Applied Ocean Research 59 (2016) 38–52

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

A semi-analytical method of stress-strain analysis of buried steel pipelines under submarine landslides

Lisong Zhang*, Xinbo Zhao, Xiangzhen Yan, Xiujuan Yang

College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, China

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
19 November 2015
Accepted 11 May 2016

Keywords:
Buried pipelines
Horizontal landslides
Mechanical behavior
Semi-analytical method

ABSTRACT

A semi-analytical method of the stress-strain analysis of buried steel pipelines under submarine landslides was proposed, considering the nonlinearities of the pipe-soil interaction and mechanical properties of the pipe steel. The pipeline was divided into three parts according to different loading conditions, and the corresponding differential equations were established based on a combination of the beam-on-elastic foundation and elastoplastic-beam theories. According to the second-order central difference method, the transverse horizontal displacement was calculated, and then the bending strain was obtained based on the relation between bending strains and curvatures. Considering the interaction between the axial and bending strains, the axial strain can be derived from the equilibrium condition by equating the axial force. The proposed method was verified through the comparison of obtained solutions to ANSYS results, with minor deviations which do not exceed about 4.6%. Additionally, the effects of the slide width, the buried depth of pipelines, the internal friction angle of soils, the cohesion of soils and the bulk density of soils are investigated through parametric studies.

1. Introduction

At present, a substantial amount of gas-main pipelines are laid in the high risk areas of submarine landslides, which makes the safety evaluation of buried steel pipelines to be one of the most important design problems [1,2]. During the period of 2008–2009, two accidents of buried pipelines occurred at landslide areas in Zhejiang province [3], China. Due to the impact of landslides, the buried pipeline developed excessive plastic deformations, and resulted in local plastic collapses at the critical locations.

To investigate the failure behavior of submarine pipelines, many researchers put emphasis on the impact force induced by the slide mass using both geotechnical and hydrodynamic methods [4–6]. Zakeri [4] provided a review of work in this area. Sahdi et al. [7] performed a centrifuge test to analyze the impact force of a submarine landslide on an offshore pipeline.

As seen from previous researches, two kinds of approaches were developed to address the pipeline behavior under submarine landslides. One approach is based on finite element method (FEM) [3,8–10]. Randolph et al. [9] established a numerical approach to simulate the large flow deformation of debris from a landslide and to quantify the load and displacement imposed on pipelines embedded in the seabed. Liu et al. [3] established an improved finite element model to predict the behavior of buried pipelines based on the non-linear stabilization algorithm, considering the nonlinear contact interaction between the pipeline and the soil. Wang et al. [10] used the vector-form intrinsic FEM to analyze pipeline behaviors under the impact of submarine landslides. Although the FEM gives a rigorous solution, the FEM has not entered yet into the pipeline design practice as a common tool.

Analytical models of the pipeline were developed by many researchers [11–14] for submarine landslides. Parker et al. [11] analytically examined the behavior of surface-laid submarine pipelines under shallow landslide impacts by idealizing the pipeline shape as the parabolic or double parabolic. Randolph et al. [12] developed a standard set of parametric solutions based on an analytical model with a small drawback of discontinuity in the bending moment. Wang et al. [13,14] improved the analytical model by guaranteeing the continuity of the bending moment, and also considered the variation in lateral soil resistance along the pipeline. Using these analytical models, a simple and fast solution of the pipeline behavior in landslides can be obtained [15]. However, some shortcomings are still found:

* Corresponding author.
E-mail address: lisongzhang1982@163.com (L. Zhang).

http://dx.doi.org/10.1016/j.apor.2016.05.007
0141-1187/

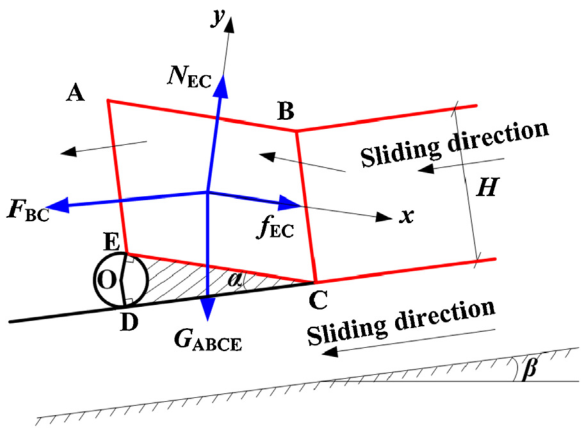

Fig. 1. Force analysis of sliding block on the wedge [16].

(1) The assumption of the elastic beam restricts the application of the models, especially when encountering large submarine landslide movements (slide width > 500 m).
(2) The contribution of bending strains to the axial tension is neglected, i.e., the effect of curvatures on the relation between the axial force and the corresponding axial strain is not taken into account, which leads to axial strains predicted that differ from the true results.
(3) Parametric investigations are focused on the drag force, lateral soil resistance and axial soil resistance. Other parameters are not investigated, such as the buried depth of pipelines, the cohesion of soils, the internal friction angle of soils and the bulk density of soils.

In this paper, a semi-analytical method of stress-strain analysis of buried steel pipelines under submarine landslides is proposed, and a series of essential modifications are made, namely:

(1) To improve the application range and the calculation accuracy of analytical models, the elastoplastic-beam theory is introduced to analyze the displacement and strain of pipelines subjecting to large submarine landslide movements.
(2) The contribution of bending strains to the axial tension is considered, i.e. the coupling between axial and bending strains is taken into account.
(3) Further parametric studies are discussed from the engineer application view-point, including the buried depth of pipelines, the slide width, the cohesion of soils, the internal friction angle of soils and the bulk density of soils.

2. Drag force analysis

In order to analyze drag forces, buried pipelines are assumed as retaining walls [16]. In such case, a rigid wedge ECD would be generated in the back of the pipeline after landslides encounter pipelines, as shown in Fig. 1. Due to the existence of rigid wedge ECD, the slide mass is separated into two parts from the point C. Part one is the slider ABCE, sliding along the EC, and the other part is rigid wedge ECD, moving forward along DC. According to the model in Fig. 1, the drag force is equal to the interaction between the rigid wedge ECD and the pipeline.

Using the limit equilibrium method, the drag force can be derived. Force analysis of slider ABCE is shown in Fig. 1, and the equilibrium equations at directions x and y can be concluded [16]. Then, N_{EC} and F_{BC} can be determined:

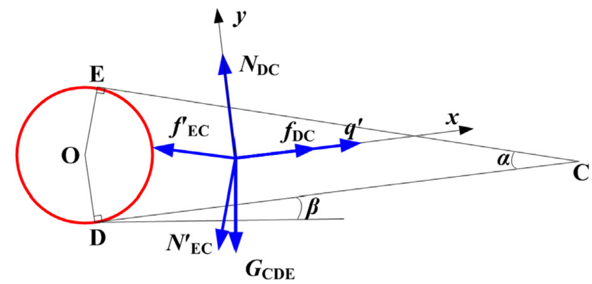

Fig. 2. Force analysis of the wedge [16].

$$N_{EC}=\frac{G_{ABCE}\left(\cos\left(\alpha-\beta\right)+\sin\left(\alpha-\beta\right)\tan\alpha\right)+D/1-\tan^2(\alpha/2)c}{1-\tan\alpha\tan\phi} \tag{1}$$

$$F_{BC}=\frac{N_{EC}-G_{ABCE}\cos\left(\alpha-\beta\right)}{\sin\alpha} \tag{2}$$

where F_{BC} is the thrust force acted on the surface BC, which results from the landslide movement, N_{EC} is the support force acted on the surface EC, G_{ABCE} is the weight of slider ABCE, f_{EC} is the friction force acted on the surface EC. Of the parameters, G_{ABCE} and f_{EC} can be expressed:

$$G_{ABCE}=\frac{D}{2\tan(\alpha/2)}\gamma_L H \tag{3}$$

$$f_{EC}=N_{EC}\tan\phi+\frac{D}{2\tan\alpha/2}c \tag{4}$$

where α is the acute angle of the wedge and approximate equal to $45-\phi/2$, ϕ is the internal friction angle of soils, β is the angle between the sliding direction and the horizontal plane, which is approximately equal to the angle of inclination of sliding surface of landslides, c is the cohesion of soils, D is the external diameter of the pipeline, H is the buried depth from the top of pipelines to the ground surface, γ_L is the bulk density of soils.

In order to further derive the drag force, the rigid wedge ECD is taken as a research objective, as shown in Fig. 2, where N'_{EC} and f'_{EC} are the compression force from slider ABCE and friction force on the surface EC, respectively, which are equal to N_{EC} and f_{EC} due to action-reaction force pairs, N_{DC} and f_{DC} are the support force and friction force on the surface DC, q' is the opposite reaction force of the drag force, which is equal to the drag force q, G_{CDE} is the weight of the wedge ECD. The equilibrium equations at directions x and y can be concluded [16]:

$$q'+f_{DC}-f'_{EC}\cos\alpha-N'_{EC}\sin\alpha-G_{CDE}\sin\beta=0 \tag{5}$$

$$f'_{EC}\sin\alpha+N_{DC}-N'_{EC}\cos\alpha-G_{CDE}\cos\beta=0 \tag{6}$$

where

$$G_{CDE}=\frac{D^2}{4}\left[\frac{1}{\tan\left(\frac{\alpha}{2}\right)}-\frac{\pi\left(180^\circ-\alpha\right)}{360^\circ}\right]\gamma_L \tag{7}$$

$$f_{DC}=N_{DC}\tan\phi+\frac{D}{2\tan\left(\frac{\alpha}{2}\right)}c \tag{8}$$

where δ is the wall thickness of pipelines.

Substituting Eqs. (6)–(8), into Eq. (5) to obtain:

$$q'=f'_{EC}(\cos\alpha+\sin\alpha\tan\phi)+N'_{EC}(\sin\alpha-\cos\alpha\tan\phi)$$
$$+G_{CDE}\left(\sin\beta-\cos\beta\tan\phi\right)-\frac{D}{2\tan\left(\frac{\alpha}{2}\right)}c \tag{9}$$