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In-Service Buckling of Submarine Pipelines with an Arbitrary Initial Out-of-Straightness

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ABSTRACT

An analytical solution has been presented for the vertical buckling of submarine pipelines laid on seabed with initial stress-free geometric out-of-straightness of arbitrary shape. The arbitrary imperfection shape as well as the deflection in the buckled portion is expressed in terms of Fourier series. The coefficients of the Fourier terms for the deflection under the action of axial force and submerged weight are obtained through energy principles. The relation between the compressive forces in the buckled portion and far away from it are obtained using both constant and deformation dependent friction models for axial friction at the pipeline-seabed interface. The obtained series solution is found to yield the same results as the classical exact solution of governing differential equations for a perfect (zero imperfection) pipeline. Numerical results are presented to illustrate the effects of the magnitude and the shape of initial imperfections on the instability temperature and the post buckling equilibrium path of imperfect pipelines. The maximum deflections and the stresses associated with the post-buckling states are also determined. The effects of the nature and the magnitude of axial friction on the buckling characteristics are investigated.

KEY WORDS: In-service buckling, submarine pipelines, initial imperfection, analytical solution, instability temperature

INTRODUCTION

In-service buckling of submarine pipelines under the action of axial compressive forces has received significant attention in recent years in view of their increasing economic importance and high repercussions of any failure during service. Such failures are even more unwanted in case of deeper water because of the difficulty and high cost involved in the rectification works in deep sea. Axial compression can build up in pipelines laid on sea bed as the longitudinal expansions due to temperature and internal pressure changes are constrained by the frictional resistance developed in the pipe-soil interface. When this axial compression exceeds a critical value, the pipeline buckles vertically (upheaval buckling) and or laterally (snaking) depending upon its initial lack of straightness induced during pipelaying operations or due to uneven seabed. Depending upon the magnitude and shape of initial imperfection, localisation of transverse deflection may take place causing excessive bending moment in the pipeline leading to failure. Appropriate modelling of initial out-of-straightness plays an important role in determining the pre and post buckling response of submarine pipelines due to axial compression induced under severe service conditions. Hobbs (1984) presented analytical solutions for the vertical and lateral modes of buckling for initially straight heated pipelines on perfectly plastic seabed with constant frictional resistance. This analysis was analogous to the more classical problem of thermal buckling in railway tracks, solved by Martinet (1936) and latter by Kerr (1974, 1978). Marek and Daniel (1971) presented a similar but apparently independent analysis for the vertical buckling of crane rails. All these studies are based on idealised lines without any initial imperfections. Taylor and Gan (1986) extended the study by Hobbs (1984) by introducing initial geometrical imperfections in the pipeline and deformation dependent axial friction at the pipe-seabed interface. Ju et al. (1988) and Pendersen et al. (1988) presented thermal buckling analysis for perfect and imperfect pipelines respectively, incorporating the material nonlinearity. Friedman (1989) presented an analysis for the lateral behaviour of an imperfect pipeline considering geometric nonlinearity. More recently, Croll (1999) has presented a simplified model based on column buckling analogy for upheaval buckling of pipelines with stress-free and stressed initial imperfections. In all these studies, however, the imperfections are idealised to have a profile similar to the prospective buckling mode, which are not ideally applicable for an arbitrary seabed or laying induced out-of-straightness. In view of the enormity of the problems associated with failure of submarine pipelines, especially in deep water, it is important to establish the sensitivity of the buckling behaviour of pipelines to the shape of initial imperfections. The fit-for-purpose study also calls for modelling the actual imperfection shape for determining the safety against in-service buckling.

In this work, we analyse the vertical buckling behaviour of submarine pipelines with an arbitrary stress-free initial out-of-straightness, resting on seabed with constant or variable axial friction. The pipe material is taken as linear elastic. The analysis consists of determining all post-buckling equilibrium states and examining their stability from the obtained equilibrium curve. The buckled shape is free to develop as it will for the given initial imperfection. The buckled mode consists of a buckled region which undergoes large transverse deformations and the adjoining regions which deforms only axially. Since a part of the constrained expansion is released in the buckled region, there is a reduction in the axial force in this region. The analysis of the buckled region involves the determination of the equilibrium