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Research Paper

Ovalization of steel energy pipelines buried in saturated sands during ground deformations

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ABSTRACT

Cross-sectional ovalization of buried steel pipes subjected to bending moment induced by end displacements is discussed. A three dimensional finite element analysis was conducted employing Abaqus/CAE. The pipe was simulated using 3D shell elements while the saturated sand soil medium was simulated by employing discrete nonlinear springs along the pipeline. The effects of normalized burial depth (H/D), diameter to wall thickness ratio (D/t), sand density and level of the internal pressure on the ovalization are investigated, and resulting ovalization distribution with respect to bending moment at critical sections is presented. The results of this study enable simple one dimensional finite element models to consider geometrical cross-sectional nonlinearities in the analysis of buried pipelines.

1. Introduction and literature review

The various types of pipelines used by the oil industry are considered as tubular structures. They normally operate under external pressures exerted by the backfill materials or by the sea water in offshore pipeline, and internal pressures generated by the transported liquid and gas products. In addition, buried pipelines are subjected to transversal and longitudinal forces induced by seismic waves and by various types of ground displacement such as downslope or lateral movements, vertical settling, fault rupturing, thawing and frost heaving in northern regions [1–3]. The pipelines should therefore be designed to withstand resulting pressures, axial/shear forces and bending moments of different origins.

Due to their importance and unique mechanical behavior under various loads, structural response of the tubes under bending has been the focus of many research studies. Ovalization and bifurcation instabilities are the most important mechanical response features of the tubular structural members under flexural loads. Ovalization is a geometric nonlinearity that changes the circular cross section of a tube to oval shape. It is caused by vertical components of tensile and compressive flexural stresses in the cross section resulting in reduction of the bending capacity due to transverse distortion. The negative effect of ovalization on the bending capacity of elastic cylindrical shells was first introduced by Brazier [4] and is sometimes called "Brazier effect". Ades [5] expanded the previous work to long elastic–plastic tubes undergoing uniform ovalization and provided nonlinear moment–curvature relationship. The ovalization due to bending is an important part of the pipe response to flexural loads and should be considered in the design of new pipelines and vulnerability assessment of the existing ones. The Canadian standard for oil and gas pipeline systems (CSA Z662-03) [6] limits flattening caused by ovalization to a critical value to be determined by "valid analysis methods or physical tests or both". Also, the American Lifelines Alliance (ALA) [7] considers the maximum allowable ovalization factor to be 15%.

Bifurcation instability, on the other hand, refers to local buckling in compressional zones that develops wave-type wrinkles. Both instabilities prevent thin-walled tubular members from reaching the ultimate theoretical bending capacity. Studies have shown that the diameter to thickness ratio (D/t) is a key parameter in determining flexural capacity of the tubes [8,9]. Kim [10] approximated plastic buckling of the pipes subjected to bending by an axisymmetric plastic bifurcation analysis under uniform axial compression combined with circumferential stresses caused by the internal pressure. It was concluded that the critical buckling strains increase with the increase of the circumferential stresses.

The effect of internal pressure on flexural response of in-air pipelines was studied for the first time by Bouwkamp and Stephen [11]. Seven 48-inch-diameter pipes ($D/t = 104$ and 85) with different internal pressures were subjected to four-point bending tests to evaluate the local instabilities and the ultimate rupture. The study revealed that highly internally pressurized pipes show more flexibility under bending. Different local buckling

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mode shapes were observed: pipes under low internal pressure exhibit an inward diamond-shaped deformation, whereas pipes under high internal pressure tend to buckle outward with a bulged shape. The authors also observed that local buckling occurred at inelastic strains in all tests.

Gresnigt [12] presented a number of formulas for assessing the bending capacity of buried steel pressurized pipelines in the settlement areas by applying the plastic theory. The analytical results were supported by few small-scale experiments. Also, a critical strain formula was presented based on the available test results from a number of studies. The proposed critical strain formula was shown to give reasonable results on the conservative side. Currently, this formula is suggested by the ALA and with few minor modifications by CAN-CSA Z662.

Murray [13] conducted tests on pipes with $D/t = 64$ and 51 under combined axial force, internal pressure and bending moment. It was shown that the finite element method could successfully capture the local buckling of the tested pipes under the mentioned combined loading. The effect of normalized length (L/D) on the mechanical response was also investigated. Although the aim of the research was the study of behavior of buried pipelines, the effect of soil confinement was neither considered in the experiments nor in the finite element models.

More recently, Schaumann et al. [14] conducted a series of scale model four-point bending experiments on steel pipes with $D/t = 132$ and confirmed conclusions of previous studies regarding the effect of internal pressure. They emphasized the stabilizing effect of the internal pressure that leads to higher critical buckling strains.

Houliara and Karamanos [15] used a special-purpose nonlinear finite element technique to predict pre- and post-buckling equilibrium path of the elastic thin-walled tubes under combined bending and internal/external pressure. They also developed a simplified closed-form solution for bifurcation that accounts for pressure and initial ovality and curvature. The behavior of a steel pipe with $D/t = 52$ subjected to internal pressure and bending moment was also investigated experimentally and numerically by Limam et al. [16]. The authors focused on the effect of internal pressure on ovalization, ultimate bending capacity and critical buckling strains.

Konuk et al. [17] conducted lab experiments on the flexural behavior of unpressurized buried pipes. They displaced laterally the ends of pipes buried in dense sand by means of two actuators at a low rate. Two D/t ratios of 43 and 64 were considered. The measured bending strains were substituted into BS 8010 [18] formula, which relates ovalization to mechanical and geometrical properties of the pipe, bending strain and pressure and the results were compared to the measured ovalization factors. An appreciable discrepancy was observed for tested buried pipes, in contrast to some studies that showed relatively good agreement between predictions of the BS 8010 formula and real behavior of the above-ground pipes. The authors attributed this difference to the confining role of the soil.

Mahdavi et al. [19] developed a three dimensional continuum finite element model in Abaqus/Standard which included soil and pipeline. The model was first calibrated against the results of Konuk et al. [17]. A parametric study was conducted afterward to understand the effect of critical parameters on the local buckling of pipes buried in firm clayey soil. An empirical equation for the critical buckling strain was proposed based on the obtained numerical results.

As it can be seen from the above review, numerous studies have been conducted in the past decades to explain the flexural behavior of pipelines. Some of them included the effect of boundary conditions, residual stresses, and experimentation method together with the assemblage and type of used materials. However, only a few of them considered the combined effect of soil and internal pressure on the response. In addition, the published results exhibit considerable variations due to the number of different parameters that influence the response, and there is no consensus on the validity and reliability of the available formulas for different loading conditions.

This study aims to determine typical non-dimensional relationships between the bending moment and resulting ovalization for buried pipes by considering effect of parameters such as normalized burial depth (H/D), diameter to wall thickness ratio (D/t), sand density and level of the internal pressure. The finite element analysis which is commonly used in practice was applied with three-dimensional (3D) shell elements since they are particularly suitable to consider the effects of internal pressure, geometric nonlinearities of the cross section and local buckling instabilities.

2. Numerical model

2.1. Soil spring representation

The ALA suggested the use of perfectly elastoplastic springs to represent the soil response of the soil–pipe systems in the three directions (longitudinal, horizontal and vertical) [7]. (Fig. 1) These relationships were derived based on experimental and theoretical studies performed in the past decades on buried pipelines and other similar geotechnical structures such as piles and anchor plates.

The nonlinear force–displacement spring curves are widely used in the design of buried pipelines and are employed in the present study. These springs can be added to beam or shell elements that represent pipelines [20]. In this study, the horizontal and vertical end displacements were considered independently and the stiffness of the soil springs in each cross-section was assumed to be distributed at the three respective semicircles (Fig. 2). As an example, the top springs were distributed over the nodes of the top semicircle and their stiffness was determined based on the projection of their tributary area on a plane perpendicular to the direction of displacement. The same method was applied to the side and bottom springs. Since the loading was monotonic, it was not

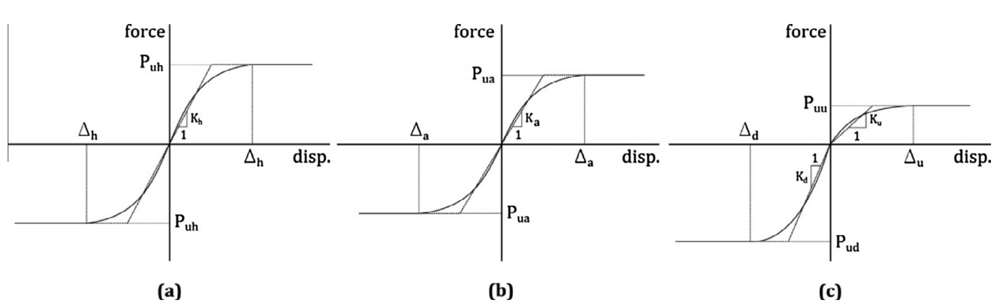

Fig. 1. Bilinear force–displacement of soil in (a) horizontal, (b) axial and (c) vertical (upward and downward) directions. [7].