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Experimental and numerical modelling of buried pipelines crossing reverse faults

Hasan Emre Demirci[a], Subhamoy Bhattacharya[a,*], Dimitrios Karamitros[b], Nicholas Alexander[b]

[a] Civil and Environmental Engineering, University of Surrey, Guildford GU2 7XH, United Kingdom
[b] Department of Civil Engineering, University of Bristol, Bristol BS8 1TH, United Kingdom

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ABSTRACT

Fault rupture is one of the main hazards for continuous buried pipelines and the problem is often investigated experimentally and numerically. While experimental data exists for pipeline crossing strike-slip and normal fault, limited experimental work is available for pipeline crossing reverse faults. This paper presents results from a series of tests investigating the behaviour of continuous buried pipeline subjected to reverse fault motion. A new experimental setup for physical modelling of pipeline crossing reverse fault is developed and described. Scaling laws and non-dimensional groups are derived and subsequently used to analyse the test results. Three-dimensional Finite Element (3D FE) analysis is also carried out using ABAQUS to investigate the pipeline response to reverse faults and to simulate the experiments. Finally, practical implications of the study are discussed.

1. Introduction

Earthquake induced permanent ground deformation (PGD) can severely affect the behaviour of buried pipelines. Ground fault rupture, which causes PGD, is one of the major seismic hazards for lifeline facilities such as gas and water supply pipelines. Past earthquakes; (see for example, 1999 Kocaeli and 1999 Duzce, 1999 Chi Chi, 2008 Wenchuan, 2009 Italy, 2010 Chile) showed that pipelines are extremely vulnerable to earthquake induced PGDs. The effects of pipeline failures on world industry, economy and society can be very devastating. For example, extensive damage occurred on Trans-Ecuadorian pipeline during 1987 Ecuador Earthquake and the economics loss is approximately $850 million in lost sales and reconstruction [31]. During the 1906 San Francisco earthquake, the water mains broke leaving the fire department with limited water resources to fight fires [36]. Thus, the evaluation of pipeline performance during and after earthquakes requires particular attention in order to mitigate effects of PGDs on buried pipelines. Table A-1 in Appendix details 13 pipeline failure case records from the fault crossing zones collated from 10 different earthquakes.

It is of interest to draw some broad conclusions from these case records:

(1) The failure type can be of following types: beam buckling (similar to Euler buckling of columns), local buckling (instability of the shell) (see in Fig. 1), tensile failure (yielding and fracture) and joint failure.
(2) Steel pipelines are commonly used in the field to transport water, oil and gas. Being long and slender, they are relatively weak under compressive loading. In this context, it is important to highlight that pipelines passing through reverse faults and some type strike-slip faults will induce compressive load on pipelines.
(3) 18th Column of the Table A-1 estimates the normalised fault displacement denoted by (δ/D) where δ is the observed fault displacement and D is the pipe diameter. In most cases, the ground moved past the pipe. Following Bouzid et al. [6], average shear strain in the soil around the mobilized deformation zone can be estimated as 2.6 × (y/D) where y is the pipe displacement. It may therefore be inferred that the soil-pipe interaction in a fault crossing zone is large strain problem and Large Deformation Finite Element (LDFE) is necessary.

1.1. A brief review of literature

A large body of research including analytical, numerical and experimental have been conducted in the past four decades to study pipeline performance during earthquakes. Newmark and Hall [32] developed simplified analytical methods for the pipeline crossing faults which is primarily subjected to tensile strain. Kennedy et al. [24]

* Corresponding author.
E-mail addresses: h.demirci@surrey.ac.uk (H.E. Demirci), s.bhattacharya@surrey.ac.uk (S. Bhattacharya), d.karamitros@bristol.ac.uk (D. Karamitros), Nick.alexander@bristol.ac.uk (N. Alexander).

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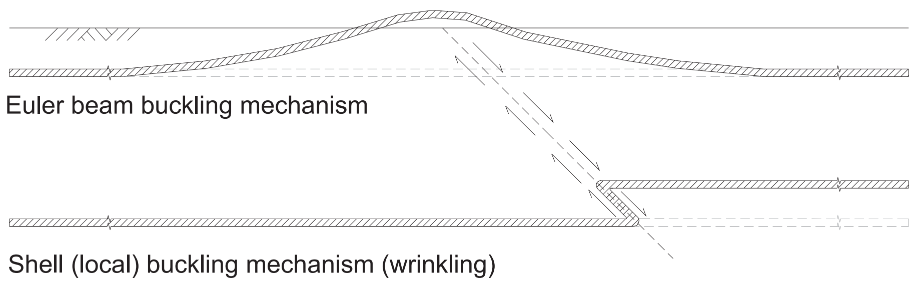

Fig. 1. Illustration of the two distinct buckling failure mechanisms.

extended the work of Newmark and Hall [32] by taking into account lateral interaction effects at the pipe-soil interface and large axial strain effects on the bending stiffness of the pipe. Wang and Yeh [50] proposed modifications to closed-form analytical model by representing the pipeline-soil system using concept of the theory of beams on elastic foundations. The pipeline was partitioned into four segments where two segments are in high deformation zone and other two segments are in small deformation zone. Beams on elastic foundation approach was used to analyse the segments in small deformation zone while the segments in high deformation zone were assumed to deform as circular arcs. Takada et al. [43] proposed a new simplified semi-analytical method to obtain maximum pipe strain in steel pipelines crossing faults considering nonlinearity of material and deformation of pipe cross-section. They proposed simplified formulations to calculate maximum tensile and compressive pipe strains by using pipe bending angle. Existing analytical methodologies were refined by Karamitros et al. [21] to achieve a wider range of applications. The equations proposed by Kennedy et al. [24] were used to take into account the effects of axial tension on the pipeline curvature together with Wang and Yeh model [50]. The nonlinear behaviour of pipeline material was taken into account by carrying out a series of equivalent linear calculation loops, where the secant Young's modulus of the pipe material is readjusted on each loop. Trifonov and Cherniy [44] developed an analytical methodology proposed by Karamitros et al. [21] to analyse the response of pipelines crossing normal faults. They considered no symmetry condition about the fault-pipeline intersection to be able to analyse different types of fault mechanisms. Karamitros et al. [22] extended the earlier analytical methodology of Karamitros et al. [21] for the stress-strain analysis of buried steel pipelines crossing strike-slip faults to normal faults. Trifonov and Cherniy [45] presented an analytical model for stress-strain analysis of buried steel pipelines crossing active faults, taking into account the influence of operational loads such as internal pressure and temperature variation on the basis of plane strain plasticity theory.

Finite Element Method is one of the useful tools to explore the response of pipeline subjected to PGD, taking into account the nonlinearity of soil and pipe and the interaction between soil and pipe. Finite element method has been recently used by several researchers for the verification and refinement of analytical methods, the evaluation of factors influencing pipe response under different types of PGD, the assessment of pipeline performance with respect to performance criteria such as local buckling, ovalization and tensile rupture [21,26,33,39,43,46–49,52,54]. In a recent study, Liu et al. [30] modelled the pipeline response to reverse faulting using FE software ABAQUS. In the study, the pipe was modelled as shell elements and pipe-soil interaction was modelled as non-linear soil springs. In the work, the effects of yield strength and strain hardening parameters is investigated from the point of view of buckling response. A review of the Finite Element (FE) models in the literature indicates that various types of models including beam, shell, hybrid (beam + shell), soil continuum-shell model are utilized in order to simulate pipeline response to PGD. However, the verification of FE analysis results is essential to obtain reliable outcomes. Due to lack of verified case histories, there is a need to perform scaled model tests not only to identify mechanisms but also for verification and calibration of analytical and numerical methodologies.

Palmer et al. [38] described the large-scale testing facility at Cornell University and the working principle behind them. O'Rourke and Bonneau [35] performed large scale tests in order to evaluate the effects of ground rupture on HDPE (High Density Poly Ethylene) pipelines and the performance of steel gas distribution pipelines with 90° elbows. Lin et al. [28] performed small-scale tests to analyse the performance of buried pipelines under strike-slip faults. Centrifuge based approach was first proposed by O'Rourke et al. [33,34] to model ground faulting effects on buried pipelines. Ha et al. [16], Abdoun et al. [1], Ha et al. [17] and Xie et al. [52] performed several centrifuge tests to investigate response of buried pipeline to ground faulting. The centrifuge based tests were performed for the verification of numerical and analytical methodologies, the evaluation of parameters affecting pipeline response to faulting and the assessment of soil-pipe interaction (soil spring model in [2]). As viewed in the literature, a significant number of studies have been performed on the pipe response to strike-slip faulting. However, there are limited experimental works on pipeline performance under reverse fault motion and is therefore the focus of this study.

1.2. Aims & Scope of the Work

The aims and scope of the paper are as follows:

1) To describe a new experiment setup developed to study the effects of reverse faulting on buried continuous pipeline.
2) To present the test results using non-dimensional groups so that a framework of understanding can be developed.
3) To compare three-dimensional (3D) FE analysis results with experimental results in order to verify/validate 3D FE model.

2. Experimental modelling

Buried pipelines subjected to reverse faulting primarily undergo compression combined with bending and shear. The combination of bending and compression strains causes different types of pipeline failure modes such as local buckling and beam buckling (Fig. 1). Particularly, local (shell) buckling failure mode are very destructive for pipeline integrity. Therefore, soil-pipeline interaction under reverse faults should be investigated to increase earthquake resilience of pipelines crossing reverse faults.

Pipelines crossing active faults can be modelled as a beam on elastic foundation, see Fig. 2. Steel pipelines in the field have small cross-sectional dimensions compared to distances along its axis i.e. distance between support points. Therefore, they can be considered as slender beams and Euler-Bernoulli beam approach can therefore be used to model these pipelines. The soil surrounding pipelines is also assumed to be uniform. The governing equation of the problem is very similar to the laterally loaded beam on elastic uniform support. Fig. B-2 in the Appendix shows a free body diagram of the segment of pipeline crossing strike-slip faults. The governing equation of laterally loaded