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AXIAL LOAD DISPLACEMENT BEHAVIOUR OF A PARTIALLY EMBEDDED PIPE USING NUMERICAL ANALYSIS

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ABSTRACT

The current trend of pumping oil and gas from deep seabed resources requires pipelines to operate at elevated temperature and pressure. As a consequence, these pipelines experience significant expansions that affect the route stability by displacing the pipe axially on clay seabed, called axial walking. But, the literature covering axial walking phenomena is limited. There are some similarities of this problem to the axial deformation of a vertical pile in the ground, but at the same time, there are major differences. This paper presents a numerical methodology based on finite element method (FEM) to analyse axial walking behaviour of sea bed pipelines. However unlike piles, the presence of free surface and the change in pipe embedment, which are exclusive to axial waking behaviour, need to be accounted for in the analysis. Therefore, a full three-dimensional analysis was carried out using the commercial FEM program *ABAQUS*. The soil was assumed to behave elastically and the pipe was assigned with rigid elements. The interaction behaviour between the pipe and the soil was assumed to be perfectly rough to avoid any relative movements. A general closed form load displacement gradient was developed as a function of axial displacement, axial load, shear modulus, pipe embedment and pipe diameter.

Keywords: Offshore, pipeline, axial walking, FEM, seabed

1 INTRODUCTION

Extra-long offshore pipelines are increasingly being required to operate at elevated temperature and pressure to transport oil and gas from deep seabed resources. Consequently, the pipe wall experiences substantial thermal expansion and contraction along the pipe length. This tendency of pipe free expansion is partially restrained by the soil friction depending on the characteristics of pipe wall and the seabed soil. However, depending on the degree of the axial pipe-soil resistance, the pipe will either undergo substantial expansion along its axis and forms virtual anchors and buckles laterally, termed as axial walking and lateral buckling respectively.

In comparison to lateral buckling, the research into axial walking behaviour is less advanced where, the available literature only serves to predict the pipe breakout resistance under undrained or fully drained conditions (Oliphant & Maconochie, 2006, White & Randolph, 2007, Senthilkumar, et al., 2011a). Some field specific experimental results were reported by Brennodden and Stokkeland (1992), Dendani and Jaeck (2007). On the basis of these results, Brunton et al. (2008) proposed a generic pipe load-displacement behaviour which consisted of a peak and residual resistance as shown in Figure 1. Here, the pre-peak linear load-displacement behaviour is elastic and critical for the unloading recovery during a shutdown. Furthermore, the subsequent residual resistance corresponds to the maximum resistance that the pipe should overcome to begin plastic walking. A similar trend was observed for the pile t-z behaviour by Coyle and Reese (1966) that was later conceived by Kraft et al (1981) for the formulation of theoretical pile load-displacement behaviour. However, due to inherent differences in the pipe-soil interface behaviour as noted above, adaptation of such generic behaviour would require sound experimental understanding especially on the parameters of pipe embedment, diameter, rate of axial loading and soil shear strength (Senthilkumar, et al., 2011b).

Therefore, parallel to the currently undertaken experimental investigations (Senthilkumar, et al., 2011b), a detailed theoretical framework is required to establish the fundamentals of the pipe load-displacement relationship. For pile load analysis, Randolph and Wroth (1978) pioneered a linear elastic theoretical analysis of load-displacement behaviour with support from 2D FE analyses. This study has employed a concentric cylindrical approach in an elastic soil medium, where shear radius relationship of Equation 1 was identified to characterise the pre-peak pile movement.

$$\tau r = \tau_0 r_0 \tag{1}$$

where τ- shear stress, r- shear radius τ_0- shear stress at the pile surface, r_0-pile radius

In the current paper, consideration is given to the similarities between the pipe and pile surface geometry and the possibility of following an approach similar to that developed by Randolph and Wroth (1978) for piles. However, due to the partial embedment, 2D axis-symmetric condition cannot be directly used. Therefore, it is necessary to examine the stresses and displacement around the pile under 3D conditions.

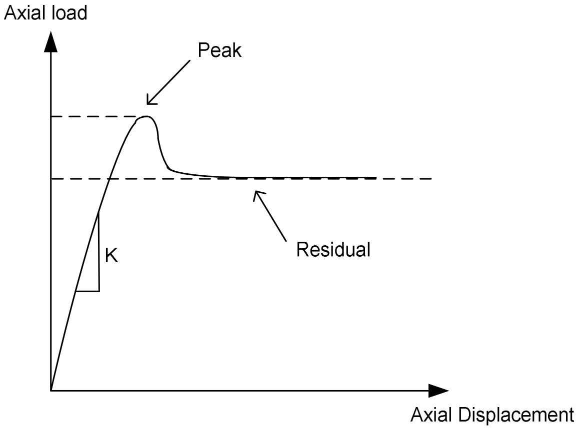


Figure 1. The generic pipe-load displacement behaviour

The current paper presents a 3D numerical method to characterise the axial load-displacement behaviour of partially embedded pipelines. The governing parameters are identified and non-dimensionally grouped to find possible relationship among them. Then *ABAQUS* (Dassault & Systèmes, 2009) finite element program is used for this analysis. On this basis, the pre-peak load-displacement behaviour is explained as a closed form equation involving governing non-dimensional parameters. The modelling techniques are further discussed for the most rigorous classification under drained and undrained conditions.

2 NON DIMENSIONAL ANALYSIS

Any generalized solution for the pipe axial displacement should be applicable over a wide range of pipe geometries and soil stiffnesses. Therefore, non dimensionless groupings of the governing parameters could lead to an optimum relationship.

The problem could be simplified to displacement of a unit length of a rigid pipe on an elastic soil medium. Therefore, the variables relevant to the pipe axial displacement are u-axial displacement, P-axial load per unit length, D-pipe diameter, G- shear modulus of the soil, v- Poisson's ratio, w- pipe embedment. Here, shear modulus (G) is preferred over Elastic's modulus (E) since the soil deforms primarily in shear and unaffected by either drained/undrained loading conditions. Accordingly the axial displacement of a partially embedded pipe on elastic surface could be explained by the following functional form.

$$u = f(P, D, G, v, w) \tag{2}$$

The relationship contains six influencing parameters. The independent parameters of diameter ([L]) and shear modulus ([ML^{-1}T^{-2}]) can be used to formulate three non-dimensional groups given in Equation 3.

$$\frac{u}{D} = \phi\left(\frac{P}{GD}, v, \frac{w}{D}\right) \tag{3}$$

These non-dimensional groupings were used to investigate the axial walking behaviour. The normalised axial displacement $\frac{u}{D}$ was compared to the corresponding normalised load $\frac{P}{GD}$ for varying normalised embedment $\frac{w}{D}$ of 0 to 0.5. The influence of Poisson's ratio was reported to be insignificant for pile load settlement behaviours (Randolph & Wroth, 1978). Despite this, the influence of values of 0.3 and 0.49 (not 0.5 as applicable to undrained conditions in order to maintain numerical stability) were investigated.

3 FINITE-ELEMENT MODEL

The axial pipe displacement was numerically investigated in 3D FEM continuum analyses using *ABAQUS.* The symmetry of the problem passing through the pipe centre was considered and only one half section of the pipe was modelled.

In order to avoid boundary effects, modelling dimensions of 50D and 100D were selected for the width and length respectively. The soil was assumed to behave linear elastically. Since pipe wall stresses and the associated deformation is not relevant for the analysis (due to extremely high stiffness of pipe material steel relative to the soil), the pipe was simply modelled using rigid elements. A wished in pipe approach where the pipe was pre placed to the required embedment prior to analysis was employed; thus the influence due to the presence of heave as in real situation was neglected. A structured mesh with identical cross section perpendicular to the pipe axis was selected. The typical mesh used for the analyses is shown in Figure 2. Here the interaction between the pipe and soil is defined as rough contact where any relative movement between the pipe wall and soil was prevented. Finally axial deformation of the pipe was simulated by applying an axial displacement boundary condition to the pipe up to a limit of the pipe diameter D.

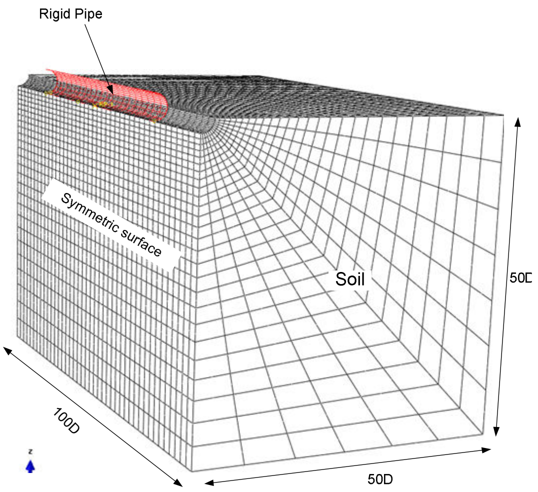


Figure 2. FEM mesh used for the analysis

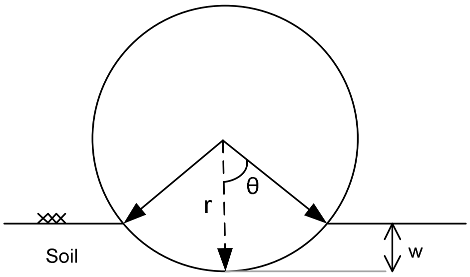


Figure 3. Cylindrical coordinate system

Despite the modelling was undertaken for a long pipe, the free ends of the pipe could still lead to boundary effects that would affect the final results. To minimise this effect, only the central section of the pipe length was selected for the interpretation. Further, due to the curved surface of the pipe geometry, the Cartesian coordinate system cannot be directly employed for the shear stresses at the pipe wall and along the soil depth. Alternatively a cylindrical coordinate system originated at the pipe centre (r and θ as shown in Figure 3) was employed for better representation. Here r is a constant equal to the pipe radius. The pipe embedment was varied from *0 to 0.5*D. And the results are only analysed for the axial shear stress τ_{rz} relevant to the problem at hand.

4 RESULTS

The authors could not find any representative pipe displacement results for comparison or benchmarking. Thus it was intended to benchmark the model against an equivalent pile model. As indicated before, the main difference of a pipe to pile is the presence of free surface due to the varying embedment. Therefore, as indicated in Figure 4, pile displacement analysis was carried out by assigning symmetry to the top and bottom surfaces of the model. In contrast, for pipe analysis, the top soil surface was assigned with a constrained free boundary condition to depict the free surface (Figure 4b).

The distribution of axial shear stress along with radius r is illustrated in Figure 5. Here, the shear stresses along the pile perimeter are the same. Figure 6 shows variation induced axial shear stress τ against increasing $\frac{1}{r}$. It should be noted that the linear correlation observed between τ and $\frac{1}{r}$ satisfies the shear-radius relationship of Randolph and Wroth (1978) given in Equation 1. Therefore, the model presents a valid 3D representation of the simple 2D axis-symmetric pile analysis.

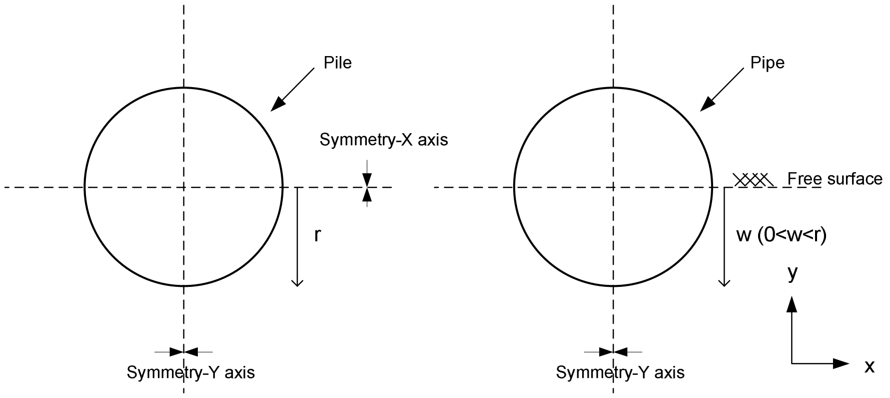
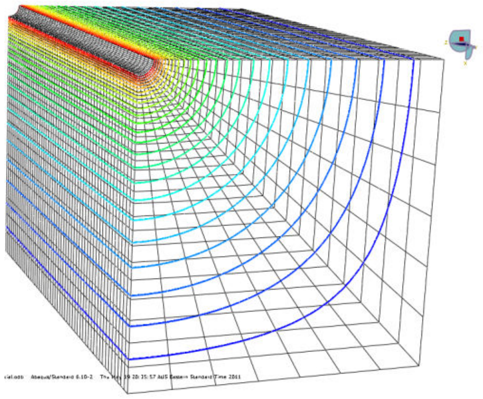


Figure 4 Boundary conditions (a). Pile and (b).Pipe



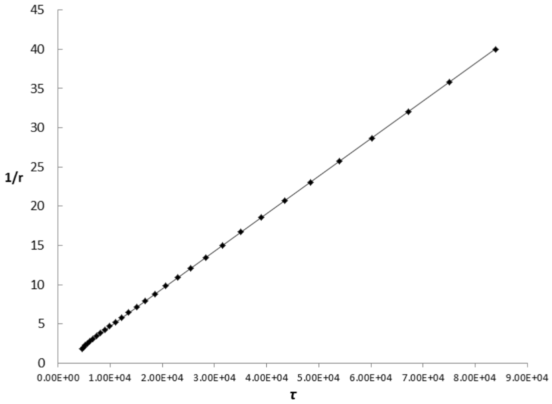


Figure 5 Shear-radius for pile loading *Figure 6 Shear Vs radius pile loading*

The above validated pile model was modified by removing the x-axis-symmetry constraint, and then used for the pipe analysis. The shear stresses around the pipe wall for embedments of 0.2D and 0.5D are compared in Figure 7. The pipe shear influence was found to be dependent on the selected θ plane and changes significantly as the free surface is approached. Furthermore, it is apparent that the pipe embedment of 0.5D has resulted in greater zone of influence in comparison to that of 0.2D. This zone will also define the corresponding axial shear stains around the pipe surface. This zone of shear influence is an important to quantify the shear induced pore pressure generation for drained and undrained axial displacements for plastic strains (for elastic shear strains no excess pore pressure generation (Muir Wood, 2004)).

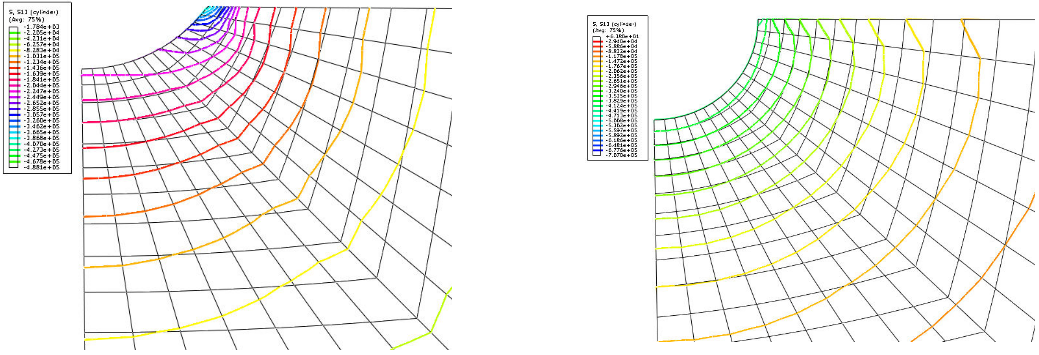


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Figure 7 Shear-radius pipe loading a.at 0.2Db. at 0.5D

The load-displacement behaviour for Poisson's ratios of 0.3 and 0.49 with varying pipe embedment is compared in Figure 8. In both instances, a linear relationship was observed to depict the pre-peak pipe load-displacement behaviour. However, the nearly incompressible medium represented by ν = 0.49 has demonstrated greater stiffness compared to that of with 0.3.

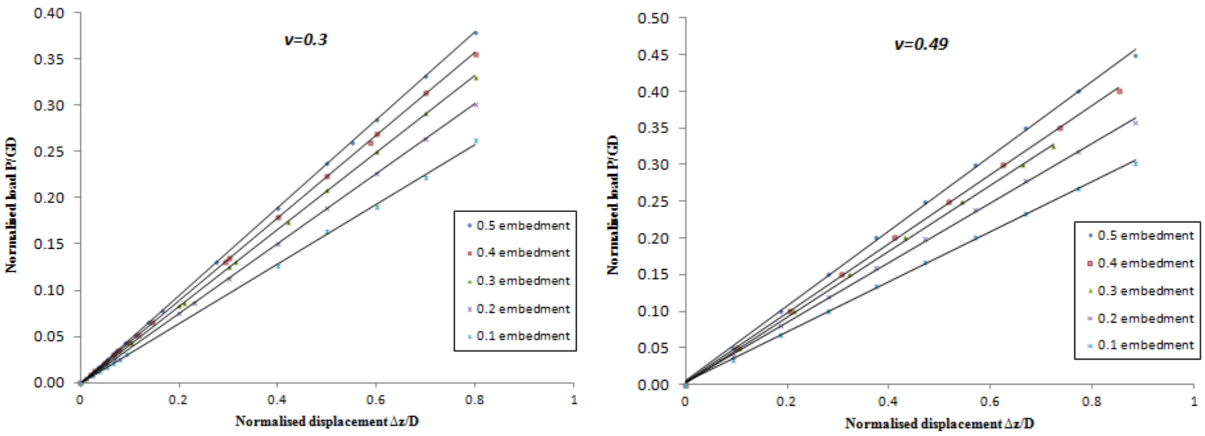

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Figure 8 a. Load-displacement behaviour $\nu = 0.3$. *b. Load-displacement behaviour* $\nu = 0.49$

Table 1 that summarises the rate of change in axial non-dimensional stiffness (K) for both instances. Regression analysis showed that the axial stiffness is proportional to the pipe embedment power of 0.25, as given in Equation 4. Based on this, the pre-peak pipe axial load-displacement behaviour and the axial stiffness can be derived as a closed form solution given in Equation 5.

Table 1. Change in K *with embedment*

$\frac{w}{D}$	$\nu = 0.30$	$\nu = 0.49$
0	0	0
0.1	0.321	0.342
0.2	0.376	0.407
0.3	0.415	0.450
0.4	0.446	0.471
0.5	0.473	0.512

$$K = \frac{P}{uG} \propto \left(\frac{w}{D}\right)^{0.25} \tag{4}$$

$$P = MGu\left(\frac{w}{D}\right)^{0.25} \tag{5}$$

Equation 5 explains the axial resistance of an expanding pipe as a product of the soil shear modulus, axial displacement and pipe embedment. Here M is a constant depended on the Poisson's ratio and the interaction behaviour between the pipe and soil. For the Poisson's ratios of 0.3 and 0.49, the M value is estimated as 0.56 and 0.61 respectively.

5 CONCLUSIONS

In this paper, the axial interaction behaviour of an as-laid pipe was studied using numerical methods. A 3D continuum finite element analyses was conducted to mimic the pipe axial interaction behaviour on an elastic soil medium. The results are studied for the non-dimensional groupings of the governing parameters u, P, D, G, υ, w

The pile analysis has indicated identical interactions around the perimeter where the shear stresses are distributed in manned of cylinders of equal radius. In contrast, the effect due to the presence of free surface is observed in pipes where the apparent shear influence has changed as the free surface is approached. Therefore, unlike pile analysis of axis-symmetric nature the pipe axial interaction behaviour was shown to be non-identical along the contact surface.

Further, the immediate pipe embedment was found to be affecting the axial interaction behaviour. This was quantified from the load-displacement behaviour of pipes on soil with Poisson's ratios of 0.3 and 0.49. In both occasions, a linear trend was observed between the non-dimensional force and non-dimensional displacement. However, the incompressible soil has resulted in greater resistance compared to that of soil with a Poisson's ratio of 0.3. Using these results, the pre-peak pipe axial displacement behaviour is explained in a closed form equation.

The elastic analyses for pipe axial walking have indicated the importance and the mutual dependency of the governing parameters. However further analysis, particularly to characterise the rate of axial displacement under drained and undrained loading would require a detailed coupled analysis with a representative material model. One possible suggestion is to use an elastic coupled analysis, similar to that of the pipe vertical settlement reported by Gourvenec and White (2010) and Krost et al.(2011). However, unlike pipe vertical behaviour that primarily fails under compression, the axial interaction is predominantly under the dominance of shear stresses. So the selected material constitutive model for axial behaviour should be capable to account shear induced pore pressures. In isotropic elastic medium however, the deviotoric component is absent and cannot be directly used for shear related pore water pressure generations. Therefore more advanced constitutive models, such as Modified cam-clay, need to be considered to better interpret the axial interaction behaviour.

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