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The effect of buried fibres on offshore pipeline plough performance

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ABSTRACT

Ploughing is a technique often used to bury offshore pipelines in the seabed. During this process the operator must ensure that a sufficiently deep, level trench is produced while towing the plough with the available bollard pull of a suitable trenching support vessel. This paper reports experimental work investigating the effect that encountering fibres or reinforcing elements such as buried tree branches in the soil (e.g. relict debris from deltaic flood washout) may have on the ploughing operation. It is shown that fibres in soil can have a reinforcing effect and hinder plough progress by both increasing tow force and leading to potential 'ride-out' of the plough (significant loss of trenching depth). This behaviour is correlated with the percentage of fibre reinforcement volume in sand and a simple method is provided to estimate changes in tow force and plough inclination during ploughing operations.

1. Introduction

Offshore oil and gas pipelines are often buried below the sea bed to typical depths of 1.2–2.5 m (depth to the base of the pipeline). This provides protection from fishing activities and hydrodynamic loading. If the trench is subsequently backfilled, upheaval buckling due to thermal expansion on commissioning can be prevented and the increased thermal insulation from the soil can reduce pipeline coating insulation requirements with consequent reduction in fabrication costs (Morrow and Larkin, 2007). Pipelines can be buried by either creating a trench before the pipeline is laid (pre-lay trenching) or after it has been laid (post-lay trenching). One common method of post-lay pipeline burial is to use a pipeline plough towed along the seabed by a support vessel. This uses a wedge-shaped blade (known as a share) to cut the soil and form the trench, which can be backfilled using a backfill plough, as required.

Typically pipeline trenching operations are preceded by a route assessment where the contractor estimates the likely tow forces and speed of ploughing whilst burying a pipeline at a particular depth, so that the duration of operations can be determined. In sands, the required tow force is normally attributed to interface frictional resistance between the plough and the sand, a passive or static resistance akin to that experienced for onshore thrust blocks and a rate dependant resistance linked to the dilation of the soil (Cathie and Wintgens, 2001). The latter two components of resistance have the potential to increase significantly with increasing depth of ploughing (Palmer, 1999; Lauder et al., 2012), thus even when ploughing at depths of 1.5–2.0 m in fine dense sands a multi-pass approach to installation may be considered to avoid very low ploughing rates for a given tow force. This approach involves creating an initial trench which is shallower than the final burial depth of the pipeline (say 1.2 m on the first pass) and a second pass to extend this to the final burial depth (Machin, 1995). While a cost–benefit analysis can be conducted to compare multi-pass and low-speed single-pass strategies, there will be significant impact on cost and time in circumstances where the need for multi-pass has not been anticipated.

One other technical issue that needs to be considered during ploughing is maintaining a consistent trench depth (Morrow and Larkin, 2007) and minimisation of vertical out-of-straightness (OOS) of the pipeline. OOS is of concern as this may result in portions of a buried pipeline that are more at risk of upheaval buckling (UHB). It would be anticipated that changes in soil resistance would increase or decrease the tow force but due to moment equilibrium the plough tends to maintain a relatively constant tow force by adjusting its ploughing depth to accommodate the changes (Zefirova et al., 2012). This response is referred to as the 'long-beam' principle (Palmer, 1999). This natural tendency to change depth can be overcome to some extent through "live"

Abbreviations: APP, Advanced Pipeline Plough; OOS, out of straightness; UHB, upheaval buckling; SS, steady state

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adjustment of the skid height at the front of the plough but the ability to limit OOS is then very much operator and plough response dependant. Thus in certain soil (e.g. very dense fine silty sands, fibrous soils) or geohazard conditions (e.g. sandwaves) there is uncertainty about a plough's ability to accommodate the resulting change in depth and the most appropriate approach to ploughing.

While geohazards (specifically sandwaves induced by the bed regime) have been investigated before (Bransby et al., 2010), the effect of fibrous soils or organic inclusions on ploughing has not received attention. Such features can occur due to the presence of fibrous soils such as peat or in the case of recent buried deltaic flood washout out deposits, where large and competent woody inclusions have become buried. The effect of such soils or soil inclusions on ploughing progress, strategy and the final trench formed is unclear. For instance, DNV (2014) suggests that fibrous material such as peat can be challenging for any burial technique but little further guidance is offered. Conversely, Beindorff and van Baalen (2013) suggest that ploughing is not hindered by cobbles, stones, (fibrous) peat or clay layers. It would be anticipated that any kind of competent fibrous inclusion in sand in the right proportions and orientation would have the potential to effectively reinforce the soil (Jewell and Wroth, 1987). This has been shown through many previous studies particularly those aimed at reducing earthquake liquefaction potential (Diambra et al., 2013) and investigations of root reinforcement of slopes through laboratory element (Mickovski et al., 2010) or scale model tests (Sonnenberg et al., 2012).

This paper aims to investigate the effect of reinforcement on ploughing operations. This form of inclusion has been chosen as there is anecdotal evidence of fibrous deposits or discrete inclusions resulting in the unanticipated multipassing of pipeline shore approaches. Unfortunately, although this is a real geohazard, such problematic ploughing operations are not recorded in the public domain. In order to investigate this further scale model plough tests were undertaken in fibre-reinforced sand with various fibre contents to explore the effects on plough response and to determine critical reinforcement levels where such effects become significant. Element testing of fibre-reinforced soil was also undertaken to complement the model testing. These combined data were used to develop simple modifications for incorporating the effects of soil reinforcement into existing plough performance prediction models.

2. Experimental plough modelling

A simplified, reduced scale model (1:25, i.e. scaling factor $N=25$) based on the Advanced Pipeline Plough (APP) currently operated by DeepOcean Ltd. was used to perform 1-g model ploughing tests (Fig. 1). The full scale APP has a mass of 190 t and is 17.5 m long, 10 m wide and 8.5 m high (note these dimensions include peripheral plough infrastructure which is not included in the model plough as these elements do not affect the ploughing process or its modelling). One of the features of the APP is its forecutter which sits ahead of its main share and is designed to reduce tow forces. For these model tests the forecutter was removed as pipeline ploughs often operate with or without forecutters (Lauder, 2011). Previous studies of model ploughing (e.g. Lauder et al., 2013) with particular focus on scaling (Lauder and Brown, 2014) have developed scaling factors which can be used to convert the results of model testing to prototype values. In this case, the key dimensions that are scaled are lengths or distances which are scaled up by multiplying by N and forces which are increased by N^3. As the tow forces measured during a test are either proportional to the projected area of the plough multiplied by a shear stress or due to soil self-weight, in either case, the model forces will need to be multiplied by 25^3 to recreate full scale behaviour. This is because the area will be reduced by 25^2 and the shear stress by a factor of 25, thus the model tow forces will be $1/25^3$ $(=(1/25^2)\times(1/25))$ times the field tow forces (Brown et al., 2006). The validity of this assumption has previously been verified by Lauder et al. (2013) by comparison of model plough performance over a range of scales (modelling of models using scales 1:50, 1:25 and 1:10) to full scale plough models (Lauder and Brown, 2014) derived from field performance (Cathie and Wintgens, 2001). The submerged weight of the reduced scale plough model was 122.6 N.

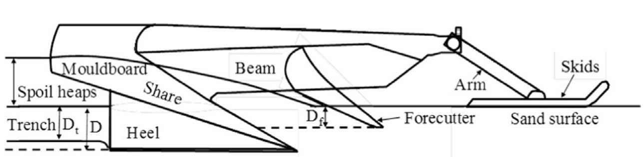

Fig. 1. Schematic of model pipeline plough with forecutter shown during trenching.

2.1. Model plough test set-up

The 1:25 scale tests were undertaken in a 2.5 m × 1.5 m × 0.75 m steel container (Fig. 2a) which included an automated slot pluviator for soil preparation and a long stroke hydraulic actuator to move the plough carriage (Fig. 2b). The tests were conducted in saturated unreinforced/reinforced soil at a constant rate of forward plough movement (i.e. towed) to study the effects of increasing fibre reinforcement volume ratio on plough performance. A 100 mm deep gravel layer covered by a geotextile was placed at the base of the container to allow saturation of the sand bed from the base up.

2.2. Sample preparation

Artificial fibres were added to the sand to reflect the natural seabed reinforcement. The fibres used in the testing as reinforcement consisted of STRUX 90/40 (Grace Construction Products Limited)

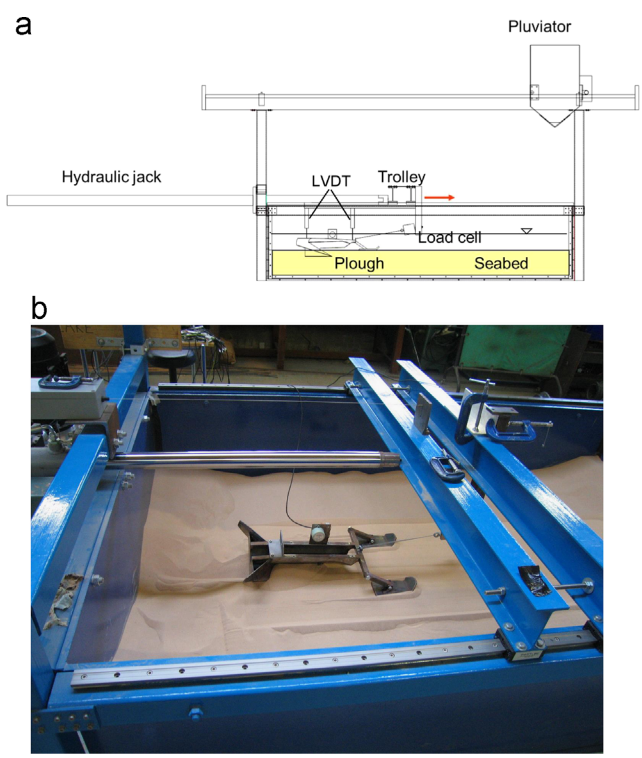

Fig. 2. (a) Schematic of apparatus showing a cross section through the sand bed with a 1:25 scale plough installed. (b) Image showing a preliminary dry plough test using the 1:25 scale plough in unreinforced sand (sand bed is not saturated and plough depth measurement apparatus shown in (a) has been removed for clarity).