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Design of steel pipe-jacking based on buckling analysis by finite strip method

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ABSTRACT

In practice, the steel pipe-jacking can be regarded as a thin-walled cylindrical shell mainly subjected to jacking force in the axial direction and surrounded by the soil which is usually simplified and modeled as an elastic foundation. In this paper, the elastic buckling behavior of steel jacking pipes primarily under axial compression and with the Pasternak foundation is analyzed by the finite strip method (FSM). The elastic foundation is considered in the stiffness matrix through the strain energy, and the deformation in the longitudinal direction is simulated by the series functions in FSM. A parametric study is conducted to analyze buckling of cylindrical shells embedded in different elastic foundations. It indicates that the Pasternak foundation is more conducive to prevent buckling of cylindrical shells under axial compression. The critical length and the lower bound of buckling loads are obtained, and they offer the basis for optimal design of steel pipe-jacking. Finally, the case study combined with the buckling accident in the steel pipe-jacking event is presented. The present buckling analysis of soil-embedded cylindrical shells under axial compression provides design guidance for steel pipe-jacking construction.

1. Introduction

Because of advantageous properties, such as high strength, high plasticity (good performance of deformation), good self-sealing and low construction cost, steel pipes are increasingly used in underground pipeline engineering. Pipe-jacking is the technique for installing pipelines through the use of the hydraulic jacking of a pipe string from a launch shaft to a receiving shaft [1], as shown in Fig. 1. To meet the growing demand for infrastructure construction, the sizes (e.g., both the diameter and length) of pipelines continuously increase and the geometrical scale of steel pipe-jacking in some of these new construction projects have even exceeded the existing engineering standards. In general, design for these projects is just based on experience without considering size effect. As a consequence, buckling problems are more likely to occur in the pipelines of large diameter and long length, which may endanger engineering safety.

The construction techniques for underground pipelines can be divided into two types: the buried pipe method and the pipe-jacking method. Local buckling occurs more frequently in the buried pipeline due to high water and earth pressure. Upheaval buckling as another form appears in the buried pipe construction due to the reason of temperature change of its surroundings or the effect of buoyancy. While for the jacking pipeline, the jacking force is usually dominant among all the external forces. It mainly leads to global buckling (including upheaval buckling), particularly for relatively long pipelines. If water and earth pressure is high, the jacking force will also induce the occurrence of local buckling [1]. The buckling modes are the primary difference between the buried pipeline and the jacking pipeline. Especially, the huge jacking force acted on a string of pipes in axial direction easily causes unpredictable buckling accidents.

Steel jacking pipes can be regarded as a kind of elastic or elasto-plastic cylindrical shells. The mechanism of buckling of cylindrical shells under the axial compression is still very complicated, though many researchers have contributed to this work. The buckling of underground steel pipelines involves the deflection of pipelines and soil. The surrounding soil is not only as a load acted on pipelines, but also provides resistance to prevent pipeline from deforming outward. The surrounding soil is generally considered as an

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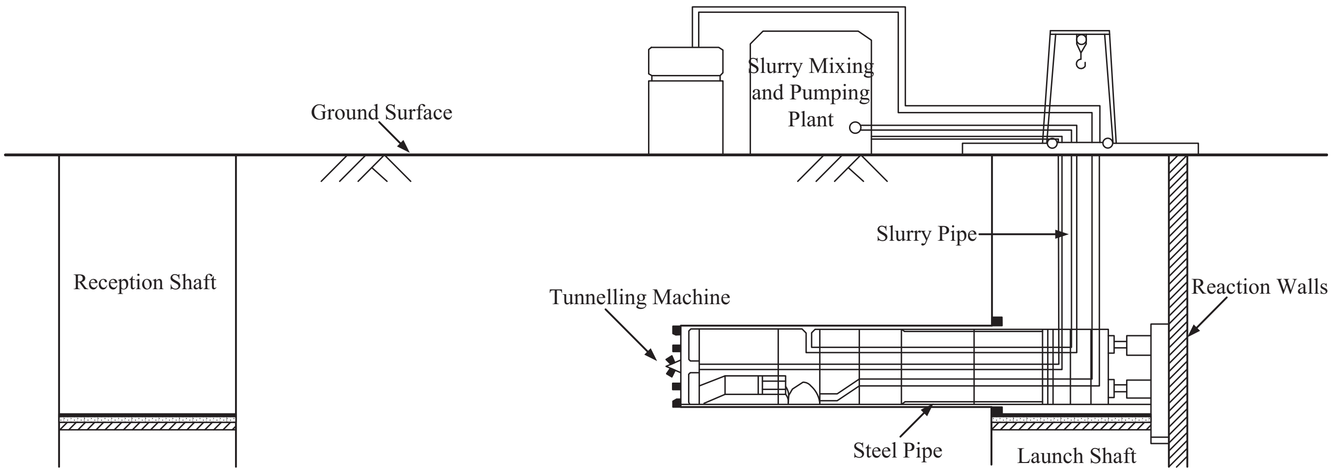

Fig. 1. Diagram of pipe-jacking [1].

elastic foundation in modeling and design analysis, so that the effect of pipe-soil interaction is not neglected.

Many researchers have studied the buckling problem of a cylindrical shell embedded in an elastic medium. Forrestal and Herrmann [2] conducted early research about the stability of a cylindrical shell embedded in an elastic medium and loaded by a far-field hydrostatic pressure [3]. Luscher [4] investigated the failure of the flexible soil-surrounded tubes using a combined experimental and theoretical approach. Soil was assumed to be a thick-walled cylinder surrounding tubes. The study indicated that buckling rather than compressive yielding might be the controlling mode of failure for thin-walled, smooth metallic tubes supported evenly, though the medium-dense sand and the surrounding soil increased the buckling resistance of a flexible tube tremendously over that of an unsupported tube. Duns and Butterfield [5] developed a simple theoretical prediction of buckling load for cylinders buried in an ideal elastic medium. The solution was derived from Donnell's stability equation for cylindrical shells extended to include the effect of the surrounding medium. Yun and Kyriakides [6] analyzed buckling of buried pipelines under compressive loads induced by seismic action through 'beam' and 'shell' modes. Cheney [7] built a 2-D model and assumed that the Winkler spring constant was taken as a function of the mode number in buckling. The solution represented an upper bound on local buckling of buried flexible tubes that might also be affected by imperfections in geometry and residual internal stresses. Muc [8] studied the influence of unilateral friction boundary on shell prebuckling deformation which was illustrated by the example of a cylindrical shell loaded locally by external pressure and restrained by a rigid or elastic outer wall. Moore et al. [9] presented the solutions capable of assessing the elastic stability of circular structures in square, circular and rectangular zones of elastic solid. Fok [3] used the energy method together with a Rayleigh–Ritz trial function to analyze buckling of a long cylindrical shell embedded in an elastic material and loaded by a far-field hydrostatic pressure. If the surrounding medium is incompressible, the solution is very similar to that given by Forrestal and Herrmann [2]. Otherwise, the solution gives lower predictions for the buckling load and provides better agreement with experiments. Kang et al. [10] used a pipe-spring model for buckling analyses of buried corrugated steel pipes. The spring coefficients in the pipe-spring model were calculated using the static analyses of soil-structure models. The ultimate or critical strengths determined were compared well with those from the American Iron and Steel Institute (AISI). The majority of the above studies focused on the buckling problem of pipes subjected to internal pressure or external pressure, and they are more suitable for the study of buried pipes. However, the axial load is dominated for steel pipe-jacking in construction stage, and buckling of steel jacking pipes is more prone to occur.

Mandal and Calladine [11] conducted self-weight buckling experiments and non-linear finite element analysis of thin, open-top, fixed-base, small-scale silicone rubber cylindrical shells, and the material, structure and loads considered were still fundamentally different from those of steel pipe-jacking. Sheng et al. [12], Bagherizadeh et al. [13] and Shen [14] analyzed functionally-graded cylindrical shells embedded in Pasternak elastic foundation under axial load. Sheng et al. [12] placed emphasis on the eigenvalue solution for buckling of cylindrical shells. Bagherizadeh et al. [13] achieved the closed-form solutions for the critical mechanical buckling loads of the FGM cylindrical shells surrounded by elastic medium based on a higher-order shear deformation shell theory (HSDT). While Shen [14] put forward the boundary layer theory and applied it to analyze postbuckling of composite cylindrical shells surrounded by tensionless Pasternak elastic foundation. Similar to the work by Shen [14], Li and Qiao [15] recently studied the buckling and postbuckling of an anisotropic laminated thin cylindrical shell of finite length subjected to combined loading of external pressure and axial compression using the boundary layer theory. Although these studies are similar to the condition of the steel pipe-jacking, the more practical method is still needed for design and construction of pipe-jacking projects.

Numerical methods have been widely used in modeling and analysis of buckling of cylindrical shells. In addition to the traditional methods, like finite differences, finite elements method (FEM), boundary element method (BEM), etc., differential quadrature (DQ) [16], discrete singular convolution (DSC) [17,18] and meshless method [19–21] have also gradually risen. However, the complicated modeling, tedious mathematical formulas, and/or programming applicability existed in the above methods, cause inconvenience when used in practice. The finite strip method (FSM) is used extensively for reducing partial differential equations to ordinary or partial differential equations of a lower order. Consequently, much shorter computing time is achieved for solution with comparable accuracy [22,23]. Especially suitable for the structures which can be divided into strip elements, the series functions are defined along the longitudinal direction instead of longitudinal element division in FEM or other numerical methods. Thus, the model in FSM is much simplified as well, particularly useful for preliminary design and analysis.