

Improving seabed cable plough performance for offshore renewable energy

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ABSTRACT: Seabed ploughing plays an important part in providing protection to subsea cables that connect offshore renewables, and the process represents a significant portion of the overall installation cost. Current models for predicting the required tow forces for seabed ploughs are based on semi-empirical methods as conventional geotechnical finite element analysis is not suited to modelling this process due to the large deformations involved. The project described in this paper aims to develop a new material point method numerical modelling software to predict seabed plough response, which will enable new designs to be optimised. This will be validated against physical modelling, a part of which is the focus of this paper. This includes both 1g and centrifuge testing as well as new techniques such as 3D soil surface scanning. The testing also provides insights into share geometry influences on plough behaviour, and will allow improvements to existing empirical models.

1 INTRODUCTION

1.1 Seabed ploughing

As the need for renewable energy increases, offshore renewables from wind, tidal and current driven devices are becoming an increasingly important energy source.

Substantial investment has been made in the development of the technologies required to harness this energy in a cost efficient manner. However, the challenging environment means that offshore energy is still more expensive to produce than either on-shore resources or fossil fuels. Given that cabling costs for connecting offshore wind turbines represent

9 % of the total installation costs (Renewables Advisory Board, 2010), this represents an area where there is scope for significant improvements in the efficiency of installation and subsequent cost savings due to the uncertainties that currently surround the process.

To provide protection from offshore hazards such as seabed trawling (Ivanovic et al, 2011), anchor damage and iceberg scour (Arnau and Ivanovic, 2015), offshore subsea power cables are required to be buried to depths of up to 3 metres. Seabed ploughing has been used extensively in the oil and gas industry to provide protection for subsea pipelines with diameters of up to 1.5 metres, and this has been the main focus of research to date (Lauder et al, 2012, Lauder et al, 2013). This is done by using a seabed pipeline plough to create a v-shaped trench into which the pipeline is placed before being covered by a second backfill plough.

However, there are significant differences between pipeline and cable ploughing such as the contrasting plough geometries due to the fact that subsea cables are significantly narrower, with a typical diameter of 200 mm (BERR, 2008). In the case of subsea cables, this is done using a cable plough (see Figure 1) to create a deep, narrow cutting in the seabed into which the cable is placed and the soil is allowed to collapse back over the cable once the plough has passed. A consequence of this is that there is a need for further research to improve the accuracy of predictions of cable plough performance,



Figure 1. Seabed cable plough (Courtesy of Serge Delestaing).

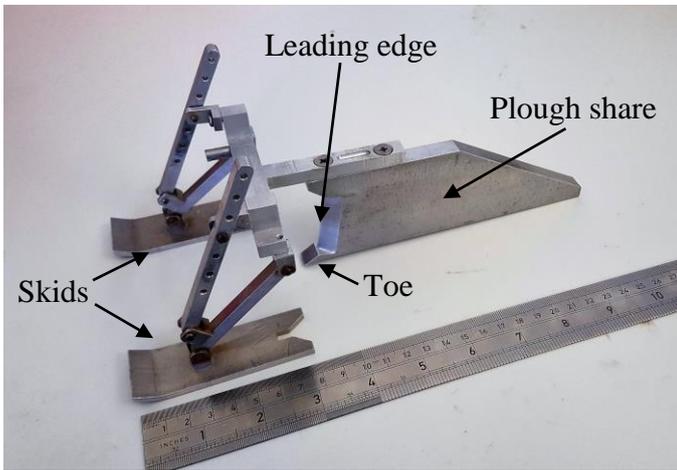


Figure 2. 1/50th scale seabed cable plough model.

such as required tow force, depth and plough speed. This information is critical to ensuring that cabling projects can be completed on time and on schedule in order to avoid costly financial penalties.

Conventional methods for predicting cable plough performance are semi-empirical, and rely on parameters derived from previous field work using existing plough geometries and known soil conditions (Cathie, 2001). Theoretical models exist, but their complexity can be a barrier to their use (Beindorff et al, 2012). However, offshore seabed characterisation is challenging, meaning that it is difficult to gain an accurate understanding of the soil state and material properties. This reduces the confidence in the derived parameters and limits their use to soil conditions which have been previously experienced. Additionally, these techniques are not useful when attempting to optimise the geometries of new plough designs to minimise tow forces and improve performance. Geotechnical finite element analysis (FEA) software is also limited in its applicability to seabed ploughing as the large deformations experienced lead to mesh distortions which cause analysis instabilities.

1.2 Project overview

The aim of this project is to overcome these challenges by developing a numerical analysis software based on the material point method (MPM) able to model seabed ploughing and other soil-tool interaction problems. The use of the MPM avoids the mesh distortions associated with conventional FEA and allows the modelling of large deformation problems. This software will allow rapid analysis of the impact of varying share geometries on plough performance, allowing optimisation of future plough designs. Another benefit is that it will be possible to predict plough response in challenging soil conditions.

The project is being carried out jointly between Durham University, where the software is being created, and the University of Dundee, where physical modelling is being carried out to provide verification

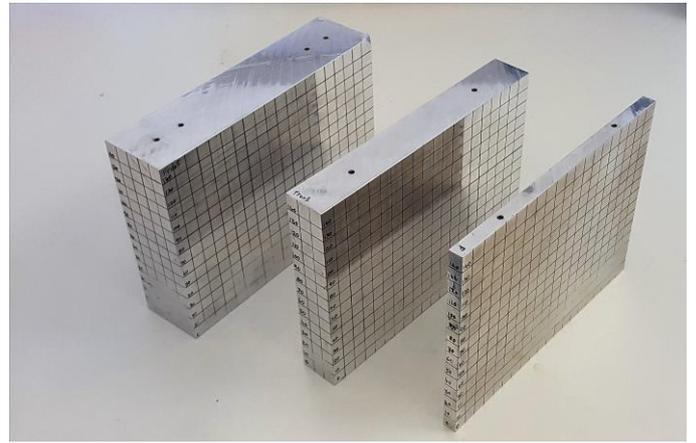


Figure 3. Simplified cable plough share analogue geometries (150 mm high x 200 mm long).

data that will be used to benchmark the software. This paper will focus on small scale model testing carried out at the University of Dundee using simplified analogues of cable ploughs which are easier to model using the numerical software which is in the development stage.

In addition to the work described here, the University of Dundee is also undertaking tests using 1/50th scale models of both cable ploughs and pipeline ploughs in order to provide validation of the final software against realistic plough geometries and provide further confidence in the predictions. Additional work is also being carried out using the University of Dundee's 3 m radius beam centrifuge at an enhanced gravity of 50 g in order to investigate the scaling of 1 g model tests up to prototype scale.

Whilst the data gathered in the project is primarily for verification of the numerical software, it will also be used to improve both the understanding of seabed plough behaviour and current empirical models.

2 METHODOLOGY

2.1 Idealised plough share geometries

The geometry of a cable plough has a number of features that complicate its numerical modelling, such as the angled leading edge and the 'toe' at the base of the share which is designed to provide additional downforce (see Figure 2). In order to make the plough shares simpler to model, they were idealised as rectangular blocks (see Figure 3). These blocks were also constrained vertically to maintain a constant embedment depth. An additional benefit of using these simplified geometries is that it allows the forces generated by the various plough share components to be deconvoluted. The blocks were manufactured from aluminium and given a polished surface finish to ensure all the blocks had a consistent interface friction ratio.

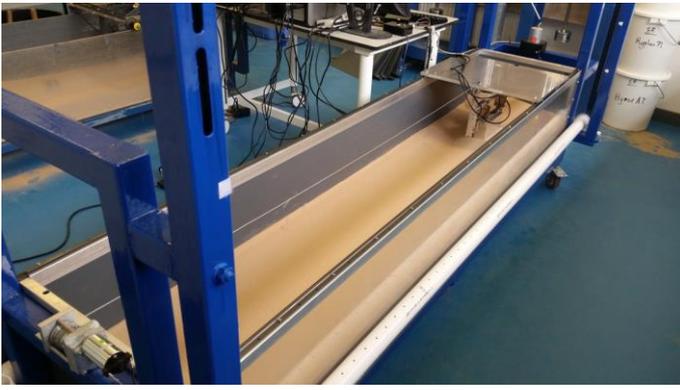


Figure 4. Ploughing tank before test commences.

2.2 Experimental setup

To provide a range of conditions for comparison with the numerical software, three parameters were varied; embedment depth, share width and sand density (see Table 1). The sand used is an evenly graded fine sand (CN HST95) whose properties are summarised in Table 2. The tests were conducted in a 2.4 m long ploughing tank to ensure that the plough geometries are displaced by a sufficient distance to reach steady state (see Figure 4). A moving platform mounted on low friction linear bearings is attached to the tank, with actuation provided by a high torque DC motor with a variable speed controller to allow the plough velocity to be set. Linear displacement is measured by a draw wire transducer (DWT) connected to the rear of the platform.

The plough share geometries were attached to the moving platform by a load frame consisting of three load cells to allow the total vertical and horizontal forces acting on the share to be measured. The load frame is shown in Figure 5 and has two 20 kg vertical load cells, one each at the front and rear of the plough share and a third 20 kg horizontal load cell at the front of the plough share. The plough share geometries attach to the frame via the lower mounting bar for easy removal. The load cells are connected using pinned connections fitted with low friction rotational bearings to prevent any moment transfer via the connections.

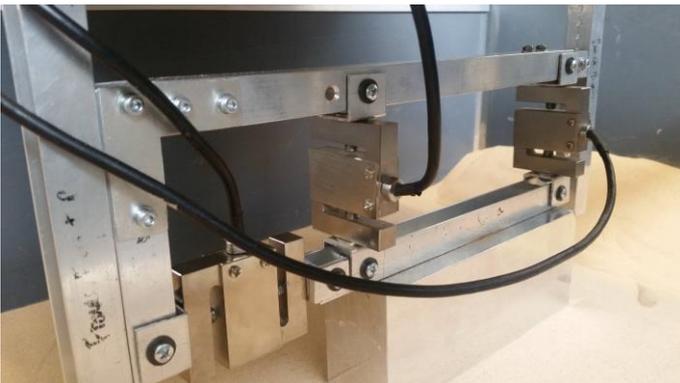


Figure 5. Load measurement frame.

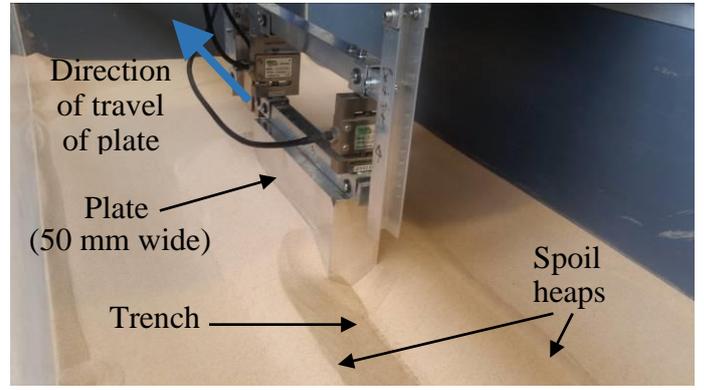


Figure 6. Model ploughing test after completion.

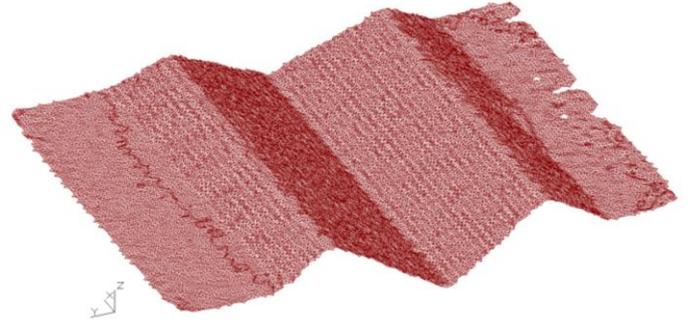


Figure 7. 3D scan of final physical model surface.

Table 1. Ranges of parameters used in physical modelling.

Test variables	Sand relative density %	Embedment depth mm	Share width mm
Range of parameters used	30 50 70	20 50 80	10 30 50

Table 2. Properties of HST95 sand (Lauder et al, 2013).

Property	Value
One dimensional Young's modulus, E'_0 * (kN/m ²)	647
Critical state friction angle, ϕ'_{crit} # (°)	32
Critical state interface friction angle, δ'_{crit} # (°)	24
Maximum dry density, ρ_{max} (kg/m ³)	1792
Minimum dry density, ρ_{min} (kg/m ³)	1487
Mean grain diameter, d_{50} (mm)	0.13

* E'_0 determined at an effective stress of 0.2 kN/m² and at a relative density of 53%

Friction angles determined at normal stresses of 0.2-70 kN/m²

Data logging for the load cells and the DWT were provided by a National Instruments NI DAQ 6211 logging system. Additionally, the surface of the sand bed was captured after ploughing using a low cost 3D scanning system to allow the final surface deformations and trench profiles to be compared with the output from the numerical model (see Figures 6 and 7). The system can capture the soil surface to an accuracy of ± 0.5 mm, and provides output in an easy to interrogate 3D model. The scanning system and its use are described in detail by Robinson et al (2016).

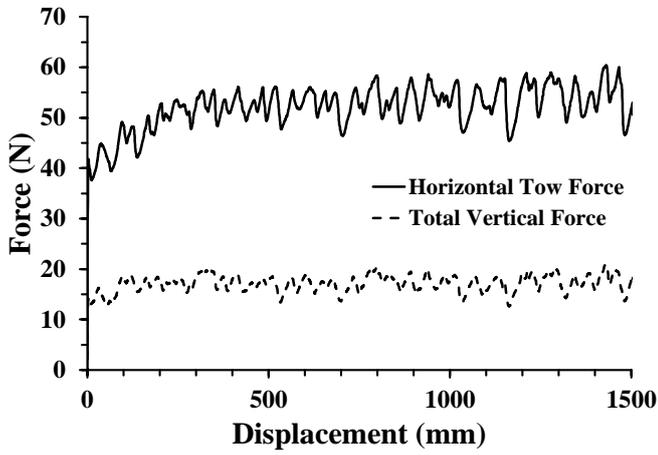


Figure 8. Typical horizontal and vertical forces.

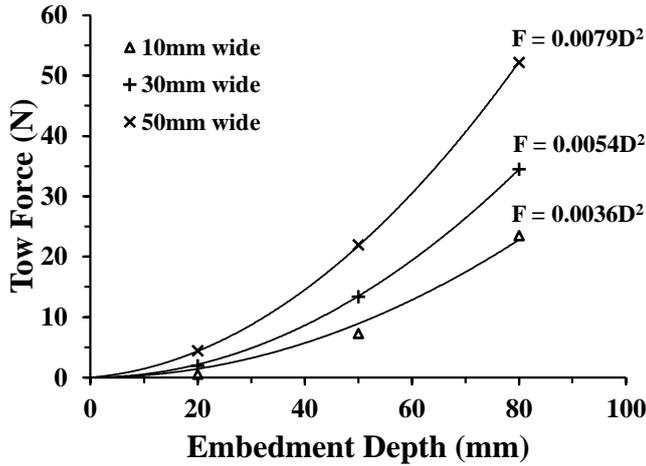


Figure 9. Tow force-depth relationship for varying share widths in medium dense sand.

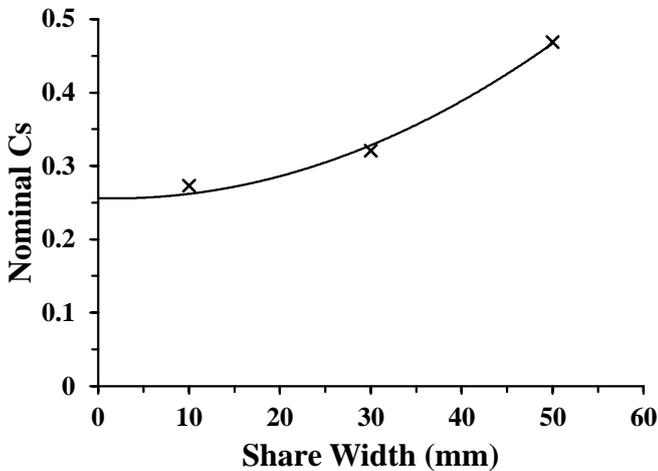


Figure 10. Variation of C_s with share width.

2.3 Test procedure

The sand beds were prepared by dry pluviation using a linear slot pluviator, and the different densities were achieved by varying the slot width to alter the sand fall rate. The pluviator was moved repeatedly across the ploughing tank at a rate of 150 mm/sec until the required sand bed depth of 200 mm was achieved. Densities were confirmed by three density measurement pots placed within the ploughing tank. The plough share was then embedded to the required depth and attached to the platform. The draw-wire

transducer was then connected to the platform and a displacement of 1500 mm was applied at a rate of 5 mm/sec whilst logging the various transducers.

After the test was complete, the plough share was disconnected from the load frame which was removed along with the platform, leaving the plough share embedded within the sand bed. This allowed the final undisturbed soil surface to be captured using the 3D scanner.

3 RESULTS AND DISCUSSION

3.1 Tow forces

The horizontal tow force and the combined force from the two vertical load cells for a typical test are shown in Figure 8. In this case, the data shown is for a 50 mm wide plough share analogue, embedded 80 mm deep into the sand bed. All of the results discussed in this paper are from tests conducted in medium dense ($D_r = 50\%$) HST95 sand. Both the horizontal and vertical forces rapidly reach steady state equilibrium after only 300 mm displacement out the 1500 mm applied. The oscillations observed in both the horizontal and vertical forces are due to the recurrence of failure mechanisms around the plough share as it displaces. As a failure mechanism forms, the soil shear resistance rises until the peak resistance is reached before reducing to the critical state. Once the share advances, the mechanism ceases to be viable and a new one forms generating the tow force fluctuations shown.

In the field, the horizontal tow forces are the primary consideration, and are key to the selection of the vessel required to tow the plough. The most commonly used tow force model is that proposed by Cathie (2001) as shown in Equation 1.

$$F_{cable} = F_w + C_s \gamma D^2 + C_d v (C_s \gamma D^2) \quad (1)$$

Where:

C_s and C_d are empirical co-efficients

γ is the soil unit weight

D is the plough share depth

v is the plough velocity

The model has three elements. The first, involving F_w , represents the tow force due to the self-weight of the cable plough and the second component determined by C_s is the portion of the tow forces generated by the static (non-velocity dependent) resistance of the soil as the plough displaces. The third dynamic component involving C_d represents the additional tow forces caused by negative pore pressures generated in saturated soil depending on the velocity of the plough.

In the case of the tests described in this paper, both the self-weight and dynamic components can be neglected, as the self-weight of the simplified shares is supported by the load cells and the tests were conducted in dry sand. Hence the model resolves to Equation 2.

$$F_{cable} = C_s \gamma D^2 \quad (2)$$

Figure 9 shows the tow force-depth relationships for three widths of plough share. A D^2 relationship has been fitted to the data points using least mean square regression to determine the value of $C_s \gamma$ for each share width. As can be seen, the D^2 relationship fits the measured data points well, indicating that the form of the model proposed by Cathie (2001) is able to accurately reflect the impact of depth variation.

After adjusting for the unit weight of the soil, $\gamma = 16.84 \text{ kN/m}^3$, C_s values have been determined for the three simplified plough shares (see Figure 10). It should be noted that these values are nominal due to the simplified nature of the geometries. This shows that C_s appears to be strongly influenced by the share width, which whilst an intuitive finding, highlights that there is further scope for improving the model proposed by Cathie (2001) by accounting for share geometry in order to allow better predictions. This will be the subject of further investigation as part of this project. The C_s value for each seabed cable plough used is currently determined empirically based on field data.

3.2 Scaling considerations

While the results discussed in this paper are all at model scale, the implications of this testing may also be of interest at prototype scale. The geometries considered in this paper are simplified, however, based on their length they could be considered to have a scale ratio, N , of 40 in comparison to a real prototype scale cable plough. The scaling factors by which the main parameters reduce from prototype scale to model scale are shown in Table 3.

Table 3. Scaling factors for 1g model testing.

Parameter	Scaling factor
Length	1/N
Volume	1/N ³
Mass	1/N ³
Stress	1/N
Force	1/N ³

The sand particle size is not scaled as provided there are a sufficient number of particles in contact with the model surface the soil can be considered as a continuum and no grain size effects are observed. A number of studies have investigated this issue (Balachowski, 2007, Garnier et al, 2007) and it has been found that provided the ratio of model width to median sand grain diameter, B/d_{50} , is greater than 50 then grain size effects are negligible. For the testing discussed in this paper, the minimum value of B/d_{50} used was 77 (for the 10 mm wide plough share) meaning that the soil could indeed be considered as a continuum.

3.3 Trench geometry and soil surface profiles

Whilst the final trench geometries from the physical modelling are primarily for validation of the numerical software, trench profiles are also of interest to industry. Cross sections of the final trench profiles have been extracted from the 3D scans using CAD software, and are shown in Figure 11. As can be seen, the trench profiles vary significantly with the share width, providing a good range of surface profiles for comparison with the numerical software being developed.

Another advantage of the 3D scan data is that it allows measurement of the areas and volumes of the various sections of the trench (see Table 4). This enables the overall volume change during ploughing to be estimated. Given the fact that dilation is an important aspect of soil behaviour during ploughing, this will provide valuable information for verifying the numerical software and confirming the suitability of the constitutive soil model used.

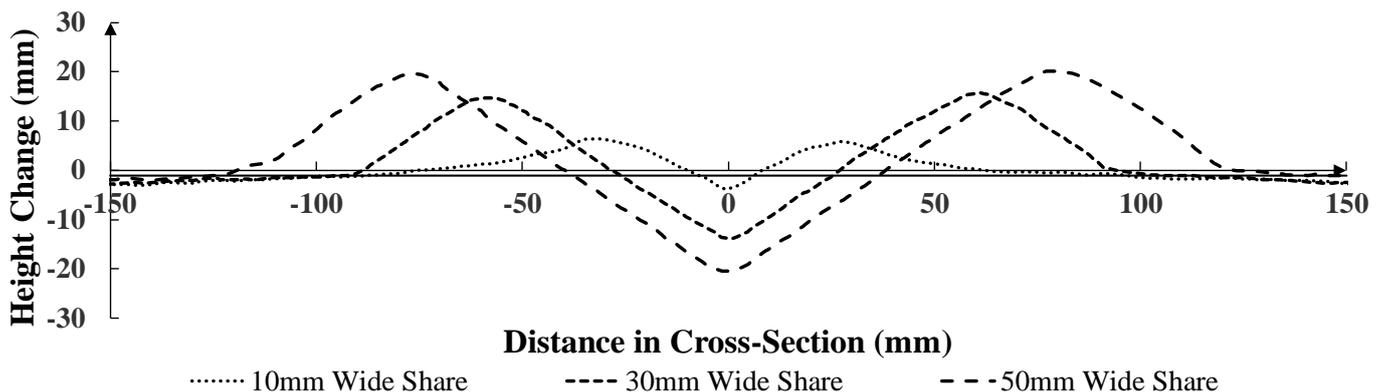


Figure 11. Cross sections for varying plate widths at an embedment depth of 80 mm extracted from 3D soil surface scans.

Table 4. Areas for each section of the surface profile at 1000 mm displacement and net volume change of the cross section (80 mm embedment depth, 50 % relative density).

Plate width mm	Trench area mm ²	Spoil heap area mm ²	Volume change mm ²
10	-36.7	+345.8	+309.1
30	-462.2	+961.0	+498.8
50	-922.6	+1590.3	+667.7

4 COMPARISON WITH NUMERICAL ANALYSIS

In order to allow comparison with measured forces from the physical modelling, the reaction forces will be extracted from the numerical models. This will allow any variation in the measured horizontal and vertical forces to be identified and facilitate refinement of the numerical software.

Importantly, the 3D scanned surfaces can be used to validate the surface deformations predicted by numerical analysis of the physical models. One way this can be done is by comparing the key geometrical properties of the trench cross section such as the spoil heap height, trench depth and angle of repose. The cross sections can either be created using AutoCAD as described previously, or alternatively by using numerical visualisation software such as ParaView. ParaView also allows quantitative estimates of error in the numerical software to be obtained by directly overlaying both data sets and automatically computing the differences in elevation and volume.

5 CONCLUSIONS AND FUTURE WORK

Cabling costs represent a significant portion of the total installation cost of offshore renewables, and there is a need for a greater understanding of the behaviour of seabed cable ploughs in order to improve the efficiency of the seabed ploughing process. This project aims to develop a new material point method numerical modelling software to allow for plough design optimisation and the prediction of plough response in a variety of soil conditions.

The software will be validated against extensive physical modelling carried out at the University of Dundee, which will also serve to provide insights into how share geometry influences plough behaviour at a fundamental level. Existing semi-empirical models have been shown to be useful, but there are opportunities for further improvement in these models.

Results from testing simplified plough analogues with three different widths show that whilst the model proposed by Cathie (2001) adequately captures the impact of changing depth on required tow forces, the coefficient C_s varies significantly with share width. Further investigation is required to con-

sider how this can be incorporated into the model. Cross sections extracted from 3D scans of the final soil surface profile show that the share width has a significant impact on both the soil volume change during ploughing as well as the final trench geometry.

The next stage in the project will investigate the impact of differing cable plough leading edge geometries on the tow forces required, as well as validating the scaling of cable plough performance using further centrifuge testing.

6 ACKNOWLEDGMENTS

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