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Research Paper

A novel approach for time-dependent axial soil resistance in the analysis of subsea pipelines

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ABSTRACT

A novel approach for modelling axial pipe–soil interaction, consisting of bespoke finite elements, is proposed. The purpose is to have a model that represents a two-dimensional slice of soil perpendicular to the pipe which is computationally cheap enough to be incorporated in global analysis of subsea pipelines, whilst capable of capturing detailed time-dependent soil response, which involves partial drainage and cyclic plasticity. This is achieved by handling the circumferential dimension analytically, reducing the behaviour of the two-dimensional soil slice to a one-dimensional case. Coupled consolidation analysis along a vertical sequence of one-dimensional elements beneath each pipeline node, tailored to represent the axial–vertical (or -radial) plane across the seabed semi-space, is supplemented by an analytical solution for the circumferential drainage. The paper presents the model development, its implementation through symbolic programming and validation against previously published continuum finite element analysis results.

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1. Introduction

1.1. Motivation

The resistance to axial sliding provided by the seabed soil is a key parameter in the design of subsea pipelines, in particular those conveying hydrocarbons under high-temperature and/or high-pressure. It governs the pipeline expansion and hence the loads imposed on bends and appurtenances. Furthermore, the load sharing between bends/appurtenances may change over the years due to cyclic contraction and expansion – caused by pipelines being shut down then brought back into operation – which may cause a ratcheting process known as “pipeline walking” [1,2]. This process is believed to have caused the rupture of at least one pipeline end connection after a few years of service in the North Sea [1]; and has cost several millions of dollars to a number of projects in preventive or corrective measures to mitigate excessive accumulated displacements [3]. Pipelines typically undergo hundreds of shutdown cycles over their design life, so predicted walking rates of only a few centimetres per cycle may become major design issues.

Recent research [4–8] suggests that the complex mechanisms governing the soil response to pipeline axial displacement, which can cause the resistance to span an order of magnitude within a single physical model test [9], involve shear-induced excess pore pressure as the pipeline moves combined with changes in soil state as it consolidates between cycles. A promising design approach is to account for this consolidation hardening in the soil in order to reduce the predicted pipeline tendency to walk over time [10–12]. Properly quantifying this gain in resistance, however, is complicated, as full consolidation between each pipeline movement may often be an unrealistic assumption. Instead, it is necessary to consider partial drainage between movements, and track the accumulation of pore pressure caused by multiple cycles, with concurrent dissipation.

1.2. Structure of study

The remainder of this introduction contextualises this study and sets the proposed model in light of the current design practice, as well as latest developments on time-dependent axial pipe–soil interaction. Section 2 presents some underpinning work, describing the one-dimensional (1D) bespoke element adopted, relevant aspects of its implementation and its validation against the results of an axisymmetric, elastoplastic, partially drained analysis from [8]. As later discussed, the models are equivalent and thus the validation exercise is solely to ensure that the symbolic programming implementation is adequate.

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In Section 3 the proposed model is presented. This section describes the modification to account for circumferential drainage, in which the analytic approximation for excess pore pressure dissipation along the circumferential direction is superposed on the 1D bespoke element. A brief validation exercise compares the results of the implemented circumferential drainage against the analytical solution for 1D consolidation.

Section 4 then presents the application of the implemented model to assess partially embedded pipelines, thus combining drainage in the radial and circumferential directions. A first example reproduces the plane strain set-up analysis results in [8]. Finally, the implemented model is used to reproduce the complete analysis of cyclic axial displacements with intervening consolidation periods, performed by Yan et al. [12] using detailed continuum 3D finite element (FE) analyses. The paper closes with comments on the expected computational benefit of this method, quantified based on an indicative example.

1.3. Pipeline-soil interaction analysis

Current industry practice – from early design stage analytical calculations through to detailed 3D FE analyses – is still to represent the axial soil resistance by a Coulomb-like friction, or eventually to consider a multi-linear "spring-slider" which is still constant over time and along the pipe length. The significant improvement in understanding the local soil behaviour over the last few years has not yet been followed by similar evolution in the available pipeline analysis tools. As a consequence, recent projects have tried to translate complex time-dependent soil behaviour into equivalent constant frictional resistances, which may incur misleading results, as different sections of the same pipeline will see different displacements, under different velocities and for different time periods, as the pipe expands [13].

Analyses of a short local length of pipeline employing detailed continuum models using 3D solid elements have been published [7,12]. The difficulty in extrapolating them to a global pipeline analysis lies in the large scale difference between the mesh required to model the continuum of underlying soil (beneath a pipe cross-section with typical diameter of a fraction of a metre) and the pipeline slender bar behaviour (over several kilometres). Hybrid 2D/3D approaches have been proposed for lateral soil resistance, but either with a simplistic representation of the soil continuum [14] or with a computational cost for complete global analyses that is still not compatible with typical design schedules [15].

The first model to properly address time dependent aspects of axial pipe–soil interaction whilst not depending on time consuming FE analyses was proposed by Randolph et al. [7]. In their model, analytical expressions describe the development and dissipation of excess pore pressure at the pipe–soil interface. These are based on extrapolation from the response of a finite thickness, infinite plane shear band at the surface of a semi-space. The model uses critical-state framework supplemented by a damage mechanism to reproduce late excess pore pressure generation observed in physical model tests.

Using two different simplified FE models, Carneiro et al. [8] discussed two aspects of the soil behaviour that cannot be captured by the planar idealisation:

(a) As the soil beneath a pipeline consolidates, pore water seeps not only radially away from the pipe–soil interface, but also around it towards the draining seabed surface. Furthermore, the radial component of the flow, rather than monotonically diminishing as pore pressure equalises, may reverse as a result of this 2D process.

(b) As the soil hardens next to the pipe, the shear band could migrate, depending on the trade-off between gain in unit strength and increased resistant area as it moves away from the pipe (as previously suggested by White and Cathie [10]). In partially drained conditions, excess pore pressure generated away from the pipe may drain towards it, eventually reducing the effective normal stress at the pipe–soil interface.

A plane strain model, similar to those used by Gourvenec et al. [16] and Krost et al. [17], was used in discussion (a). It cannot capture axial displacements as all degrees of freedom are limited to the plane ρ–θ (see Fig. 1). For discussion (b), an axisymmetric model, with a mesh of 2D solid elements in the plane ρ–x, was employed. Multi-point constraints were used to force nodes of same coordinate ρ but different x to have identical responses in all degrees of freedom. As such, the model represents boundary conditions around a 2D slice perpendicular to an infinite pipeline, with axial displacements permitted. This same artifice was previously used in the detailed continuum models using 3D solid elements by Randolph et al. [7] and Yan et al. [12].

1.4. Conception of the proposed model

The aim of the present model is to realistically capture the soil response to pipeline axial movement, whilst maintaining low computational costs to permit its use in global pipeline analysis. The model was conceived to bridge between the two models in [7]: the detailed soil continuum model, which captures in details the complexity of the pipe–soil interaction but is impractical for design purposes; and the elegant planar model, which provides essentially instantaneous results but does not capture the two-dimensionality of the drainage behaviour. In particular, the new model was intended to capture the two aspects of behaviour raised in [8] and noted above.

As derived hereafter, the model is based on a 1D mesh of bespoke finite elements along z, as illustrated in Fig. 1. This is equivalent to the axisymmetric model used in discussion (b) of [8] – which uses a 2D mesh of axisymmetric elements in the plane ρ–x, having the dimension x eliminated using multi-point constraints. It is then supplemented by an approximate analytical solution for the circumferential drainage of the excess pore pressure (along θ), thus reproducing the 2D consolidation process observed in the plane strain set-up continuum FE model used in discussion (a) of [8].

A succinct comparison between these four models (two from [7] and two from [8]) is presented in Table 1. Within it, the low computation cost is obtained by minimising the "soil mesh dimensions", whilst the realistic response is achieved by maximising the other two parameters.

The model was written using symbolic programming in Mathcad [18], which provided the flexibility required for development and sufficient accuracy for proof of concept. All the results presented herein were obtained from this symbolic programming

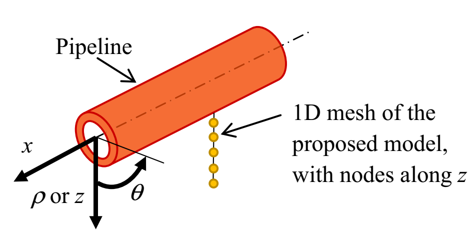

Fig. 1. Cylindrical coordinate system (ρ, θ, x) and vertical direction z; and 1D mesh of the proposed model.

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