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Technical Note

Application of force-resultant models to the analysis of offshore pipelines

Mark Jason Cassidy†

Centre for Offshore Foundation Systems, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009, Australia

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1. Introduction

Traditional approaches to soil-structure interaction of offshore pipelines have been based on bearing capacity methods and the use of numerous *ad hoc* empirical factors. These theories are adequate (if somewhat conservative) in predicting failure. However, the important issues of predicting plastic strains and displacements pre-failure are usually neglected. Furthermore, difficulties in implementing them within structural analysis programs limit their applicability when the integrated assessment of fluid-structure-soil interaction is paramount. An alternative methodology is the use of force-resultant models, where the entire foundation behaviour is encapsulated with a plasticity theory framework. This expresses the shallow foundation behaviour purely in terms of the loads on the foundation and the corresponding displacements. Importantly, geotechnical behaviour can be incorporated directly into the structural analysis as "point" elements.

2. Analysis of untrenched pipeline

Vertical self-weight is the dominant loading on offshore pipelines. During a storm, however, wave and current forces impose horizontal loads and possibly alter the vertical load. These combined loading and corresponding displacements are shown in Fig. 1. Based on centrifuge test data of a pipeline on calcareous sand a suite of plasticity models has been developed by Zhang (2001) and Zhang *et al.* (1999, 2002). The most simplistic is a single-surface strain-hardening model. This note concentrates on the implementation of the this model (known here as UWAPIPE) into the commercially available finite-element package ABAQUS (Hibbit *et al.* 1998).

† Professorial Fellow, E-mail: mcassidy@civil.uwa.edu.au

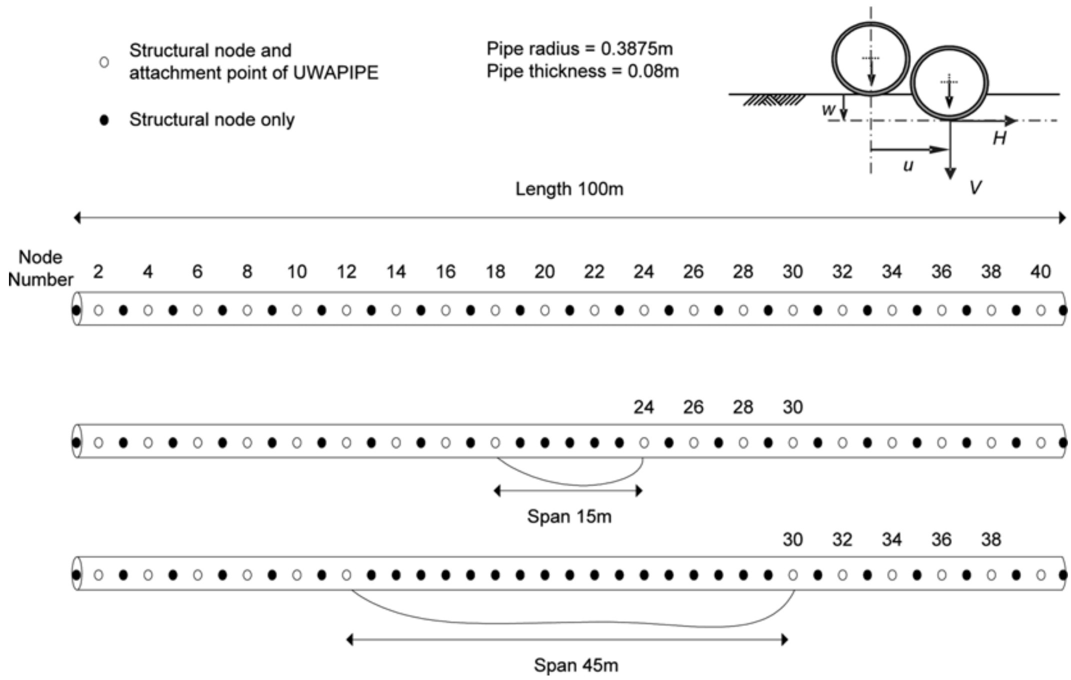

Fig. 1 Load and displacement sign convention and numerical model of pipeline system

3. Outline of UWAPIPE

UWAPIPE describes the behaviour of a circular pipe resting on calcareous soil. It is assumed that the pipe is rigid and is placed on a flat surface of homogeneous isotropic soil and the pipe is initially embedded into the soil under a specified vertical load, V_0. The model consists of four components: a yield surface, hardening rule, elastic response and flow rule, which are all related by the constitutive relationship. The components are described by the eight independent parameters of Table 1, with typical values given.

With loading applied incrementally, the UWAPIPE plasticity model computes updated tangent stiffnesses for each step. The hardening concept adopted is that at any given plastic penetration of

Table 1 UWAPIPE parameters

Parameter	Description	Typical value
k_{ve}	Elastic stiffness of vertical loading (per unit length)	7000 kPa
k_{vp}	Plastic stiffness of vertical loading (per unit length)	350 kPa
k_{he}	Elastic stiffness of horizontal loading (per unit length)	7000 kPa
μ_0	Shape parameter for the yield surface (at surface)	0.1
k	Gradient of the parameter μ with increasing depth	0~0.1625
μ_t	Shape parameter in the plastic potential equation	0.15
β	Shape parameter for the yield surface	0.06
m	Exponent in the plastic potential equation	0.18

the pipe into the soil, a yield surface of a certain size is established in vertical and horizontal loading space, and is expressed as:

$$f = H - 4\mu(V + \beta V_0)\left(1 - \frac{V}{V_0}\right) = 0 \tag{1}$$

where V_0 is again the apex of the surface, and μ and β are shape factors determining size. As the pipe is pushed further into the soil the surface enlargens (with V_0), and the relative shape slightly increases, due to increase in lateral reistance with imbedment (Zhang *et al.* 2002), by:

$$\mu = \mu_{surface} + \kappa\frac{w}{B} \tag{2}$$

where B represents the width of the pipeline. The 'backbone' curve of vertical bearing capacity against plastic vertical penetration can be determined either theoretically or empirically. The expression:

$$V_0 = \frac{k_{ve}k_{vp}}{k_{ve} - k_{vp}}w^p \tag{3}$$

where w^p represents the plastic vertical displacement is used here to evaluate the vertical capacity. As in standard plasticity theory, changes of load within the current yield surface result only in elastic deformation, expressed as:

$$\begin{pmatrix} dV \\ dH \end{pmatrix} = \begin{bmatrix} k_{ve} & 0 \\ 0 & k_{he} \end{bmatrix}\begin{pmatrix} dw^e \\ dh^e \end{pmatrix} \tag{4}$$

A loading path that intersects the yield surface also gives rise to plastic deformation, with the components of incremental plastic displacement being determined from the flow rule and hardening law. Non-association was observed in the experimental results and a flow rule defined by a plastic potential of:

$$g = H - 4\mu_t\left(\frac{V}{V_0} + \beta\right)^m(V_0 - V) = 0 \tag{5}$$

4. Implementation of UWAPIPE into ABAQUS and example analyses

UWAPIPE has been incorporated as a user subroutine in the commercially available finite element package ABAQUS (HKS 1998). It can be used as a one element force resultant model with a single nodal attachment onto any of the library of ABAQUS structural elements. The attachment point represents the positions where the pipeline is embedded into the soil, and the UWAPIPE user-element represents the behaviour of soil structure interaction at that position. A numerical structural model representing a 100 m pipeline has been configured using standard ABAQUS B31 structural elements. Initially, UWAPIPE models were "attached" at every second node as shown in Fig. 1. Structural properties were chosen to represent a section of the Goodwyn Interfield Pipeline on the North West Shelf of Australia. The geotechnical properties are as described in Table 1.

By removing UWAPIPE models free spaning, possibly due to an irregular seabed or even local scouring, could be analysed. In this note three cases are compared: no free span and spans of 15

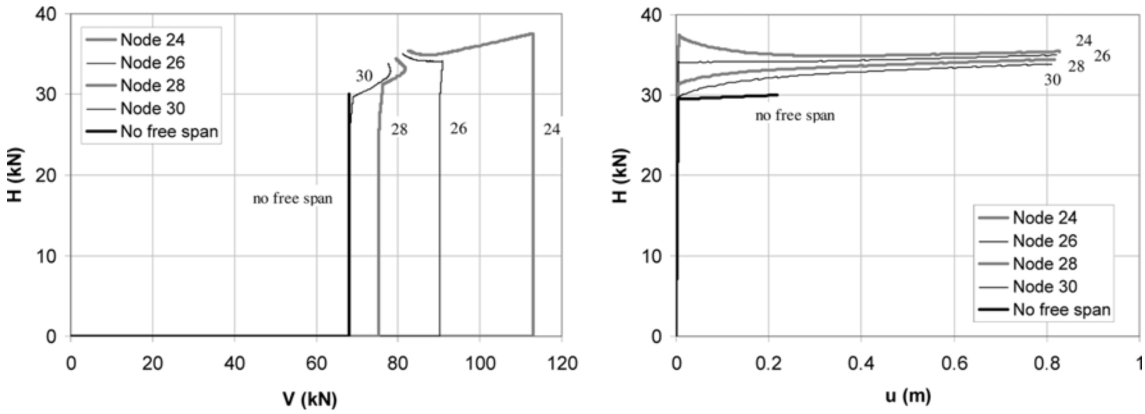

Fig. 2 Load and displacement for the no free span and 15 m span systems

and 45 m (Fig. 1). In all the cases horizontal loading of 6 kN/m was applied by slowly ramping up the load along the entire length of pipe (a simplistic loading model, though more sophisticated loadings could easily be applied).

Fig. 2 shows the changes in vertical and horizontal load that occurred at the foundation points along the pipeline section for the no span and 15 m span cases. Initially, more vertical load is applied to the soil at the nodes close to the onset of the span (nodes 24, 26 and 28). Node 30 has the same vertical load as the pipeline with no span (even distribution of vertical load). With application of the horizontal load, initial elastic behaviour can be observed. However, one by one the load states within the soil models touch the yield surface and non-linear elasto-plastic behaviour begins. Interestingly for the 15 m span case, this occurs progressively from the outer elements (node 30) to the closest (node 24). The additional vertical load in the inner nodes increased the footings initial elastic capacity. Once yielding occurs, there is a redistribution of the vertical load, with loading being shed from the nodes closer to the free span to the outer nodes. Eventually, a critical state is reached for all of the foundation elements and failure within in pipeline system predicted. This sliding failure can be observed at all of the nodes in the right-hand of Fig. 2.

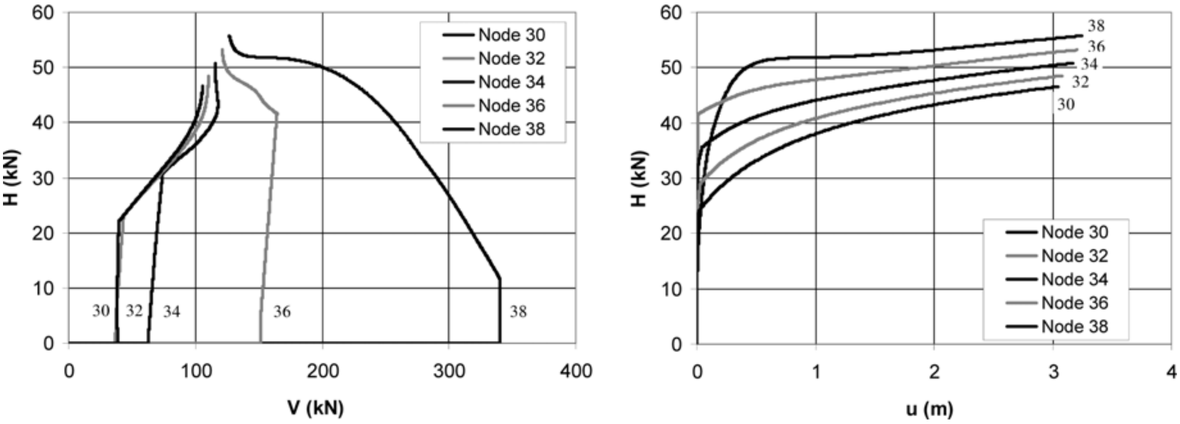

Fig. 3 Load and displacement for pipeline with a 45 m span

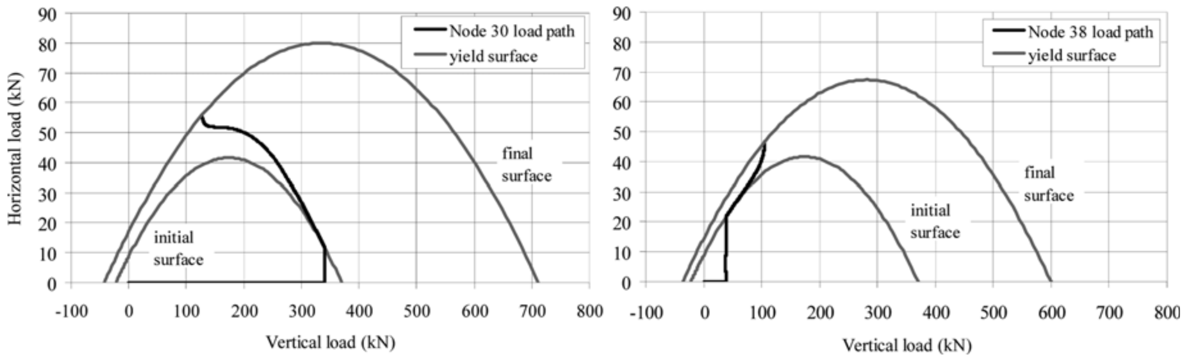

Fig. 4 Load paths of Node 30 and 38 showing the yield surface expansion

The results for the pushover of the 45 m span are shown in Fig. 3. In this case a different order of plastic behaviour was initiated, with the node closest to the span yielding first (node 30). This was due to the high vertical load at that position pushing the pipe close to a pure vertical bearing failure (and close to the apex of the yield surface). Although in this simulation a failure point has yet to be reached, significant horizontal movement has occurred. However, the increased capacity of the pipeline occurs as the pipeline embeds itself further in the soil. The expansion of the yield surface is illustrated in Fig. 4 for the inner and outer nodes 30 and 38. The load paths can be seen to diverge once it touchs the initial inner yield surface. In this case, the surfaces expanded to V_0 = 711.5 and 599.4 kN for nodes 30 and 38 respectively.

Acknowledgements

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