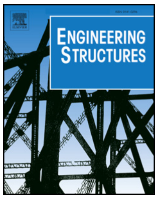
Engineering Structures 167 (2018) 393–406

Contents lists available at ScienceDirect

Engineering Structures

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



Simplified evaluation of pipe strains crossing a normal fault through the dissipated energy method

Pengpeng Ni[a,*], Sujith Mangalathu[b]

[a] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore
[b] Department of Civil and Environmental Engineering, University of California, Los Angeles, CA 90095, USA

ARTICLE INFO

Keywords:
Buried pipeline
Normal fault
Dissipated energy
Analytical solution
Fragility analysis

ABSTRACT

A dissipated energy method is proposed in this paper to calculate the maximum and minimum pipe strains crossing a normal fault perpendicularly. Two plastic hinges are assumed to form on either side of the fault plane. The curved pipe segment between plastic hinges has different lengths on the footwall and hanging wall sides due to the difference in bearing and uplift soil resistances. A curved pipe length ratio is determined for use in deriving simplified geometric relations. Four energy components are then computed considering rotations at plastic hinges, plastic elongations of the curved pipe segment, and yielding of axial, uplift and bearing soil springs. Minimization of dissipated energy is carried out to find the optimal position of the curved pipe segment for different fault offset. The pipe strains evaluated from the proposed technique are compared with calculations using the existing three-beam analytical method and centrifuge experiments. Upon the successful calibration of the calculation model, a sensitivity analysis is performed to assess the influence of backfill material, dip angle, burial depth and pipe strength. In the end, an illustrative example is presented to employ the developed analysis framework to run fragility analysis for three pipelines with different diameter to thickness ratios.

1. Introduction

During post-earthquake reconnaissance, damages to buried pipelines have been induced by two aspects: (a) the propagation of seismic wave results in transient ground strains across wide geographic areas, and (b) the magnitude of permanent ground dislocation corresponds to a localized displacement demand acting on the pipes. It has been documented that permanent ground deformations could produce higher damage rates in pipes than wave propagation [1]. Among different types of ground displacement discontinuities, surface faulting is a typical example that can deteriorate the serviceability of pipeline networks. Takada et al. [2] reported an incident of severe pipeline buckling to 90° due to a normal fault of 4.0 m in the 1999 Chi-Chi earthquake in Taiwan. Eidinger et al. [3] summarized the field observations for the development of wrinkles in a 2.2 m diameter steel water transmission pipeline subjected to a strike-slip fault of 3.0 m during the 1999 Kocaeli earthquake in Turkey. A global buckling failure of water pipe at a reverse fault crossing in the 1990 Manjil earthquake in Iran was also documented by Towhata [4]. The devastating failures of pipelines can interrupt any efforts of conducting rehabilitation work due to fire events induced by ruptures of gas lines and electricity lines and also result in the loss of water because of leakage and breaks in water lines.

The pipe response subjected to a strike-slip fault is a symmetric problem, since the lateral soil resistance in the horizontal plane is equal in opposite loading directions. However, the dip-slip (including normal and reverse) fault-pipeline interaction problem is more complex due to the difference in the upward and downward soil reaction models in the vertical plane [5–7] and will be investigated in this paper. To better understand the detrimental effect of dip-slip fault ruptures, experimental facilities have been developed worldwide. The performance of pipelines crossing a reverse fault has been investigated extensively using centrifuge-scale experiments [8,9], 1 g shaking table tests [10], and large-scale laboratory tests [11–14]. To date, less experimental evidence is available to study the normal fault-pipeline interaction problem. Ha et al. [15] initially conceived the idea of modeling normal fault ruptures by a split-box apparatus in the centrifuge environment. They studied the behavior of high-density polyethylene pipelines under a normal fault with a dip angle of 90°. Similarly, Moradi et al. [16] tested reduced-scale steel pipelines with varying diameter to thickness ratios experiencing a normal fault with a dip angle of 60° at elevated gravity. Recently, Saiyar et al. [17] carried out a series of centrifuge tests on buried pipes with varying flexural stiffnesses straddling a 90° normal fault. The only effort of evaluating the normal fault-pipeline

---

* Corresponding author.
E-mail addresses: pengpeng.ni@ntu.edu.sg (P. Ni), sujithmangalath@ucla.edu (S. Mangalathu).

https://doi.org/10.1016/j.engstruct.2018.04.047
Received 4 January 2018; Received in revised form 13 March 2018; Accepted 13 April 2018

Nomenclature

H	burial depth
β	dip angle
Δf	fault offset
Δx	axial component of fault offset
Δz	vertical component of fault offset
Δz_d, Δz_u	vertical fault offset resisted by bearing capacity and uplift resistance, respectively
D	pipe outside diameter
t	pipe wall thickness
c	soil cohesion
γ	soil unit weight
K_0	at-rest earth pressure coefficient
α	adhesion factor
ϕ	soil friction angle
f	coating dependent factor
t_u, q_{uu}, q_{ud}	maximum axial, uplift and bearing soil forces per unit length of pipe, respectively
x_u, z_{uu}, z_{ud}	elastic deformation for axial, uplift and bearing soil springs, respectively
k_{vd}	stiffness of bearing soil spring
N_{cv}, N_{qv}	uplift factors for clay and sand, respectively
N_c, N_q, N_γ	bearing factors
l_{ratio}	curved pipe length ratio
F_a	tensile force along the axial direction of circular arcs
q	uniformly distributed soil reaction in the radial direction
R_d, R_u	radii of curvature of circular arcs for the bearing and uplift sides, respectively
L_p	plastic hinge length
θ	pipe rotation
$\hat{\theta}$	infinitesimal increment of rotation
$\hat{\delta}$	infinitesimal (visual) increment of fault displacement
$\hat{s}_d$, $\hat{s}_u$	infinitesimal elongation of the bearing and uplift sides, respectively
x, x'	distance from the plastic hinges A and C, respectively
$\hat{\delta}_d$, $\hat{\delta}_u$	downward and upward relative soil-pipe displacement, respectively
P_r	total dissipated energy
P_{rr}	dissipated energy due to rotation of pipe segment at plastic hinges
P_{re}	dissipated energy due to plastic elongation of pipe
P_{rt}, P_{rq}	dissipated energy by soil springs in the axial and vertical directions, respectively
R_e, R_i	external and internal radius of pipe, respectively
σ_y	yield stress
M_p	plastic moment
F_p	axial force at fully mobilized plastic response
κ	pipe curvature
L_{ph}	length of the plastic hinge
ε_a, ε_b	axial and bending strains, respectively
$\varepsilon_{\max}$, $\varepsilon_{\min}$	maximum and minimum strains, respectively
Δf_{cr}	critical fault offset
E	modulus of elasticity

interaction problem using large-scale laboratory tests was reported by Ni et al. [18].

Different numerical techniques have been developed to study the performance of pipelines crossing fault ruptures. However, most investigations were not benchmarked against any experimental results [19–21], and design implications derived from these numerical analyses could be biased. Experiment data of pipe strains induced by fault ruptures are of importance to calibrate numerical tools. Researchers attempted to use simplified Winkler-based beam-on-spring analysis to characterize the pipe strains due to displacement-controlled boundaries, and satisfactory results could be obtained once the soil springs were revised from specifications defined in design guidelines [11,14,17,18,22]. Sophisticated continuum-based numerical approach was also employed to solve the pipe response under dip-slip fault offsets [12,22,23], but the associated computational cost could prevent its further application.

Analytical solutions are often preferred by practical engineers to solve problems in a short time span. The most widely recognized calculation model for the interaction between pipe and fault is to tackle the three-dimensional fault offset in isolation and solve the equations of equilibrium and compatibility of displacements. Newmark and Hall [24] originally proposed cable-like deflection profiles of pipelines under a strike-slip fault without considering the contribution of lateral soil resistance. The method was extended by Kennedy et al. [25], where soil resistance was taken into account. Wang and Yeh [26] pointed out the limitation of cable-like deformed pipe in neglecting the contribution of pipe's flexural stiffness, and initially partitioned the pipeline into four segments with two circular arcs proximal to the fault plane and two beams at the far ends. Advances of this type of analysis include the work of Trifonov and Cherniy [27], Karamitros et al. [28], Wang et al. [29] and Kouretzis et al. [30], where two curved pipe segments near the faulting zone were tackled using elastic-beam theory and two straight pipe segments in the far field were evaluated as beams-on-elastic foundations. Other types of analytical models have also been developed, such as the incorporation of a bending point based on the Kennedy's formulation into beam-shell analysis [31], the boundary integral method [32], the shape function method for beam-type deformed (S-shaped "shearing type") pipelines [20,21], and the empirical calculation from Winkler-based analyses [33]. Alternatively, Paolucci et al. [34] derived a "plastic hinge" approach to estimate the pipe strains under a strike-slip fault.

It should be emphasized that all existing analytical models need the input of empirical soil springs. It has been demonstrated from Winkler-based analyses that calculations using soil reaction models suggested in design guidelines [5–7] could overestimate the pipe strains under normal faults significantly, especially for pipes with low flexural stiffness [17,18,22]. Wijewickreme et al. [35] conducted a series of large-scale pullout tests on steel pipelines, and confirmed that design specifications could over- and under-predict axial force on pipes in loose and dense sand, respectively. Liu et al. [36] performed uplift tests on steel submarine pipelines and measured much softer force–displacement responses than design recommendations. Similar uplift tests were carried out on steel pipes by Wijewickreme et al. [37], and they obtained reasonably consistent results compared to calculations of Honegger and Nyman [7]. This was because the estimates of Honegger and Nyman [7] could under-predict the soil resistance by approximately 35% compared to other design suggestions [5,6]. Analyses of O'Rourke et al. [38] demonstrated that a reduction factor of 1/3 should be employed for the conventional bearing capacity approach presented in ASCE [6]. Therefore, all criticisms regarding empirical soil reaction models should be directly applicable to existing analytical solutions.

Fragility analysis is often conducted to assess the probability of exceedance of a specific performance limit state for structures. Recently, the integration technique has been used combining the geographic information system to provide a probabilistic map to optimize the management of pipeline networks [39–41]. However, this process can hardly take into account the variation of soil properties [42,43], which might result in misleading interpretation. Winkler-based numerical analysis has been used to generate a large number of data for fragility analysis of pipelines [44]. However, the calibration of the