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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.

Keywords: offshore pipeline ploughing; fibre reinforced sand

Abreviations

APP- Advanced Pipeline Plough

OOS- Out Of Straightness

UHB- Upheaval Buckling

SS- Steady State

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 to 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 this is referred to as the 'long-beam' principle (Palmer, 1999). This natural tendency to change depth can be overcome to some extent through "live" 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 & 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.

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) macro fibre reinforcement designed to control shrinkage cracking in concrete. The fibres are a polymer blend synthetic monofilament (Table 1) that are rectangular in plan (40 mm long, 2 mm wide) but only 0.1 mm thick. At the early stages of the project other reinforcing products were investigated including Jute, string, wood (natural fibres) and Loksand (man-made fibres). After initial preparation trials these products were dismissed based upon issues regarding the practicality of repeatable fibre and sand bed preparation (where large volumes of fibres were required). For example Loksand is a tortuous 'springy' fibre which has a tendency to collect together in large bundles which would have

made it difficult to control the repeatability of preparation. Based upon the 40 mm length of the STRUX fibre this would approximate a 1 m long inclusion at full scale for a 1:25 scale test. It is clear that there are significant differences between the reinforcement elements experienced in the field and the material adopted here, but it was felt that it was more important to be able to produce repeatable beds in an efficient manner and investigate the generic effect of reinforced sand on ploughing.

Fibre reinforced sand layers were prepared based upon a percentage volume approach where the volume of the sand replaced was calculated based upon the volume of fibres. Beds were prepared with sand layers reinforced with fibres at 0.5, 1.0, 1.5, 2.0 and 4.0% volume ratios. The percentages used were decided based upon the extreme percentage replacement that could be practically prepared (4%).

Sand beds were prepared by dry pluviating sand to a depth of 60 mm above the base gravel drainage layer using the slot pluviator. The pre-measured fibre amounts were hand sprinkled over the sand to achieve the required coverage. Several trials were undertaken to refine this methodology prior to preparation in the test sand beds. Sand was then pluviated over the fibres to a depth of approximately 13 mm and the process repeated until a total bed depth of 390 mm had been achieved for the 0.5%, 1.0% & 1.5% fibre reinforcement levels (i.e. the reinforced zone was 230 mm thick). For the beds containing reinforcement of 2.0 & 4.0% the same preparation procedure was followed but the reinforced sand layer was 300 mm deep. These beds were the first to be tested and it was decided later that such deep reinforcing layers were not required. In all cases the fibres were laid down on a horizontal flat plane of sand but were randomly orientated on that plane. To allow for efficiencies in bed preparation, given

the large volume of sand required, each bed contained fibre reinforcement prepared at two different volume ratios, so that two tests could be conducted in the same bed. Fig. 3. shows in plan how the two zones were arranged.

The soil used was a uniform fine silica sand (Manufacturer reference: HST 95) with $d_{50} = 0.18$ mm, $d_{10} = 0.10$ mm, $\rho_{max} = 1760$ kg/m^3 and $\rho_{min} = 1461$ kg/m^3. The dry density of the soil in the unreinforced zone was measured and found to be uniform with $\rho = 1676\text{-}1679$ kg/m^3. This gave a relative density, $D_r = 72\text{-}73\%$ (i.e. dense sand). Previous interface testing with this sand and the plough surface material (steel, centre line average roughness, $R_a = 1.65$ μm) revealed an ultimate interface friction angle of $\delta = 24°$ (Lauder et al. 2013).

Once the dry sand bed had been prepared the sample was allowed to saturate from the base up by controlled injection of water through a network of pipes embedded within the gravel layer, over a period of 24 hours. The model was filled with water to approximately 300 mm above the final sand bed height, completely submerging the model plough.

2.3   *Testing method*

Once the beds had been prepared the final sand surface was surveyed relative to the top of the sample box along the intended plough run. The plough was pre-embedded in the unreinforced sand to approximately 90 mm below the sand surface to allow rapid transition to steady state plough conditions (Lauder et al. 2013) before entering the reinforced zone of soil. This allowed the behaviour of the plough as it transitions

into fibre-reinforced soil to be studied, in addition to the steady-state behaviour in the unreinforced and fibre-reinforced soils.

The plough was then connected to the tow line which in turn attached to a calibrated load cell mounted on the carriage and a linear variable differential transformer (LVDT) for measuring horizontal displacement (Fig. 2.). Plough depth was defined as the depth of the heel of the plough (rear of the share) below the initial sand bed level prior to ploughing. Depth monitoring LVDTs were set on the body of the plough and the hydraulic ram brought in contact with the carriage. During testing logging of the outputs from the load cell and LVDTs occurred at 1 second intervals. The plough was then towed forward at a constant velocity (v) of 11.7-12.2 mm/s (42-44 m/hour). The speeds adopted in this study may be considered relatively slow compared to full scale ploughing which is typically at speeds between 150 to 300 m/h (42-83 mm/s), while extremes of speeds from close to zero to 560 m/h (156 mm/s) may occur (Cathie and Wintgens, 2001). A low speed was adopted to minimise the rate dependant component of plough resistance and allow the study to focus on the effects on the static or passive components of resistance to ploughing. Once testing was complete and the plough had moved through both the unreinforced and reinforced sand the final trench and spoil heap profile was measured along the length of the plough run.

3. Element testing of fibre reinforced sand

Direct shear box elements tests were undertaken using a standard 60 mm square shear box to BS1377 (BSI, 1990). During the tests horizontal load was measured using a calibrated load cell and vertical and horizontal displacements were measured using LVDTs. Samples were sheared at a constant rate of 1.2 mm/minute.

The shear box testing was undertaken on dry reinforced and unreinforced sand samples prepared at relative densities designed to mimic those used during the model plough testing. For all samples this involved pluviation (using the same technique as in the ploughing tests) and fibre sprinkling. The samples in the shear box consisted of multiple layers of 5 mm of sand and a premeasured volume of fibre depending on the required fibre volume ratio. The fibres were installed inclined at 20° to the horizontal to mimic the typical shear plane inclination observed in front of plane strain ploughs by Lauder (2011). All samples were tested dry to ensure drained conditions with normal stresses, σ_n' ranging from 4.4 to 17 kPa to mimic the low *in-situ* effective stresses experienced in the plough models. Fibre densities in excess of 2% were not tested in the shearbox due to difficulties in preparing such densely reinforced samples.

3.1   Effect of fibre inclusion

The effects of increasing fibre content on sand shear strength (or shear stress, τ) are clearly shown in Fig. 4a. with a significant increase in peak shear strength of fibre reinforced samples with increasing fibre content of 26% and 40%, for 1% and 2% fibre reinforcement by volume, respectively. The other noticeable effect of fibre content is on sample volume change shown in Fig. 4b. where increased dilation is observed with increasing fibre content. The dilation angles presented (ψ') on fig. 4b. are those measured directly from the vertical and horizontal displacement data rather than inferred from the difference between friction angles. For the 2% reinforcement sample shown there is ongoing dilation throughout the tests with no indication of a tendency to constant volume shearing. In both the 1% and 2% cases the shear stresses tend to those seen for the unreinforced soil (fallow) at large displacements. This

behaviour is considered significant for ploughing as Lauder (2011) observed the formation of successive passive sand wedges ahead of the plough with a characteristic shear plane emanating from the plough tip to the sand surface in unreinforced sand. In unreinforced sand the resulting friction angle over this shear band is assumed to vary such that it is only the leading edge or tip domain that displays a reduction from peak frictional behaviour to critical state (Vardoulakis et al. 1981). As peak behaviour and dilation/volume change extend to significant displacements in the shear box tests it is likely that ploughing in reinforced sands will be influenced more by peak soil behaviour than is normally observed for such a relatively large strain event (Lauder et al 2013). A summary of the failure envelope parameters derived from the shear box testing is shown in Table 2.

4. Results of ploughing tests in reinforced sand

4.1. Example 4% fibre test

At the start of full scale ploughing operations the plough rests on the surface of the sand. As the plough is towed forwards it starts to penetrate into the sand to a depth determined by the height of the skids relative to the share. In the example test profile shown in Fig. 5a. for the model test undertaken here, the plough was partially embedded to affect transition to steady-state conditions in as short a distance as possible prior to encountering the fibres. In this case the plough was embedded too deeply at the beginning of the test which resulted in a spike in tow force (F) with a sudden reduction in depth of the plough (D) (Fig. 1) due to the long-beam principle. This may not occur in the field because of the flexibility and geometry of the tow line. At approximately 200 mm horizontal displacement (x) (Fig. 5b.) the plough reaches a steady depth and the tow force remains relatively constant until elements of the

plough encounter the reinforced areas of the sand bed (at around 700 mm). This state is referred to as the 'steady state (SS)' by Lauder et al. (2013) and is not only associated with relatively constant plough depth and tow force ($F_{unreinforced}$) but also with the formation of regular spoil heaps on the seabed (used for later backfilling) and relatively constant final trench depth ($D_{t,unreinforced}$ or $D_{t,0}$).

As the plough continues to move forward, first the skids running on the surface encounter the reinforced soil (denoted by line 1, Figs. 5a. and 5b.) with little apparent effect on tow force. Later, the tip of the plough share encounters the reinforced soil (line 2) which corresponds to an increase in tow force but not an immediate change in plough depth. Line 3 denotes the point at which the entire length of the plough is within the reinforced soil. At some point between the plough tip entering the reinforced zone and the plough share being entirely within the reinforced soil the plough begins to reduce in depth from 77 mm (1.93 m at prototype scale) in the unreinforced soil. The onset of this depth reduction occurs close to the peak tow force (F_{peak}) (line 4) and at the point of maximum rate of tow force increase (1 N/mm or 625 kN/m at prototype scale) results in the plough pitching upwards at an average of 11.6° to the horizontal. As the plough reduces in depth for the remainder of the test the tow force reduces to magnitudes similar to the steady state values when ploughing in the unreinforced soil. The final depth of the plough is 16.5 mm (or 0.41 m at prototype scale). The results suggest that if the plough encountered soil reinforcement at 4% the tow force has the potential to increase by 94 N (1469 kN prototype) within 156 mm (3.9 m prototype) of forward progress which is within one share length. This results in a total prototype tow force increase from 1530kN prior to encountering the reinforcement to 2972 kN at peak load. This may exceed a typical vessel's 2452 kN

bollard pull limit with a very rapid change in tow force (within 5 minutes at 44 m/h or 24 seconds at 500 m/h). In the worst case this may lead to a potentially dangerous situation if the vessel/ploughing crew are unable to respond to this rapid change which has the potential to cause damage to the product or pipeline being installed. More realistically the vessel would not be able to maintain the same rate of forward velocity without significant increase in power output and the plough would come to a halt or stall.

The other negative impact of encountering the fibres is that the resulting rapid change in depth of the model plough results in a final trench that reduces in depth (D_t) (Fig.1). From Fig. 5b. it can be seen that trench depth is typically 72% of the plough share depth at steady state and prior to encountering the fibres; this reduces to a minimum of 67% on encountering the fibres (between 1000-1155 mm displacement), i.e. the final trench depth is only 28.6% of the initial value which would lead to the pipeline being out of specification. This would then result in the need to re-plough the section, if indeed this was technically possible. The effect on trench depth and also the spoil heaps formed can clearly be seen in Fig. 6. which shows the visible reduction in the trench width and spoil heap size associated with reducing depth on encountering the fibres. It is noted that the trench depth at the end of the test is shown to be deeper than the final plough depth which is thought to be due to excessive forward pitching of the plough where the plough depth is determined at the rear of the plough share.

4.2. Comparison of results for different fibre volume ratios

Fig. 7a. to 7d. show a comparison of the results from all of the ploughing tests in terms of tow force and depth. Fig. 7a. shows the variation of tow force with plough

displacement. The 2% data displays higher tow forces than the 4% case throughout the test due to an increased ploughing depth as a result of a different skid setting in this test. Due to this difference the results are re-plotted in Fig. 8b. after normalisation by the steady state tow force where this is the average tow force determined over the distance where a steady state depth has been reached (prior to encountering the fibre reinforcement). Both the 4% and 2% levels of fibre reinforcement show similar peak behaviour on encountering the fibres with reduction in depth until a return to the steady state tow force. There then seems to be some difference in behaviour at lower reinforcement volumes where the increase in tow force is far more gradual at 1 and 1.5% fibre volumes (no peak behaviour displayed) resulting in depth reduction not occurring until greater plough displacement has been achieved. The tow force increases achieved in these lower fibre volumes are also far more modest. Results for the 0.5% fibre volume show very little discernible effect on tow force (Figs. 7a. and 7b.), plough depth or trench depth (Figs. 7c. and 7d.).

The results of fibre reinforcement level on tow force increase and trench depth reduction are summarised in Fig. 8. This figure suggests that at 0.5% fibre reinforcement and below there is very little noticeable effect on ploughing with only a slight reduction in trench depth at 0.5% levels. The results then suggest there is a transition in behaviour between 0.5 and 1.0% where, by 1% there has been only a small reduction in trench depth but the tow force has increased significantly. Above 1.5% the tow forces have reached their maximum values but the trench depth still reduces until fibre volume reaches 2%. Above 2% fibre volume there is little change in behaviour suggesting that for the fibres used here a plateau may have been reached

where behaviour is controlled more by the mass of fibres i.e. fibre-fibre interaction with increasing fibre volume rather than fibre-soil interaction.

5. Estimating peak tow force and in fibre reinforced soils

5.1 Existing model for unreinforced soil

To predict prototype plough forces or progress rates in unreinforced soil it is usual to use an empirically based calculation method similar to that proposed by Cathie and Wintgens (2001), Eq.(1):

$$F = C_w W' + C_s \gamma' D^3 + C_d v D^2 \qquad (1)$$

where C_w is a dimensionless friction coefficient, W' is the buoyant plough weight, C_s is a dimensionless passive pressure coefficient, γ' is the buoyant unit weight of the soil, D is the depth from the original sand surface to the heel of the plough main share (i.e. the trench depth) and C_d (units of $t.m^{-3}.h$) is a dynamic or rate effect coefficient. The values used for the three coefficients are typically selected from back analysis of full scale ploughing records. The friction term C_w is assumed to correspond to an interface friction ratio similar to $\tan\delta'$; $C_w = 0.45$ in this study (based upon an interface friction angle of $\delta' = 24°$, Lauder et al. 2013). The passive term C_s, which is assumed to represent the formation of a passive wedge of sand in front of the plough, typically varies from 12.2 (loose sand) to 13.6 (dense sand) with the latter value adopted in this study for the dense sand beds (Lauder et al. 2013). In the original Cathie and Wintgens (2001) method the C_d term is selected based upon the density of the soil and the particle size (d_{10}) to reflect permeability or consolidation ($C_d = 0.284\ t.m^{-3}.h$ at prototype scale). More recently a dimensionless form of C_d was

16

proposed by Lauder et al. (2013) where dilation potential was assessed and the coefficient of consolidation was measured for the specific soil used in this study.

5.2   Adaptations to existing model for fibre reinforced soil

Unfortunately there are no records of ploughing at prototype scale in fibrous soils. The effect of encountering fibres can be summarised by comparing the change in tow force with plough depth (Fig. 9.) which also allows the behaviour to be compared with anticipated fallow (un-reinforced) conditions predicted From Eq. (1). The plough data in Fig. 9. differ from how it would look if it were plotted for a real ploughing field case that started with the plough on the seabed surface (i.e. an increase in plough depth and tow force could be plotted emanating from the origin until reaching the steady state tow force and depth consistent with the intercept of the line representing Eq. (1) and that representing steady state, Zefirova et al. 2012). In this case the plough is initially pre-embedded (slightly too deep in this case) to maximise the data that can be obtained from the plough run and guarantee transition to steady state behaviour in the unreinforced soil. There is an initial spike in the load due to this as previously explained, followed by a slight reduction in depth towards the steady state (SS) ploughing depth determined in unreinforced soil which is very close to that predicted by Eq. (1) for the measured towing force (i.e. where the SS line and that representing Eq. (1) intersect). Once the plough encounters the fibres the load increases sharply, followed by a significant reduction in depth until the tow force returns to the same SS value observed in the fallow soil.

The form of the enhancement due to the fibres seen in Fig. 9. suggests that the relationship between tow force and depth variation is similar in form to the fallow prediction based upon Eq. (1). It is therefore proposed that this equation can also be

17

applied to fibre reinforced soil if appropriate modifications to the dimensionless parameters can be determined, informed by the underlying soil mechanics of fibre reinforced soils. It is initially assumed that the interface friction component to resistance described by C_wW is insensitive to the presence of fibres. It has been suggested that the passive term C_s relates to the continuous formation of a series of consecutive passive wedges that forms in front of the plough as it advances, as observed by Lauder (2011) in fallow soil. On this basis C_s may be related (Reece and Hettiaratchi, 1989, Ivanovic et al. 2011) to the passive earth pressure coefficient K_p adopted in retaining wall design (Knappett and Craig 2012).

$$K_p = \frac{1 + \sin \phi'}{1 - \sin \phi'} \qquad (2)$$

So that

$$C_s = F_s K_p \qquad (3)$$

where ϕ' is the friction angle in the soil and F_s is a shape factor to convert from plane strain retaining wall conditions, to the complex three-dimensional shape of the wedges ahead of the plough share. Assuming that the shape of the wedges will be geometrically similar in the fallow and fibre reinforced soils (i.e. F_s is the same) then the C_s value will be proportional to K_p, such that the fallow value of C_s can be multiplied by the ratio of $K_{p,reinforced}$ to $K_{p,fallow}$ to obtain a value representative of conditions in the fibre-reinforced soil, Eq. (4):

$$F = C_w W' + \left[\left(\frac{K_{p,reinforced}}{K_{P,fallow}} \right) C_s \gamma' D^3 \right] + C_d v D^2 \qquad (4)$$

Peak friction angles in this case were determined based upon extrapolation of the results of the shear box tests (Fig. 4a.) to match the low effective overburden stresses in the model ploughing as even the 4.4 kPa shear box tests were at a higher normal effective stress than in the model plough (Lauder and Brown, 2014). If the approach adopted here for model ploughs, were used in the full scale field case, then appropriate parameters for peak friction angle would be required to reflect field relative density and insitu stress conditions. The results of adopting this approach for the model ploughs is shown in Fig. 9. for the case of 4% fibre reinforcement and in Figs. 10a. and 10b. for the 1 and 2% cases, respectively. It can be seen in both the 1 and 2% cases that this proposed enhancement of C_s is capable of capturing the increase in peak tow force as the share tip enters the reinforced soil. It also appears to capture the resulting reduction of force as the plough's depth reduces as the plough continues to advance in the reinforced soil. It is interesting to note in both Figs. 9 and 10a. that the tow force acting on the plough tends to the fallow steady state tow force (through a reduction in ploughing depth). In the case of the 4% fibre reinforcement the modification to C_s alone under predicts the tow forces developed in the reinforced soil where the C_s enhancement is based upon shear box results for 2% fibres as shear box data was not available to for the 4% fibre ratio.

Although this modification to the C_s term appears to capture the peak tow force behaviour at lower fibre volumes it fails to capture the apparent constant offset in the

tow force – plough depth relationship in fibre reinforced soil. It is proposed that this could be modelled by also modifying the interface friction resistance term (C_w) in Eqs. (1) and (4). This would appear logical as the fibre reinforcement increases the soil-soil friction angle (ϕ') and the interface friction angle may be expressed as a function of this (i.e. it may be related to the strength of the parent material). If this is expressed as δ'/ϕ' (Knappett and Craig, 2012), then C_w would be approximately proportional to tan ϕ', and the ratio of this parameter in the reinforced and the fallow soil could be used as a multiplier on C_w for fallow soil. This may then be incorporated into the tow force – ploughing depth relationship as:

$$F = \left[\left(\frac{\tan \phi'_{pk,reinforced}}{\tan \phi'_{pk,fallow}} \right) C_w W' \right] + \left[\left(\frac{K_{p,reinforced}}{K_{P,fallow}} \right) C_s \gamma' D^3 \right] + C_d v D^2 \qquad (5)$$

This modification to the interface friction term ($C_w = 0.64$, increased from 0.45) improves the prediction of peak tow force in the 2 and 4% reinforcement cases and only has a small effect in the 1% case. It also appears to better capture the post-peak tow force behaviour up to a certain degree of depth reduction as the ploughing depth reduces in the reinforced soil. Noting from earlier that the tow force in the reinforced soil (2 & 4%) tends back to the SS value for fallow conditions it could be envisaged that it would be possible to predict the final plough depth in the reinforced sand by inserting the SS tow force, F into Eq. (5). Unfortunately though both Eqs. (1) and (5) are only designed for steady state conditions and horizontal ploughing. Post peak tow force, the plough is inclined and transitioning to a reduced depth and thus Eq. (5). underestimates the tow force as the plough becomes shallower. It should be noted that while Eq. (5) incorporates a rate or velocity dependent term the effect of

reinforcement on this term of behaviour has not been considered here. It should also be noted that behaviour captured in Equations (4) & (5) only captures enhanced plough resistance due to the flexible fibres effectively "strengthening" the soil. It cannot capture the effects of encountering a much stiffer inclusion or the potential for collecting fibres that may build up on the main share. Both of these additional potential mechanisms would effectively change the geometry of the plough and lead to enhanced passive resistance.

6. Implications for engineering practice

Estimation of out of straightness of a trench and the pipeline is difficult as it is not possible to accurately estimate the final plough and trench depth as mentioned above. It would appear possible though to predict the typical pitch or plough inclination that may be experienced on encountering fibre reinforcement. It is notable from Fig. 7c. that this transition is approximately linear. The measured inclination of the plough when moving into the reinforced soil is compared to the change in dilation angle due to the addition of fibres measured in direct shear in Fig. 11. This suggests that the gradient of the transition zone is directly related to the increased dilation in the fibre reinforced soil. It can be seen that this gradient also becomes steeper with increasing fibre content. Using these observations, it may be possible to anticipate the likely plough inclination and the subsequent effect on operations.

7. Summary and conclusions

There is anecdotal evidence of problems being encountered with nearshore pipeline burial associated with flood washout out features where the soil is effectively reinforced with a network of competent organic wood inclusions. When these deposits

21

have been unexpectedly encountered they have required multiple passes at significant additional cost.

To understand this phenomenon, scale model plough testing was undertaken in fibre-reinforced sands. The study has demonstrated that ploughing operations may be sensitive to reinforcing levels above 0.5% fibre volume ratio. Above this value the plough is subject to significant and rapid increase in tow force as it enters a reinforced zone. The plough compensates for this kinematically by reducing the depth of ploughing. The tests revealed that at 2% fibre volume ratio trench depth reduced to approximately 22% of the depth it was ploughing at before encountering reinforced soil (for the particular plough and soil conditions investigated). Both of these effects have the potential to cause significant disruption to ploughing operations in terms of vessel progress and installation rates along with out of straightness of the trench or inadequate burial depth. It should be noted that these conclusions are based upon small scale model testing for a single fibre type with one set of material properties, i.e. length, flexibility, roughness and bending strength.

Based upon the results of this study, modifications have been proposed to an existing tow force – trench depth ploughing model. Based upon shear strength enhancement observed in direct shear testing, the passive and interface components of plough resistance were modelled and this was able to capture observed model changes in peak tow force on entering the fibrous zone. In addition the plough inclination during transition to shallower depths was also found to correlate with dilation angles for different fibre volumes measured from element testing. This may allow plough pitch

in reinforced soils to be predicted, and along with the increased tow force prediction allows the effect of encountering reinforced soil to be considered.

Acknowledgements

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Figure Captions

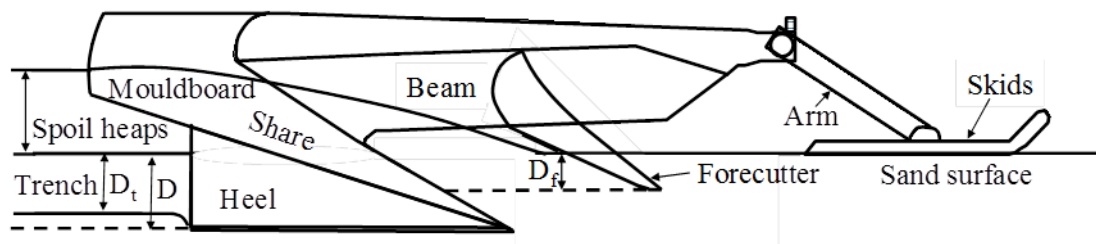Fig. 1. Schematic of model pipeline plough with forecutter shown during trenching.

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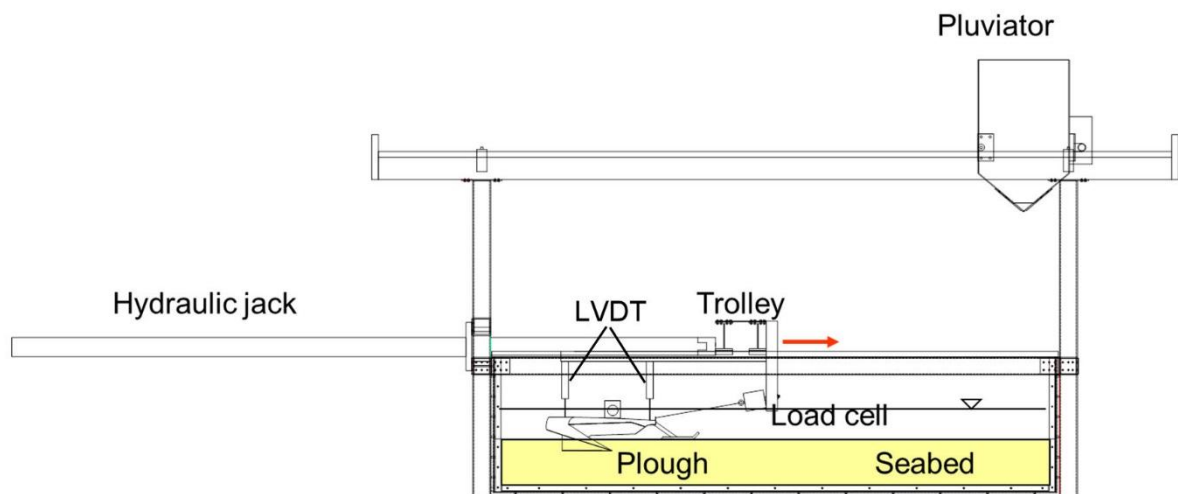
Fig. 2b. Image showing a preliminary dry plough test using the 1:25 scale plough in unreinforced sand (sand bed is not saturated and plough depth measurement apparatus shown in Fig 2a has been removed for clarity).

Fig. 3. Schematic plan view of typical ploughing set-up (dimensions in mm, not to scale).

Fig. 4a. Shear stress-displacement relationship from direct shear tests of reinforced sand compared with that for unreinforced sand at low normal stress (σ'_n = 4.4 kPa).

Fig. 4b. Sample volume change measurements during direct shear box testing of reinforced sand compared with that of unreinforced sand at low normal stress, σ_n'.

Fig. 5a. Tow force variation with horizontal plough displacement in unreinforced and then reinforced sand (4% fibre content). Results at model scale.

Fig. 5b. Plough and trench depth variation with horizontal plough displacement in unreinforced and then reinforced sand (4% fibre content). Results at model scale.
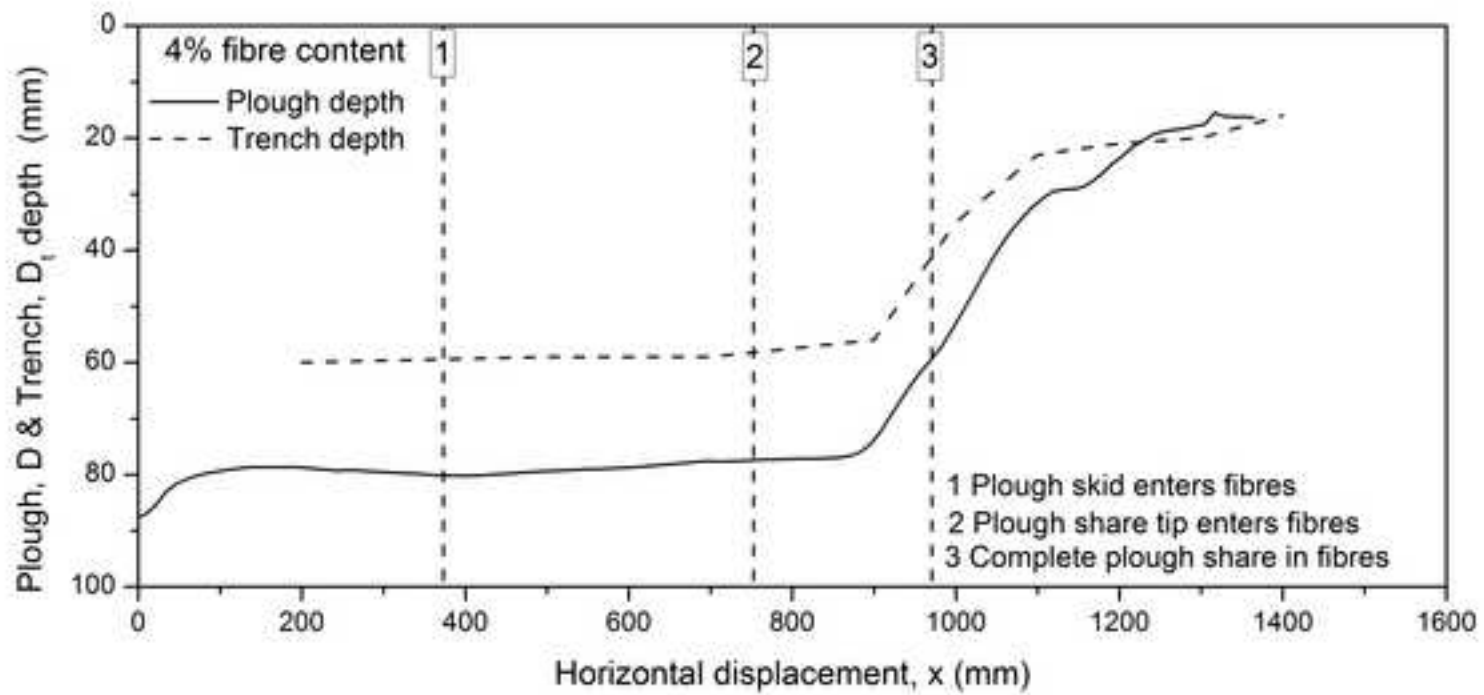
Fig. 6. Image of the trenching operation in 4% fibre reinforcement taken from above and behind the plough highlighting the change in trench depth and spoil heap profile.
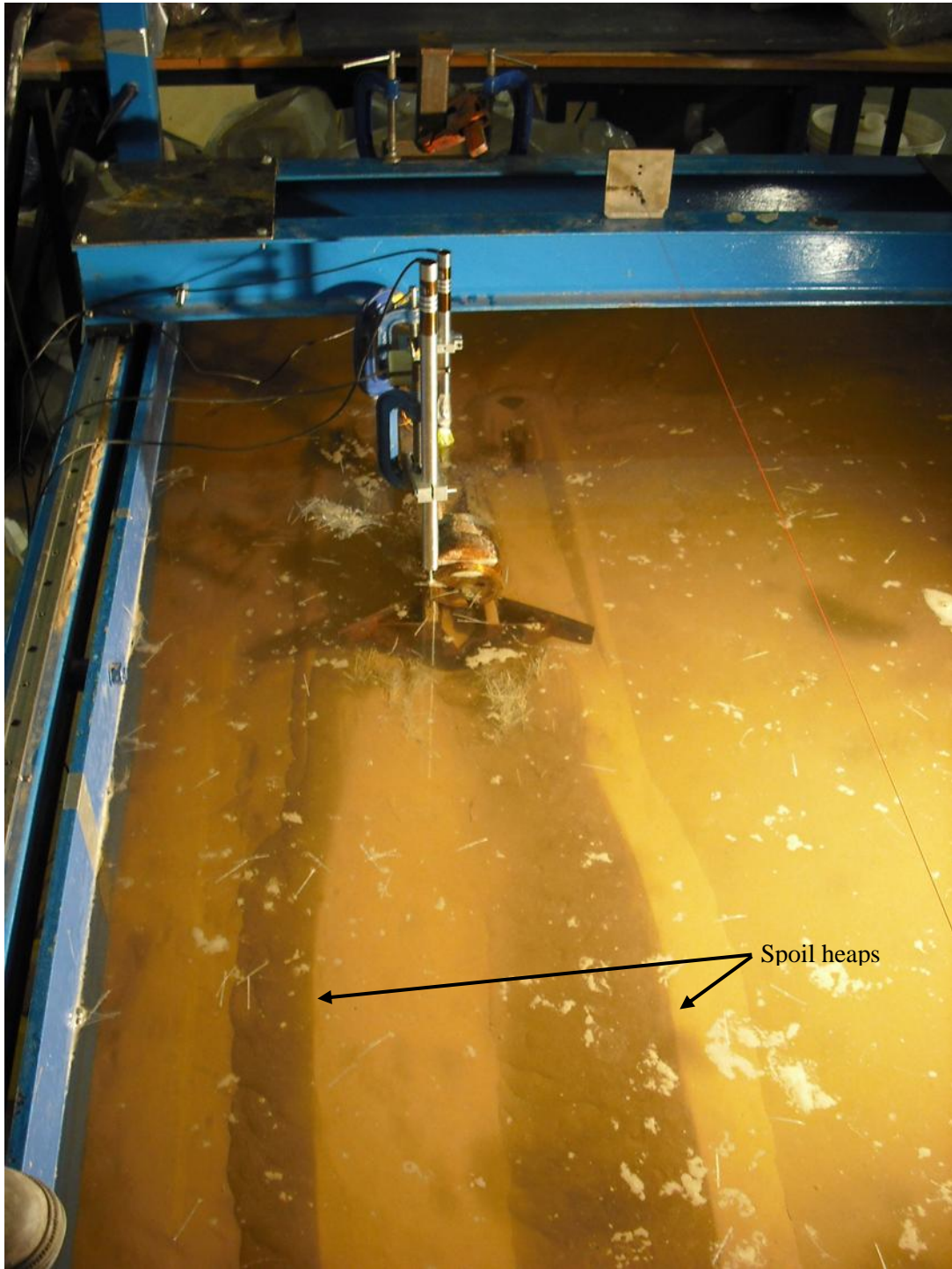
Fig. 7a. Summary of the effect of fibre reinforcement volumes on plough tow force (model scale).
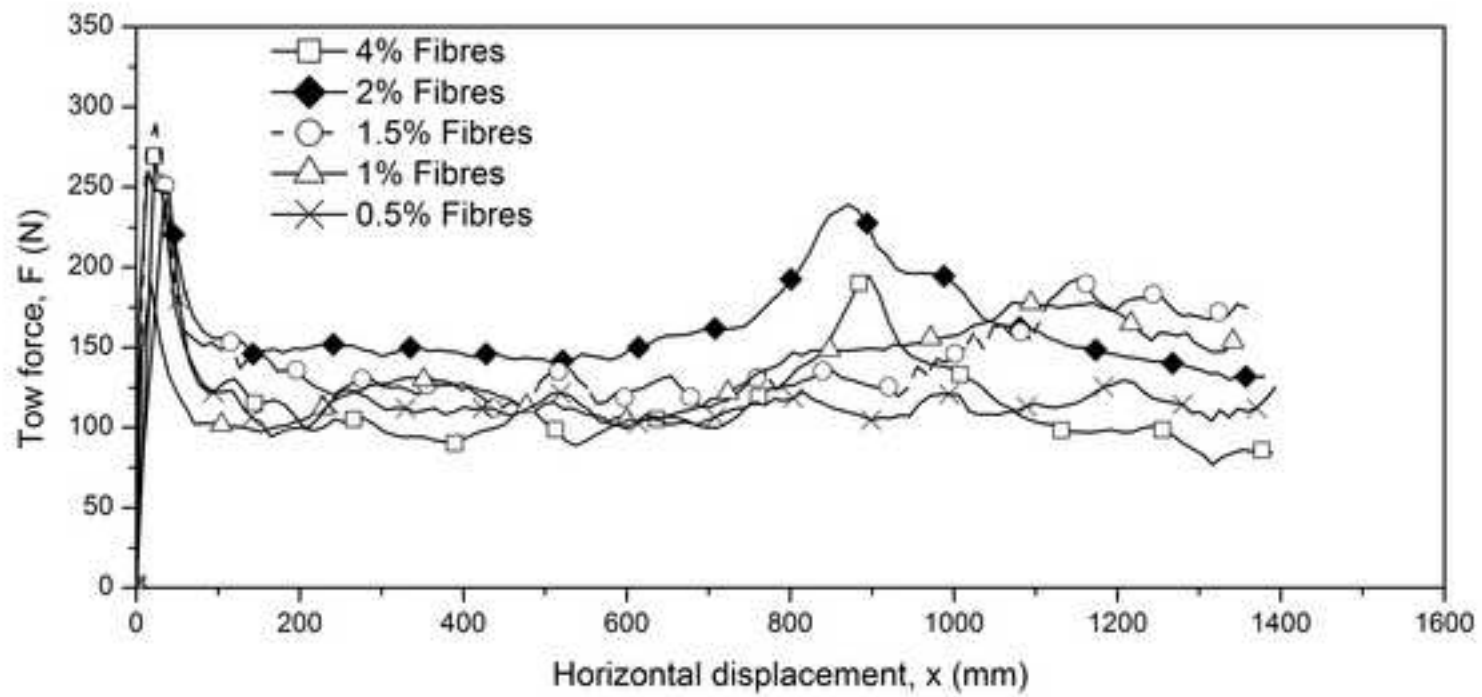
Fig. 7b. Summary of the effect of fibre reinforcement volumes on the normalised plough tow force (model scale).
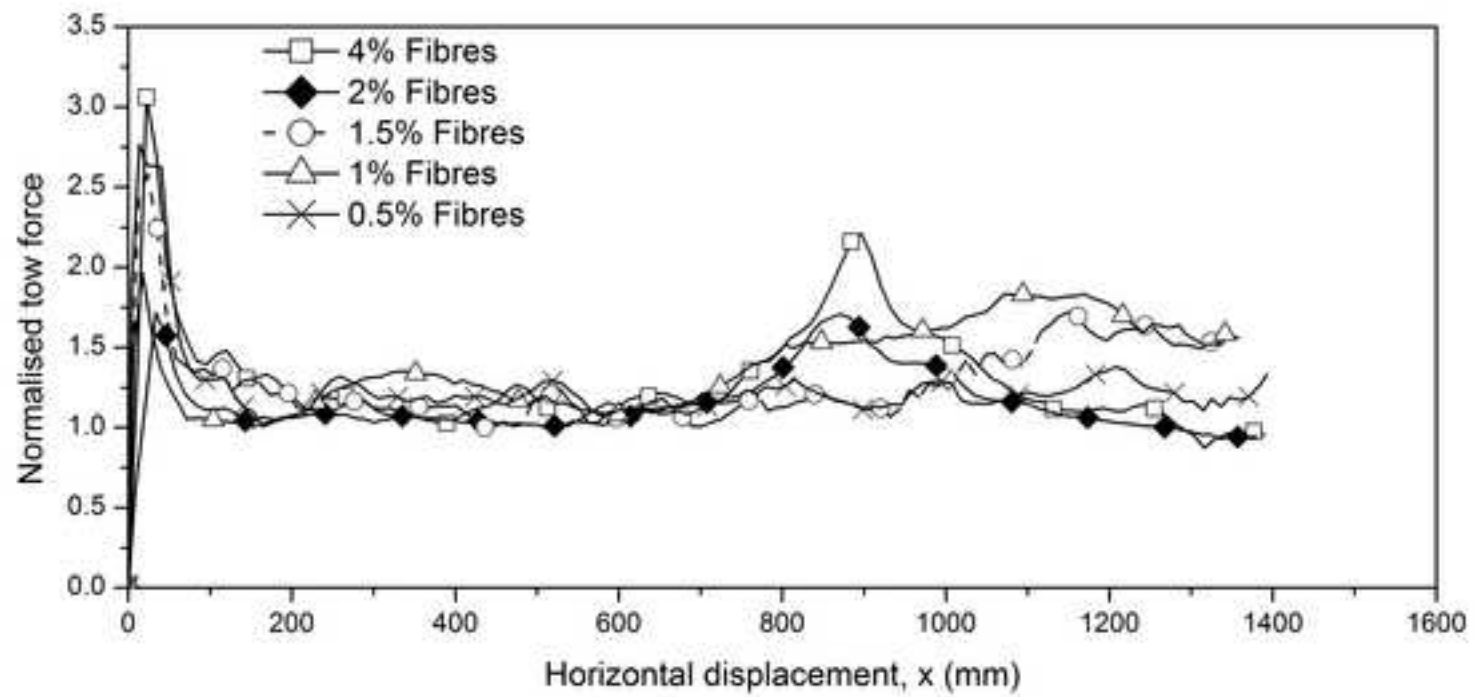
Fig. 7c. Summary of the effect of fibre reinforcement volumes on plough depth (model scale).
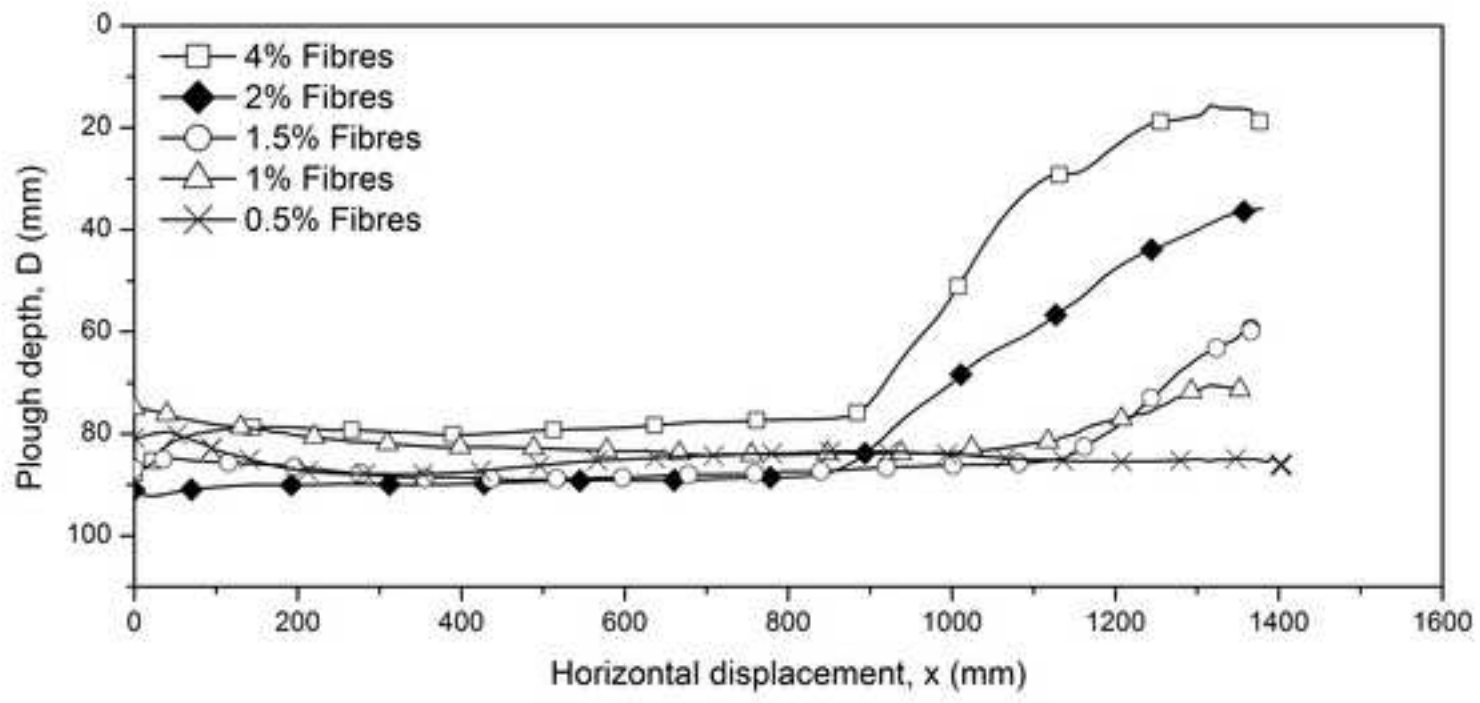
Fig. 7d. Summary of the effect of fibre reinforcement volumes on normalised final trench depth (model scale).

Fig. 8. Summary of the effect of fibre reinforcement volumes on tow force and trench depth (Peak tow force shown at prototype scale).

Fig. 9. Variation in trench depth and tow force during ploughing in the 4% reinforced sand.

Fig. 10a. Variation in trench depth and tow force during ploughing with predictions of the tow force depth relationship in unreinforced soil (fallow) and incorporating passive and interface term enhancement (2% fibre volume ratio results).
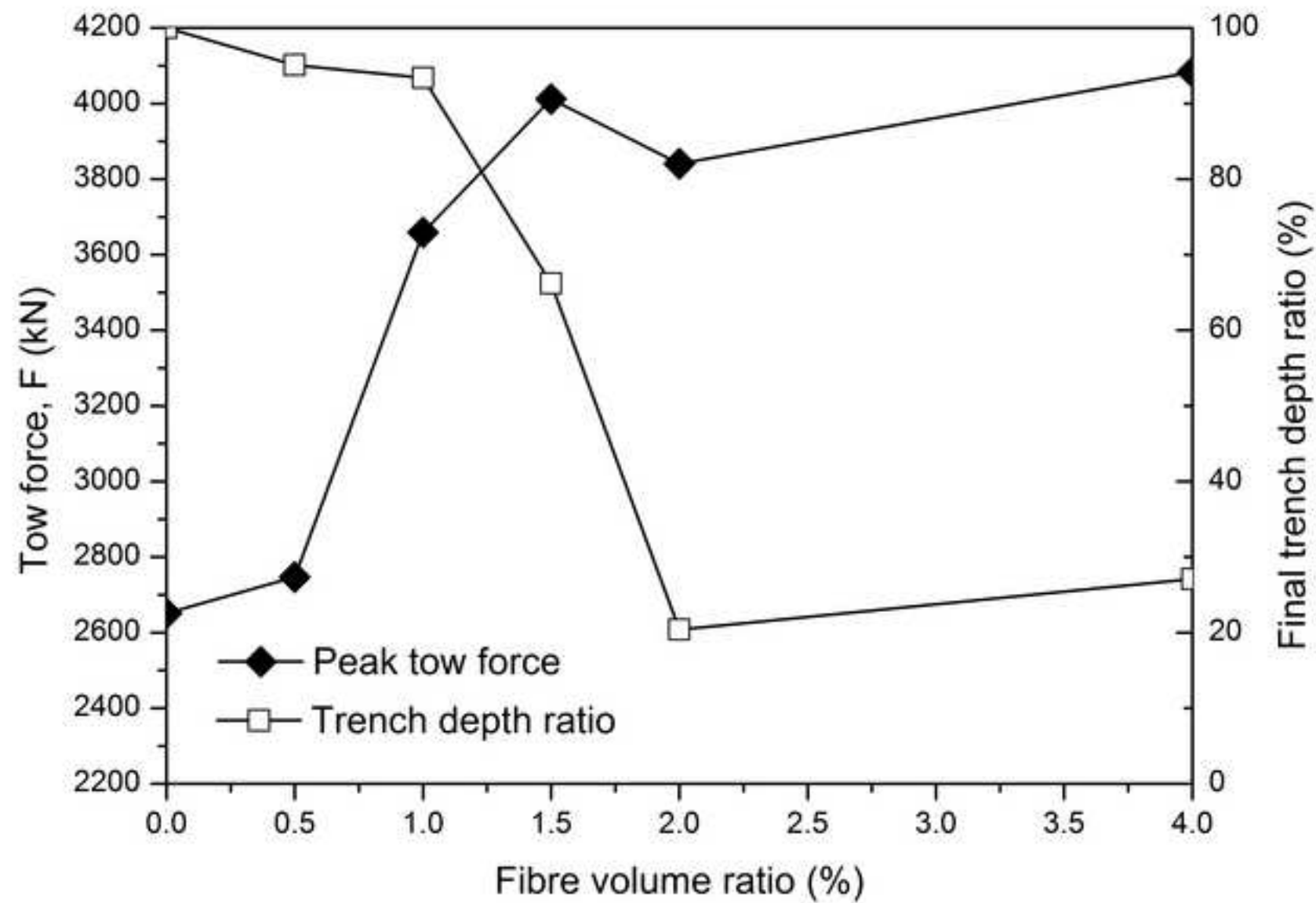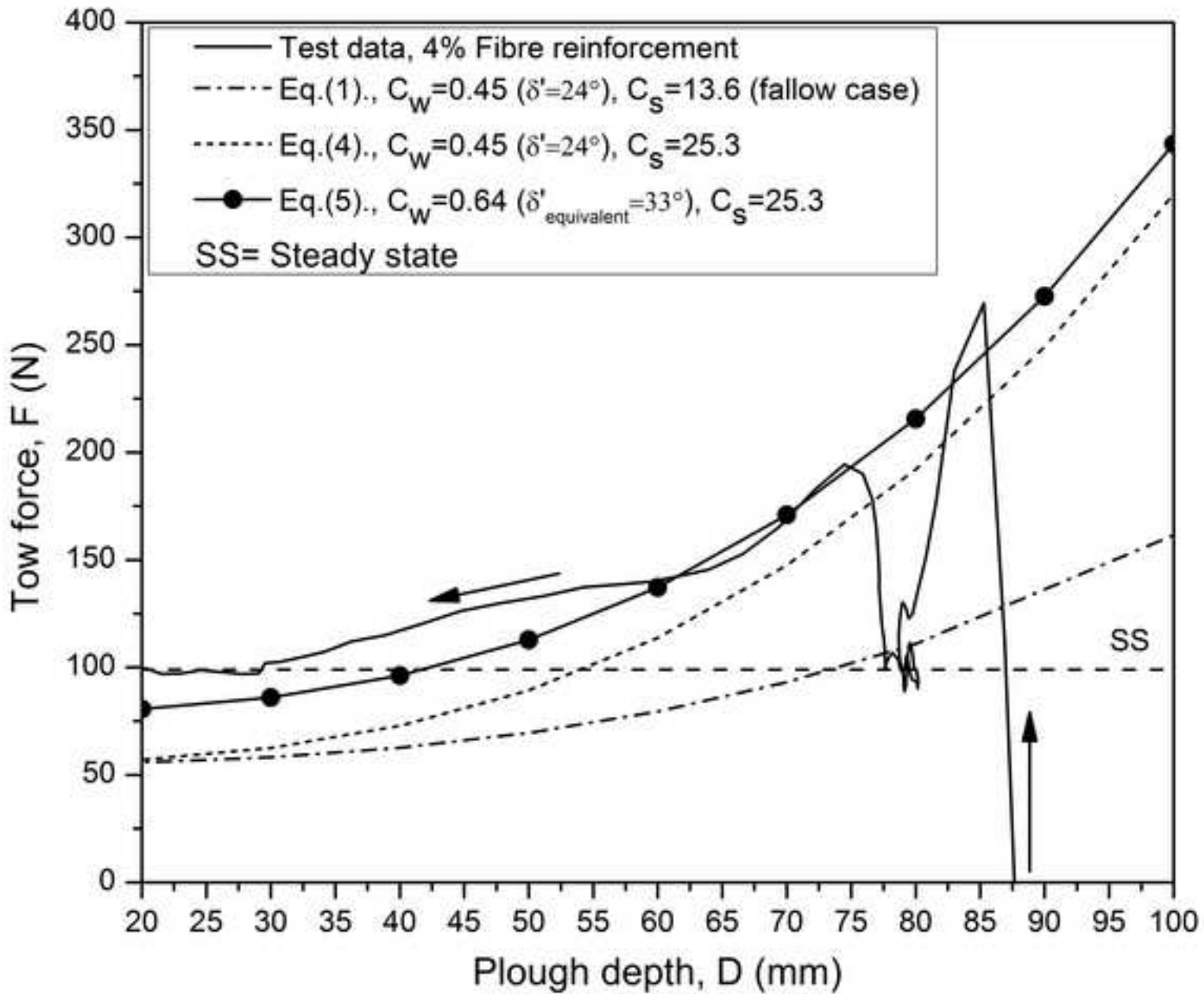
Fig. 10b. Variation in trench depth and tow force during ploughing with predictions of the tow force depth relationship in unreinforced soil (fallow) and incorporating passive and interface term enhancement (1% fibre volume ratio results).
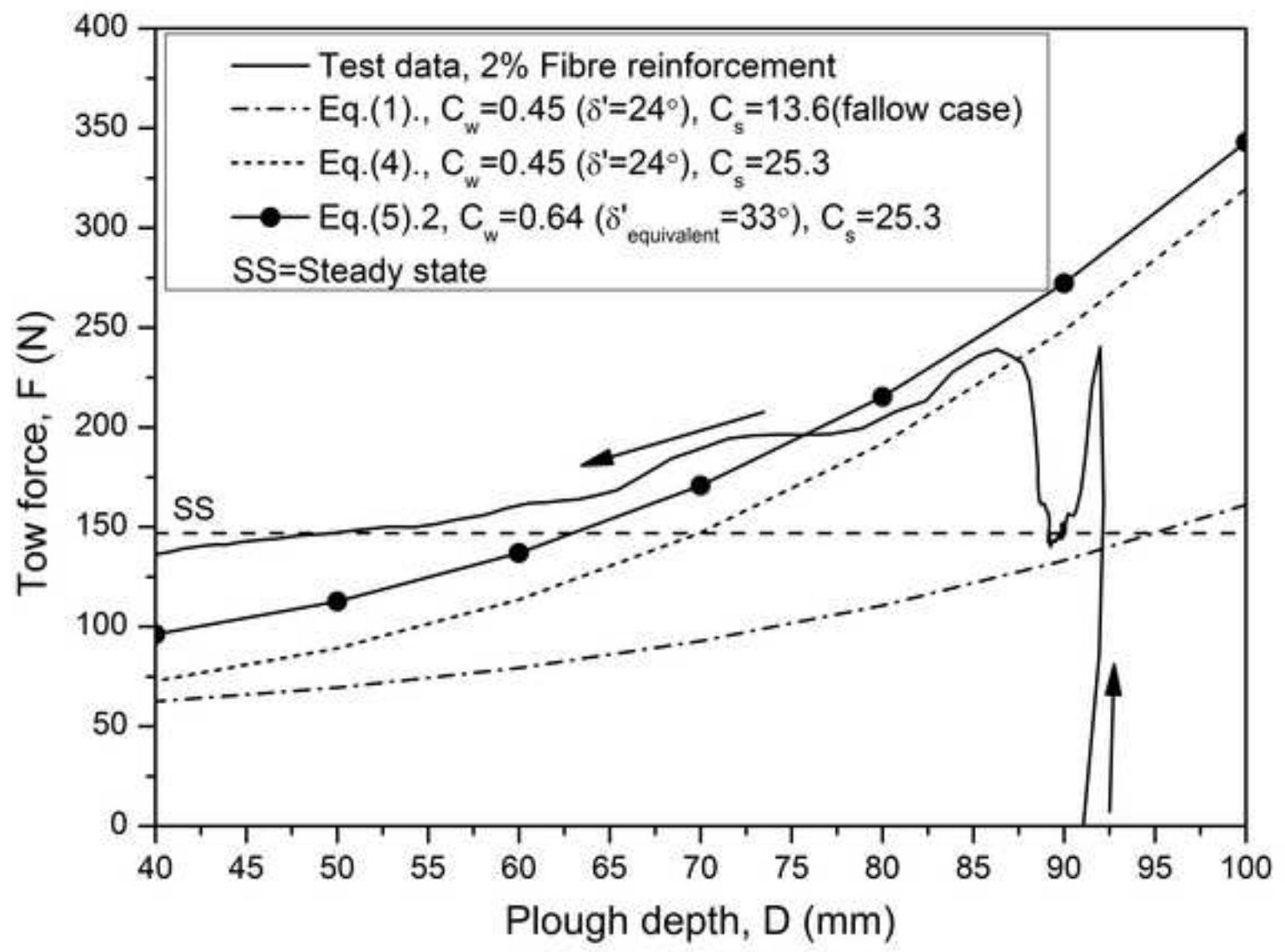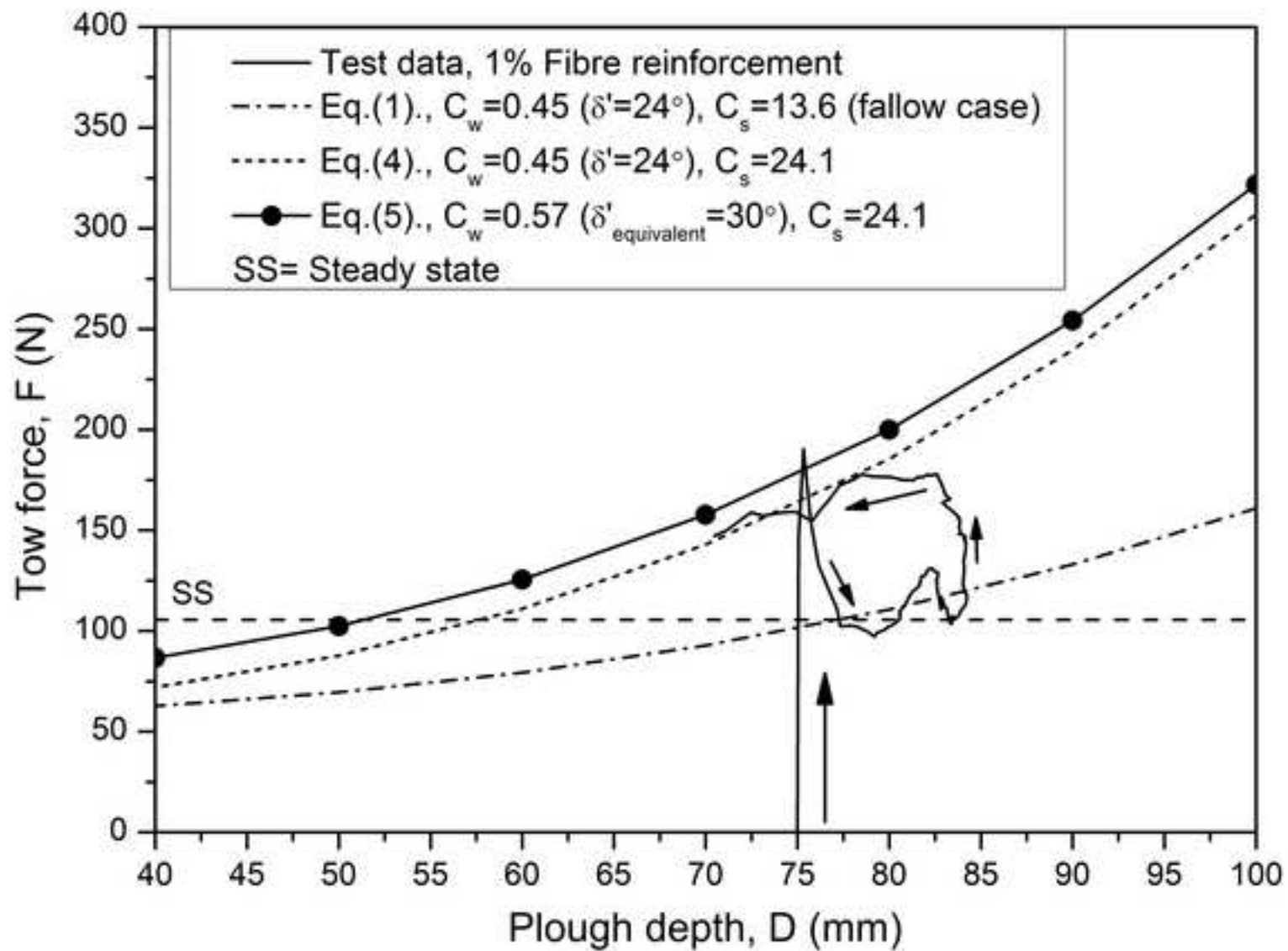
Fig. 11. Variation of plough and trench depth inclination compared to the change in dilation angle with increase in fibre reinforcement content.

Table Captions

Table 1 Properties of the reinforcing fibres.

Table 2. Summary of failure envelope parameters from direct shear box testing direct shear box testing at normal stresses, σ'_n from 4.4 to 17 kPa.

Table 3. Summary of 1/25$^{\text{th}}$ scale ploughing tests in saturated sand presented at prototype scale.

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Fig. 10b. Variation in trench depth and tow force during ploughi

Table 1 Properties of the reinforcing fibres.

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Property	Model value	Equivalent prototype value
Length	40 mm	1000 mm
Width	2 mm	80 mm
Thickness	0.1 mm	2.5 mm
Specific Gravity	0.92 mm	-
Modulus of Elasticity	9.3 mm	-
Tensile strength	620 MPa	-
Tensile breaking force	124 N	77.50 kN
Axial stiffness	46.5 N.m^{-1}	1.16 kN.m^{-1}

Table 2. Summary of failure envelope parameters from direct shea

Table 2. Summary of failure envelope parameters from direct shear box testing direct shear box testing at normal stresses, σ_n' from 4.4 to 17 kPa.

Fibre content (%)	Peak shear stress, τ_{peak}			Ultimate shear stress, τ_{ult}		
	$\phi'_{peak}{}^a$, $c'=0$ (kPa)^b	c' (kPa)	ϕ'_{peak}	ϕ'_{ult}, $c'=0$ (kPa)	c' (kPa)	ϕ'_{ult}
0	45.8º	2.0	41.1º	34.8º	1.82	28.8º
1	47.2º	3.2	45.0º	33.2º	1.69	31.8º
2	52.3º	5.0	41.9	38.1º	1.84	32.5º

[a]Peak internal friction angle, [b]Apparent cohesion

Table 3. Summary of 1/25th scale ploughing tests in saturated sa

Table 3. Summary of $1/25^{th}$ scale ploughing tests in saturated sand presented at prototype scale.

Fibre content (%)	Peak tow force during test, F_{peak} (kN)	Tow force increase (%)[a]	Trench depth ($D_{t, peak}$) at peak tow force (m)	$D_{t, peak}/D_{t,o}$[b] (%)	Final trench depth (m)	Final trench depth ratio (%)[c]
4	4081	51.4	1.40	95.0	0.40	27.1
2	3845	60.5	1.36	100.7	0.28	20.4
1.5	4012	36.2	1.52	81.9[e]	1.23	66.2
1	3659	40.8	1.50	98.2	1.43	93.4
0.5	280	4.9	1.95	95.0	1.95	95.1
0	2747[d]	-	1.65[d]	-	1.65[d]	-

[a]Tow force increase $= (F_{peak}-F_{unreinforced})/F_{unreinforced}$
[b]$D_{t,0} =$ steady state trench depth prior to encountering the fibrous region
[c]Trench depth ratio $= D_{t, reinforced}/D_{t, unreinforced} = D_{t, reinforced}/D_{t, 0}$
[d]Data uses average of test results before fibre encountered.
Note: Calculations of [a] and [c] use unreinforced values from each specific test.
[e]Reduced value caused by sand flowing from rear of plough down incline at the end of testing