Applied Ocean Research 35 (2012) 95–104

Contents lists available at SciVerse ScienceDirect

Applied Ocean Research

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

# A refined analytical model for landslide or debris flow impact on pipelines. Part I: Surface pipelines

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ARTICLE INFO

*Article history:*
Received 14 April 2011
Received in revised form 3 August 2011
Accepted 4 December 2011
Available online 29 December 2011

*Keywords:*
Light pipeline
Analytical model
Submarine landslide
Impact
Pipe–soil interaction

ABSTRACT

As one of the most destructive geohazards, submarine landslides pose significant risks to pipelines and seabed installations. Deepwater pipelines are often laid on the seabed without pre-trenching or cover, and especially light pipelines are often laid on the surface of the seabed, which makes them directly exposed to debris flows. Determining a pipeline behavior subjected to a landslide is a great challenge and still is a matter of further research. In this work, an analytical model is established to analyze the behavior of light pipeline subjected to a landslide. In this model, the pipeline is divided into four segments according to the different loading conditions along the pipeline. The governing equations of different segments are established on the basis of beam theory. Then, by virtue of the continuity conditions and boundary conditions, the explicit expressions of different segments are obtained. The influences of the drag force, slide width, the lateral and axial soil resistance are investigated through parametric studies, and some important and valuable conclusions are obtained.

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## 1. Introduction

Submarine landslide is among the most destructive geohazards, economically and environmentally, for pipelines and seabed installations. Landslides are common, especially at the times of earthquakes or hurricanes. The Grand Banks earthquake set off a 20 km$^3$ submarine landslide, which severed the Trans-Atlantic submarine telegraph [1]. In the Gulf of Mexico, numerous landslides and debris flows were triggered by the hurricanes Ivan and Katrina, which resulted in serious pipeline damage [2,3]. The resulting debris can travel hundreds of kilometers on gentle slopes of 0.5–3°. Deepwater pipelines are at greater risk from landslide and debris flow impact than other subsea structures, for mainly two reasons: their length which increases exposure to landslide hazard, and their low structural resistance [4].

A pipeline will be subjected to active loading in form of drag force when interacting with a landslide. The drag force occurs over a defined length determined by the slide and it could be decomposed in three directions at lateral, axial and vertical depending on the attack angle. The lateral resistance to pipeline is related to the pipeline layout, and Bruschi et al. [5] pointed out that there were generally three fundamental pipeline layouts: free-spanning, resting on the seabed and embedded. Pipelines resting on the seabed are those laid on the seabed surface or very shallowly embedded, which are defined as surface pipelines in this work. The "free-spanning" is a condition where the pipeline is suspended over a valley crossing. Most available studies focus on pipelines embedded or buried in the seabed [6], while in deepwater the light pipelines are always laid on the seabed surface, which makes it directly exposed to landslides and susceptible to debris flow impact. Light pipeline is defined by the ratio of the pipe submerged weight $w$ per unit length to the seabed strength $s_u$ and the outer diameter of the pipe $D$. A pipeline is considered light when $w/s_uD < 1.5$ [7]. Surface pipelines are exposed to turbidity current and mass flow, and soil slides directly to the pipeline resting on the seabed. The drag forces of landslide flow on surface pipelines have been mainly estimated from two perspectives: a geotechnical approach and a fluid dynamics approach [8,9]. Pazwash and Robertson [10] has measured the force acting on bodies in Bingham fluids and their method can be expanded to cylindrical objects. Georgiadis [11] concluded that the available methods provided a range of different results by carrying out a literature survey. More recently, Zakeri et al. [12] experimentally investigated the drag forces, and the results were then complemented through numerical analysis [13]. The available reviews of state-of the art of drag forces on submarines pipelines are [14,15], which indicate great difference among results of different researchers. The lateral and axial pipe–soil interactions, which are closely related with the seabed soil strength and the pipeline embedment, have been vastly investigated by some pioneering researchers for pipelines installed in unstable slopes [7] [16,17].

In order to investigate the pipeline behavior by the landslide drag forces, Bruschi et al. [5] has discussed the impact of

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0141-1187/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apor.2011.12.001

landslide on deepwater pipelines using finite element method. Parker et al. [4] examined the behavior of surface laid submarine pipelines under shallow landslide impact. The shapes of pipelines after the landslide are assumed to be parabolic and double parabola shape, which makes the calculation results deviate from the real situation. Randolph et al. [3] has developed a standard set of parametric solutions based on an analytical model. The analytical model provides a simple and fast solution of the pipeline behavior in landslide. Yet, there is a significant room for improving the analytical model mainly for three reasons: the continuity of bending moment is not guaranteed, which makes the bending moment deviate from numerical results; the lateral soil resistance is assumed to be uniformly distributed, which is different from the real situation; the accuracy of solution cannot be maintained beyond a certain parameter range.

This paper aims to provide a refined analytical model for surface pipeline in deepwater under the impact of landslide. The pipeline is divided into four segments according to different loading conditions along the pipeline and the continuities of the displacement, inclination slope, bending moment and shear are guaranteed. A numerical method is adopted to get the final solution. Although some simplifications were made in the analysis, the model can provide reliable and useful frameworks for more detailed numerical analysis for the particular governing conditions.

## 2. Loading conditions

In general, pipelines are preferably aligned along the steepest angle of the slope. The transverse impact of the landslide on the pipeline is normally the most critical one [5]. In this work, the loading condition of the surface pipeline is shown in Fig. 1, where $q$ is the drag force of the moving slide which is assumed to be perpendicular to the pipeline, $p$ is the passive soil resistance, $\varphi$ is the slope angle, $w_t$ and $w_n$ are the tangential and normal components of the pipeline submerged weight $w$ to the slope direction, $f$ is the axial soil resistance to the pipeline. The coordinate system $XOY$ is established, and the pipeline is assumed to be geometrically symmetrical and symmetrically loaded with $Y$-axis as shown in Fig. 1.

Zakeri [14,15] pointed out that there have been many available works on landslide and debris flow drag forces. The results in these works deviate from each other and some even obtained opposite conclusions about the pipeline safety in landslide [6,18], which brings great uncertainty in calculating the drag forces and its influence on the pipeline. This work simplifies the drag force as a uniformly distributed force $q$ in the landslide zone.

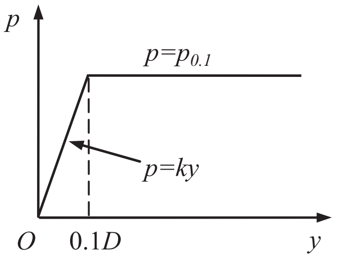

**Fig. 2.** Load–displacement relationship.

Conventional design practice models the response of the soil to lateral pipeline movement $y$ to be linear-elastic perfectly plastic [19], which results in a bilinear $p$–$y$ relationship, as shown in Fig. 2. Bruton et al. [7] pointed out that the relationship between the displacement and the soil resistance depends on the pipeline weight. For shallowly embedded light pipelines, the residual soil resistance after breaking out is approximately constant, while for heavy pipelines, the soil resistance after breaking out may increase as the pipeline moves laterally. The soil response for shallowly embedded pipeline has been obtained by Hodder and Cassidy [20] through experiments and a plasticity model with a bilinear relationship. Before reaching its maximum, the lateral resistance $p$ increases linearly with the rate of $k$. The displacement to mobilize the maximum resistance $p_{0.1}$ is commonly 0.1$D$, where $D$ is the outer pipe diameter [21,22]. So the linearly increasing rate for displacement within 0.1$D$ should be $k = 10p_{0.1}/D$. A simple way to obtain the maximum lateral resistance is multiplying the pipeline weight with the friction coefficient which is 0.2–0.8 as suggested by White and Randolph [16].

In the axial direction, the resistance to the pipeline depends on the restraint condition. The pipeline may terminate in a free-end or some form of anchoring, which brings about uncertainty in calculating the axial resistance. A simple approach to quantify the soil resistance is to multiply the friction factor by the pipeline weight [16]. In order to focus on the main points without redundancies, this work simplifies the boundary constraint as a uniformly distributed constant load $f$. Different boundary conditions can be modeled by changing the magnitude of $f$: a small $f$ for free end and a large one for an anchoring end.

## 3. The governing equations

From Fig. 1, both the pipeline and the external loads are symmetrical, so one half of the pipeline is taken into consideration. This half of the pipeline model is then divided into the following four segments according to the different loading conditions as shown in Fig. 3:

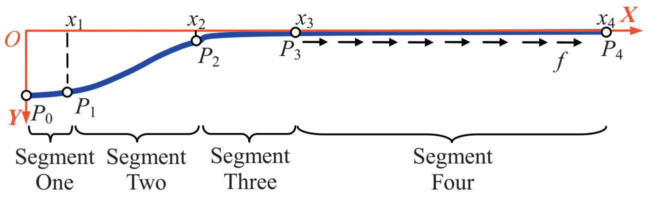

**Fig. 3.** Scheme of the pipeline.

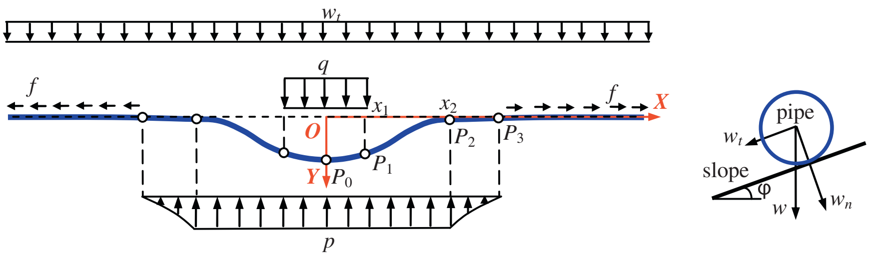

**Fig. 1.** Sketch of the model.

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