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Seismic behavior of buried pipelines subjected to reverse fault motion

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A R T I C L E I N F O

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A B S T R A C T

Network of buried pipelines is one of the critical elements in infrastructure of today's modern cities that cover large geographic distances. Therefore, they could experience a variety of failures due to permanent ground Displacements (PGD) or wave propagation along on their path. Permanent ground deformations caused by fault deformation, landslide, and liquefaction-induced soil movements. The reports suggest that the main cause of damage to these pipelines is not seismic vibrations but large and permanent ground deformations are major causes of infrastructures' failures. In the past, most researchers to investigate the behavior of buried pipelines crossing the strike-slip faults, and researchers have less to study the behavior this Structures subjected to reverse fault motion. Thus in this study investigates the structural response of buried pipelines crossing reverse-slip faults under various fault displacement quantities in different soil conditions and faulting plane angles by Finite element models. Typical steel material for this study API-5L-X65, and Four different soil conditions categorized as cohesive and non-cohesive used investigated in the analysis. In this study, the interaction between soil-soil and soil-pipe has been considered in modeling terms. Pipe as shell element and the material behavior as elastoplastic as well as the soil around the pipeline as continuous volumetric elements were designed and analyzed.

1. Introduction

Earthquake is a natural disaster that leaves a lot of life loses and property damages every year. In addition to the casualties and property loses in residential areas, earthquakes can have huge industrial, environmental, financial impacts in industrial areas. Researchers studied the behavior of these structures against the movements of faults using the analytical methods. But due to the use of simplifying assumptions accuracy of responses were reduced (Newmark and Hall, 1975). Newmark and Hall were first people who investigated the crossing of buried pipelines. They considered lateral and axial deformation of pipe as the axial and lateral deformation of soil in their method while they ignored the relative displacement between the soil and the pipes. Moreover the model they delivered was applicable to pipes under traction and slip faults (Newmark and Hall, 1975). Then in 1977, Kennedy and colleagues developed Newmark and Hall model. In their model, they considered the interaction between the water and the soil components (Kennedy et al., 1977). In recent years finite element methods have been booming more and more. For example, in 2001, Takada et al (2001) found out that pipes do not show shell behavior against the movement of fault, hence they modeled pipelines as shell elements. In 2011, Joshi et al. analyzed pipes buried under reverse fault displacement using a three-dimensional finite element model. In this analysis pipe was studied by beam and soil elements and was modeled by using spring elements. Mr. Rofooei and colleagues' works in 2012 can be mentioned as one of the laboratory works compared with the numerical results obtained from finite element method. In his study, he investigated laboratory model of pipe buried under the reverse fault movement. Then, using a three-dimensional finite element model, responses and results of these two methods were surveyed and compared.

2. Modeling

This model has three main sections. Two sections of soil are related to faults and one section is related to pipe. Dimensions of the models made were chosen accurately according to previous research and studies. A parametric study showed that a Length 60 times the diameter of the pipe in the longitudinal direction and the cube dimensions in height and lateral dimension equal to 10 and 5 times the pipe diameter is sufficient (Vazouras and Karamanson,

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2010). For this reason, and given that the assumed diameter for the pipeline is equal to 0.9 meter the extent of the selected length, width and height for the model is respectively 80, 5, and 10.

Steel AIP5L-X65 is used for pipes. Moreover, due to the variety of different soils two kinds of soils, Sticky and non-sticky soil were used in this research. Technical specifications of soils used were presented in Table 1. Ramberg – Osgood criteria is used for steel pipeline. The stress-strain diagram of the given steel is shown in (Fig. 1). The mechanical characteristics of the pipeline are presented in Table 2 Mohr-Coulomb elastic model is dedicated to Continuous element representing the soil around the pipe.

In the above table according to Mohr-Coulomb criteria the following signs are presented respectively:

(γ) is density, (*E*) is the Modulus of elasticity, (ν) is the Poisson's ratio, (φ) is the internal friction angle of soil; (ψ) is dilation angle, (*C*) cohesion.

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

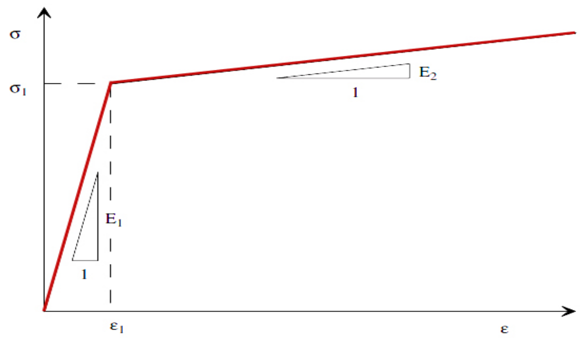

Fig. 1: The steel stress strain diagram AIP5L-X 65

Table 2: Surrounding soil properties (Tarinejad et al., 2012)

Soil Type	(KN/m³) γ	φ	ψ	*c* (Kpa)	*E* (Mpa)	ν
Soft clay	18	0	0	50	25	0.35
Stiff Clay	18	0	0	200	100	0.35
Loose Granular	18	30	10	5	8	0.3
Dense Granular	18	39	10	5	50	0.3

2.1. Interactions

In this study interaction is specified as a surface to surface interaction. This means that surfaces which can have contact are recognized and for each one a separate surface is defined. These surfaces mean parts of two substances which are in contact with each other, so that these surfaces may be formed in any geometric shape (Bolvardi and Bakhshi, 2010).

2.2. Loading and model's boundary conditions

At this stage, first the acceleration of gravity 9.81 N/m^2 is imposed in the direction of (- y) so that the weight of the model is applied automatically. The pipe's internal pressure is also applied as a compressive force to the inner surfaces. In the next stage, surfaces and fixed walls are closed in the desired directions. Regarding the static motion of the fault movement, static displacement of each surface will be applied to the movable wall in order to simulate the movement of the fault completely.

2.3. Meshing the model

Since the pipeline is a kind of shell element, it can be modeled by Four-node mesh (S4R). This element is used in large and nonlinear deformations and follows Romberg Osgood relationship. Soil that is a kind of solid element is modeled with 6-sided 8-noded mesh (C3D8R). Having complex linear and nonlinear behavior, this element is suitable for plasticity and contact issues along with great deformations. After selecting the proper meshing, the smaller and finer mesh is used in those areas due to the stress concentration at the confluence of the fault and pipes.

3. Parametric analysis

Given that the mass of the pipe is insignificant versus hardness; therefore, the forces of inertia caused by the mass of pipes is insignificant comparing with forces such as hardness of soil and pipe system and the period of the system is very small as well. Considering that the period of the System Compared to the time of the displacement caused by fault is low, using static analysis In order to investigate the behavior of buried pipes against large faults movements would be logical. Besides, in researches conducted so far, dynamic response is considered trivial and small compared to the deformation caused by the fault (Bolvardi and Bakhshi, 2010; Esmaili and Hamilton, 2014; Hampton, 2014; Kashani et al., 2015). Regarding the point mentioned in this article, it is assumed that nonlinear static analysis offers acceptable result. In the other section the following types of parameters affecting the pipeline' response such as depth of the buried pipe, pipe thickness, pipe diameter, angle of inclination of the fault, the type of soil around the pipe and soil internal friction angle are examined.

3.1. Checking the soil type on the pipeline response

As the results show (Fig. 3) pipelines in the cohesive soils have the greatest impact compared to granular soils. This is because of the larger central component of granular soils resistance.

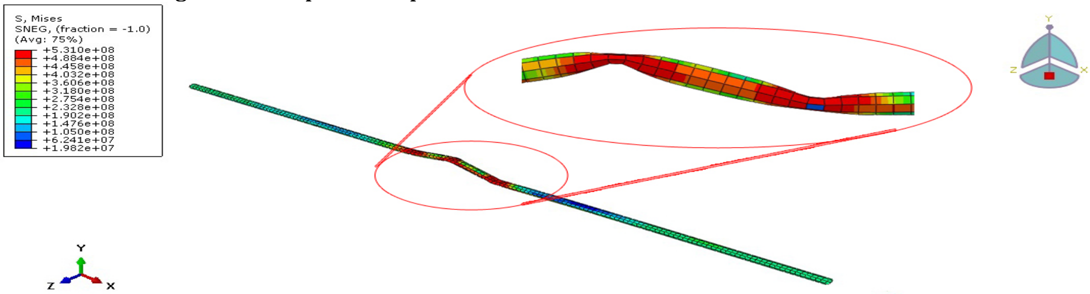

Fig. 2: The deformation and buckling in the pipeline caused by the reverse fault displacement

Moreover, the extent of the maximum strains in soft soils in both granular and cohesive ones is lower than the maximum strain in hard cohesive and granular soil. In other words, by increasing the hardness of the soil around the pipeline the extent of the strain in the pile is increased as well. This type of pipeline's response can be assumed so that by reducing soil hardness compared to the hardness of the pipeline, interaction between the soil and the pipe is increased and this causes slip between the outer surface of the pipe and soil and reduces responses.

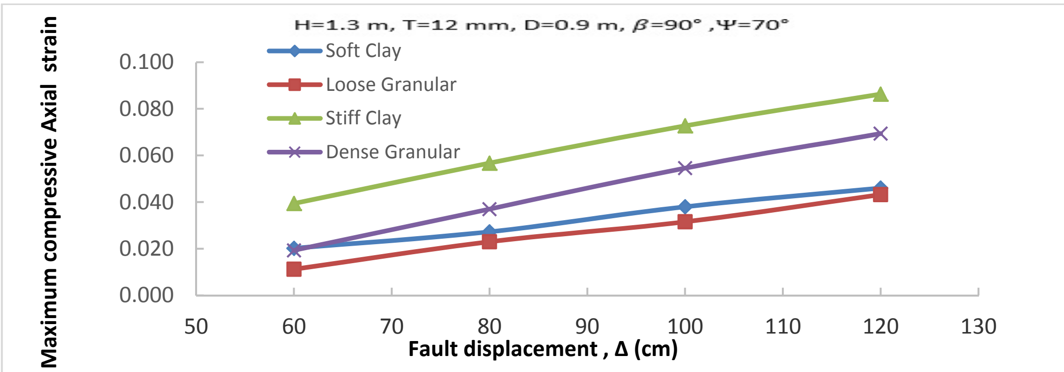

Fig. 3: The effect of different types of soils on the axial compressive strain of pipeline under the influence of the reverse fault movement

3.2. Checking the depth of the buried pipeline

Results of (Fig. 4) show that when the depth of the buried pipeline increases, axial strain increases as well. According to the results, we can say that with the rise of the burial depth, interaction forces between soil and pipe is enhanced comparing with hardness of the pipeline and thereby the response capacity of the piped is reduced.

3.3. Checking pipe diameter effect on the pipeline response

According to the results of Fig. 5, an increase in the diameter of the pipeline causes the reduction of the amount of axial strain. Enhancing the pipe diameter increases the flexural hardness of the pipe. The reason of reduction of axial strain is the reduction effect of increased flexural hardness of pipeline on the interaction between soil and pipe which slightly leads into higher pipeline's response capacity.

3.4. The impact of increased thickness on the pipeline response

As the results indicate enhancement of the pipeline wall reduces axial strain in the pipeline. In other words, by increasing the pipe wall thickness, cross-sectional area and moment of inertia are increased as well. Therefore, levels of resistant anchor is increased which in turn reduces the stress and strain in the pipeline.

3.5. Checking the internal friction angle of granular soils on the pipe response

According to the results of (Fig. 7), it can be deduced that by increasing the angle of internal friction the interaction between soil and pipe is also enhanced and this in turn increases the strain and stress in the pipeline.

3.6. Checking the fault angle effect on the pipeline response

Results of Fig. 8 show that with increasing reverse and normal fault angel the maximum axial strain is decreased significantly. The reason is reduction of central component of movement of these faults that is having a significant impact on results. Therefore, in the fault with higher angle, pipelines are much more vulnerable.

4. Conclusion

-Given the very significant effect of soil type on the response of these infrastructures, it is recommended to use loose granular soils at the confluence of these pipes with faults.

- Reduction in the depth of the buried pipeline increases pipeline capacity; therefore, it is recommended to use lower burial depth as far as possible for the implementation of these structures considering environmental and geographical conditions.

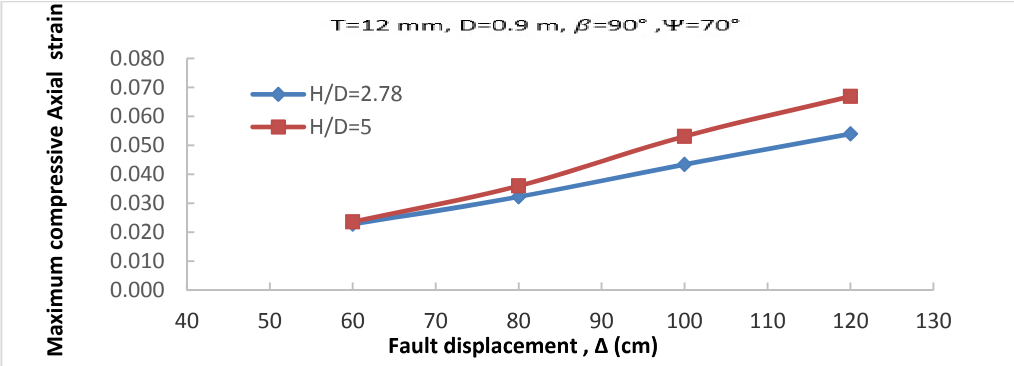

Fig. 4: The effect of increase in the depth of burial pipeline under the influence of reverse fault movement in the cohesive soft soil

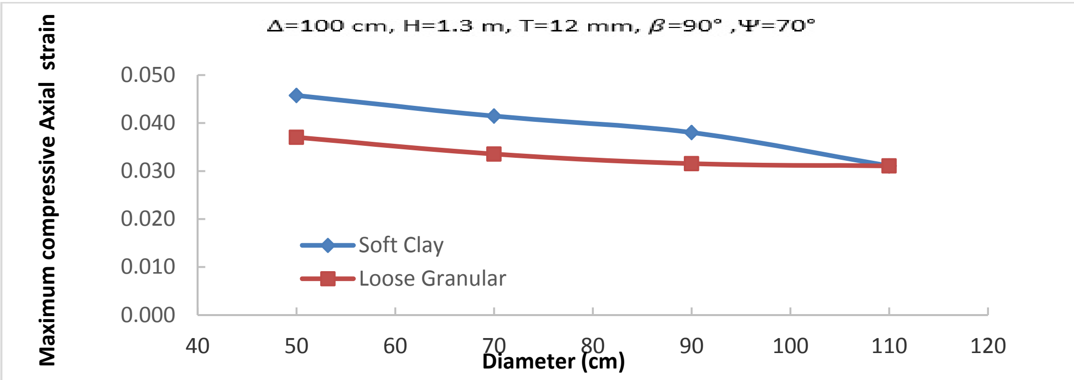

Fig. 5: The effect of increase in the pipeline diameter on the axial compressive strain of pipeline under the influence of the reverse fault movement

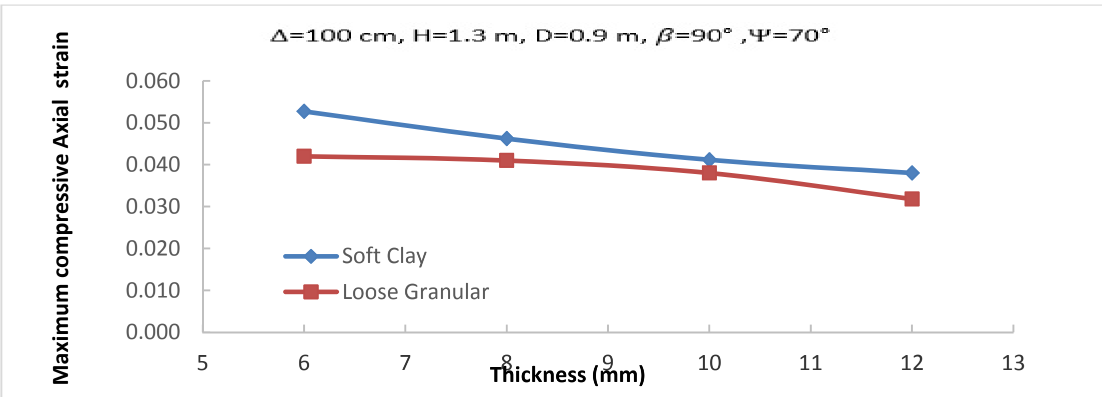

Fig. 6: the effect of the increase in the thicknesses of the pipe wall on the axial compressive strain of pipeline under the influence of the reverse fault movement

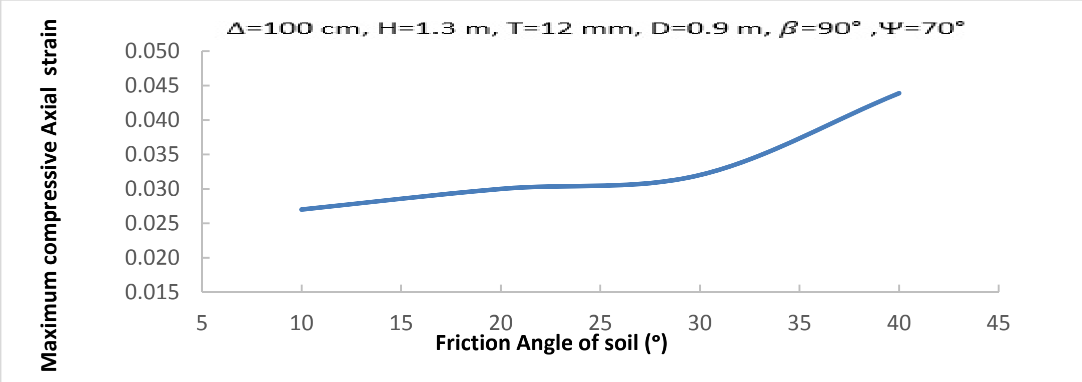

Fig. 7: The effect of the increase in the internal friction angle on the axial compressive strain of pipeline under the influence of the reverse fault movement

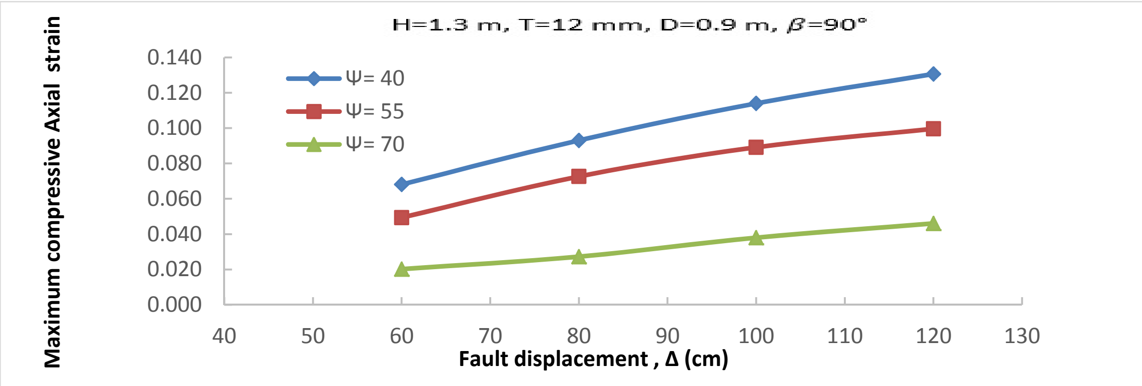

Fig. 8: the effect of the increase in the fault angle on the axial compressive strain of pipeline under the influence of the reverse fault movement

- Increasing the diameter of the pipeline as long as economic issues allow will enhance the pipeline capacity.

-in the fault area, pipelines with higher thicknesses and more formable materials should be used and the use of reflective coatings to reduce the interaction between the soil and the pipeline in the areas of fault is recommended.

- Given that the compressive strength of steel materials is much less than the tensile strength and when facing with reverse fault, compressive forces generated in the pipeline cause buckling and deformation in the cross section; therefore, it is recommended that pipelines crossing the intersection of reverse faults in the fault zone be implemented on the slippery bases and supports to ensure system safety.

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