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An effective stress analysis of partially embedded offshore pipelines: Vertical penetration and axial walking

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ABSTRACT

A study on quantifying offshore pipeline resistance during vertical penetration and axial walking is presented, based on coupled pore pressure and displacement finite element analysis with the Modified Cam Clay model. Following the validation of the numerical method against published centrifuge test results and limit analysis solutions, we present the findings of a detailed parametric study on the response of partially-embedded pipelines under vertical and axial movements, employing 2-D plain strain and full 3-D soil–pipeline models. Emphasis is put on practical findings, and on proposing simplified expressions for the estimation of the contact enhancement factor and of the equivalent friction factor, that can be used at least for preliminary design purposes.

1. Introduction

Deep water pipelines are either laid directly on the seabed or are further stabilised through constraining techniques, e.g. trenching, anchoring, or burial. The main objective of such costly constraining measures is to restrict pipeline axial and lateral displacements due to internal and external loads, i.e. temperature fluctuations and pressure variations. When the pipeline axial compressive load reaches some critical value, the pipeline becomes unstable and displaces in various directions – vertical (upheaval buckling), lateral (lateral buckling) or axial (pipeline walking) which can all jeopardise its structural integrity. The resisting force developed at the pipe–soil interface directly affects both lateral buckling and longitudinal expansion. Quantification of this force, both of its initial and steady-state value, is critical for the safe and economical design of pipelines. These aspects of pipeline axial movement have not been investigated in detail, though some remarkable studies have been published recently [1,2], providing new insight on this multifaceted problem.

A determining factor of pipeline resistance against both lateral buckling and longitudinal expansion is the pipeline embedment, resulting from the dynamic forces during touch-down and the static submerged weight of the pipeline. Studies of pipeline vertical penetration and embedment in soft clays involve classical plasticity analyses under vertical loading [3,4] and numerical analyses under combined vertical and horizontal loads with the finite element method [5,6], accounting for the effect of soil heave [7]. More recently, Martin and White [8] presented exact horizontal–vertical failure envelopes for "Wished-in-Place" (WIP) pipelines under undrained loading conditions via finite element limit analysis. Furthermore, Krost et al. [9] and Chatterjee et al. [10] published results of transient finite element analyses using elastic and elasto-plastic soil models, respectively, which focus on contact stress development along the soil–pipeline interface. All the above mentioned studies contribute towards our understanding of the mechanisms of axial resistance development on partially-embedded pipelines, which is influenced by the immediate and long-term distribution of contact stress components, an issue that is further investigated in this study.

As mentioned above, Randolph et al. [1] proposed a theoretical framework to predict the time-varying axial resistance of pipelines, based on a semi-analytical planar sliding model, which appears to be sensitive to the rate of shear strain, and the elapsed time after initiation of axial movement. The conceptual model proposed by Randolph et al. [1], substantiated by experimental results presented by White et al. [2], provides a solid basis for describing the mechanisms that govern the frictional behaviour at the pipeline–soil interface of partially-embedded pipelines. Yet, as also mentioned by Randolph et al. [1], more work is required to derive a universal model for analysing pipelines subjected to vertical and axial displacements, as far as the variation of its input parameters is concerned.

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This study attempts to shed some light on the mechanisms governing pipelines response during penetration and axial displacement, using a coupled pore pressure and displacement finite element model (named CPDFE hereinafter for brevity's sake) that takes advantage of the simulation capabilities of ABAQUS/Standard. This model can adequately describe the slow axial and vertical movement of pipelines, ignoring inertia effects but accounting for time dependent soil–pipeline interface behaviour, meanwhile allowing for the variation of excess pore pressure distribution at the interface and below to be directly taken into account in the estimation of the evolution of the contact normal force with time, which is critical for resistance force predictions.

Accordingly, the presentation can be divided into two parts: The first part focuses on the validation of the numerical model against experimental, analytical and other numerical solutions in terms of pipeline penetration resistance, soil–pipeline contact width and perimeter and surface heave profiles around a penetrating pipeline. In the second part, we interpret results of a parametric study for determining the axial resistance of partially embedded pipelines via a simplified expression. The factors that govern both the evolution with time and the ultimate value of axial resistance, as well as the limitations that should be considered in pipeline design, are outlined in this part. In this context, the second part of the study could be considered as an extension of the Randolph et al. [1] model, discussing their assumptions in the light of numerical results, and attempting to extend the practical applicability of their conceptual model by presenting the variation of its parameters with the soil properties and the embedment ratio.

2. Coupled pore pressure–displacement finite element model

We consider two different cases in this study, with respect to the pipeline construction procedure: "Wished-in-Place" (WIP) and "Pushed-in-Place" (PIPs) pipelines, referring to pipelines laid on a pre-trenched foundation, or penetrating into the seabed, respectively. To model PIP pipelines, a rigid cylindrical body is pushed into the soil to a target embedment depth, which results in generation of surface heave around the pipeline. For WIP pipelines, the pipe is positioned into its pre-embedment depth, and subsequently a vertical load equal to the submerged weight of the pipeline is applied as an external force. Both a two-dimensional plane strain model and a three-dimensional model are employed to simulate vertical and axial movement, respectively. Details on the numerical methodology are presented hereinafter.

2.1. Two-dimensional plane strain model for the simulation of vertical penetration

The geometry and finite element mesh of the 2-D model (Fig. 1a) corresponds to the plane strain problem of a pipeline resting on horizontal surface, assuming uniform soil conditions along the length of the pipeline. By taking advantage of symmetry, only half of the problem domain is simulated. We use 8-noded reduced-integration elements (CPE8RP) to simulate the foundation soil, whereas the pipeline is modelled as an impermeable rigid body (RB2D2 elements). Parametric runs using full-integration elements (CPE8P) to simulate soil response resulted in trivial discrepancies (less than 3%) in terms of bearing capacity prediction, compared to reduced-integration elements. By using full-integration elements, however, the predicted mode of failure in some cases is influenced by element locking. The reduced-integration formulation of elements with hourglassing control was thus employed in consequent stages of this study, as it exhibits superior performance in similar cases. Simulating the pipeline by rigid elements does not affect the accuracy of the analyses, since pipeline experiences negligible deformations in comparison to the soft clay.

The surface-to-surface contact formulation is used, with master and slave surfaces being the pipeline and the soil contact areas, respectively. The soil mesh in the contact area is more refined, to avoid significant penetration of the slave surface into the rigid body (master surface) and also to provide more accurate results in the area of interest. Two scenarios were considered in terms of the friction coefficient at the soil–pipeline interface: smooth (frictionless) contact ($\mu = 0$) and rough contact ($\mu = \infty$). In the case of rough contact, no slippage at the soil–pipeline interface is permitted. The frictional response of the contact interface is defined via the classical Coulomb friction model. Furthermore, the common "penalty" method of contact enforcement is employed to evaluate normal pressure at the contacting surfaces.

Effect of mesh size on the finite element predictions was addressed via a mesh sensitivity analysis, which was carried out to identify the optimum mesh density for the soil element domain. The results of this analysis are not presented here, to maintain the limits of the presentation.

The embedment ratio $E_R = w/D$ defines the initial embedment of the pipeline into the seabed (Fig. 2), where w is the initial depth of embedment and D is the diameter of the pipe, here $D = 0.8$ m. The pipeline is placed sufficiently far from the lateral and bottom boundaries of the model. Initial pilot analyses have shown that placing the lateral boundaries at distance equal to $4D$ from both sides of the pipeline, and the bottom boundary at a distance equal to $5D$ from the bottom of the pipeline (Fig. 1a) is sufficient to eliminate boundary interaction effects. Drainage is allowed only through the top boundary of the mesh during all analysis steps, by setting the total pore pressure equal to zero, while all other boundaries are modelled as impermeable.

Each analysis is run in three distinct steps. An initial geostatic step ensures equilibrium conditions. During this initial step, the hydrostatic pore pressure at the top boundary of the finite element mesh is assumed to be zero. Once the equilibrium is achieved, a vertical load equal to the pipeline submerged weight (per unit length) is applied on the WIP pipeline, with the duration of this step being 1 s. Alternatively, for the PIP pipeline case, the rigid pipe is pushed downward by applying a particular displacement, w, increasing from zero to its ultimate value within 86,400 s (1 day). This duration corresponds to $1.08D/k_{\max}$ and $1.08D/k_{\min}$, with $k_{\max}$ and $k_{\min}$ being the maximum and minimum value of soil permeability, respectively. Such a specific duration is selected so as to effectively cover both undrained and fully-drained response as the permeability of the seabed soil varies, as discussed in the following sections. This type of displacement-controlled analysis allows for the effect of soil heave to develop, and here $E_R = w/D$ is the penetration depth.

Once the pipeline self-weight is applied, during the second step of the analysis, the soil surrounding the pipeline is deformed, and excess pore pressure is generated. Time duration for the third, consolidation step is long enough so that the full consolidation settlement develops, and excess pore pressures dissipate. The initial time increment of the consolidation step is critical for the convergence of the solution, and is determined by the Vermeer and Verruijt [11] criterion, as:

$$\Delta t_{initial} = \frac{h^2 \gamma_w}{6E'k} \qquad (1)$$

where h represents the average element dimension, k is the soil permeability, and E' is the effective Young's modulus of the soil. The NLGEOM parameter is set to on during all analyses, to account for geometric nonlinearity effects in the solution.