Soil Dynamics and Earthquake Engineering 105 (2018) 127–138

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Numerical modeling of normal fault-pipeline interaction and comparison with centrifuge tests

Pengpeng Ni[a], Ian D. Moore[b,*], W. Andy Take[b]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
[b] GeoEngineering Centre at Queen's – RMC, Department of Civil Engineering, Queen's University, Kingston, ON, Canada K7L 3N6

ARTICLE INFO

Keywords:
Normal fault-pipeline interaction
Finite element analysis
Centrifuge modeling
Approximate design equations
Earthquakes

ABSTRACT

Pipelines extend thousands of kilometers across wide geographic areas to provide products for modern life. It is inevitable therefore that pipelines must pass through active faulting zones. The safety of pipe networks should be maintained by employing an appropriate design method. Beam-on-spring analysis is the normal design approach, but it is difficult to choose the spring stiffness for pipelines crossing a dip-slip (normal/reverse) fault, since the native soils beneath the pipe trench may provide extra restraints on relative pipe-soil movement. Alternatively, three-dimensional finite element analysis has the potential to provide useful design calculations which account for (a) axial and flexural stiffness of the pipe, (b) geometry and kinematics of the problem (including the actual trench size and correct ground motion), (c) stiffness of the pipe relative to the soil stiffness assembled from the different components of the surrounding soil (the undisturbed native soil material, the bedding soil, the sidefill and the backfill), and (d) nonlinear effects like formation of gaps and shear failure of the soil. Using geotechnical centrifuge test measurements, three-dimensional finite element models are developed to capture the behaviours observed for buried pipelines of various materials subjected to differential ground movements associated with normal faulting. Material nonlinearity, geometric nonlinearity, and the contact, detachment and slippage behaviour on the soil-pipe interface are explicitly modeled. Using hexahedron continuum elements, satisfactory reproductions of the centrifuge experiments are achieved for flexural responses of the test pipes. The finite element analysis is then used to investigate the impact of trench burial conditions.

1. Introduction

Historical loss of life and property after earthquakes in general have resulted from devastating structural damage as well as fire events. One typical situation involves ruptures of gas lines and electricity lines, which induce fire. Leakage and breaks in water lines become a hindrance when emergency personnel work to suppress fires, and loss of wet lifelines may also lead to multi-month shelter requirements for people without domestic water and sewer service.

These lifeline failures associated with earthquakes can be attributed to either wave propagation hazards or permanent ground deformation hazards. From the performance of pipelines in past earthquakes, it appears that permanent ground deformation at fault rupture zones produces more substantial damage than the effect of dynamic wave propagation [1]. The 1971 San Fernando [2], 1979 Imperial Valley, 1994 Northridge [3], 1999 Kocaeli [4] and 1999 Chi-Chi [5] earthquakes are all examples where permanent ground deformation induced pipeline damage. Pipelines cover wide areas and their seismic design when crossing active faulting zones should be a high priority.

There are limited experimental data on the fault-pipeline interaction problem due to the difficulty and cost of reproducing the fault in the laboratory. Large-scale testing only emerged recently, which sets an upper bound on the deformation caused by an abrupt fault rupture [6–9]. As an alternative, reduced-scale model tests at increased gravity are easier to control and more affordable. O'Rourke and his collaborators initially introduced the application of a split-box to perform centrifuge tests, originally conceived for the evaluation of pipe responses subjected to seismic faulting [10]. Due to their similarity, the tests conducted for fault-foundation interaction provide evidence that the application of split-box testing of pipelines could be effective [11–17]. Successful centrifuge experiments for a strike-slip fault [18,19] and for reverse fault [20] have been reported. The welded steel pipeline response to the 1999 Izmit earthquake provides evidence that centrifuge modeling can credibly reproduce field buckling observations [21]. Choo et al. [22] performed centrifuge modeling of strike-slip fault-pipeline interaction to verify the effectiveness of low-density backfill to mitigate seismic damage. To date, pipelines crossing a normal fault with a dip angle of 90° have been studied by Ha et al. [23],

---

* Corresponding author.
E-mail addresses: pengpeng.ni@ntu.edu.sg (P. Ni), ian.moore@queensu.ca (I.D. Moore), andy.take@queensu.ca (W.A. Take).

https://doi.org/10.1016/j.soildyn.2017.10.011
Received 21 October 2015; Received in revised form 26 July 2017; Accepted 17 October 2017

Saiyar et al. [24,25].

Pipeline response under seismic faulting has been investigated extensively using analytical approaches [26–35]. They all follow the assumptions originally made by Newmark and Hall [29] and Kennedy et al. [28], where pipe strains associated with faulting geometry and pipe deformations are calculated and an iterative procedure is required to get the convergence of pipe responses. However, the complexity of these methods hinders their application and understanding by engineers in practice. Beam-on-spring analysis is recommended in design guidelines [36], but the selection of spring stiffness is not well defined for different burial conditions (i.e., the interaction between the native soils outside the pipe trench, the backfill material and the pipe, and the influence of different pipe materials on mobilized friction resistance). Furthermore, imposing the correct ground motion at the pipe burial depth is challenging for this kind of analysis (e.g. decisions are needed whether to impose discontinuous ground motion associated with the fault dislocation or a continuous displacement wave). Alternatively, numerical simulations could provide reliable design as long as they can be calibrated by field data or laboratory tests, although a number of difficulties have been identified by researchers attempting to execute such modeling of strike-slip fault-pipeline interaction [35,37–39] and of normal fault-pipeline interaction [40]. Three-dimensional finite element analysis can account for (a) axial and flexural stiffness of the pipe, (b) geometry and kinematics of the problem (including the actual trench size and correct ground motion), (c) stiffness of the pipe relative to the soil and (d) nonlinear effects like formation of gaps and shear failure of the soil.

In this paper, the detrimental effects of a normal fault on model pipes observed through the geotechnical centrifuge tests conducted by Saiyar at the Centre for Cold Ocean Resources Engineering (C-CORE) [41] are summarized. A massively parallel super computer system at the High Performance Computing Virtual Laboratory (HPCVL) makes it feasible to conduct explicit three-dimensional finite element modeling of the centrifuge tests. The finite element procedures of [42] are used to: examine the behaviour of buried pipes of different stiffnesses; evaluate the ability of the analysis to reproduce the centrifuge test results; examine nonlinear behaviour associated with shear failure and separation of the pipe from the ground (i.e. development of gaps under the pipe structure); and investigate the impact of backfill soil when the pipe is placed in a trench with different backfill characteristics.

2. Centrifuge modeling

A pipeline (burial depth H and bedding depth BD, which all measure to pipeline centerline) buried in a uniform soil deposit straddling a normal fault having a dip angle of 90° is portrayed in Fig. 1. Above the base rigid (rock) stratum, soil can be distinguished as the footwall and the hanging wall side by the fault trace. When a normal fault displacement occurs, the soil block remains stationary on the footwall side and it moves downward (δ_0) on the hanging wall side. Fault propagation through soil is normally regarded as a relatively slow quasi-static process even during earthquakes [43]. Inertial effects of pipeline are considered negligible given that the combined weight of the pipe and its contents are very close to the soil being replaced [1].

Reduced-scale experiments were conducted under increased gravity (30g) using the 11 m diameter geotechnical centrifuge facility at C-CORE [25]. The corresponding prototype-scale counterpart can be reproduced through a set of well-established scaling laws [44,45]. This paper presents all results in the centrifuge-based scale, unless otherwise stated. Fig. 2 shows the imposed dislocation (δ_0 equal to 0.5 mm per step) on the floor of the soil box to represent the case of a ground fault in a rock stratum underlying the soils, which contains a pipe. The loading rate was not recorded in the tests since it has been proven that fault offset rate does not influence the flexural responses of pipe, although polymeric materials are rate sensitive [19]. This special problem geometry can also provide valuable information regarding pipe response under other faulting conditions, though the magnitudes and patterns of deformation would be changed.

The model pipes were fabricated to be solid rods 800 mm long and 9.5 mm in diameter with equivalent flexural stiffness of thin-walled pipes without anchorage of the pipe ends (the 'free end' condition is better than a 'fixed end' condition, since it produces flexural response that is somewhat higher than, i.e. conservative relative to 'very long pipeline' response, and flexural response rather than axial response controls pipeline strength). Half of a solid rod is used because the glass wall of the centrifuge test box has a low coefficient of friction, and the flat surface of the half-rod is painted with a speckled pattern to permit monitoring of deformations using Particle Image Velocimetry (i.e. Digital Image Correlation). There was a 50 mm clearance at each pipe end to the sides of the testing chamber to minimize the boundary effects [41]. The pipe was loaded in the elastic range and shear deformations of the pipe cross section were ignored. This facilitates use of thin beam theory to determine flexural responses including bending curvatures from deformation profiles when the pipe length is far larger than its diameter (20 times).

The properties of the test pipes and the soil are tabulated in Table 1. Using air-pluviation, Fraser River sand was used to backfill the testing chamber. The soil had specific gravity of 2.71, uniformity coefficient of 1.88, coefficient of curvature of 0.92, mean grain size D_{50} of 0.26 mm, effective grain size d_{10} of 0.17 mm, and maximum and minimum void ratios $e_{\max}$ and $e_{\min}$ of 0.94 and 0.62, respectively [46]. Density achieved was 1610 kg/m^3 at the target relative density of 80%. Laboratory element testing data are available in the literature [46–48] for the selection of the drained soil parameters in finite element simulations.

First, the free field soil response was investigated to gain the insight into shear localization within the soil. Deformations for a half pipe model placed against the window at the side of the test box were compared to a full pipe model monitored using strain gauges. Saiyar [25] then conducted tests using half pipe models to examine influence

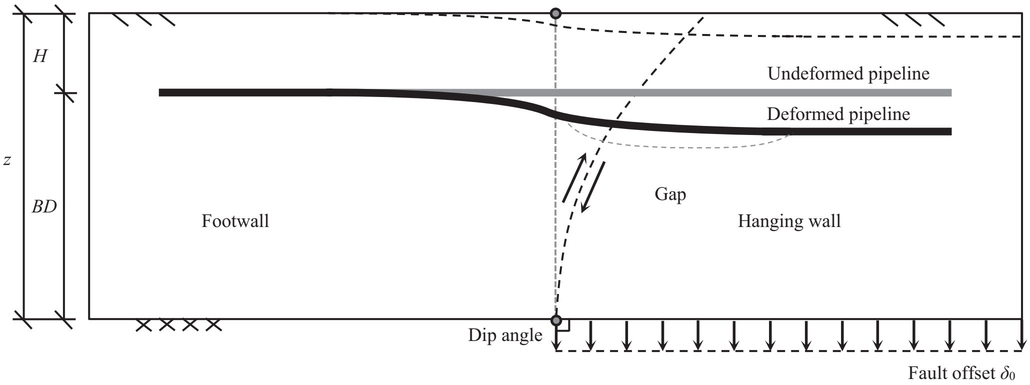

Fig. 1. Definition and geometry of the problem (see Ni et al. [42]).