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Buckling failure mode analysis of buried X80 steel gas pipeline under reverse fault displacement

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A B S T R A C T

High strength steel pipeline is widely used in long distance transportation of natural gas. These pipelines are vulnerable under active faults in strong seismic areas. The buckling failure modes of high strength X80 gas pipeline crossing reverse fault were analyzed systematically in this paper. Based on the nonlinear finite element method, a pipe-elbow hybrid model was developed for buckling failure analysis of X80 steel pipeline under reverse fault displacement. The pipe soil interaction relationship was simulated by a series of elastic-plastic soil springs. The nonlinearity of pipe material and large deformation were also considered. The non-linear stabilization algorithm was selected due to the convergence of the numerical model. Engineering parameters used in the Second West to East Gas Pipeline in China were selected in this study. Typical features for beam buckling and local buckling failure in the proposed numerical model were derived. Based on a series of parametric studies, the influences of the fault displacement, fault dip angle, pipe wall thickness, buried depth of pipe and soil conditions on the buckling failure modes were discussed in detail. The proposed methodology can be referenced for failure analysis and strength evaluation of pipelines subjected to reverse fault displacement.
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1. Introduction

Buried steel pipeline is a main option for long distance transportation of natural gas. In recent years, several large diameter and high pressure pipelines, which are applied for long distance transportation, have been constructed in China, such as the West to East Gas Pipelines. The complicated geological environment around these pipelines makes them vulnerable by a series of nature geological disasters. Active fault is one of the most dangerous hazards [1]. Fault displacements will cause large axial and bending strain in the pipe, probably resulting in rupture and buckling failure of pipelines.

Newmark [2] and Kennedy [3] did some pioneering work for the mechanical analysis of pipeline under fault displacement. Wang and Yeh [4], Karamitros et al. [5], and Trifonov [6] proposed some enhanced analytical strain analysis methods. Though various analytical methods have been proposed above, they are all based on several assumptions and can only calculate the tensile strain.

Numerical simulation is the most effective tool to analyze the pipeline under compression. Takada [7] developed a beam-shell hybrid finite element model to study the relationship between the maximum strain and bent angle. A. W. Liu [8] proposed an

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equal boundary shell model to decrease the model dimension. Karamitros et al. [9] improved Takada's hybrid model by simulating pipe soil interaction with a series of soil springs. M. Liu [10] conducted some case studies of pipelines under fault displacement with pipe soil interaction simulated by soil springs. Xie [11] proved that both pipe and shell element model can predict reliable pipe strain by comparing with experimental results derived by DaHa [12]. X. B. Liu [13,14] proposed a strain prediction model for X80 pipeline crossing strike-slip fault under compression and bending based on numerical results.

More recently, some advanced numerical simulation tools have been used recently in the study of complex mechanical behavior of buried steel pipelines crossing active faults. Vazouras et al. [15,16,17] studied the local buckling failure and strain reaction of X65 and X80 steel pipeline under strike-slip fault displacement. Trifonv et al. [18] developed a 3D numerical model with two different types of fault representation for stress and strain analysis. Uckan et al. [19] derived the critical length of pipeline under strike-slip fault with interaction angle of 90°. Zhang J. [20,21]. studied the local buckling behavior of X65 steel pipeline under strike-slip and reverse fault displacement. Zhao L. et al. [22] discussed the failure modes of X60 steel pipelines under reverse fault displacement with different dip angles. Joshi et al. [23] studied the beam buckling failure of X65 steel pipeline. Although the buckling behavior of steel pipelines has been discussed more or less in above researches, none of them considered the buckling behavior of high strength X80 steel pipelines under reverse fault displacement, which is commonly faced in actual engineering cases [24].

To fill this gap, buckling failure modes of high strength X80 steel gas pipeline under reverse fault was studied systematically in this paper. Typical engineering parameters used in the Second West to East Gas Pipeline in China, the longest X80 gas pipeline in the world, were adopted. A suitable hybrid finite element model with high efficiency algorithm was established for buckling analysis. Typical features for both beam and local buckling of X80 steel pipeline were investigated. The relationships between the failure modes were obtained. What's more, effects of the dip angle, pipe wall thickness, soil properties and buried depth on the failure modes of X80 pipeline were derived quantitatively. This study can provide a reference for the design and safety evaluation for high strength gas pipelines under reverse fault displacement.

2. Pipe material property

The stress-strain relationship of high strength X80 pipe steel used in the Second West to East Gas Pipeline is round-house type and has no plastic plateau [25]. The elasto-plasticity of the pipe steel was described by Ramberg-Osgood model [26], and the expression of this relationship is as follows.

$$\varepsilon = \frac{\sigma}{E}\left[1 + \frac{\alpha}{1+r}\left(\frac{\sigma}{\sigma_s}\right)^r\right] \tag{1}$$

where, E is initial elastic modulus; ε is strain; σ is stress, MPa; σ_S is yield stress; α and r are parameters of the Ramberg-Osgood model. For X80 pipe steel used in the Second West to East Gas Pipeline Project, $E = 2.07 \times 10^6$ MPa, $\sigma_S = 530$ MPa, $\alpha = 15.94$, $r = 15.95$. The true stress-strain curve is shown in Fig. 1.

3. Pipe-soil interaction model

Buried gas pipelines are surrounded by soils, and the pipe soil interaction relationship can be simulated by discrete nonlinear soil springs in the directions of axial, lateral, and vertical, as shown in Fig. 2. Based on numerous experiment studies and engineering data, ALA-ASCE guideline [27] proposed the force-displacement relationship of soil springs for buried steel pipelines, in which all the force-displacement relationships are elastic-perfectly plastic and can be defined by two parameters, i.e., the maximum soil

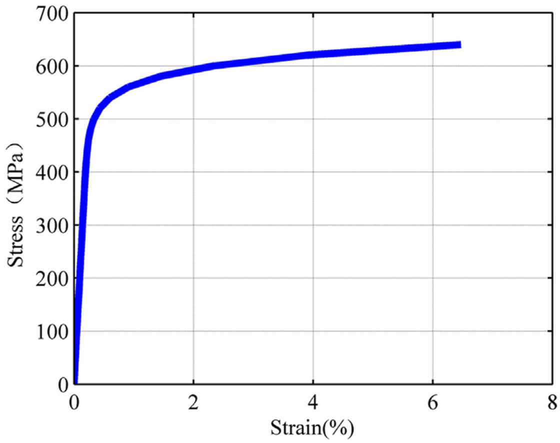

Fig. 1. True stress-strain curve for X80 pipe steel of the Second West to East Gas Pipeline Project in China.

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