Model testing to prove up existing theoretical models for subsea pipeline friction coefficients in purely undrained soil

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Abstract

The lateral friction factors used to assess the stability of subsea pipelines and flowlines have traditionally been taken from empirically based design codes. These codes have been developed from a relatively small data base and are therefore confined to limited material types and for limited loading conditions. A more accurate approach, using plasticity models based on fundamental soil mechanics has been previously developed. Experimental results which prove up the applicability of this approach for pipe-soil interaction in undrained conditions are presented. Components of this plasticity model, and friction coefficients for pipe-clay interaction were determined.

1.0 Introduction

Increasing amounts of offshore oil and gas projects, has led to extensive amounts of offshore pipelines being laid around the world. Recently, untrenched or unburied pipelines have become progressively more common, as it was found that a properly covered concrete pipe could be safely laid directly onto the seabed without the need for trenching (Moshagen and Kjeldsen, 1980).

However, untrenched pipelines are exposed directly to the hydrodynamic impact of environmental forces such as currents and waves. This makes the interaction between the pipe and the soil it sits on, increasingly important to understand. The resistance that the soil provides becomes crucial to the stability of the pipeline, especially during extreme loading events from currents.

This paper aimed to increase the understanding of the interaction of pipe loads on purely undrained soils. Prototype model testing was performed to prove up existing models of pipe-soil behaviour. In particular, this paper aimed to: 1) Define the yield surface of purely undrained soils; and from that; 2) Determine the friction co-efficient for pipe-soil interaction on undrained soil. By implementing a plasticity model, this paper also aimed to; 3) Define the flow rule for the assumed yield surface shape; and 4) Define the vertical load/displacement response.

2.0 Theoretical Background

The first pipe-soil interaction model used was that of the Coulomb frictional model which was formulated using static equilibrium of the form: $F_H = \mu_f (W_S - F_L)$, where μ_f is the pipe-soil friction coefficient and $(W_S - F_L)$ is the net submerged weight of the pipe. By estimating the maximum lateral force, minimum pipe design weights could be designed. However, after several experimental findings (eg. Lyons, 1973; Lambrakos, 1985), it was soon found that the Coulomb frictional model did not realistically represent physical pipe-soil interaction, and in particular did not address additional lateral resistance due to pipe embedment (Karal, 1987). This problem was addressed with the development of empirical models which followed the basic form of: $F_H = F_F + F_R$, where F_F is the resistance provided by friction and F_R is the additional passive resistance.

While many of these empirical models could accurately predict the ultimate lateral load under monotonic loading, there were still several flaws in this process. Firstly, the empirical models were only able to predict the ultimate lateral soil resistance. This limit state, however, only represented one point in the whole loading process, and thus these methods lost their efficiency in evaluating soil response corresponding to smaller loads (Zhang, 2001). Secondly, many of these models could not always explain the load-displacement relationship. For example, no explanation could be given as to why in some cases a pipeline moves vertically upward and in other cases downward under the action of a horizontal load.

2.1 Development of Plasticity Models

Following the problems with empirically based pipe-soil interaction models, there have been recent efforts to develop theoretically based pipe-soil interaction models. Such models have usually taken the form of incremental plasticity models, as it was found that this would be well suited to deal with the non-linearity and irreversibility of the deformation parameters (Nova and Montrasio, 1991). Most recently, a model proposed by Zhang (1999), aimed to improve the understanding of pipe-soil interaction. The model was directly applicable to unburied pipelines, and was built on a theoretical understanding of the physical mechanics of pipe-soil interaction.

Zhang's initial model was a single surface strain-hardening plasticity interaction mode, which is of a similar structure to the model adopted in this paper. The major components of this plasticity model that were investigated in this paper were:

- A yield or bounding surface, which is an envelope in combined V-H loading space that defines the yield of the soil-footing system.
- A hardening law, which is a description of the evolution of this yield surface.
- The flow rule, which is a function that defines the relative displacement vector at yield.

3.0 Testing Methodology

Model testing was performed at unit gravity on heavily over-consolidated clay soil using two model aluminium pipelines. The smaller pipeline measured 160mm in length and 20mm diameter, and the larger model pipeline was 350mm in length and 70mm in diameter. No attempt was made to model the pipeline weight, as this was effectively controlled by the actuator loading.

A total of 20 pipe tests were successfully performed on five Kaolin clay samples. The testing program comprised of three different types of tests to help achieve the experimental aims outline in Section 1. The different tests completed were:

1. Vertical load/unload tests, where the pipe was penetrated vertically into the clay and then unloaded. These tests helped determine the vertical load-displacement response.

2. Sideswipe tests, in which the pipe is penetrated to a particular depth. The vertical position is then held constant as the pipe is displaced laterally to a target displacement. As shown by Tan (1990), the purpose of these tests is to trace out the yield envelope under combined V-H loading. Further work (eg. Bransby and Randolph, 1998), has confirmed that the load path in swipe tests traces very close to the failure envelope in V-H loading. Both the small and large model pipes were used for sideswipe tests.

3. Probe tests, where after the pipe has been embedded to a certain depth, the vertical load is held constant while the pipe is loaded laterally. These tests help determine the direction of the plastic displacement vector and thus help outline the flow rule for the pipe-soil system.

4.0 Results

4.1 Vertical Load/Unload Tests

To evaluate the vertical load/displacement response, the pipeline was loaded vertically then unloaded to a lower vertical load. The results from this test can be seen in Figure 1.

The early part of the load-penetration curve shows a significant increase in the vertical load. This is due to an increase in the surface contact area, as well as the rapidly increasing undrained shear strength with depth. The unloading loops show an elastic stiffness that is approximately 50 times the plastic stiffness. After full surface contact area has been established at around ≈8mm depth (=0.4 z/D), the vertical load continues to rise, albeit slower, due to slower increasing shear strength with depth. It must be noted however, that in real applications, flow over and infill of the hole created by the pipe would change the vertical load registered on the pipe. As testing was conducted at unit gravity, these effects could not be modelled.

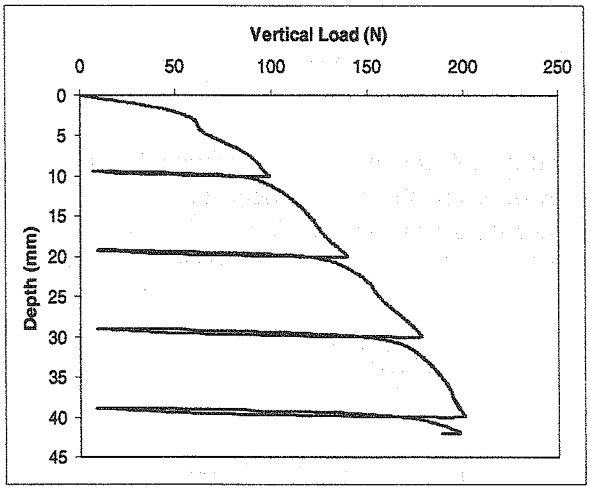

Figure 1. Vertical Load/Unload Test

4.2 Sideswipe Tests

To allow comparison between sideswipe tests of different embedments, and to determine the minimum yield surface, two adjustments had to be made to the loading paths traced out by the sideswipe tests. Firstly, all the tests were normalised against the maximum vertical load, V_{max}, to account for differences in loading levels. Secondly, to deduce the resistance caused solely by frictional effects, passive resistance had to be estimated and then eliminated from the horizontal load recordings. An estimate of passive resistance was taken as: $F_R = 2.571zs_u$ and was applied using the following adjustment:

$$H = H_{recorded} - \left(\frac{H_{recorded}}{H_{max}}\right)2.571zs_u \tag{2}$$

where z is the depth of the sideswipe test, and s_u is soil shear strength at that depth determined through T-Bar testing.

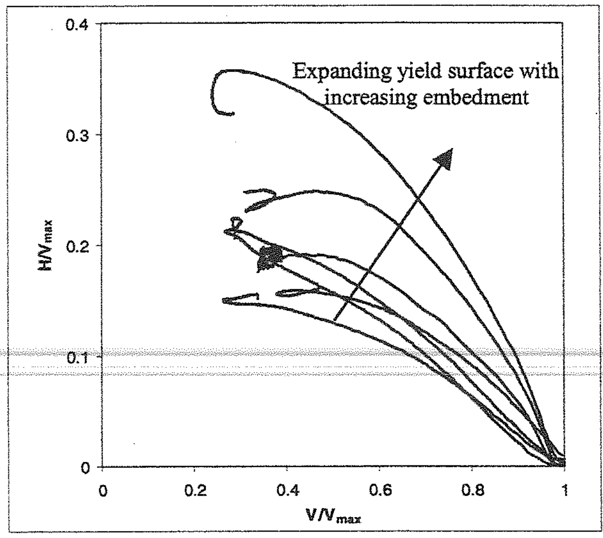

Figure 2(a). Normalised Sideswipe Results

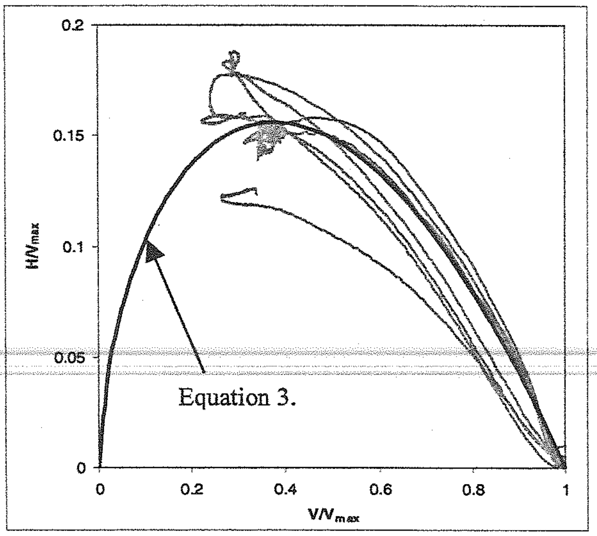

Figure 2(b). Normalised Sideswipe Results Adjusted for Passive Resistance

The yield surfaces, after being adjusted to eliminate passive resistance, can be seen in Figure 2(b). As can be seen, the paths traced out in V-H space are roughly parabolic in shape. The horizontal load reached a peak value of around 16% of V_{max} in combination with a vertical load at 38% of V_{max}. To model this behaviour, a yield surface of the following form was used to fit the loading paths:

$$f=\left[\frac{(\beta_1+\beta_2)^{\beta_1+\beta_2}}{\beta_1^{\beta_1}\beta_2^{\beta_2}}\right]^2\left(\frac{V}{V_{\max}}\right)^{2\beta_1}\left(1-\frac{V}{V_{\max}}\right)^{2\beta_2}-\left(\frac{H}{h_0V_{\max}}\right)^2=0 \qquad (3)$$

where $h_0 = H_{max}/V_{max}$ and β_1, β_2 are aspect ratios. Best fit parameters of $h_0 = 0.155$, $\beta_1 = 0.60$ and $\beta_1 = 0.99$ were used to fit the experimental results. Equation 3 was proposed by Martin (1994) in modelling the interaction of spud-cans on clay and as shown in Figure 2(b), this function agrees well with the results of the load paths traced out during the sideswipe tests.

The shape of this yield surface however is still uncertain at low V/V_{max} levels ($V/V_{max} < 0.3$). Previous theoretical models (eg. Brinch Hansen, 1970; Vesic, 1975) predicted that maximum horizontal capacity would be available for vertical loads down to $V/V_{max} = 0$ through a undrained sliding mechanism. However there has been much conjecture as to whether this is overly optimistic for purely undrained conditions (Martin & Houlsby, 2000). Further testing would be needed to determine the shape of the surface at low V/V_{max} levels.

4.3 Friction Factors

The friction factor for pipe-soil interaction is defined as $\mu_f = H_{max}/V$, where V is the vertical load corresponding to maximum horizontal load. Using the minimum yield surface that was determined, the friction factor for pipe-soil interaction on undrained conditions was calculated to be 0.41. This value is slightly larger than the value of 0.37 that was predicted by Zhang & Erbrich (2004) from their perusal of similar approaches on shallow foundations.

It is believed this difference is due to the estimation of passive resistance caused both by pipe embedment, but also heave around the pipeline during lateral movement.

4.4 Flow Rule

The results from the normally loaded probe tests show that the displacement vectors measured were not normal to the assumed yield surface. This variation from normality is known as non-associated flow.

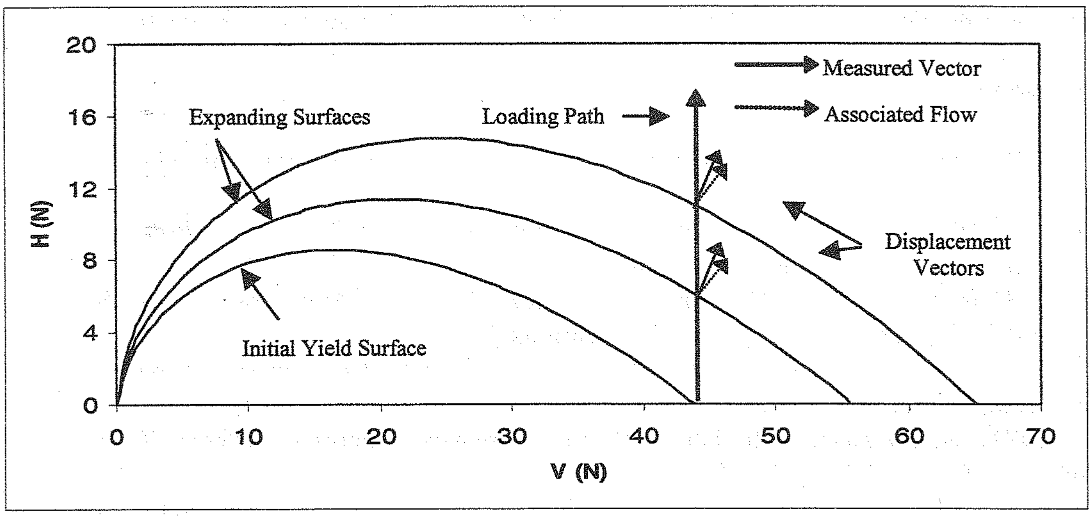

Figure 3. Expanding Yield Surfaces and Plastic Displacement Vectors

As can be seen in Figure 3, the measured vertical plastic displacement was larger than was predicted from plasticity theory. To model this, an empirical scalar multiplier, ζ, was introduced into the associated flow equation to adjust for the variations of the vertical plastic displacement vector from normality.

$$\begin{pmatrix} \delta x_p \\ \delta z_p \end{pmatrix} = \lambda \begin{pmatrix} \dfrac{\delta f}{\delta H} \\ \zeta \dfrac{\delta f}{\delta V} \end{pmatrix} \tag{4}$$

Similar results were also observed by Martin (1994), in the study of spud-can footings on clay. The expression for this flow rule also follows a similar form as expressed by Martin (1994), but with the value of the 'association parameter', $\zeta = 0.48$. By adjusting the associated flow equation, a separate plastic potential function does not have to be explicitly defined.

5.0 Conclusions

A plasticity model had been proposed in previous studies, for pipe-soil interaction in drained conditions (Zhang, 2001), and experimental testing has proved the applicability of this approach in undrained conditions. Analysis of these results has determined:

- A function, and its associated parameters, which describes the shape of the yield surface
- A form of hardening law, which describes the load-displacement response
- A flow rule to model the direction of the plastic displacement vectors at yield

From this plasticity model, an average value for a friction factor was calculated to be 0.41. This was marginally larger than the value of 0.37 that had been estimated from previous studies (Zhang and Erbrich, 2004). The variation of values is believed to be due to the estimation of passive resistance from pipe embedment and soil heave. Further work is needed to accurately determine the amount of passive resistance in the lateral loads to determine the friction factor for pipe-soil interaction.

6.0 References

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