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Buckling analysis of steel jacking pipes embedded in elastic tensionless foundation based on spline finite strip method

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ABSTRACT

Buckling of steel jacking pipes subjected to axial compression and surrounded by soil is investigated. The jacking pipes are simplified as simply-supported circular cylinders embedded in tensionless Winkler-Pasternak foundation that reacts to soil compression only. The governing equation for tensionless buckling analysis is established based on the spline finite strip method (SFSM), and the critical buckling load is obtained by solving the governing equation through an iterative procedure. Numerical examples are analyzed, and the comparison of buckling loads with available solutions and finite element results shows good accuracy of the SFSM. Based on a parametric study, the variation of tensionless buckling loads with slenderness ratio of jacking pipes is first studied. Moreover, the effects of diameter-thickness ratio and foundation stiffness are also investigated. The present SFSM-based tensionless buckling analysis is applicable to cylinders of any length and on tensionless foundation, and it is capable of efficiently and effectively predicting buckling of steel jacking pipes subjected to axial compression and surrounded by soil.

1. Introduction

Pipe jacking is a trenchless technique for creating tunnels, and it minimizes the influence of tunnel construction on ground infrastructure and environment. Therefore, pipe jacking is necessary in situations where direct excavation from the ground surface is difficult, or where open-cut trenching would cause a high level of disruption, e.g., installation of tunnels under canals, highways, and building-intensive areas. The pipe jacking construction process can be illustrated by Fig. 1 [1].

During the construction, pipes have to sustain considerable jacking forces in axial direction. The axial compressive forces dominate design of jacking pipes. Therefore, jacking pipes are often regarded as circular cylinders subjected to axial compression. In addition, the pipes are also surrounded by soil, which is usually simplified as an elastic foundation. The modeling of jacking pipes is shown in Fig. 2. Because thin-walled cylinders are prone to failure by buckling, understanding of their stability response under axial load and surrounded by soil foundation is essential for safe and efficient design of jacking pipes.

The buckling problem of circular cylindrical shells surrounded by elastic foundation has been investigated by many researchers. Forrestal and Herrmann [2] and Fok [3] conducted early buckling analyses of cylindrical shells surrounded by an elastic medium, which was considered to be attached to the shell in any situation. Zhen et al. [4] studied the buckling problem of thin-walled cylinders subjected to axial compression and surrounded by soil, where the elastic foundation was simplified as Winkler and Pasternak models. In these studies, the foundation and the cylinder were assumed to be perfectly bonded, and hence, both normal compressive and tensile forces were admissible between them, as shown in Fig. 3(a). In contrast to this two-way assumption, there are situations in which cylinders are not bonded to the foundation but simply rest on it. When the cylinder surface buckles outwards, it is compressed by the foundation and thus the outward deformation is restrained. However, when it buckles inwards, the cylinder surface may lose contact with the foundation, and no tension is transferred, as demonstrated in Fig. 3(b). Therefore, in such cases, the foundation only provides compressive restraint, and the assumption of two-way foundation is not realistic any more. These problems are termed as tensionless buckling, or unilateral contact buckling.

Analysis of tensionless buckling problem is quite challenging because the restraining area is not known a priori. Although the foundation reacts linearly to compression, iterative analysis is needed in tensionless problems. As a result, only a few limited studies on tensionless buckling problem of plates have been presented, and even less

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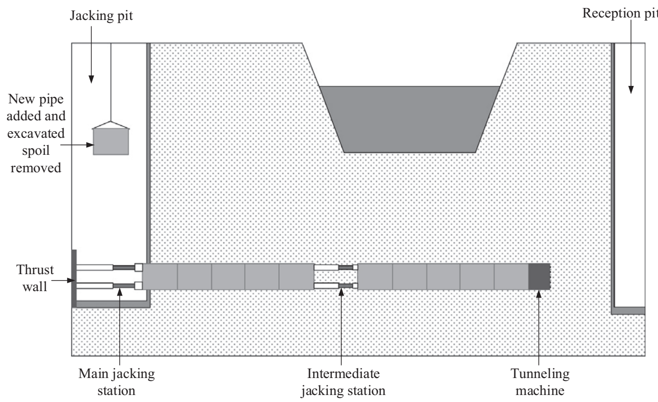

Fig. 1. Typical components of a pipe jacking operation [1].

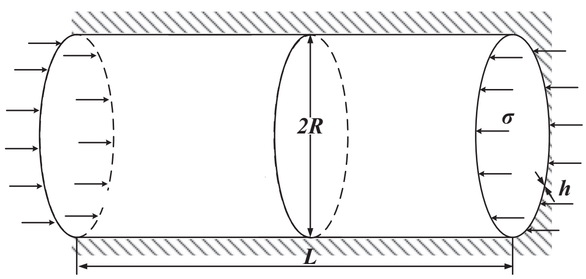

Fig. 2. Modeling of jacking pipes embedded in soil.

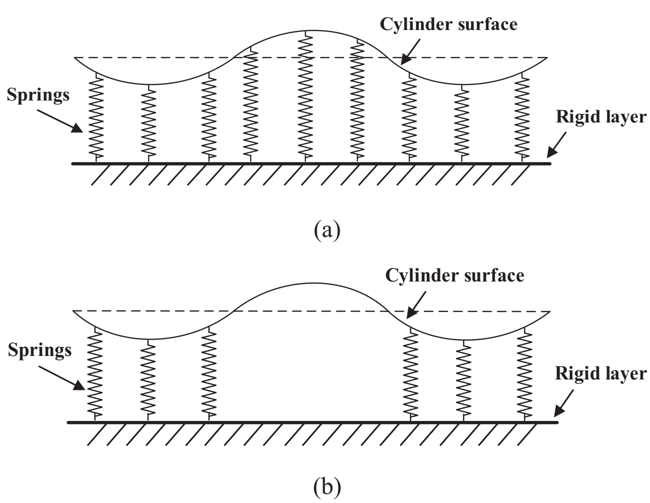

Fig. 3. Elastic foundation models: (a) Traditional foundation, and (b) Tensionless foundation.

is known about tensionless buckling of cylindrical shells. Seide [5] conducted an early study on the tensionless buckling of plates in which the compressive buckling of an infinitely long plate resting on an tensionless elastic foundation was analyzed. Shahwan and Waas [6] studied the buckling of unilaterally-constrained finite rectangular plates. Smith et al. [7] investigated the unilateral plate buckling problem using the Rayleigh-Ritz method. Li et al. [8] studied the effect of end conditions on buckling performance of thin plates resting on tensionless elastic or rigid foundations. Some researchers [9–11] also investigated the unilaterally-restrained plates on postbuckling analysis by means of analytical, experimental or numerical studies. The unilateral contact model was also utilized in stability analysis of composite plates with delamination, such as Nilsson et al. [12], Ma et al. [13] and Ovesy and Kharazi [14].

The existing studies on tensionless buckling of shells were mainly conducted for buried pipelines or cylinders with elastic cores. Some analytical solutions have been given by modeling the pipelines as "infinitely" long circular cylindrical shells restrained by a one-way (tensionless) foundation [15–18]. However, these analytical solutions are restricted to infinitely long cylinders, and they cannot reflect the variation of tensionless buckling loads with respect to the length of cylinders. For cylinders with finite length restrained by tensionless foundation, the stability problem was only studied by a few researchers through numerical simulations. Shen [19] investigated the tensionless response of a laminated cylindrical shell with finite length through postbuckling analysis. Surprisingly, few studies have been made on buckling analysis of cylindrical panels supported by tensionless foundation. Panahandeh-Shahraki et al. [20,21] investigated tensionless buckling behaviors of cylindrical panels resting on tensionless foundation through Rayleigh–Ritz method, but no study on buckling of finite-length cylinders embedded in tensionless foundation has been found.

The spline finite strip method (SFSM) [22] is an efficient, effective and versatile numerical tool with good convergence characteristics, and it has been proven accurate for stability analysis and capable of handling structures under various boundary conditions and different loads. In this paper, the jacking pipes surrounded by soil are modeled as finite-length cylindrical shells which are in tensionless contact with Winkler-Pasternak type of foundation and loaded by axial compression. Based on the first-order shear deformation plate theory (FSDT), the SFSM formulations for buckling analysis of thin-shell steel jacking pipes embedded in tensionless foundation are established. An iterative procedure is then adopted to obtain the solution for critical buckling loads. The formulation is capable of conducting tensionless buckling analysis for cylinders with any length. The validity of the SFSM tensionless analysis is demonstrated through numerical examples in comparison with the existing analytical solutions and results of numerical finite element method (FEM) analysis. Finally, a parametric study is conducted using the proposed SFSM-based method, and the variations of tensionless buckling loads with slenderness ratio and diameter-thickness ratio are studied. Moreover, the influence of foundation stiffness is also investigated.

2. Theoretical formulations based on SFSM

The jacking pipes surrounded by soil are modeled as cylindrical shells under axial compression and in tensionless contact with surrounding elastic foundation. The cylindrical shell is discretized into a series of plate strips, which can be equivalent to the circular cylinder as long as the number of plate strips n is sufficiently large (see Fig. 4).

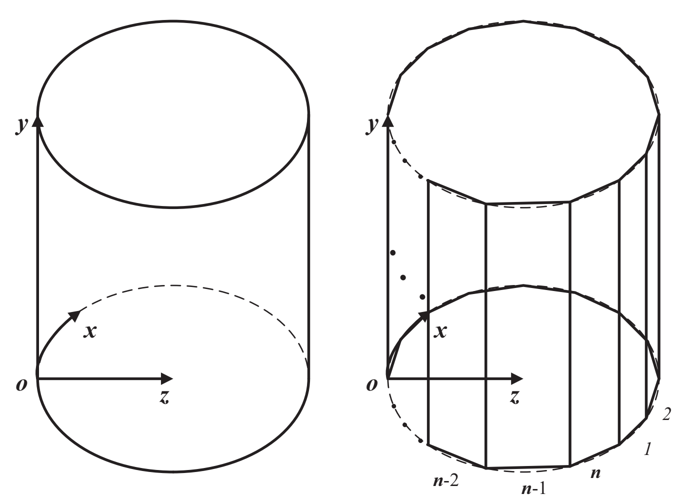

Fig. 4. Discretization of a cylinder into plate strips.