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An exponential matrix method for the buckling analysis of underground pipelines subjected to landslide loads

Eugenio Ruocco[a,*], Raffaele Di Laora[b], Vincenzo Minutolo[a]

[a]Second University of Naples, Department of Civil Engineering, Design, Building and Environment, Via Roma 29, Aversa 81031,Italy
[b]University of Ferrara, Department of Ingegneria, Via Saragat 1, Ferrara 44122, Italy

Abstract

Due to their dimensions, long pipelines often cross areas that are highly susceptible to landslides. In Italy, this problem requires special attention, as many slow-moving landslides interact with buried pipelines. The paper analyzes such interaction problem with particular reference to buckling analysis, tackling the solution of the governing equations by an exponential matrix method. In the paper the basic equation, its computational aspects and numerical analysis options are outlined. Representative results of the proposed methodology and potential applications on buckling analysis of buried pipes are presented.

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Keywords: Buckling; buried pipelines; landslides.

1. Introduction

In recent years the use of pipelines for the transportation of oil and gas has greatly increased in many parts of the world. Long pipelines often cross areas susceptible to slow-moving landslides[1] and it is therefore important to ensure their integrity under the stress deriving by the compressive load induced by the ground motion. In some circumstances buckling phenomena can also occur[2]. As critical load is in inverse proportion to the square root of the pipe length embedded in the moving ground, long pipes can buckle under very low values of the compressive load, and can be cause of human loss as well as economic and environmental damage. For example, the Guanabara oil spill, which occurred in Brazil on January 2000 and caused the spread of 1.3 million liters of oil into Guanabara bay, was caused by lateral buckling of offshore pipeline that eventuated in local buckling and rupture of the pipe wall[3].

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: author@institute.xxx

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Nomenclature

E	modulus of elasticity
I	Second moment of cross-sectional area
L	Overall length of pipeline
L_0	Imperfection half-wavelength
P_i	Concentrate load (anchorages)
R_e	External radius of circular pipe
R_i	Internal radius of circular pipe
q	Distributed load (landslides)
k_s	Winkler springs (elastic foundation)
u	Generalized in-plane displacement in buckling mode
w	Generalized out-of-plane displacement in buckling mode
θ	Bending rotation

Similarly, buckling of onshore inclined pipelines was observed during construction in Colombia in the last years of the twentieth century[4].

Consequently, effective constant monitoring[5] and prediction of buckling load and effective measures against this phenomenon are important aspects of design of pipelines[6,7]. However, buckling of pipes is quite complicate, involving complex pipe-soil interaction, dependence of initial imperfections and effect deriving from second-order displacement field.

The scientific interest on the different aspects of the buckling analysis of buried pipes is proved by the growing number of papers devoted to this topic. For instance, Zhang *et al.*[8] proposed a finite element model for analyzing the buckling behavior of a buried pipeline impacted by a cube-shaped rockfall, analyzing the effects of the impact velocity, buried depth, impact position, and base area on the stress of the pipeline. Xue *et al*[9]. presented a first order shear theory for the buckling analysis of cylindrical sandwich pipes subjected to undersea water pressure. In their model the authors examine the change of the circumferential radius due to the radial deflection of the cylindrical sandwich shell and its effect on the bending moments.

This paper presents a simplified numerical model that captures the main features of the buckling of a beam on an elastic foundation. The effects of various parameters such as the amplitude of initial imperfection and presence of anchorage points are investigated. In the ensuing, the numerical model is derived in detail and some representative results are discussed.

2. Method

The problem under investigation consists of a circular pipeline of length L and mean radius R depicted, with the local coordinate system adopted in the paper, in Fig. 1. Let the pipeline be subjected to a lateral external pressure q and concentrated loads P applied in different points of the pipe, both acting in the axial direction, and characterized by a continuous elastic restraints of stiffness k_s. Also, in order to simulate the presence of local geometric imperfection, a variable cross-sectional moment of inertia $I(z)$ has been considered.

The main assumptions are that a) the plane section remains plane and normal to the axis of the beam before bending and b) the axis of the beam is inextensible. Such hypotheses are satisfied by the following choice of the displacement field:

$$s_x(x,z)=w(x),\ s_z(x,z)=u(z)+x\theta(z),\ \theta(z)=-\frac{dw(z)}{dz} \tag{1}$$

In order to capture the non-linear behavior ruling the buckling of the beam, one can consider the strain tensor: