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A Simplified Analysis of Imperfect Thermally Buckled Subsea Pipelines

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ABSTRACT

An alternative model for the one-way buckling of thermally compressed subsea pipelines is briefly described and shown to provide very close agreement with a new, more precise analysis. Compared with past analyses of the problem the present approach is shown to have considerable practical advantages. First, it is based upon staightforward physical concepts and involves little analytical complexity. Second, even for the situation in which the pipeline contains initial imperfections resulting from the lay process, the approach provides very simple and explicit analytical expressions for both upper and lower bounds of the buckling loads. As a consequence, this new and simplified method recommends itself as a practical basis for both future design and in-service strength assessment.

NOMENCLATURE

A_2, A_4 : constants used in exact solution, Eq. 24
E : elastic modulus of pipeline
I : second moment of area of pipeline
k : parameter introduced for more precise solution, Eq. 24
L : length of uplifted region of pipeline
L_f : length of continuous foundation imperfection, Eq. 11
L_b : wavelength at maximum buckling load
P : axial load in pipeline
P_c : critical load of clamped column
P_b : maximum, buckling load for continuous imperfection
P_L : initial liftoff load
P_p : propagation load for perfect pipeline
q : relative weight/unit length of pipeline
w : displacement relative to flat seabed
w' : displacement relative to liftoff points on continuous foundation imperfection
$\bar{w}_l$: equivalent loading imperfection, Eq. 4
$\bar{w}_f$: foundation geometric imperfection, Eq. 17
$\bar{w}_g$: stress-free geometric imperfection of pipeline, Eq. 32
x : position along pipeline axis
ξ : total equivalent imperfection, Eqs. 18 and 34
η : foundation and/or pipeline geometric imperfection parameter, Eq. 20
θ_0 : end slope at liftoff point on foundation imperfection

INTRODUCTION

Problems of thermal buckling could be even more important in polar regions than in temperate regions because the temperature differentials between pipe-lay and operational conditions are likely to be rather more extreme in the former. Furthermore, recently reported increases in the frequency of upheaval failures make the problem one of currently increased concern. While past work has been very successful in establishing the basic phenomena of thermal upheaval buckling, the sometimes complicated associated analysis has perhaps masked the inherent simplicity of the essential mechanics involved.

The following provides an alternative model for the one-way buckling associated with thermally loaded pipelines. The model is based upon the simple buckling of a clamped ended column. In its approximate form this alternative model has already been discussed by Croll (1996). In the following this approximate model will be briefly reviewed. It will first be used to reproduce the classical analysis (see Martinet, 1936) or more accessibly Hobbs (1984), and in the process highlight the physics in a way that contrasts with the somewhat different approach employed in previous work. This approximate modelling will be shown to result in analytically explicit expressions for the classical, perfect, propagation uplift buckle behaviour, and more importantly the imperfection sensitive maximum buckling loads experienced when pipelines are lain with initial stress-free out-of-straightness or over rough and undulating seabeds. The simplicity and explicit analytical expressions are particularly suited to the setting of imperfection tolerance limits, or to the provision of buckling estimates when distortions exceed design tolerance limits.

As confirmation of the simplified, clamped column modelling, a more precise solution for both the perfect and the imperfect pipeline buckling is also presented. Although analytically less convenient, this more exact solution provides reassurance of the accuracy of the simplified approach. While the following is presented in the context of thermally buckled pipelines, the new analysis could equally well be applied to the thermal upheaval of continuous concrete road pavements or steel railway track. Furthermore, although just a single mode of upheaval buckling is treated, a very similar approach could be adopted for other mode forms, and especially those associated with lateral buckling.

SIMPLIFIED UPHEAVAL BUCKLING MODEL

Perfect Buckling Behaviour

The classical problem of thermal buckling (Martinet, 1936) is well established and has been used in many previous works. See for example: Kerr, 1974; Palmer and Baldry, 1974; Hobbs, 1984; Taylor and Gan, 1986; Maltby and Calladine, 1995. It basically involves the solution of the clamped column, with the difference that a third boundary condition of zero curvature is added to the requirements of zero displacement and slope at the end boundaries. This has the effect of producing an eigenvalue problem which allows unique definition of the wave length characterising the buckling at a prescribed buckle amplitude. This same prob-

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