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The performance of pipeline ploughs traversing seabed slopes

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ABSTRACT

Ploughing is a method used to bury pipelines beneath the seabed. In this method, a large purpose built plough is pulled by a support vessel to create a trench into which a pipeline is lowered. The soil that has been removed is then placed or back filled over the pipeline to provide thermal insulation, protective cover and to prevent upheaval buckling (UHB) due to pipeline thermal expansion. The majority of previous research effort has focussed on the behaviour of ploughs on level seabeds and has not investigated common geohazards such as sloping seabeds. There is also limited guidance available to industry on the limitations of ploughing on slopes. This paper reports a series of experimental tests conducted to investigate how ploughs may behave when seabed slopes are encountered and ploughing has to traverse cross-slope. The results show that ploughing operations can still be undertaken when traversing a slope but that the efficiency of operations is reduced with increasing slope inclination, leading to a reduction of trench depth and spoil heap sizes on steeper slopes. This may result in reduced pipeline cover depths on slopes if these effects cannot be mitigated.

1. Introduction

Offshore pipelines are often buried within the seabed in order to protect them from fishing activity, boat anchors, environmental loading and to mitigate upheaval buckling (UHB). One method of post-lay burial is to create a trench into which the pipeline is lowered by pulling a large "V" shaped plough through the seabed (Palmer et al., 1979) using a trenching support vessel. Burial of the pipeline can be achieved by running a backfill plough over the pipeline route and pushing the spoil heaps, generated at the edge of the trench, back into the trench (Cathie et al., 1998). The method has the advantage of being able to bury a plough in a wide range of soil conditions, in a continuous process with little mechanical intervention. Typical ploughing rates may be in the range of 150–1000 m/h, but will be slowed if more difficult soil conditions are encountered such as dense, silty sand (Cathie and Wintgens, 2001) where mobilisation of the maximum support vessel tow force (bollard pull) will limit the rate of progress. To avoid slow progress (or reduce tow force) it is normal in these soil conditions to limit the ploughed depth to 1.5 m below seabed. Where deeper ploughing is required a multi-pass approach is often used to avoid these issues (Machin, 1995) or the use of new generation high bollard pull vessels.

Following installation, the pipeline is likely to be used to transport high-temperature hydrocarbons. This causes a temperature change which may lead to upheaval if insufficient vertical soil restraint is supplied by the soil cover (Morrow and Larkin, 2007). Upheaval buckling is exacerbated with initial imperfections of the pipeline due to 'out-of-straightness (OOS)' (i.e. a lack of level trench leading to reduced soil cover) of the trench base (Cathie et al., 2005). Consequently, the required depth of cover is dependent on the properties of the soil backfill and the out-of-straightness achieved during trenching. The out-of-straightness may be significantly influenced by the plough encountering various seabed geohazards such as sand waves or sloping seabeds for instance.

The current understanding of offshore pipeline plough behaviour has been gathered from small-scale beach tests (Grinsted, 1985; Reece and Grinsted, 1986), back-analysis of ploughing projects (Cathie and Wintgens, 2001) or by laboratory testing at various scales (Bransby et al., 2005; Brown et al., 2006; Lauder et al., 2013). Initial attempts have been made to investigate behaviour using numerical simulations (Peng and Bransby, 2010) but these efforts are limited by the large strain nature of the problem (Cortis et al., 2017) or have focused on structural

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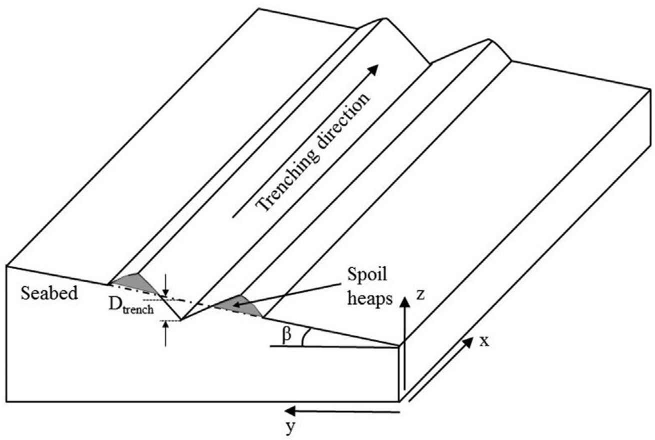

Fig. 1. The geometry of the trench and slope.

performance of the plough (Wang et al., 2015). Beach tests and back analysis of trenching projects have the uncertainty of unknown soil properties (e.g. typical geotechnical site investigation may only involve one cone penetration test (CPT) per kilometre for a pipeline route) and the difficulty of deconvoluting the elements of plough behaviour. Alternatively, 1 g scaled laboratory simulations and testing has the advantage of allowing careful control of both soil conditions (e.g. soil types, relative density, surface profile) and plough settings (e.g. plough depth and velocity) to allow parametric study, albeit introducing the need to consider scaling issues (Lauder and Brown, 2014). By combining these and other findings there is relatively good understanding of the force-trench depth-velocity relationships in uniform, level seabed conditions (Palmer, 1999; Cathie and Wintgens, 2001; Lauder et al., 2012, 2013).

To date though very little work has been carried out examining the effect of geohazards for example either non-uniform seabeds (i.e. layered soils) (Bransby et al., 2005) or non-level seabed surfaces on pipeline plough performance. The study of non-level or inclined seabeds has previously focused on the investigation of the performance of ploughs in sand wave fields (Allan, 2000; Chen et al., 2001; Bransby et al., 2010) but has not considered seabed slopes. There is little current guidance in the public domain on the offshore industry's approach to ploughing on slopes (down or across) or how decisions are made on the viability of ploughing on slopes. Anecdotal evidence suggests that normally cross slope ploughing on slopes up to 5° does not pose any significant risk to operations but that at slopes steeper than this specific assessment of viability is required. With this apparent lack of guidance to allow industry to make informed decision making on cross slope ploughing (which might be encountered on continental slopes or in smaller geohazards, e.g. pock marks, iceberg scour etc.). The response of ploughs traversing slopes has been investigated by performing a series of 1/50th-scale laboratory tests in which the slope angle was varied from 0 to 30°. This paper reports the experimental methods used, the results obtained and discussion of implications for ploughing practice.

Table 1
Slope test conditions and average results obtained for shallow depth ploughing conditions.

Slope angle, β (°)	Plough depth (mm)	Trench depth (mm)	Tow force (N)
0	20.4	19.8	8.0
5	23.4	19.7	8.8
10	22.4	12.5	8.7
15	22.9	14.8	8.2
20	22.0	11.9	8.5
25	22.9	14.7	8.6
30	25.7	12.2	8.5

Table 2
Slope test conditions and average results obtained for medium depth ploughing conditions.

Slope angle, β (°)	Plough depth (mm)	Trench depth (mm)	Tow force (N)
0	28.1	28.0	11.6
5	29.9	24.8	11.8
10	28.2	17.6	10.6
15	26.9	11.3	9.8
20	27.6	13.1	10.0
25	26.9	10.2	10.1
30	31.6	10.3	9.3

2. Experimental plough modelling

2.1. Introduction

Before presenting the experimental methodology, the conditions investigated in the experiments are first introduced. A pipeline can cross a slope in three ways: (i) by traversing it, (ii) by going directly up or down the slope line, or (iii) by going obliquely up or down and across the slope. Clearly, the third case is the general one, where an angle of incidence to the slope fall line could be used to define all cases. Case (ii) is likely to be the worst in terms of changes in tow force as tow forces are likely to increase with slope angle if going uphill. Case (i), traversing the slope is likely to give the biggest problems in terms of plough roll, spoil heap stability and availability for back filling and this is studied in this paper. The typical geometry and definition of terms for the problem is shown in Fig. 2. The main performance indicators investigated were the influence of slope inclination on tow force, plough depth and position, trench depth and position and the availability of spoil for backfilling. Seven different slope conditions were studied corresponding to slope angles, β = 0, 5, 10, 15, 20, 25 and 30° (Tables 1 and 2). It is acknowledged that a 30° slope angle may be considered too steep for ploughing in practice but this high slope angle was adopted to explore the extremes of behaviour and to investigate plough performance when the slope angle is close to the critical state friction angle of the soil.

Apart from varying the slope inclination the effect of initial plough depth was also considered. This can be fixed on the model ploughs at the beginning of testing (Fig. 2) by changing the inclination of the mounting arm for the front skids. In this study this was set at the beginning of each test to allow two different initial plough settings to be considered resulting in average plough depths of 20.36 mm and 28.07 mm defined for the flat sea bed case. Where plough depth is defined as as the vertical

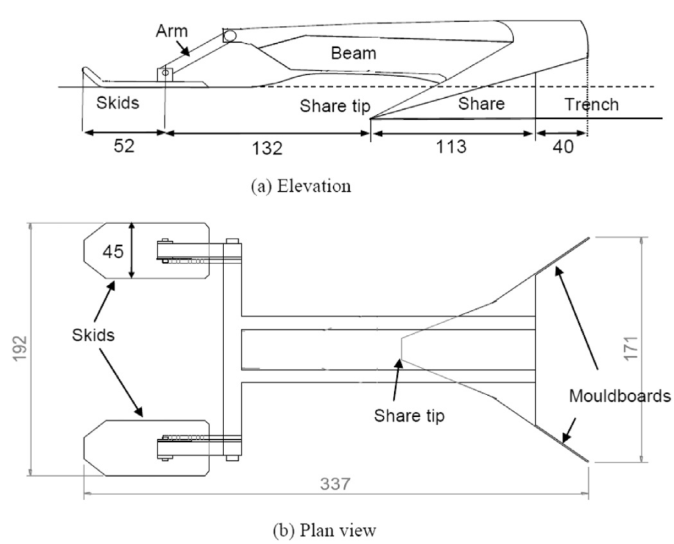

Fig. 2. Schematic of the model plough geometry. Dimensions in mm.