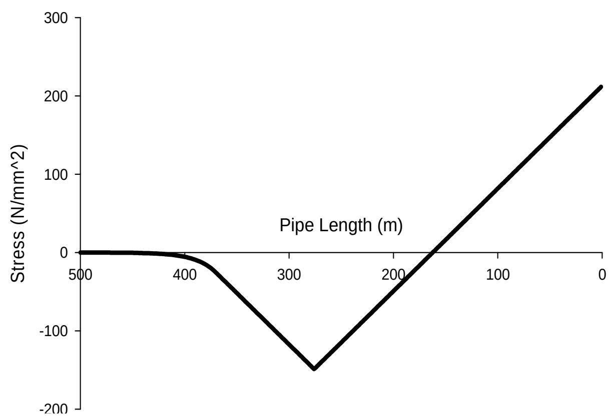
(a) FE model of pipe



(b) Pipe displacements

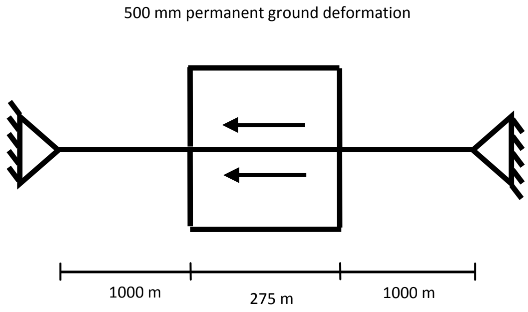


(c) Strains in the pipeline

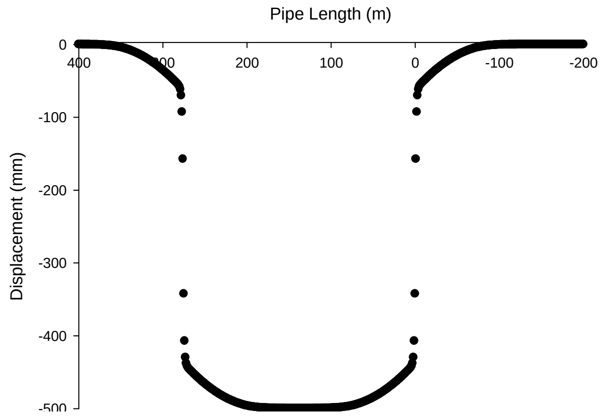


(d) Stresses in the pipeline

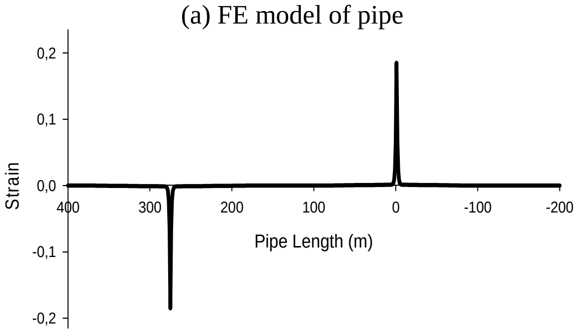
Figure 4. The FEM results for the Mobil Oil Line



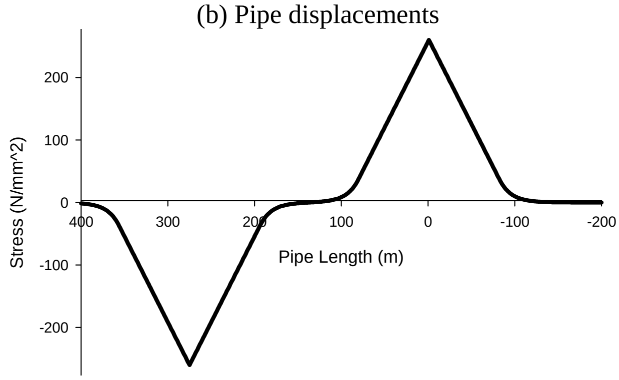
(a) FE model of pipe



(b) Pipe displacements

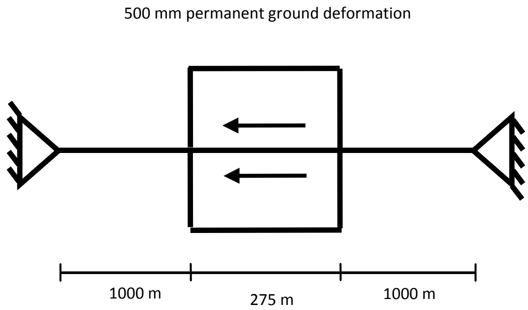


(c) Strains in the pipeline

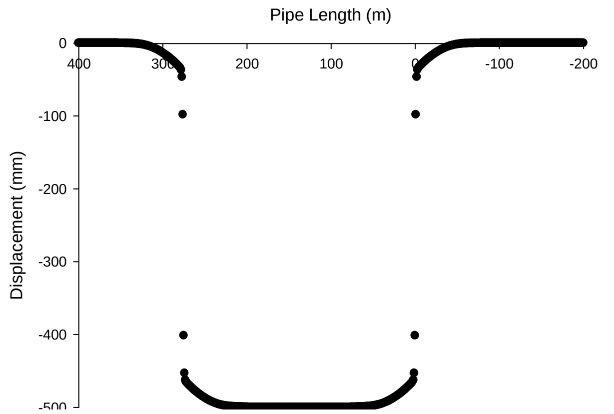


(d) Stresses in the pipeline

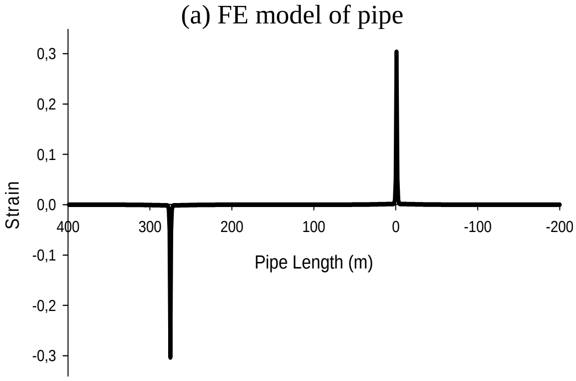
Figure 5. The FEM results for the Old Line 120 (cohesionless soil)



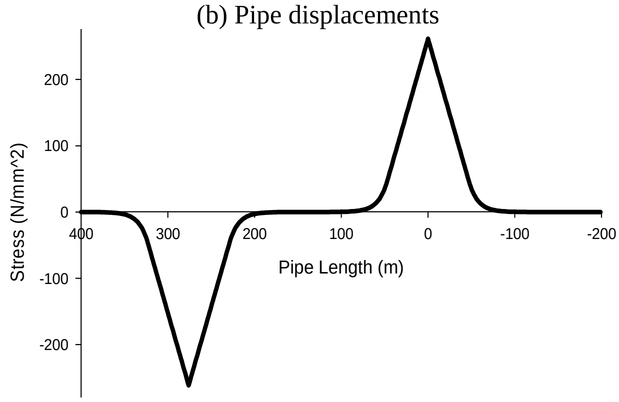
(a) FE model of pipe



(b) Pipe displacements

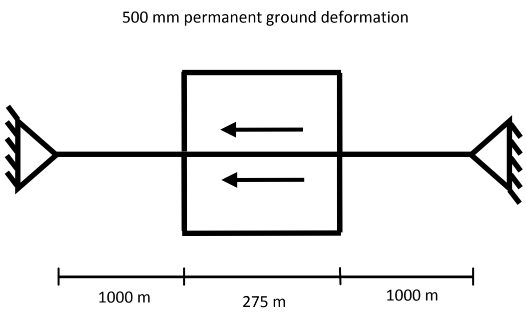


(c) Strains in the pipeline

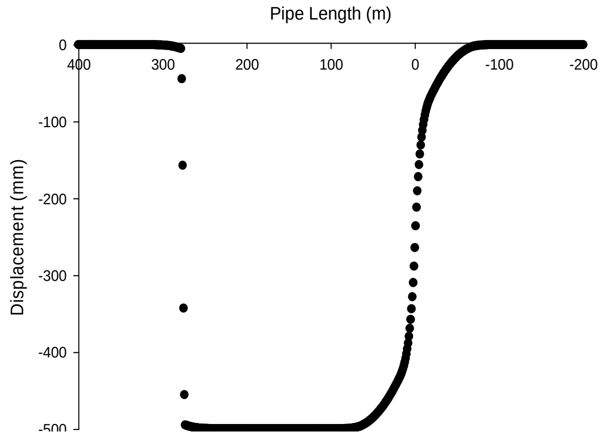


(d) Stresses in the pipeline

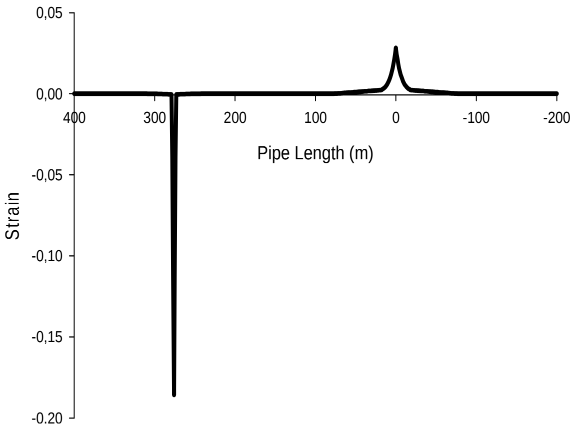
Figure 6. The FEM results for the Old Line 120 (cohesive soil)



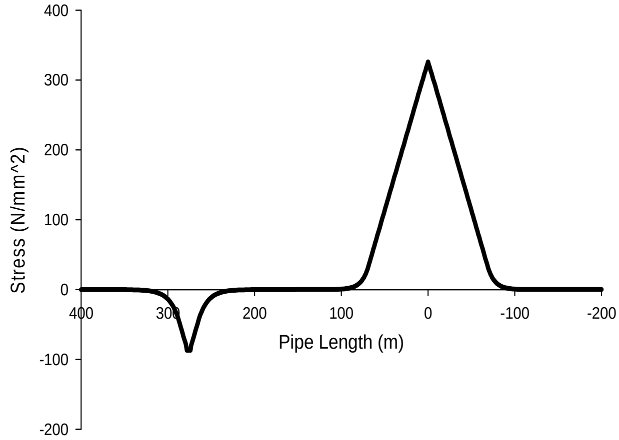
(a) FE model of pipe



(b) Pipe displacements



(c) Strains in the pipeline



(d) Stresses in the pipeline

Figure 7. The FEM results for the Rinaldi Trunk Line

Figure 7 shows the results for Rinaldi Water Trunk Line. This pipeline has a nominal diameter of 1727 mm with a wall thickness of 9.5 mm. The external coating of the pipe is cement mortar and burial depth is 2.7 m. The yield stress of the pipe material is 249 MPa. The wrinkling capacity of pipeline at welded slip joints is determined as 87 MPa. Because pipe extended beyond the compressive and tensile zones as a straight line, the supports were placed about far away (Figure 7a). FEM results show that pipeline displacement became equivalent to the 500 mm displacement of 275 m soil block (Figure 7b). Maximum pipe strains of 18 % were calculated at compression zone (Figure 7c). Tensile strain of 2.8 % was calculated in the pipe at the tensile ground rupture zone. This strain corresponds to an axial tensile stress of 326 MPa, which is high likely to exceed the tensile capacity of a welded slip joint (Figure 7d). Accordingly, the FEM results agree with the observed pipe failures in the compression and tension zones.

4. SUMMARY AND CONCLUSIONS

Performance of buried pipelines during earthquakes is affected by many factors related to geotechnical properties of the surrounding soil and physical properties of pipe itself and its coating. Analysis results of four pipelines, two of which failed and two of them were not damaged during the 1994 Northridge earthquake, are presented herein. Two pipelines which performed well have relatively higher yield stresses and low axial frictional values compared to failed pipelines. Coatings of the pipelines are coal tar epoxy, fusion bonded epoxy, cement mortar, and polyethylene for Old Line 120, New Line 120, Rinaldi Water Trunk Line, and Mobil Oil in the respective order. Axial soil friction force measured by Honegger (1999) for Old Line 120 pipeline (in cohesive soil) was used and the results were compared with results from the assumption that the pipeline is in cohesionless soil. The FEM results are consistent with the observed results.

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