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Ductile failure analysis and crack behavior of X65 buried pipes using extended finite element method

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ABSTRACT

This paper aims to study the ductile fracture mechanism of API X65 buried pipes including crack initiation and propagation using the extended finite element method (XFEM). First, the crack evolution histories of X65 specimens with initial crack-like flaws during tensile and three-point bending tests are illustrated, and the numerical results are compared with experimental data. In addition, effects of different crack configurations, damage initiation and evolution criteria are investigated. Second, the burst processes of straight pipes with initial gouge flaws are presented, and the FE results are compared with assessment in related standards and experiments. Finally, the crack onset and growth of buried pipes due to deflection arising from landslide movements are predicted, and the numerical results are compared with previous study. Particularly, the internal pressure, wall thickness, and soil properties on crack behavior and limit load-bearing ability are investigated. This paper provides a fundamental support for the integrity assessment and safety evaluation of buried pipes.

1. Introduction

With the acceleration of global industrialization, demand for resources such as oil and natural gas grows rapidly. At present, long-distance buried pipelines become a significant method to transport these resources from remote area. Because these pipelines have to pass through complex areas, they will inevitably meet potential threats from surrounding environment. In recent years, safety problems of buried pipes that are subjected to permanent ground deformations (PGD) such as fault movements and landslides have aroused increasing attention since related accidents occurred frequently. Those pipes are often subjected to excessively plastic deformations, and the high stress level in the local areas can easily result in local instability or buckling at the critical regions of underground pipes.

Already, the failure analysis and safety evaluation of buried pipes triggered by PGD activities have been studied for many years since the first research was made by Newmark et al. [1] in 1975. After then, many scholars including Wang et al. [2], Kennedy et al. [3] and Trifonov et al. [4,5] proposed their respective methods to analyze the mechanical responses of buried pipes that were mainly subjected to fault movements arising from earthquakes. Our previous papers including Liu et al. [6] and Zheng et al. [7] used finite element method to predict the load-bearing ability of underground pipes due to large offset displacement during landslide process. Although most of these studies indicated the ductile fracture was one of the most

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Nomenclature

a	crack depth
D_i, D_o	inner diameter, outer diameter
D/t ratio	ratio of diameter to thickness
E	Young's modulus
G	energy release rate
G_{IC} G_{IIC} G_{IIIC}	critical energy release rate of three fracture modes
G_C	critical equivalent energy release rate based on mixed-mode criteria
l	crack length
P_b	burst pressure
P_i	internal pressure
S_u	tensile strength
S_y	yield strength
t	wall thickness
U_{max}	maximum deflection displacement of buried pipe along the axial direction
w	height of specimens in tensile and three-point bending tests
σ_{maxps}	maximum principal stress in damage initiation criterion

significant failure modes when buried pipes developed excessive tensile deformations in the local regions, the damage evolution of pipeline materials was not considered yet. Particularly, since the solutions of these papers were based on classical elastic–plastic mechanics, the fracture histories including crack onset and growth could not be demonstrated, either.

So far, many scholars have realized the ductile failure mechanism of buried pipes is quite necessary to study because these materials normally have great toughness. Oh and his group [8–11] have done a lot of work to demonstrate ductile failure histories of different pipeline materials through tensile and 3-point bending tests using the GTN model [12]. However, the solutions of these papers were based on damage mechanics, the complex formulas and meaningless parameters restrained the development of this method. Recently, the elasto-plastic fracture mechanics, which can timely record the damage evolution history, has been widely used to simulate the ductile fracture procedure including crack initiation and propagation. Nowadays, the Cohesive Zone Method (CMZ), Virtual Crack Closure Technique (VCCT) and eXtended Finite Element Method (XFEM) are the three most representative methods. Since XFEM can simulate discrete crack initiation and propagation along arbitrary paths (i.e. the crack can cut through the elements) without re-meshing the crack-tip domain, it becomes a very effective way to study the ductile fracture mechanism of buried pipes even subjected to actually complex loads such as landslide actions. Our previous paper [13] preliminarily used XFEM to illustrate the fracture history of buried pipes during landslide process, yet the soil in that paper was still assumed as linear-elastic which reduces prediction accuracy. Furthermore, the effects of some significant factors including damage initiation and evolution criteria, soil properties on the crack behavior were not investigated, either.

Therefore, this paper focuses on studying the ductile fracture mechanism and crack evolution history of buried pipes subjected to complex loads using XFEM. First, the crack propagation property of X65 specimens with initial crack-like flaws during tensile and three-point bending tests are demonstrated, and effects of different crack configurations, damage initiation and evolution criteria are discussed. Second, the burst histories of buried pipes with initial gouge flaws are studied, and the results are compared with related standards and experiments. Finally, the crack onset and growth of buried pipes due to deflection arising from landslide actions are predicted, and the numerical results are compared with previous study. In this paper, the mechanical property of surrounding soil is employed by Drucker–Prague hardening model.

2. Extended finite element method

Compared to the traditional FE method, two additional functions are enriched in the XFEM solution space. One is discontinuous function that reflects the displacement jump across the crack surface, the other is near-tip asymptotic function that captures the singularity in the neighborhood of the crack tip field [14]. The XFEM displacement function can be given by:

$$u = \sum_{I=1}^{N} N_I(x)\left[u_I + H(x)a_I + \sum_{\alpha=1}^{4} F_\alpha(x) b_I^\alpha\right] \quad (1)$$

where $N_I(x)$ is the general nodal shape function. In the right-hand side, the first term u_I is the general nodal displacement vector that is applicable to all the elements; The second term is used only for the elements that are cut by the crack surfaces, where $H(x)$ is the discontinuous jump function, a_I is the associated freedom vector; The third term is used only for the elements that are cut by the crack tip, where $F_a(x)$ is the elastic asymptotic crack-tip function, b_I^α is the associated enriched freedom vector. The discontinuous jump function $H(x)$ across the crack surfaces is given by