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Design Issues of Buried Pipelines at Permanent Ground Deformation Zones

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Abstract This paper provides an overview of earthquake response of buried pipes subjected to permanent ground deformation hazards. Observed damage at segmented and continuous buried pipes, typical failure modes for segmented and continuous pipes, numerical modeling and provisions for design and analysis of welded steel pipelines are covered. Both simplified and 3D continuum finite element models are presented to estimate the response of soil-pipe interaction models to fault offsets. Effects of soil and pipe properties, fault crossing angles and possible measures for the earthquake risk mitigation in pipelines are summarized.

***Index Terms*— Oil, gas and water pipelines, earthquake damage, numerical modeling.**

I. INTRODUCTION

Buried pipelines are considered as lifelines since damage to such critical infrastructures may cause disruption of power and water systems which are vital for people in aftermath of earthquakes. They are considered massless and non-inertial elements. In contrast to buildings, the earthquake response analyses of pipes are based on deformation analysis rather than inertial one.

Pipelines differ in relation to fluids they transport such as gas, liquid fuels, potable water, sewage, etc. and their material such as steel, cast iron, concrete, etc. They also differ in relation to geometric properties such as diameter, wall thickness, burial depth, etc. However, in terms of seismic behavior and design, the most important difference is in relation to their connection type. Buried pipelines consist of segmented and continuous pipes. For a segmented pipeline, stiffness of the joints is significantly lower than that for the portion away from the joint.

Cast iron pipe with lead-caulked joints, ductile iron pipe with push-on rubber gasketed joints, concrete cylinder pipe with rubber gasketed joints are examples of the segmented pipelines. Due to their comparatively low stiffness, segmented pipelines subject, for example, to axial tension will pull-apart at the joints before experiencing material failure in the pipe section between the joints [1]. For continuous pipeline, the axial and rotational stiffness of the pipeline joint is comparable to that for the pipe section away from the joint. Steel pipe with butt welded joints, steel pipe with bolted flanges, and HDPE pipe with fused joints are examples of a continuous pipeline. They all generally perform better than a segmented pipeline when subject to earthquake hazards. Past earthquakes demonstrated that behavior and damage forms of these pipes could be quite different. Specifically, it is not unusual for continuous pipelines to be damaged by the permanent ground deformation (PGD) hazard, but it is unusual when they are damaged by the wave propagation (WP) hazard.

In this study, design issues related to buried continuous steel pipes due to abrupt permanent ground deformation (PGD) is discussed.

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II. PGD HAZARD

There exist two main sources of ground-induced seismic deformations on buried pipelines, namely the transient actions and the permanent deformations.

Transient actions are caused by WP within the soil. WP is usually effective in large areas typically in distribution networks. The induced ground strains in WP hazard as well as the pipe damage rates are low.

PGDs are due to fault movements, landslide activation and liquefaction-induced lateral spreading. PGD is a significant hazard for water oil and gas pipelines. Effective areas are more localized, but the ground strains as well as damage rates can be very high compared to WP hazard. Herein only PGD hazards are considered.

A. Spatially varying PGD (Landslide-Liquefaction)

Spatial distribution of ground hazard in a liquefaction zone is shown in Fig.1. A damaged pipeline subjected to likely ground hazard in the Van is shown in the next section.

B. Abrupt PGD (Faults)

Fault crossing is an abrupt PGD type of hazard in which soil deformation is immediate, such as the step function. As such, high axial and rotational deformation demands usually occur in the pipe. Schematic representation of steel pipes crossing different types of faults (reverse normal and strike slip) is shown in Fig 2.

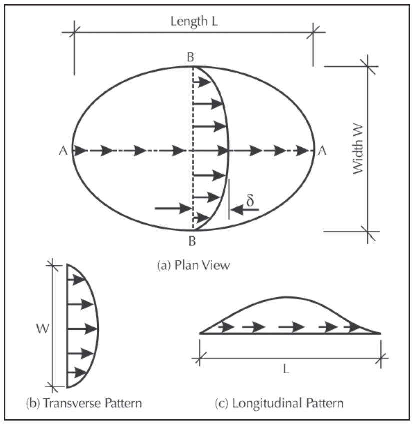

Fig 1. Characteristics of Spatially varying ground hazard representation [1]

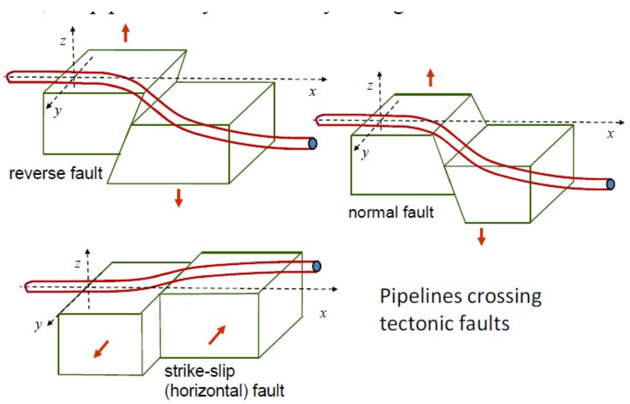

Fig 2. Schematic representation of pipelines crossing tectonic faults (abrupt PGD) [11]

III. EARTHQUAKE DAMAGE TO BURIED PIPES

In PGD zones, pipes are subject to bending as well as axial tension or axial compression. Strain limits are well above yielding state. Therefore, small changes in stress are associated with large changes in strain, particularly for steel. As such, strain is a better measure of pipe behavior and it is the most important engineering demand parameter for pipes. Recent empirical and analytical fragility expressions are based on pipe axial strains.

Fragility relations for pipelines are defined as the number of pipe breaks (repair rates - RR) per km. Most commonly these empirical relations are for various type of segmented pipes. This is due to two factors. Firstly, segmented pipelines are more common than continuous pipelines. Secondly, segmented pipelines are much more susceptible to seismic damage than continuous pipelines.

A. Damage to segmented pipes

Water and waste water pipes usually consist of segmented pipes. Failure modes for segmented pipelines are axial pull-out at joints, crushing at the joints and round flexural cracks in pipe segments away from the joints.

The seismic performance of segmented pipeline is not as good as that for continuous pipelines. Specifically, it is common that segmented pipelines are damaged by the WP as well as the PGD hazards. In the 2011 Van, Turkey earthquake, pipe damage was observed at 5 locations along a water transmission pipeline in northern Van. Damage was due to liquefaction induced lateral spreading [2]. The damaged and repaired pipes are shown in Fig.4.

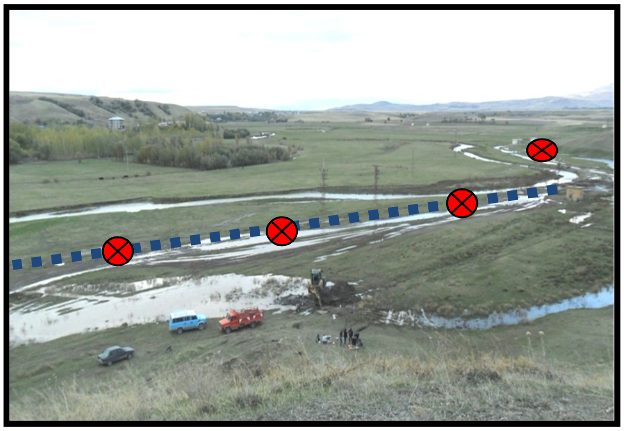

Fig 3. Damage locations of water transmission pipe due to liquefaction induced lateral spreading and settlement in 2011 Van, Turkey earthquake (spatially varying PGD hazard)

Fig 4. Damaged and repaired joints of segmented A/C water pipes (2011, Van earthquake) [2]

B. Damage to continuous pipes

Oil and gas pipelines usually consist of high quality, high strength welded steel pipelines which are not likely be damaged due to WP hazards. Damage at such high quality pipes usually happen in PGD zones in the form of local buckling (wrinkling) or global (beam) buckling (Fig. 5).

Possibly one of the best documented damage case study was the one in Kullar region of Kocaeli province in which a 2.0 m diameter steel pipeline was wrinkled at three locations due to strike slip fault crossing in the 1999 Kocaeli earthquake.

Fig 5. Wrinkling of the main water transmission pipe due to strike slip fault offset (abrupt PGD) in the 1999 Kocaeli earthquake [7], [12]

Figure 6. Failure of ductile welded steel water pipe due to excessive compression strain (abrupt PGD) (fault crossing) in Kullar [5, 12]

The outer and inner views of the wrinkled 2.0 m diameter water pipe in the 1999 Kocaeli is shown in Fig. 6. The pipe was crossing the fault with an angle of 55^0 and the right lateral fault movement imposed net compression and consequently shortening in the pipe. As a result, pipe wrinkling's with up to finger width cracks were observed at three locations along the pipe at both sides of the faults.

C. Failure criterion for continuous steel pipes

The principal limit states or failure modes for continuous pipelines (e.g., steel pipe with welded joints) are rupture due to axial tension and/or bending, and local buckling due to axial compression and/or bending. If the burial depth is shallow, continuous pipelines in compression can also exhibit beam-buckling behavior.

IV. DESIGN PHILOSOPHY OF COUNTINOUS PIPE AT FAULT CROSSING

The main novelty in the design of buried pipelines is to determine accurately pipeline behavior subjected to permanent fault offsets. The overall goal is to reduce the risk of damage to buried pipelines from fault displacements by minimizing the pipe strains. The potential for damage to a continuous pipe subject to PGD is reduced as the line is oriented perpendicular to the direction of the ground movement. Similarly, a pipe subject to the fault crossing hazard should be oriented such that the fault movement places the line in tension.

Theoretically, the optimum situation corresponds to the right angles to the fault. However due to uncertainty in the ground motion an angle of about 60^0 is recommended.

It should be emphasized that the design philosophy is to promote tension failure in the pipe. The schematic representation of a typical fault crossing problem is shown in Fig. 7. The axial and lateral nonlinear soil springs are used to represent the soil resistance to pipe.

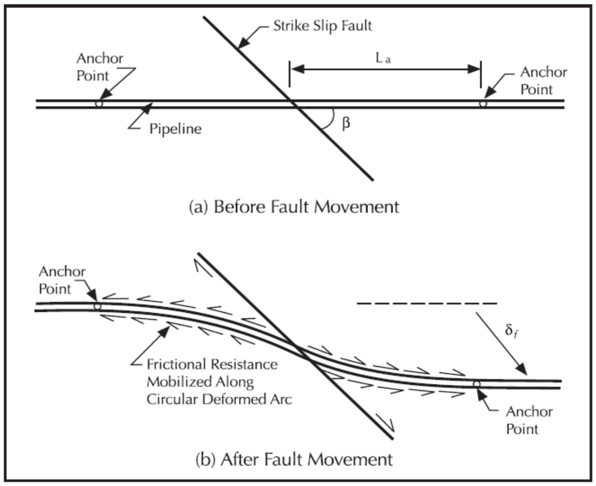

Fig 7. Plan view of a pipeline crossing a right lateral strike slip fault offset [1]

The distance between the anchor points represent the Critical Length of the S shaped deformation for a tension controlled deformation. Critical length for 90^0 of a crossing angle can be calculated as a function of the soil and pipe properties (D/t ratio) as shown in Fig.8.

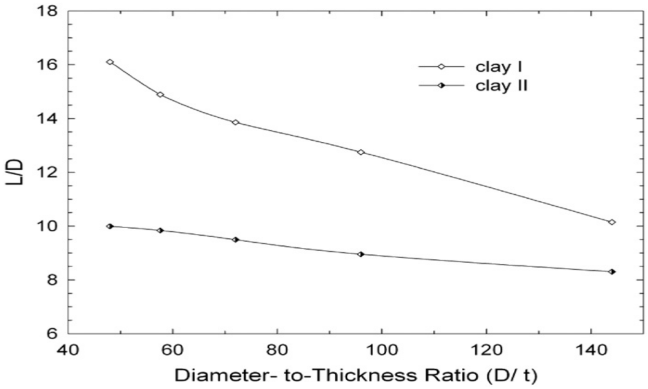

Fig 8. Variation of normalized effective length, L (with respect to diameter) vs. pipe slenderness ratio (D/t) for soft and stiff clays (Clay I and Clay II) [9]

It is clear that pipes with lower D/t ratio embedded in soft soils have longer critical length than a softer pipe buried in stiff soil. This is an expected and desirable case as lower soil resistance will reduce the interaction forces. As a result pipe strain decrease and allowable fault displacements increase.

Three stages are identified for the response of buried pipes at fault crossings. In small offsets, both axial and bending strains are important and both increase with respect to fault offset. There is net compression in the pipe in this case. In intermediate offsets, the axial strain is beyond yield, the bending strains are decreasing and net compressive strains approach zero. In large offsets, the bending strain remains constant while axial strains increase with respect to fault offsets. Pipe strain vs. fault offset for 90^0 intersection angle and given pipe and soil properties are shown in Fig 9.

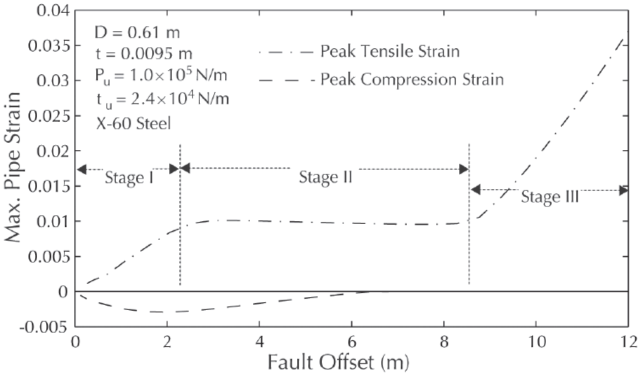

Fig 9. Pipe strain vs. fault offset for 90^0 intersection angle, [1]

A. Methods for calculating pipe axial strains due to strike-slip fault offsets

The pipe-soil interaction of buried pipes at fault crossings is a complex problem. Therefore, both simplified and detailed 3D numerical modeling techniques need to be employed. Analysis of pipes crossing PGD zones is performed by incrementally applied PGD hazard in which a nonlinear static analysis is performed.

B. Analysis methods

A simple numerical model is needed to determine the seismic demand of buried steel pipes at fault crossings. A practical nonlinear analysis model is presented in Fig. 10 to compute the critical response parameters. The soil springs acting in the transverse, vertical and axial directions to the pipe can be computed from ALA 2005 [3] and ASCE 1984 [4].

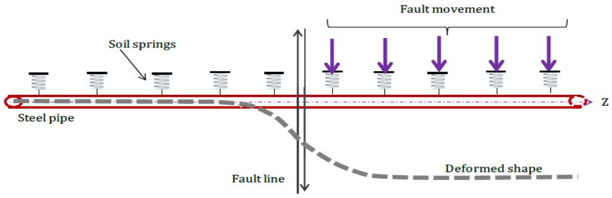

Fig 10. Simplified nonlinear model [5]

The suggested model in Fig. 10 permits plastic hinge formation in the pipe due to incrementally applied fault movements, allows determining the critical length of the pipeline and calculate strains developed on the tension and compression sides in the pipe. The effect of bending as well as axial strains due to stretching are also considered.

Another simplified model which is an elastic-plastic model proposed by Karamitros (Fig. 11). The beam segment consists of two sections, beam on elastic foundation and the transition zone. The model in Fig. 11 allows determining the pipe strain for various angles of intersection in tension controlled deformations.

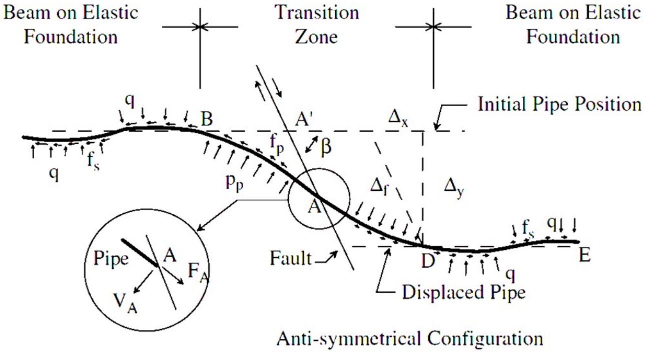

Fig 11. Simplified elastic plastic model, [6]

A hybrid model which consists of beam and shell elements has been proposed by Takada [7]. The model can predict the local buckling in the pipe.

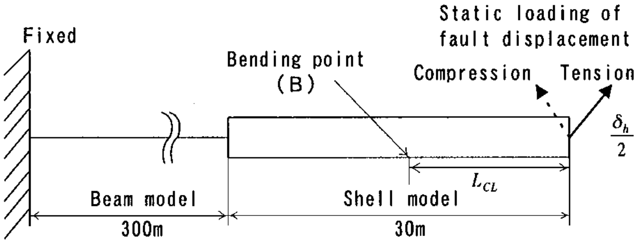

Fig 12. The hybrid model [7]

The most detailed model is a 3D continuum models which can be used to identify local buckling and wrinkling effects in the post elastic phase [8- 9]. Moreover, the use of three-dimensional finite element model offers a rigorous numerical tool to simulate buried pipeline behavior under PGD, but requires computational expertise. Such a model can describe the nonlinear geometry of the deforming soil-pipe system (including distortions of the pipeline cross-section), the inelastic material behavior for both the pipe and the soil, as well as the interaction between the pipe and the soil.

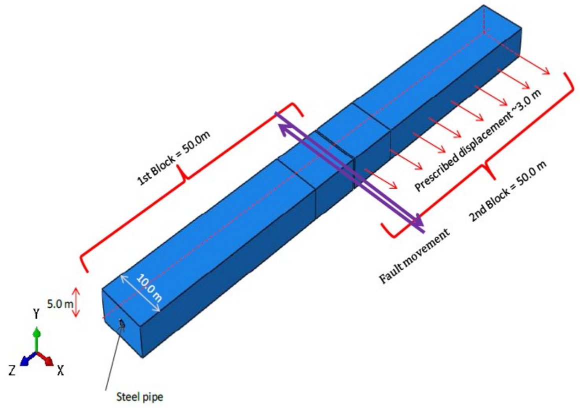

Fig 13. 3D continuum FE model [8- 9]

C. *Design criteria: ASCE-ALA (2005)*

The design guidelines do not propose a method to verify that the pipeline movement will not be affected by the native soil; it is up to the pipeline designer to estimate the geometry of the developing failure surface, and the necessary trench dimensions to contain it within the sand backfill. The lateral soil restraint on buried pipelines are provided in ASCE 1984 and ALA 2005 [3- 4].

Factors effecting the pipe response depend on some factors such as fault type, orientation angle soil properties and nonlinearity, burial depth, steel grade, D/t ratio, coating (friction), backfill material as a remedial measure.

The optimal orientation of a pipeline in the horizontal plane involves selection of the best pipe crossing angle. Allowable axial tension strains are larger than those for axial compression. Therefore, any angle that results in net axial compression should be avoided if possible. For a north-south fault with right lateral offset a pipeline orientation North-West to South-West is recommended [1].

Normalized allowable fault displacements with respect to crossing angle for a given soil and pipe property is shown in Fig.14.

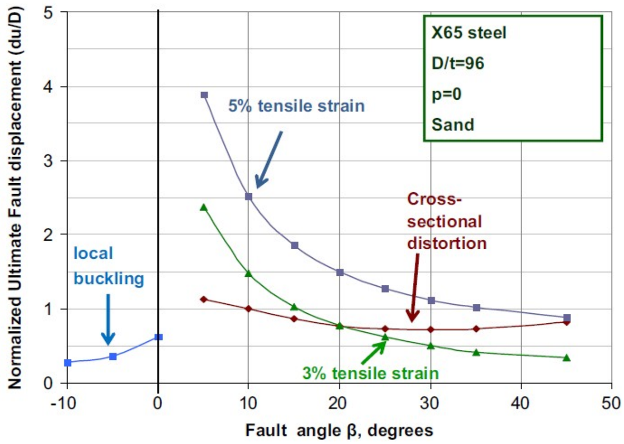

Fig 14. Normalized ultimate fault displacement for various performance limits for different crossing angles, [9]

V. MITIGATION REMEDY AT FAULT CROSSING

Buried pipelines are commonly installed in trenches, and subsequently backfilled with loose sand in areas at fault crossings. The dimensions of the trench must be adequate so as the pipeline response will not be affected by the properties of the possibly much stiffer surrounding soil. The spring forces should be estimated while considering the native soil properties, an approach that could lead to over-design of the pipeline. An example of fault crossing trench is shown in Fig. 15

Fig 15. Fault Crossing Design of 66-inch Pipeline San Francisco Hetchy Hetchy Water System in special trench [10]

Several measures can be employed to mitigate seismic damage to pipelines. Possibly, the first criteria is to consider the rerouting of the pipeline and adjust the pipe fault intersection angle so as to provide lowest pipe strain for a given fault displacement. . However, in several cases, this may not be possible. For example, if natural gas service is needed along a given street, alternate locations may be severely limited; therefore, other mitigation measures should be adopted.

VI. CONCLUSIONS

Response of buried steel pipes at fault crossings is based on fault type, orientation angle, soil properties and nonlinearity, burial depth, steel grade, D/t ratio, coating (friction) and backfill material as a remedial measure. Seismic data, such as time-frequency and magnitude of wave acceleration are also important parameters for this cause.

Effects of soil and pipe properties, fault crossing angles and possible measures for the earthquake disasters mitigation in pipelines are summarized in this study. More specifically, the increase of pipeline wall thickness increases pipeline strength against seismic action. Design related issues such as the use of higher grade pipe material, burial depth and orientation of crossing angle is also presented.

Performance-based design methodology should be adopted in the design of buried pipelines. Fragility expressions for buried pipelines at fault crossings are also needed for simplified methods to be developed.

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