Soil Dynamics and Earthquake Engineering 75 (2015) 55–65

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

A simplified analysis model for determining the seismic response of buried steel pipes at strike-slip fault crossings

E. Uckan [a,*], B. Akbas [b], J. Shen [c], W. Rou [d], F. Paolacci [e], M. O'Rourke [f]

[a] Department of Earthquake Engineering, Kandilli Observatory and Earthquake Research Institute, Bogazici University, Istanbul, Turkey
[b] Department of Earthquake and Structural Engineering, Gebze Technical University, Turkey
[c] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA, US
[d] Sharma & Associates, Inc., Countryside, IL, US
[e] Department of Engineering,University of Roma Tre, Italy
[f] Department of Civil and Environmental Engineering, Renssealer Polytechnic Institute Troy, NY, US

ARTICLE INFO

Article history:
Received 13 January 2014
Received in revised form
14 January 2015
Accepted 4 March 2015
Available online 21 April 2015

Keywords:
Buried steel pipes
Continuous pipelines
Damage
Fault crossings
Critical pipe length

ABSTRACT

The seismic response analysis of buried pipelines at fault crossings is a complex problem requiring nonlinear 3D soil-structure and large deformation analyses. Such analyses are computationally expensive and the results are hard to evaluate. Therefore, a simple numerical model is needed for engineering and design offices to determine the seismic demand of steel pipes at fault crossings. This paper presents a simplified numerical model for buried steel pipes crossing strike-slip faults and oriented perpendicular to the fault. Two pipes with different diameter to thickness (D/t) ratios and steel grades are used in the study. The proposed model permits plastic hinge formations in the pipe due to incrementally applied fault movements, allows determination of 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 as well as axial strains due to stretching.

1. Introduction

Buried steel pipes are commonly used in industry for transmitting oil and gas from the sources to the end points. High quality steel pipes with welded joints are usually preferred in oil and gas industry. There are two main ground hazard parameters for buried segmented (brittle) and continuous (ductile) pipes to estimate the pipe damage: a) wave propagation (WP), and b) permanent ground deformation (PGD). For high quality and high strength continuous pipes, the strains associated with transient waves (WP) are much smaller than the strain limits of such pipes. Critical conditions for such pipes occur when the pipes are in PGD zones and subject to critical ground hazard such as liquefaction-induced lateral spreading: landslides and fault crossings ([20,22]). Among these, the fault crossing is considered as one of the most important extreme events for buried pipes since the axial strains can reach to very high levels as a result of excessive bending and axial elongation due to stretching due to static fault offset (fault movement) [31,25].

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 [10]. 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 [30,31]. In Turkey most of the pipe damage data is available for segmented pipes in PGD zones [28]. O'Rourke et al. [22] 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 [21,11]. A welded steel, $D=2.2$ m water transmission pipe with ($D/t=122$) crossing the Sapanca Segment of the North Anatolian Fault at an angle $\beta=125^\circ$ in Kullar, southeastern Izmit, Kocaeli, Turkey (Fig. 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 pipe suffered significant distortion (Fig. 1a) due to fault rupture producing bending and net compression in the pipe. Close-up view of the wrinkled pipe is shown in Fig. 1b.

The limit states for buried steel pipes are a) the maximum tensile strain, b) local buckling due to axial compressive strain (critical buckling strain), and c) distortion of pipeline cross section [30]. The

* Corresponding author. Tel.: +90 532 568 5882; fax: +90 216 516 3324.
E-mail address: eren.uckan@boun.edu.tr (E. Uckan).

http://dx.doi.org/10.1016/j.soildyn.2015.03.001
0267-7261/

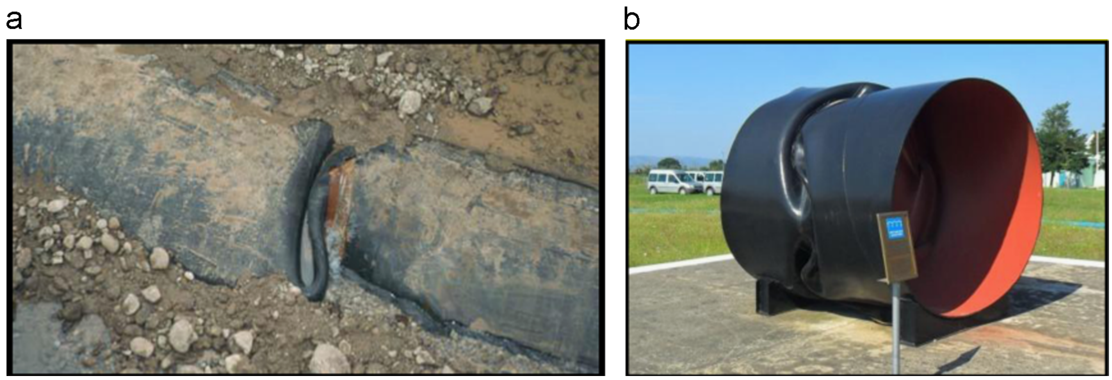

Fig. 1. (a) Wrinkling of a 2.2 m diameter steel water pipe at a fault crossing in Kullar, Izmit in the 1999 Kocaeli Earthquake [6]; (b) a close up view to the wrinkled pipe in Kullar (Uckan, E.).

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 [30,17].

Substantial amount of the literature on the seismic response of buried steel pipes at fault crossings exist ([7–9,13–15,1,30,31,26,27,17]). Vazouras et al. [30] mentioned that in soft soils the pipeline has larger deformation capacity whereas in stiff ground conditions the critical fault displacement decreases. Critical fault displacement corresponds to the fault displacement at which any of the limit states described above is reached. Chaudhari et al. [8] suggested to carry out a 3D FE model to compute the pipeline performance of buried pipeline subjected to fault motion including material non-linearity and large geometric deformations. Keaton et al. [18] investigated the resilience of the pipeline in response to fault displacement using a 3-D finite element (FE) stress analyses. They studied the Wasatch fault, the largest active fault in Utah to calculate the displacement capacity of the fault. Li et al. [19] studied the seismic response of soil-pipeline systems considering directivity effects of earthquake, burial depth, pipe diameter, and wall thickness.

A simple numerical model is needed for engineering and design offices to determine the seismic demand of steel pipes at fault crossings. Takada et al. [25] proposed a simplified model considering non-linearity of material and geometry of pipe section for the design of buried steel pipes crossing active faults. Karamitros et al. [16] used equations of equilibrium and compatibility of displacements to derive the axial force applied on the pipeline and adopts a combination of beam-on-elasticfoundation and elastic-beam theory to calculate the developing bending moment. Paolucci et al. [23] suggested a model which is based on the minimization of the total dissipated energy during faulting, taking into account the basic factors that affect the problem.

This paper presents a simplified numerical model to determine the seismic demand on steel pipes at fault crossings. A typical cross section of such large transmission system would be expected to have a diameter of 900–1400 mm and thickness of 15–20 mm. In this study, two steel pipes with different geometric and material properties are used. 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 as well as axial strains due to stretching.

2. Steel pipelines at fault crossings

Design of steel pipelines crossing a major fault line with and angle of 90° is based on the determination of axial strain which has mainly two components

a. Axial strain due to bending.
b. Uniform axial strain due to stretching during fault movement.

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° 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 [31]. A series of centrifuge tests with HDPE pipes are performed by Choo et al. [7] for the remediation of buried pipes subjected to PGD. A numerical modeling technique of HDPE pipes at normal fault crossings is recently studied by Xie et al. [29].

The most significant deformation will happen in an effective length, L, of the S shaped segment of the pipeline (Fig. 4). 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 (Fig. 2). Seismic design and analyses of steel pipes crossing fault lines are provided by ALA [3], Eurocode 8 [12] and ASCE [5] in detail. Seismic evaluation of these pipes should be based on performance-based design principles. However, to the authors' knowledge, no such guidelines exist.

3. Soil reaction for a laterally loaded pipe

Behavior of a laterally loaded pipe can be determined using linear/nonlinear p–y curves for simplified analyses. p–y curves represent the nonlinear soil deformation at a certain depth from the surface. Soil yields when the ultimate shear resistanse is reached at a certain depth due to lateral load/pressure. After the ultimate shear resistance is exceeded, deformation increases under constant load. p–y curves are assumed independent of the shape of the pipe and its rigidity.

Lateral soil resistance–deflection relationship for piles in soft clay is non-linear (Fig. 3) [4]. In Fig. 3, p is the actual lateral