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Seabed Characterisation and Models for Pipeline-soil Interaction

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Pipelines and flowlines represent major cost items in the development of deepwater fields. Accurate modelling of the axial and lateral pipe-soil resistance can lead to significant cost reductions by optimising design. Critical design issues include axial motion, or walking, of pipelines due to cyclic thermal changes, lateral buckling due to thermal expansion, and fatigue damage to risers in the touchdown region. Traditionally, interaction between a pipeline and the seabed has been simplified into frictional models for axial and lateral resistance during walking or buckling. Improving these models is a priority, but is hampered by difficulties in characterising the behaviour of very low strength, near-surface, seabed soils, and by a lack of detailed understanding of the soil mechanics of pipe-soil interaction. The cylindrical geometry of a pipeline invites comparison with the behaviour of tubular piles. Recent advances in pile design methods generated by considering the underlying soil mechanics indicate that the same potential exists for improving the understanding of pipeline behaviour. This paper describes recent advances in measuring the low shear strengths associated with near-surface seabed soils, using both in situ methods in the form of cylindrical (T-bar) and spherical penetrometers, and laboratory shear tests at very low effective stresses. The relationship between penetration resistance and the vertical and lateral resistance of pipelines is explored, taking account of the depth of burial and the cycles of movement. New approaches for assessing the axial and lateral resistance of on-bottom pipelines are described. Future trends and recent developments are summarised.

INTRODUCTION

New offshore oil and gas fields are being developed at increasing distance from land, and in increasingly deep water. As a consequence, the cost of in-field flowlines and pipelines exporting product to shore is of growing significance in the overall field development. In turn, this has prompted generic and site-specific studies for the improvement of design models in an effort to reduce costs without compromising reliability. At shallow and moderate water depths, the critical geotechnical design issues are generally associated with the pipeline's lateral stability under wave and current action. In deep water, however, the most critical design issues are more typically pipeline buckling and so-called axial walking or ratcheting, associated with thermal expansion and contraction of the pipeline with successive startup and shutdown cycles.

In deep water, it is rare for pipelines to be deliberately embedded, for example by trenching or ploughing. Instead, they are laid on the seabed, embedding by a certain amount through a combination of self-weight and the additional contact stresses acting in the touchdown zone during the laying operation. The amount of embedment, or penetration of the seabed, must be estimated in order to assess the in-service resistance to axial and lateral motion. For pipeline diameters in the range of 0.3 to 0.8 m, and seabed penetration by perhaps 20% to 80% of the diameter, the seabed properties in the upper 0.1 to 0.7 m are crucial for design calculations. Accurate characterisation of the seabed at such shallow depths is challenging, not just because of the very low shear strengths exhibited by most deepwater deposits, but also because of the very low effective stress levels (a few kPa only), hence material response that falls outside the common experience for geotechnical design.

An overview of pipeline geotechnical design has been provided by Cathie et al. (2005). Additionally, a series of papers presented at the 2006 Offshore Technology Conference (Brown et al.; Brunner et al.; Bruton et al.; Carr et al.; Mebarkia) summarises current industry practice regarding the geotechnical design of deepwater, high-temperature and high-pressure pipelines. A recent paper by Bruton et al. (2007) demonstrates the significant influence of pipe-soil interaction on walking and lateral buckling behaviour.

Over the last decade, advances in understanding have come from joint industry projects such as SAFEBUCK (www.safebuck.com, Bruton et al., 2006) and HOTPIPE (Spinazze et al., 1999). The SAFEBUCK JIP has included extensive physical modelling for the exploration of pipeline-soil interaction during penetration, axial shearing and lateral motion under monotonic and cyclic displacement paths.

This paper focuses on the fundamental aspects of pipeline-soil interaction under different modes of deformation, rather than on the overall design, and is restricted to fine-grained (cohesive) clay soils, as are typically found in deep water. Recent developments in soil characterisation techniques for the upper metre or so of the seabed are reviewed, and an attempt is made to link the resisting forces between pipeline and soil to strength data, through the use of simple models—including plasticity limit analysis—based on the observed deformation mechanisms.

PIPELINE GEOTECHNICAL DESIGN ISSUES

Before addressing the different modes of deformation during pipe-soil interaction, the main design issues are discussed.

Embedment During Laying

The degree of penetration of the pipe into the seabed is fundamental to assessing the lateral resistance, since the amount of passive resistance provided by soil in front of a translating pipe is affected strongly by embedment. As shown below, the axial resistance is also affected, because of what may be loosely referred to

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