Buried Pipeline Subjected to Ground Deformation and Seismic Landslide: A State-of-the-Art Review

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Abstract. Pipelines are commonly used for transporting different materials namely water, gas, sewage, and oil from one place to another. The different past earthquakes (1923 Kanto earthquake, 1971 San Fernando earthquake, 1994 Northridge earthquake, 2010 Chile earthquake) induced hazards such as landslide, fault movement, liquefaction, etc., resulting in the damage of buried pipelines. These hazards induced ground deformations are known as permanent ground deformation (PGD), and the deformation resulting from wave propagation is called transient ground deformation (TGD). Further, soil can move along or normal to the pipe axis, and accordingly, it can be further categorized as axial and transverse ground deformation respectively. Apart from seismic excitation, ground deformation and vibration can also be generated from other sources like pipe bursting, underground explosion etc. Failure of pipelines due to ground deformation can cause the source of firing, contamination to the environment, explosion, economic loss etc. Therefore, it is vital to design the buried pipeline incorporating the effect of possible ground movement on buried pipelines. Thus, the focus of the present review study is to understand the various possible patterns of ground deformation, estimation of additional forces on pipeline due to ground deformation, and their influence on the response of buried pipeline, which can be implemented in practice to carry out performance-based design of buried pipelines subjected to earthquake loadings.

Keywords: Buried Pipe, Ground Deformation, Seismic Landslide.

1 Introduction

Buried pipelines may be subjected to ground movement or vibration either resulting from earthquake induced hazards like fault movements [1-4], soil spreading [5-11], liquefaction [12-17], or pipe bursting induced ground movement [18-23], surrounding explosion [24-28], etc. Underground pipe failure may disrupt the whole pipe network and even be the source of a disaster based on the substance carried by the pipeline. Fig.1 shows some past failures of pipeline. Hence, it is pivotal to understand the response of buried pipeline under such kind of ground deformation or vibration. Pipe-soil system can be modelled using various available techniques such as beam on elastic foundation, shell model, plane-strain model, and Hybrid model [29]. Each model has its own merits and demerits. For instance, beam on spring foundation concept will not be able to capture the buckling and fracture phenomenon of the pipe. Still, the method has advantages in terms of less time-consuming, input parameters, and complexity. Hence, before performing a detailed continuum-based numerical or rigorous experimental study, beam on elastic foundation model can be used in the initial design stage. Further, Psyrras and Sextos [30] mentioned four types of mode of failure (such as shell-mode buckling, beam-mode buckling, tensile failure, and cross-section ovalization) of buried steel pipes under seismic loads. Shell-mode buckling is generally found for large diameter pipe buried at greater depth—such type of buckling induced from pure bending or compressive load. Beam-mode buckling is observed for small diameter pipes buried at shallow depth. Such bending occurs under compression. Pipes under tensile force lead to a tensile mode of failure. When pipe is subjected

(a) (b)

(c)

Fig. 1. (a) Buckling of steel pipe during 1971 Sanfernando earthquake (after Chenna et al. [31]) (b) Failure of pipe during 1999 Kocaeli Earthquake (after Chenna et al. [31]) and (c) Water leakage from pipe near IIT Bombay main building (3 June, 2019).

to bending stress, and it leads to the change of pipe diameter from circular to oval shape, it is called cross-section ovalization. The present study highlights past studies performed in the area of pipe subjected to ground deformation, mainly focused on some of the past analytical and semi-analytical works to estimate the response of pipe subjected to ground deformation.

2 Pipe Under Horizontal Transverse Ground Deformation

The horizontal transverse ground deformation patterns can be divided in two ways such as abrupt horizontal transverse ground deformation and spatially distributed horizontal transverse ground deformation [32,33]. A typical representation of both types of ground deformation patterns are shown in Fig.2.

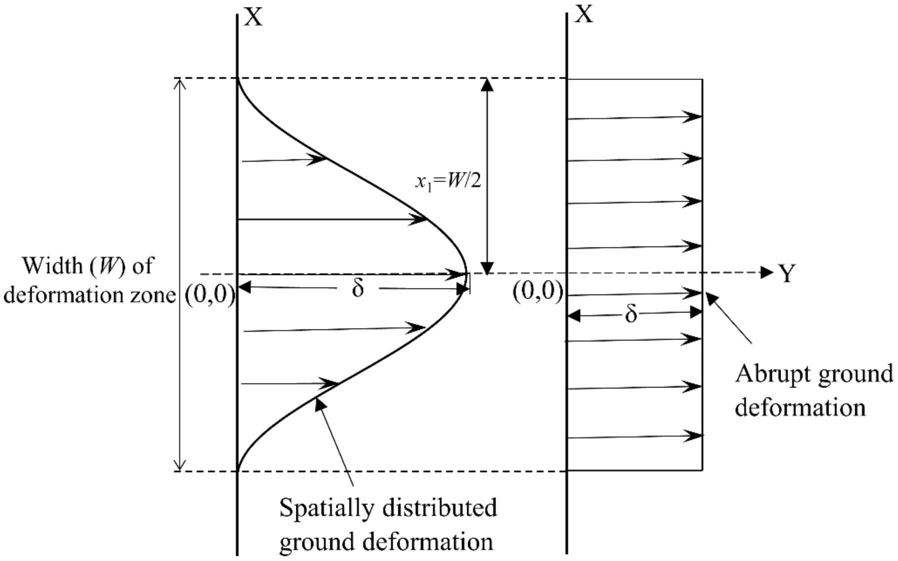


Fig. 2. Spatially distributed and abrupt horizontal transverse ground deformation.

O'Rourke and Lane [12] used an improved beta function to represent lateral ground deformation pattern obtained from liquefaction. The effect of this lateral ground movement pattern on underground pipeline was obtained by UNIPIP coding [34]. Miyajima and Kitaura [35] investigated the influence of transverse permanent ground deformation on buried pipeline through a theoretical approach based on the theory of beam on spring foundation without considering the axial tension of the pipe. Later on, Chaudhuri and Choudhury [36] presented a semi-analytical approach adopting the pipe axial tension for estimating the response of buried pipe under lateral ground deformation. A spatially distributed cosine function was used to represent the pattern of lateral ground deformation. The soil and pipe were idealized as single parameter Winkler spring foundation and conventional Euler Bernoulli’s beam respectively. The study was further extended by Chaudhuri and Choudhury [37] considering pipe as Timoshenko beam to take care of the effect of transverse shear deformation and soil as Winkler springs along with the shear interaction between individual springs. The study also used the cosine function to represent the ground deformation pattern (w_g) as shown in equation (1) (modified after O’Rourke [38])

$$w_g = \frac{\delta}{2}\left(1 + \cos\frac{\pi x}{x_1}\right) \tag{1}$$

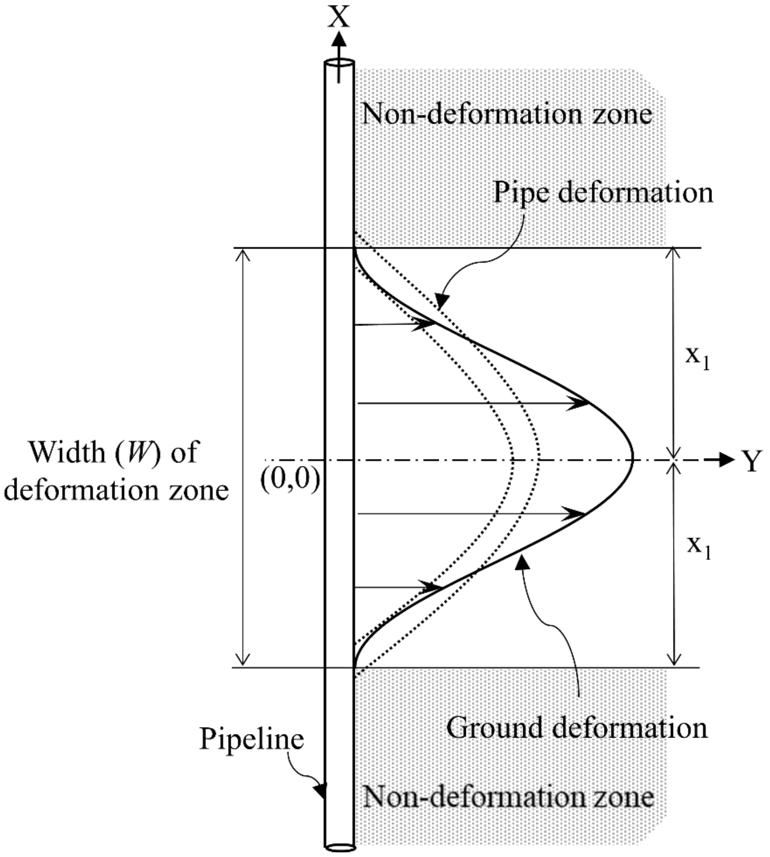


Fig. 3. Pipe deformation under spatially distributed lateral ground deformation (modified after Chaudhuri and Choudhury [37]).

Chaudhuri and Choudhury [37] assumed that the ground deformation pattern is symmetric (refer Figs.2-3). Hence, only half of the model is considered to obtain the governing differential equations and their corresponding solutions. The pictorial representation of the deformation pattern of pipe and soil under spatially distributed lateral ground deformation is shown in Fig.3. Axial resistance within the ground deformation zone was neglected because the resistance against pipe deformation will mainly be provided by transverse soil springs in the deformation zone. However, in the non-deformation area, both the axial and transverse resistance were taken into account. ALA guidelines [39] were used to model the Winkler spring stiffness and axial soil resistance. The plasticity part of the bi-linear soil-springs were not considered in the study. ALA guidelines provide the following expressions to model the lateral soil springs.

$$P_u = N_{ch} cD + N_{qh} \bar{\gamma} HD \tag{2}$$

$$N_{ch} = a + bx + \frac{c}{(x+1)^2} + \frac{d}{(x+1)^3} \le 9 \tag{3}$$

$$N_{qh} = a + b(x) + c(x^2) + d(x^3) + e(x^4) \tag{4}$$

Where, P_u is the peak soil force in the lateral direction per unit length of the pipe. N_{ch} and N_{qh} are the lateral bearing capacity factors for clay and sand respectively. c is the cohesion of soil, D is the exterior dia of the pipe, H is the burial depth up to pipe center, and $\bar{\gamma}$ is the effective unit weight of soil. The value of x depends on the ratio of H/D. a, b, c, d, and e depend on the soil friction angle mentioned by ALA guidelines. Displacement at P_u is $0.04\ (H+D/2) \le 0.10D$ to $0.15D$.

Further, soil force in the axial direction can be evaluated using the following expressions [39]

$$T_u = \pi D \alpha c + \pi DH \bar{\gamma} \frac{1+K_0}{2} \tan\delta \tag{5}$$

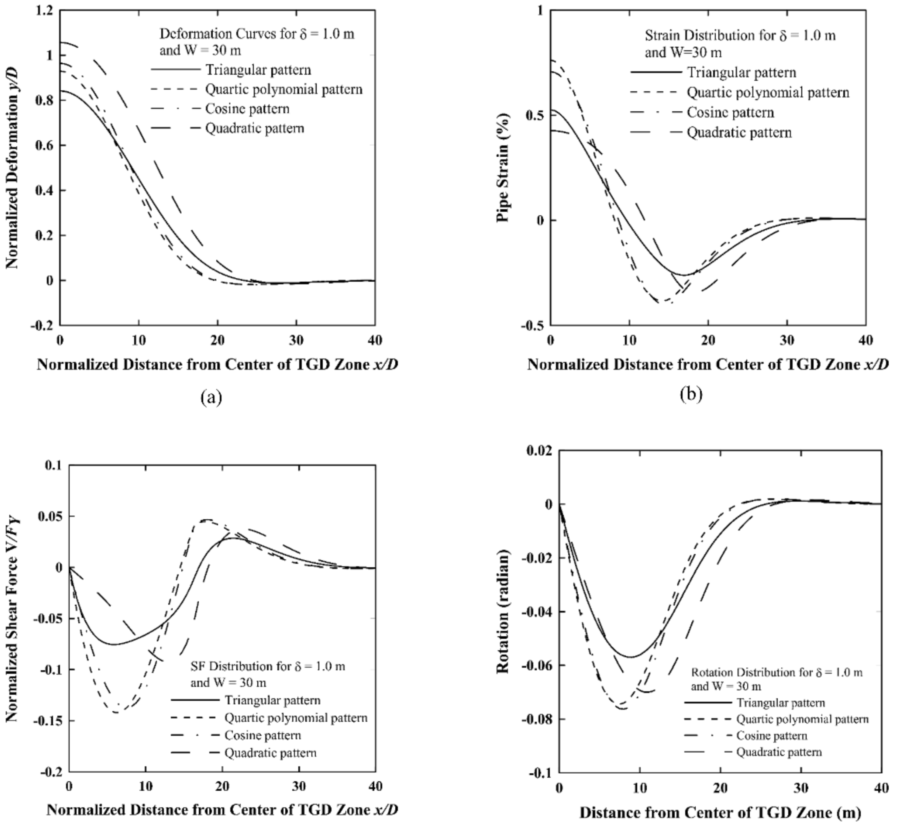
$$\alpha = 0.608 - 0.123c - \frac{0.274}{c^2+1} + \frac{0.695}{c^3+1} \tag{6}$$

Where, K_0 is the earth pressure coefficient at rest condition, α is the adhesion factor, δ is the interface friction angle for pipe and soil. Displacement at T_u is 10 mm, 8mm, 5mm, and 3mm for soft clay, stiff clay, loose sand, and dense sand respectively.

The governing differential equations of pipe deflection (w) and pipe rotation (φ) considering pipe as Timoshenko beam subjected to ground deformation as shown in Fig.3 can be represented as follows [37]:

$$D' \frac{d^4 w}{dx^4} - \frac{D'}{C} \frac{d^2 q(x)}{dx^2} - T \frac{d^2 w}{dx^2} + q(x) = 0 \tag{7}$$

$$\varphi = \frac{D'}{C}\frac{d^3w}{dx^3} + \frac{dw}{dx} - \frac{D'}{C^2}\frac{dq(x)}{dx} - \frac{T}{C}\frac{dw}{dx} \tag{8}$$



(a) (b)

(c) (d)

Fig. 4. (a)Normalized deformation of pipe (b) Pipe strain in percentage (c) Normalized shear force, and (d) Pipe rotation in radian, distribution for various shapes of ground deformation (after Chaudhuri and Choudhury [37]).

Where, *D′* is the bending stiffness of pipe, *C* is the shear stiffness of pipe, *T* is the pipe tension, and q(*x*) is the soil pressure acting on the pipe. From the end boundary conditions and continuity conditions between the deformation and normal zone of Fig.3, the complete solution of prior mentioned differential equations is obtained. From the detailed parametric study, it was noticed that after a specific range of peak ground deformation, the maximum pipe deformation started reducing with respect to peak ground deformation. Further, beyond the ground deformation zone pipe deformation was also observed up to a certain extent. Pipe stability against such lateral ground movement can be increased by reducing pipe diameter, increasing pipe wall thickness, or providing loose soil around the pipe. Further, along with the cosine pattern of ground deformation, additional three types of pattern namely triangular, quartic polynomial, and quadratic were taken for the semi-analytical study. It was recognized that pipe responses change substantially with varying the expected shape of ground deformation, as depicted in Fig.4.

3 Pipeline Under Seismic Landslide

Landslide is under the category of permanent ground deformation (PGD) [30]. Zheng et al. [40] mentioned two accidents of buried pipeline in the landslide area in Zhejiang province of China (Yuyao city and Ningbo city) and failure segment of buried pipeline is detected by electromagnetic induction. Field investigation shows deflection is non-uniform and mainly in the horizontal direction. The non-uniform distribution of horizontal deflection is close to the quartic polynomial curve. Zheng et al. [40] and Luo et al. [41] carried out FEM-based numerical analysis to investigate the influence of seismic landslide on buried pipeline. In the numerical analysis, a quartic polynomial distribution of lateral displacement was applied on the soil to simulate the seismic landslide. The piping system is deformed under the given ground-induced actions. Ma et al. [42] and Zheng et al. [40] performed the numerical analysis considering soil as linear-elastic material whereas, Luo et al. [41] adopted Drucker-Prager model for soil to simulate seismic landslide problem. Later on, Chaudhuri and Choudhury [43] proposed a theoretical solution to obtain the impact of seismic landslide on buried pipeline. In theoretical solution, pipe was assumed as conventional Euler Bernoulli's beam and soil was represented by Winkler foundation. Following quartic polynomial function was used to simulate the pattern of ground deformation induced by seismic landslide (modified after Luo et al. [41]):

$$w_g = \frac{2\delta}{x_1^2}(x - x_1)^2 - \frac{\delta}{x_1^4}(x - x_1)^4 \qquad (0 \le x \le x_1) \quad (9)$$

Chaudhuri and Choudhury [43] also performed numerical analysis using FEM based program Abaqus 3D. In the numerical analysis, block pattern ground deformation was simulated and obtained the impact of the ground deformation on the buried pipeline. A typical 3D model of a soil-pipe system subjected to block pattern ground deformation and pipe response is shown in Fig.5 (a)-(c).

4 Pipe Under Static Pipe Bursting Underneath

Nowadays, the static pipe bursting technique gained popularity over conventional cut and cover method for laying the new pipe or replacing the existing one due to the involvement of minimum excavation and disturbance on the ground surface during pipe bursting operation. During this operation, an outward force will act surrounding the expander (which is used for pipe bursting operation) and hence ground heave will generate. Pipe bursting induced ground movement may have severe effects on the

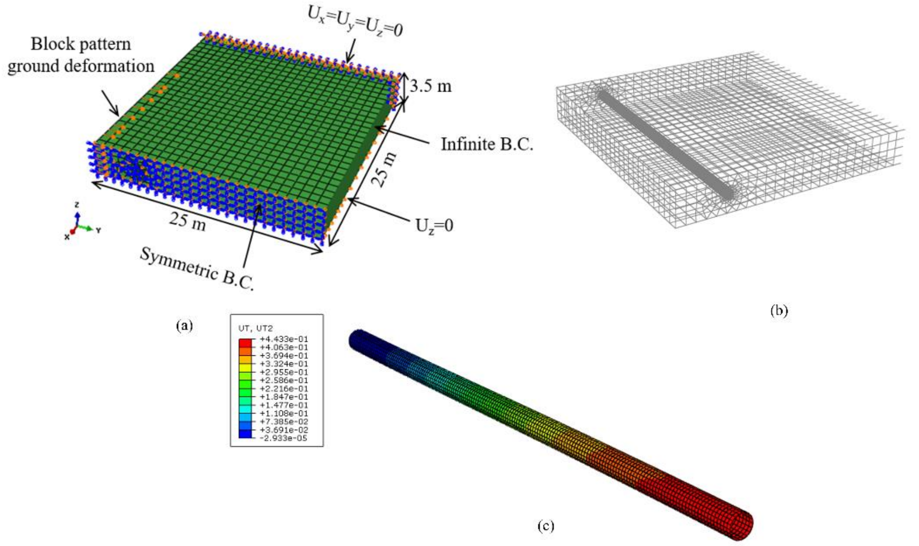


Fig. 5. Finite element model of soil-pipe system with (a) Boundary conditions (b) Mesh discretization, and (c) Deformed buried pipeline

surrounding existing structures, if any. Cholewa et al. [21] performed a laboratoty experiment, where a polyethylene pipe was used to replace an existing unreinforced concrete pipe using static pipe bursting technique. Another PVC (Polyvinyl chloride) pipe was laid in cross-sectional direction above the concrete pipe. During pipe bursting process, the response of surrounding PVC pipe in terms of pipe strain and displacement were recorded. Later on, Shi et al. [23] performed prior mentioned study through a simplified numerical analysis using FEM based Abaqus program. In the numerical analysis, pipe and soil were modelled by hollow beam and PSI (pipe-soil interaction) elements respectively. From literature, it is realized that pipe bursting induced upward ground heave can be well simulated by a Gaussian function [20,21]. Chaudhuri and Choudhury [44] investigated the behaviour of an adjacent buried pipe exposed to pipe bursting underneath through an analytical study. The mathematical formulations were proposed considering soil as Pasternak foundation and adjacent pipe as both Bernoulli's beam and Timoshenko beam. Fig.6 replicates the simplified assumptions in the analytical model. The Gaussian error function was used to simulate the ground heave pattern obtained from static pipe bursting operation. The following error function was used in the study:

$$S(x) = S_{\max} \exp\left[-\frac{x^2}{2(\frac{i}{\sin\theta})^2} \right] \tag{10}$$

Where, i and θ are the distance from the pipe center to the inflection point of the error function and the intersection angle between the pipes respectively.

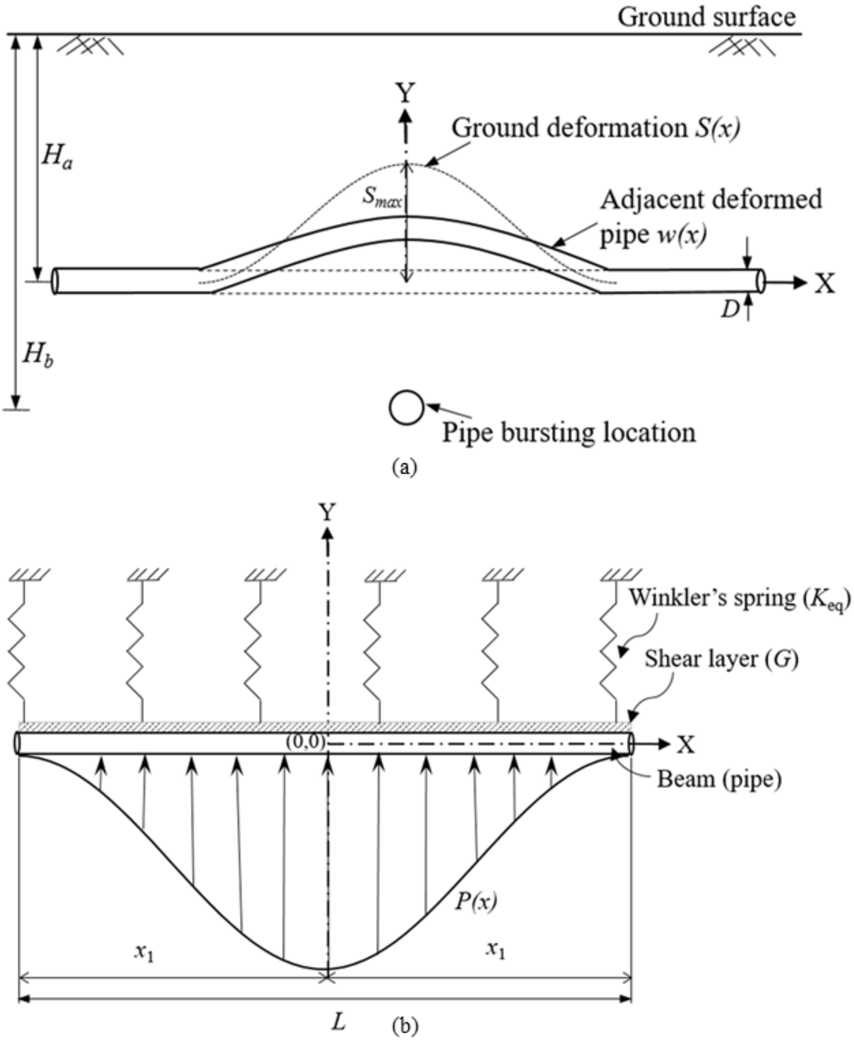


Fig. 6. (a) Adjacent buried pipe exposed to pipe bursting underneath (b) Beam-spring model (modified after Chaudhuri and Choudhury [44]).

The additional load $P(x)$ acting on the neighboring pipe owing to pipe bursting underneath can be calculated as:

$$P(x) = K_{eq}S(x) - G\frac{d^2}{dx^2}S(x) \tag{11}$$

Chaudhuri and Choudhury [44] found that the closed-form solution built on Timoshenko beam formulation provides more appropriate results compared to Euler Bernoulli's beam formulation from a comparative study as shown in Fig.7. Further, it was noticed that for flexible pipe, pipe will move along the ground movement and for rigid pipe, pipe movement is significantly less but moment is high. For the particular case adopted by Shi et al. [23] and Chaudhuri and Choudhury [44], Maximum pipe curvature was recorded at 30° and 35° intersection angles respectively.

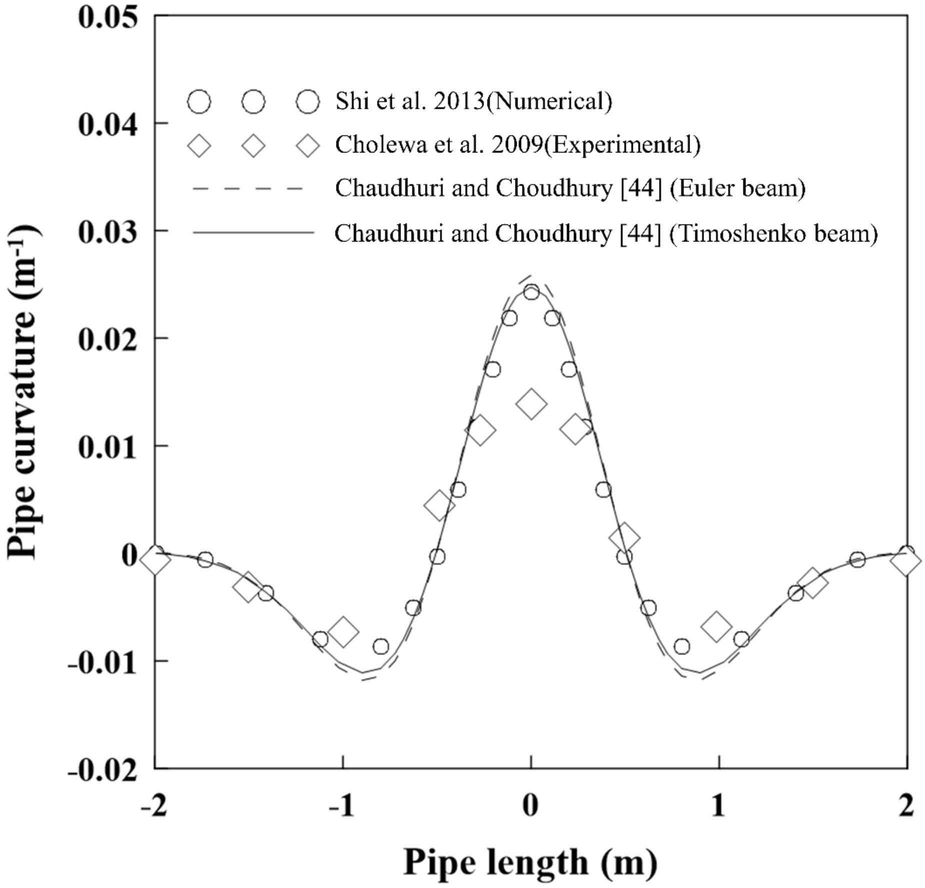


Fig. 7. Comparison of pipe curvature distribution (modified after Chaudhuri and Choudhury [44]).

Hence, it is essential to estimate the influence of intersection angles between the pipes on adjacent pipe's response.

5 Conclusions

The current study highlights past studies performed on burier pipelines subjected to ground deformation induced from various sources. However, rigorous experimental works or three-dimensional continuum based numerical analysis provides more accurate results and insights of the problem than simplified mathematical analysis based on the beam-springs model. But from the economic point of view, mathematical solution has advantages as the method involves fewer input parameters, less complexity and less time consuming and can provide reasonable results with moderate accuracy. Hence, for the initial stage of the design mathematical solution can be used to get quick and reliable results. In the beam-springs model, it is better to model the pipe as Timoshenko beam over Euler Bernoulli's beam and soil as two-parameter model instead of single parameter Winkler's model. Timoshenko beam can capture the shear behaviour of the pipeline and two-parameter foundation provides shear interaction between the individual Winkler springs. To estimate the response of pipe subjected to ground deformation, it is important to identify the peak ground deformation, width of deformation, and deformation pattern. Pipe stability against ground movement can be increased by providing loose backfill, or rising the pipe wall thickness. For the case of the adjacent buried pipe subjected to static pipe bursting underneath, the critical intersection angle is not always 90°. It can vary with the input parameters. The present review study shows that the analytical works can further be extended by incorporating the plasticity and non-linearity of pipe and soil material.

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