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Mechanical behavior of pipelines subjecting to horizontal landslides using a new finite element model with equivalent boundary springs

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ABSTRACT

A new finite element model was developed to analyze the mechanical behavior of pipelines subjecting to horizontal landslides, where equivalent boundary springs were used at the pipeline end. The equivalent boundary spring was used to simulate the interaction of the pipeline-soil outside the model. More specially, an analytical method was derived to calculate the stiffness coefficient of the equivalent boundary spring. The new finite element model was validated by comparing the results of the axial displacement and strain to the referred model, with minor deviations of less than 5.53%. Meanwhile, the effects of different parameters on the mechanical responses of pipelines were discussed, including the friction coefficient, the landslide displacement, the landslide width and the constraint condition at the pipeline end. The results show that larger landslide displacements lead to larger axial displacements and strains of pipelines. Also, larger kinetic friction coefficients can decrease the axial displacement and strain, and constraint conditions at pipeline ends have an impact on the axial displacement and the axial strain.

1. Introduction

Currently, to reduce the length of the pipeline route and the engineering cost, a substantial amount of gas-main pipelines are laid in the high risk areas of landslides [1–3]. In such case, some accidents of buried pipelines maybe occurred due to the large impact of horizontal landslides, causing excessive plastic deformations and local collapses at critical locations [4–7].

Under the impact of landslides, the mechanical behavior of pipelines can be obtained by analytical methods and finite element methods. Analytical models were developed by many researchers, due to a simple and fast solution. Parker and coworkers [8] developed an analytical model to evaluate the stress and strain of pipelines under the large impact of landslides. Randolph et al. [9] proposed a method to calculate analytically the displacement and strain of pipelines under the impact of the landslide. Wang et al. [10,11] established a model to predict analytically the mechanical behavior of pipelines under the impact of the landslide. According to the models mentioned above, the strain and stress of pipelines can be calculated quickly.

Although analytical methods can provide an approximate and fast solution, finite element methods (FEM) can give a more comprehensive and rigorous analysis. Bruschi et al. [12] used a finite element model to calculate the displacement and strain of pipelines, considering a horizontal landslide. Cheong et al. [13] used a finite element model to analyze the mechanical behavior of the elbow-pipe, considering the effect of the horizontal force. Liu et al. [14] investigated the stress and strain of pipelines under the deflection force based on a finite element model. However, the model is not suitable to be used directly to analyze the pipeline behavior under landslides, due to the difference of the deflection load and the landslide. Zhu and Randolph [15] analyzed the mechanical response under the impact of the landslide based on a finite element model. However, the model was based on the plane strain condition, maybe leading to the prediction that differs to the actual results. Zheng et al. [4] calculated the strain and stress of pipelines using a numerical model. However, two shortcomings in this model were mentioned as follows: (1) the model length was only assumed 1.5 times of the landslide width; (2) the fixed constraint was used at the pipeline ends. In such case, the interaction of pipeline-soil outside the model can not be reflected, mainly because the dimension of FEM is far smaller than the slippage length of pipeline-soil. Kinash and Najafi [16] proposed a numerical model to calculate the strain and stress of pipelines under the landslide movement. Yuan et al. [17] evaluated the

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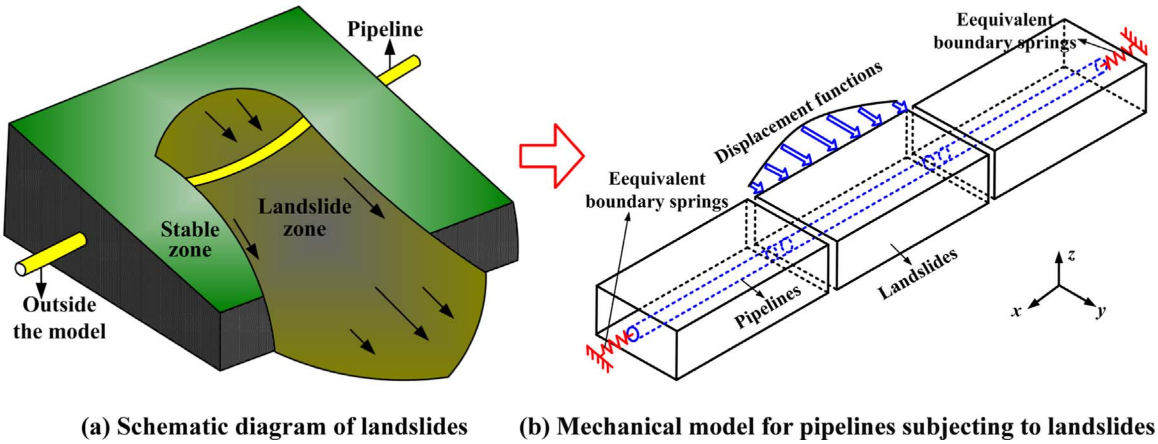

Fig. 1. Analysis model for pipelines subjecting to horizontal landslides.

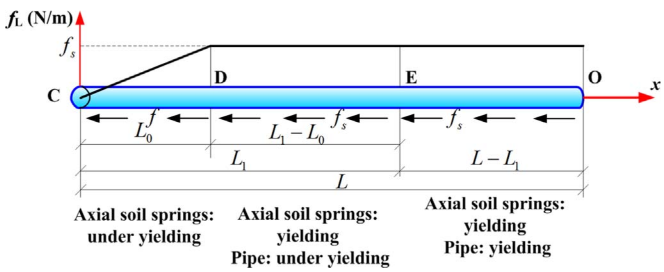

Fig. 2. Pipeline-soil interaction of buried pipelines.

strain and stress of pipelines under the impact of the landslide by a finite element model with a large length of more than 3000 m. In this model, the pipeline was simulated as the bar element, while soil mass was simulated as the spring element. Dou and Liu [18] established a finite element model to investigate the mechanical behavior of the pipeline under the lateral impact, considering the effect of the inner pressure of the pipeline. Yu et al. [19] proposed a finite element model to analyze the deformation of the pipeline when subjecting to the transverse impact caused by the dropped anchor. Using this model, although the interaction of pipeline-soil can be considered fully, the pipeline behavior can not be predicted comprehensively, especially for the local buckling and the cross-section deformation. Furthermore, a series of models were developed to obtain the horizontal impact force of the landslide [20–24].

Although important improvements have been achieved using finite element models, some shortcomings were still mentioned: (1) larger landslides lead to larger slippage length of the pipeline-soil, but the dimension of the finite element model did not cover the whole slippage length; (2) the fixed constraint was applied at the pipeline ends, neglecting the interaction of the pipeline-soil outside the model. In such case, the current finite element models are difficult to predict the pipeline behavior accurately.

In this paper, the equivalent boundary spring was proposed to model the pipe-soil interaction outside the model. Meanwhile, the stiffness coefficient of the equivalent boundary spring was given based an analytical method. After that, a new finite element model was established to predict the displacement and strain of pipelines subjecting to the horizontal landslide, considering the equivalent boundary spring. Based on the conclusion of the validation, the equivalent boundary spring can be used at the pipeline end as a constraint condition.

2. Mechanical models

2.1. Description of models

Under the horizontal landslide, larger horizontal deformation of pipelines occurs at the landslide zone, as shown in Fig. 1(a). To analyze the pipeline response subjecting to horizontal landslides more accurately, a new analysis model was established in Fig. 1(b), where an equivalent boundary spring was proposed specially at the pipeline end, to simulate the pipeline-soil interaction outside the model. In this model, the interactions of pipeline-soil inside and outside the model were simulated by the contact model and the equivalent boundary spring, respectively. Additionally, the landslide process was simulated by the non-uniform displacement in the form of parabolic.

2.2. Stiffness coefficient of equivalent boundary springs

The stiffness coefficient of equivalent boundary springs can be derived based on the interaction of the pipeline-soil. In this analysis, the model of the pipeline-soil interaction was established as shown in Fig. 2. As seen from Fig. 2, three different segments were used to simulate the pipeline-soil interaction, with $0 < x \le L_0$, $L_0 < x \le L_1$ and $L_1 < x \le L$. At the first segment of $0 < x \le L_0$, the interaction of the pipeline-soil belongs to the static friction stage. At the second and third segments of $L_0 < x \le L_1$ and $L_1 < x \le L$, the interaction of the pipeline-soil belongs to the slippage friction stage, and the friction force per unit length is a constant. Especially, some key points were described as follow: (1) point C represents the anchor point, where the displacement and strain are equal to 0; (2) point D represents the point that axial soil spring yields; (3) point E represents the point that the pipeline yields; (4) point O represents the midpoint of the horizontal landslide zone.

(1) At the first segment of $0 < x \le L_0$

The pipe elongation Δx and the axial force F can be given:

$$\Delta x = \int_0^x \frac{f_s x^2}{2AE_1 L_0} dx \tag{1}$$

Table 1
Mechanical parameters of API 5L-X70 steel.

Mechanical properties	Yield stress (σ_1)	Failure stress (σ_2)	Yield strain (ε_1)	Failure strain (ε_2)	Elastic Young's modulus (E_1)	Plastic Young's modulus (E_2)
Values	485 MPa	550 MPa	0.23%	3.0%	210.00 GPa	2346.57 MPa