FIS002 - Modelling the physical Impact of demersal fishing gears on the seabed

A REPORT COMMISSIONED BY FIS
AND PREPARED BY

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Published by: Fisheries Innovation Scotland (FIS)

This report is available at: http://www.fiscot.org.

Suggested Citation:
Ivanovic, A. 2015. Modelling the physical Impact of demersal fishing gears on the seabed. A study commissioned by Fisheries Innovation Scotland (FIS) http://www.fiscot.org/

Title: Modelling the physical Impact of demersal fishing gears on the seabed

ISBN: 978-1-911123-01-9

First published: October 2015

UNIVERSITY OF ABERDEEN

FIS02 - Final Report to Fisheries Innovation Scotland (FIS)

Title of the project: Modelling of physical impact of demersal fishing gears on the seabed

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August 2015

Executive summary

Towed demersal fishing gears interact with the water column and the seabed through which and on which they are towed. The initial impact is physical and studies have shown that these physical effects (i) can have broader ecological, environmental and biological implications and (ii) can affect the economic performance of the fishing operation. It has been shown that towed demersal fishing gears damage habitats, cause benthic mortality, release nutrients and resuspend phytoplankton cysts and copepod eggs and studies of the fuel efficiency of fishing trawlers have demonstrated that the combined contact and hydrodynamic drag of a demersal towed gear can account for up to 80% of the fuel consumed.

To develop predictive methodologies to assess and quantify the ecological and environmental impact of towed fishing gears and to be able to evaluate their economic performance we must first be able to predict their physical impact. Here we further develop the numerical modelling approach of Ivanović et al. (2011), Esmaeili and Ivanović (2014) and Ivanović and O'Neill (2015) who use finite element methods to model the interaction of the seabed and fishing gear components. These models can calculate the penetration into the seabed, the sediment displaced and the associated drag and contact forces that occur when a fishing gear is towed across the seabed. They have focussed on sandy sediments and here we extend these studies to account for saturated cohesive muddy sediments. This allows us to model the physical impact of towed fishing gears on a range of sediments which is reflective of the range of sediments on which fishing takes place.

The resulting predictions correspond very well with data from experimental trials at sea and underline the potential of using deterministic methodologies to assess and quantify the impacts of towed gears. To develop these types of methodologies the physical impacts need to be related directly to the resulting geochemical, biological and environmental effects such as nutrient enhancement and benthic mortality. The development of such a hierarchy of models would provide management tools to direct fishing effort, identify and establish closed areas and develop environmentally friendly fishing techniques. With sufficient spatially and temporally refined fishing effort data and spatially refined data on sea bed typology it will be possible to assess the impact of fishing at the fleet level and hence permit a comparison with the environmental and ecological impact of other anthropogenic activities or naturally occurring events such as storms and tidal currents.

Introduction

The initial impact that a towed demersal fishing gear has on the benthic substrate is physical, and these impacts have been classified as being either geotechnical or hydrodynamic. The geotechnical effects refer to the contact drag, the penetration and piercing of the substrate, lateral displacement of sediment and the influence of the pressure field transmitted through the sediment; whereas the hydrodynamic effects refer to the hydrodynamic drag and the mobilisation of sediment into the water column (O'Neill and Summerbell, 2011).

These physical effects can have broader ecological, environmental and biological implications and many studies have shown that towed demersal fishing gears damage habitats, cause benthic mortality, release nutrients and resuspend phytoplankton cysts and copepod eggs (Kaiser et al., 2006; Dounas et al., 2007; Gilkinson et al., 1998; Brown et al., 2013; Drillet et al., 2014; O'Neill et al., 2013). There can also be economic consequences and studies of the fuel efficiency of fishing trawlers have demonstrated that the combined contact and hydrodynamic drag of a demersal towed gear can account for up to 80% of the fuel consumed (Curtis et al., 2006).

To fully appreciate these issues and to develop more environmentally friendly and fuel efficient fishing techniques we must understand the impacts at the level of the individual gear components (i.e. trawl doors, sweeps, groundgear element, beam trawl shoe, etc.), on a range of sediment types. To date, most studies employ an empirical based approach and only distinguish between gear impacts at the level of a gear category (eg beam trawl versus otter trawl) and not between the differential effects of gears within a category.

In this project, to address these shortcomings, we further develop the numerical modelling approach of Ivanović et al. (2011), Esmaeili and Ivanović (2014) and Ivanović and O'Neill (2015) who use finite element methods to model the interaction of the seabed and fishing gear components. These models can calculate the penetration into the seabed, the sediment displaced and the associated drag and contact forces that occur when a fishing gear is towed across the seabed. They have focussed on sandy sediments and here we extend these studies to account for saturated cohesive muddy sediments.

In particular we

(i) identify the correct constitutive stress strain relationship for noncohesive sediments and incorporate it into the numerical finite element modelling code

(ii) carry out experimental sea trials to collect data with which to validate the numerical methodology, and

(iii) carry out numerical simulations of the physical impact of a range of gear components on sand to muddy sediments

This will allow the prediction of the physical impact of fishing gear components on a range of sediment types from sandy sediment (typically associated with the whitefish and scallop fisheries) to the muddy sediments (more typically associated with the nephrops fishery). The results will permit the development of deterministic methodologies that are based on an understanding of the fundamental processes at work. Thus, allowing us to assess and quantify the implications of fishing to the wider ecosystem; to provide advice to policy makers in relation to the establishment of marine protected areas and the prioritisation of seabed usage; and to develop more environmentally friendly and fuel efficient fishing gears.

Objective 1.

The first objective has been successfully achieved through establishing a constitutive soil model for sandy sediment to be used in the numerical model that closely matches all the data obtained from the full experiments undertaken previously by Marine Scotland Science.

The schematic of the model used for simulating the soil–disk interaction using coupled Eulerian and Lagrangian method (CEL) is described in Esmaeili and Ivanović (2014) and Esmaeili and Ivanović (2015). The bed of soil consists of two regions, i.e. initial seabed material and the absence of material (void). The void region is necessary because the material flows into the mesh within the Eulerian domain, therefore the space is needed to retain this deformed material. This region is initially empty, but once the contact between the object and bed is made this region will occupy both the Lagrangian elements or/and Eulerian material.

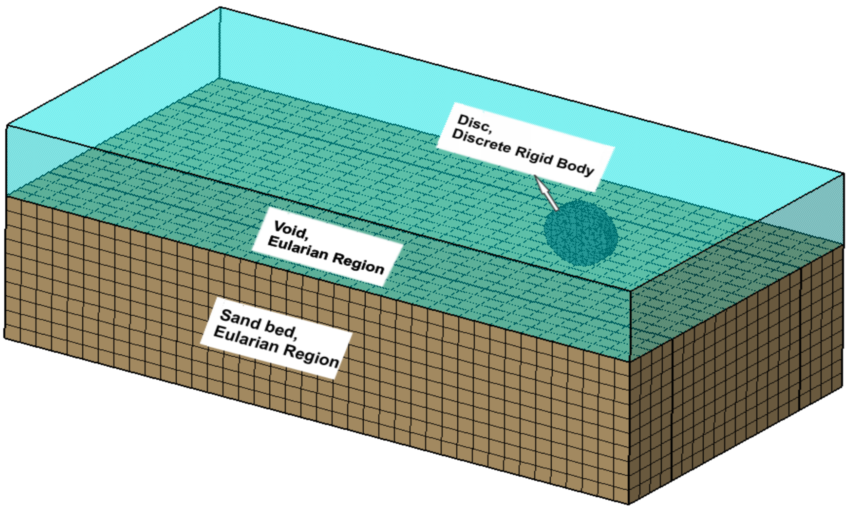

Figure 1 schematic representation of the FE model

The sand is modelled as an Eulerian domain where the flow of the material in the mesh is tracked by computing its Eulerian Volume Fraction (EVF). The length of the sand bed is chosen long enough to ensure that the towing force has reached a steady state. Since the disk and roller were assumed to be non-deformable during the towing process it was modelled as a rigid body and discretised by using Lagrangian mesh. The weights are applied at a node located at the centre of the objects. To avoid large deformations at the beginning of the simulation, the object is allowed to penetrate in vertical direction without any movement in the horizontal direction. The geometry of the object is defined by two variables: diameter d and thickness t. The vertical penetration of the object, so-called sinkage is denoted as z. The vertical and horizontal component of the reaction force at the centre of the object are denoted as $\mathrm{F_V}$ and $\mathrm{F_H}$, respectively.

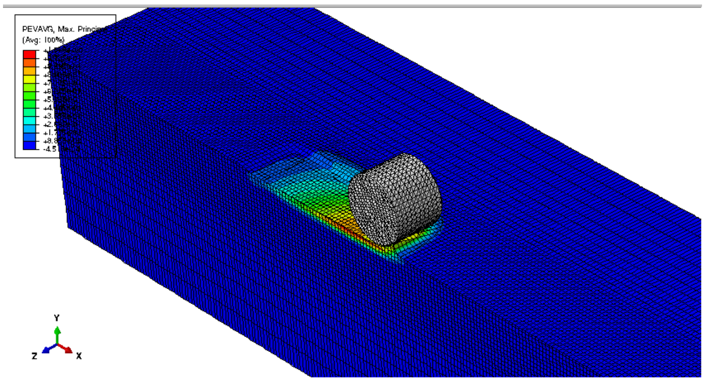

Figure 1 FE model of the roller clump

In order to refine the model a range of densities (2000 – 2500kg/m^3) and Young Modulus (10 – 50 MPa) were selected which required a number of simulations to be run. The final material properties used in these simulations are as shown in Table 1. This model was more accurate than that used previously and the simulations undertaken on a range of roller clump models (see Table 2) show a very good match between the numerical and experimental results. (Figure 1)

The Mohr–Coulomb failure criterion represents the linear envelope for peak stresses obtained from the shear box tests undertaken at several relative densities, (i.e. loose $\mathrm{D_r} = 15\%$, medium dense $\mathrm{D_r} = 48\%$ and dense $\mathrm{D_r} = 70\%$) at normal effective stresses of 10-150 kPa when c is fixed at zero. Lauder (2011), however note that the peak angle is higher at lower normal effective stresses. This study shows that the shear and normal effective stresses relationships show a slight non linearity at normal effective stresses less than 10 kPa. For instance, the peak friction angle $\varphi_{\mathrm{peak}} = 60°$ over the normal effective stress range 1-5 kPa for $\mathrm{D_r} = 75\%$ decrease to $\varphi_{\mathrm{peak}} = 44°$ for higher normal effective stresses of 10-70 kPa. Lauder (2012) indicate that the tests conducted at lower effective stresses show higher level of dilation whereas the tests conducted at the higher normal effective stresses show the least dilation. The influence of the peak friction angle on normal effective stress was therefore deemed important to the numerical modelling of the small scaled model conducted at low levels of normal stress. As this study is attempted to model the interaction between an object with the sand in loose condition, the angle of internal friction of Mohr-Coulomb constitutive model used in FE simulation is based on the critical angle of friction.

Table 1 Material properties

Specific weight *γ* (kN/m³)	Young's modulus *E* (MPa)	Poisson's ratio *υ* (-)	material Cohesion *c* (kPa)	angle of friction *β* (◦)	cap eccentricity	initial yield surface position	transaction surface rad	flow stress ratio
19.6	20	0.3	0.003	50	1.2	0.0	0.05	1

Table 2 Geometrical properties of the clump weight

Component	Geometry		Speed (m/s)	Weight (kg)
	Thickness (m)	Diameter (m)		
Clump	0.15 0.3 0.6	0.2	1.0 1.5 2.0	60 120 180
Clump	0.225 0.45 0.6	0.3	1.0 1.5 2.0	60 120 180
Clump	0.3 0.6	0.4	1.0 1.5 2.0	60 120 180

Since the shape of the models used in experiments is mainly of a cylindrical shape, it was used for both the clump and the discs, as can be seen in Figure 2.

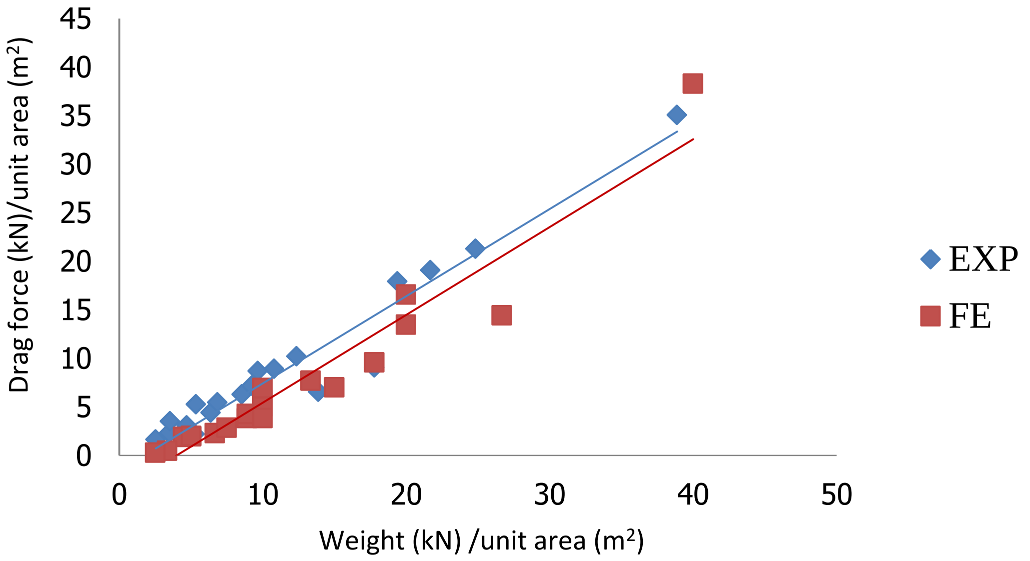

Figure 2 Comparison between the numerical and experimental (sea trials)

The simulations for other gear elements – otter door and ground gear elements have also been undertaken. Two cases of ground gear elements were looked into (Figure 3) and the results obtained are shown in Table 3.

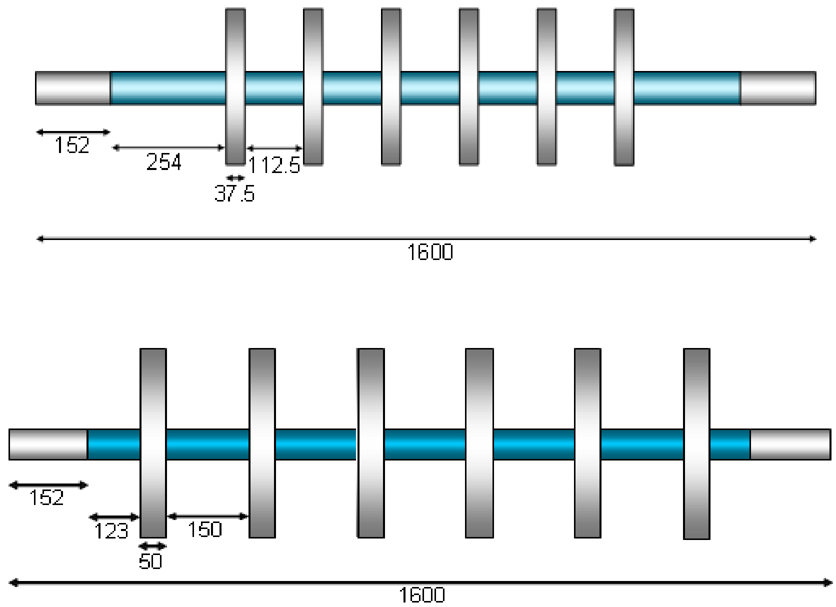

Figure 3 Schematic view of the ground gear assemblies (200mm dia of the top and 400mm dia of the bottom)

Table 3

Component	**Finite Element Method**			**Experiment**	
	Mass (Kg)	Drag force (N)	Penetration (m)	Mass (Kg)	Drag force (N)
Case 1	588	210	0.022	644	324
Case 1	1176	537	0.050	1160	652
Case 1	1764	1018	0.070	1676	896
Case 2	588	150	0.012	632	217
Case 2	1176	398	0.029	1148	419
Case 2	1764	697	0.048	1664	570

As can be seen the smaller diameter of the ground gear (Case 1) produces larger penetration which indicates that they act as a cutting tool. A good comparison between the experiment and finite element results are shown.

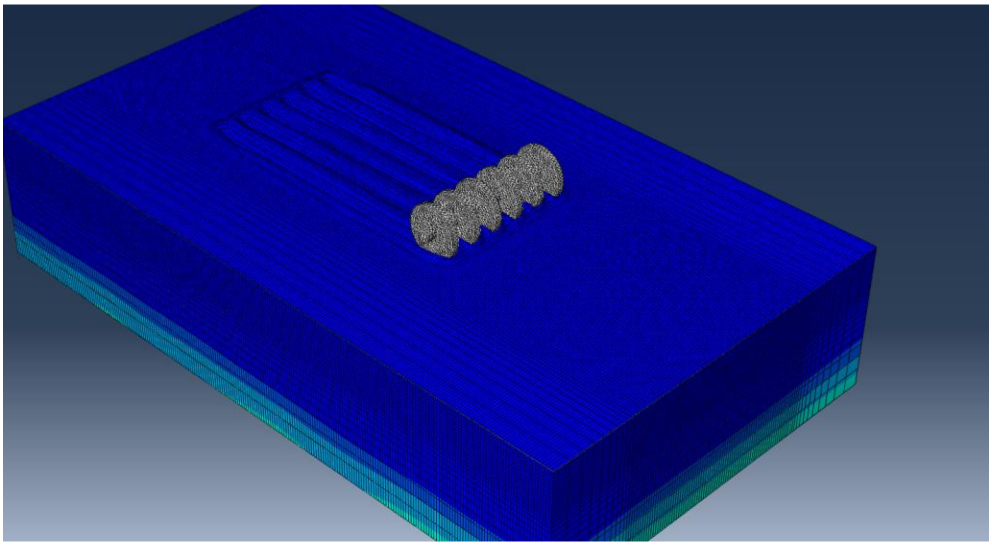

Figure 4 An image from Abaqus (rockhoppers on sandy sediment)

Simulations on otter door provided the following

Table 4

Length (m)	**Width (m)**	**Depth (m)**	**Angle of attack (◦)**	**Mass(Kg)**	**Drag force (N)**	**Penetration (m)**
1.83	0.169	0.16	35	300	2320	0.037
1.83	0.169	0.16	35	380	2698	0.044
1.83	0.169	0.16	35	460	3913	0.075

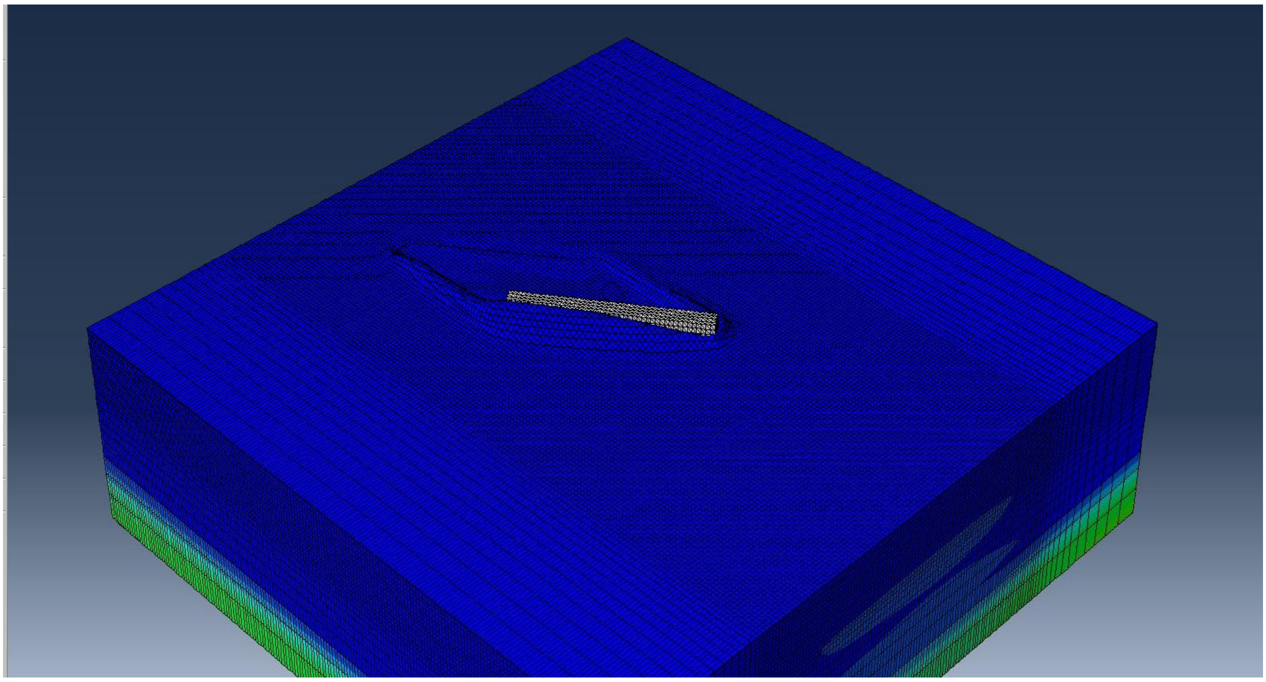

Figure 5 An image from Abaqus (otter door shoe on sandy sediment)

Objective 2.

Experimental sea trials were carried out on the RV Alba na Mara during May 2015 in the inner Moray Firth, Scotland to collect experimental data with which to validate the numerical methodology. The grounds worked were (i) approximately 8 miles east north east of Tarbat Ness and (ii) in the Dornoch Firth (Figure 6). The first of these grounds was chosen as it has soft muddy sediment and most of the trials were carried out here. A number of runs were also carried out on the sandier sediment in the Dornoch Firth so as to provide a comparison with previous trials carried out in 2013.

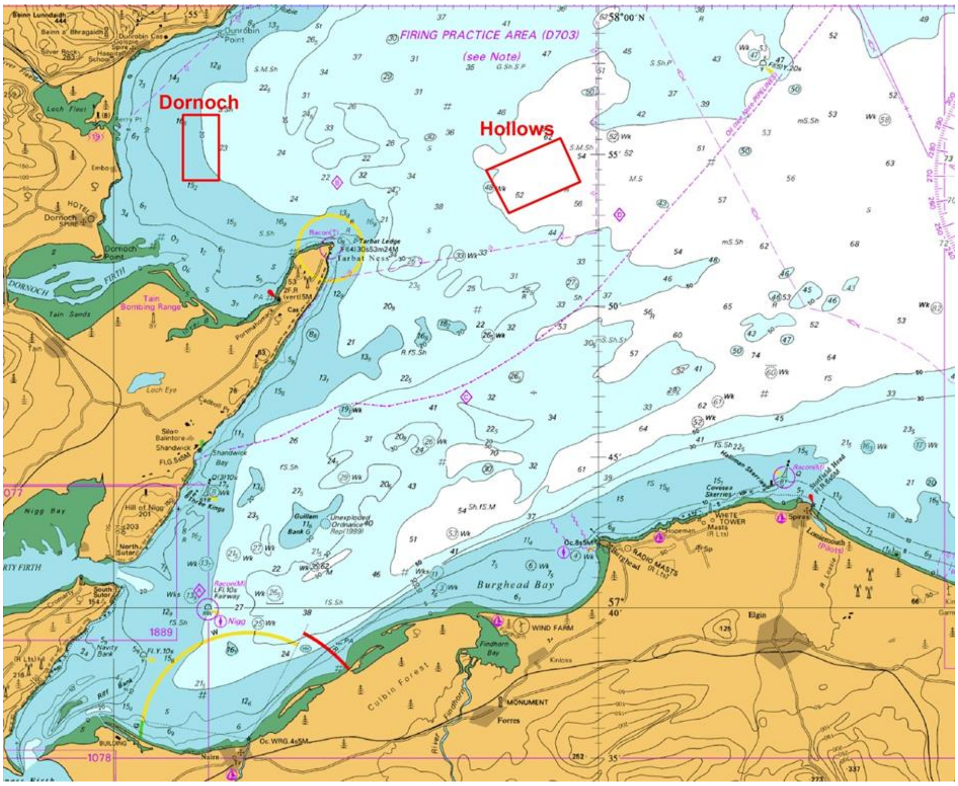

Figure 6. The two site in the inner Moray Firth where the trials took place.

Towed sledge and instrumentation

A towed sledge, of height 0.9m, width 2.1m, length 3.0m and weight 530kg was used to tow a range of cylindrical objects supported on an axle, which were chosen to simulate some of the groundgears and clump weights used in demersal fisheries (Figure 7). The full range tested is presented in figure 3 and comprises disks and cylinders of diameter 200, 300 and 400mm. In total 8 different configurations were successfully examined on the grounds east of Tarbat Ness, six different cylinder designs and two configurations of separated disks (Figure 8). These were fixed onto an axle that is 1.3m long and of 63mm in diameter and Strainstall 500kg X-Y load cells were fitted at each end of the axle to measure forces in the horizontal plane at a rate of 10Hz. The axle was attached to a framework (via the load cells) that was free to move in the vertical direction. Hence, the vertical forces the gear elements exerted on the sea bed were the gravitational forces associated with the gear element and that part of the supporting framework that was free to move. It was also possible to increase the applied vertical forces by attaching weights to the framework and each of the configurations was tested having vertical weights (in water) of approximately 60, 120 and 180kg (Figure 9). During each deployment the speed at which the sledge was towed was increased incremently over a thirty minute period from 1 to 2 m/s.

All drag, speed and concentration data were time-averaged into 10s intervals and it is these data that are examined in the following analyses. Two types of experiments were carried out: the first set were related to measuring the hydrodynamic drag, during which the elements were not in contact with seabed; while during the second set the elements were in contact with the seabed, and the geotechnical forces were investigated.

In order to provide comparison with trials carried out in 2013, three of the cylindrical configurations were also tested in the Dornoch Firth.

To classify the sediment on which the trials took place a LISST 100X Particle Size Analyser was used to measure particles in the plume in the size range 2.5–500 μm which were categorised in 32 logarithmically increasing size ranges.

Figure 7. The towed sledge used to tow the range of cylindrical objects supported on an axle.

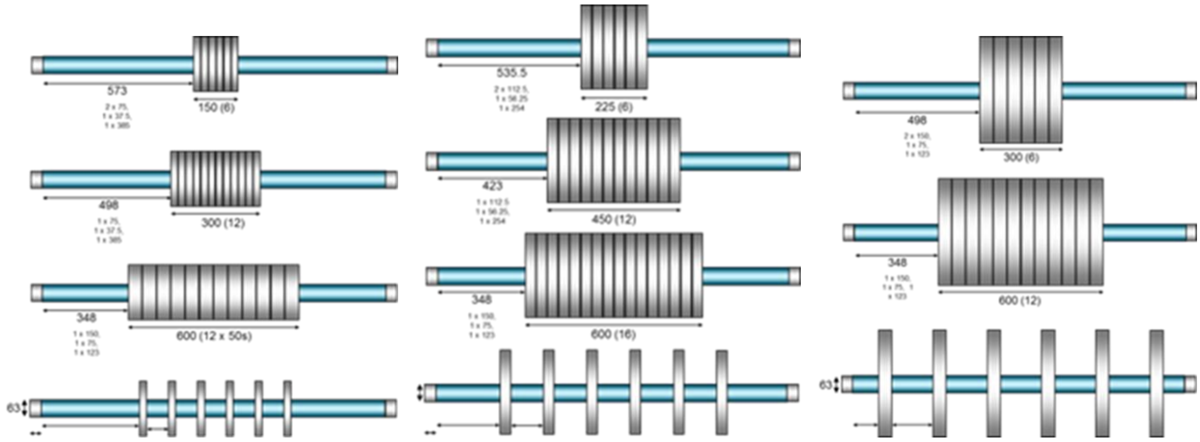

Figure 8. The range of gear components chosen to simulate some of the groundgears and clump weights used in demersal fisheries comprising disks and cylinders of diameter 200, 300 and 400mm.

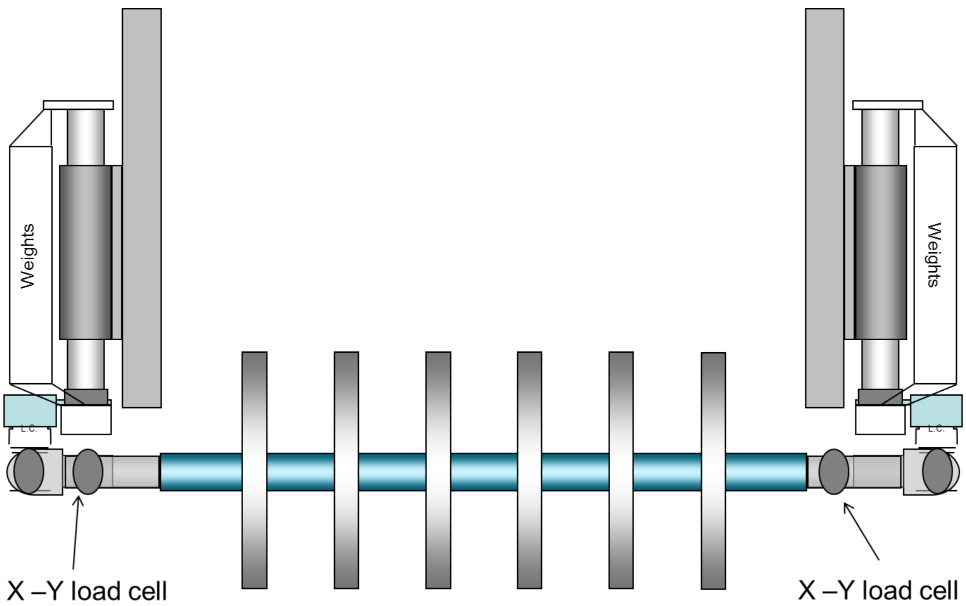

Figure 9. The framework to which the gear components and axle were attached showing where the additional weights were fitted and the position of the two Strainstall 500kg X-Y load cells.

Hydrodynamic drag

In the first set of experiments, in order to estimate the hydrodynamic drag acting on them, the cylindrical elements were held between 2 and 5 cm above the seabed and towed at speeds of between 1 and 2 m/s. The hydrodynamic drag, D (N), on a body is usually expressed as

$$D = 0.5\rho A_d U^2 c_d$$

where A_d (m^2) is the frontal area, U (ms^{-1}) is the flow or towing speed, ρ (kgm^{-3}) is the density of water, and cd is the hydrodynamic drag coefficient of the body, a dimensionless quantity that characterises the drag on a body. Here we assume that the hydrodynamic drag comprises the drag of the cylindrical element and the drag of the exposed part of the axle. Hence we fit a curve of the following form to the hydrodynamic drag data

$$D = 0.5\rho A_{elem} U^2 c_{cyl} + 0.5\rho A_{axle} U^2 c_{axle}$$

where A_{elem} is the frontal area of the gear element and A_{axle} is the exposed frontal area of the axle. c_{cyl} is the hydrodynamic drag coefficient of the cylinders and c_{axle} is the hydrodynamic drag coefficient of the axle. Hoerner (1965) collates data from a number of studies and demonstrates that as the diameter (or height) to breadth ratio (*d/b*) increases, the drag coefficient for truncated cylinders, goes from having a value of about 1.17 (and being fully two dimensional in nature) to having a value of about 0.67 for $d/b > 0.33$. Given that the *d/b* values of the cylinders we are dealing with are ≥ 0.33, the analysis we carry out assumes that we have a common c_{cyl} coefficient for all six cylinders. Hence c_{cyl} and c_{axle} are the two unknowns that need to be estimated from the hydrodynamic data.

Contact/geotechnical drag

In the second type of experiment, the components were in contact with the seabed and hence the drag measurements comprised a hydrodynamic and a contact component. These trials were carried out with vertical force loadings of approximately 60, 120 and 180kg and again at speeds of between 1 and 2 m/s. To calculate the contact (geotechnical) drag, the hydrodynamic drag was estimated using the equation above and subtracted from the measured drag. In order to standardise and compare the data we consider the drag and weight per unit area where for the cylinders the area scale is *bd* and for the disks it is 6*bd*. Initial analysis of the data suggests that the geotechnical drag per unit area has a linear dependence on the towing speed and a quadratic one on weight per unit area. Furthermore, Hambleton and Drescher (2009) have shown that for the cylinders on the cohesive sediments they investigated there was a dependency on the diameter to breadth ratio (*d/b*). Hence, to help identify these types of relationships, the geotechnical drag data for the cylinders and disks were fitted to curves of the form

$$D = \beta_1 W + \beta_2 UW + \beta_3 W^2 + \beta_4 UW^2 + \left(\beta_5 W + \beta_6 UW + \beta_7 W^2 + \beta_8 UW^2\right) d/b$$

which allows for linear changes in *U* and *d/b* and quadratic ones in weight per unit area.

Results

The LISST 100X measurements at the experimental sites are presented in Fig 4 in terms of the percent volume in each particle size bin. The silt and clay component (% of sediment < 63 µm) of the site ENE of Tarbat Ness was 42% and the d50 was 74 µm. At the Dornach Firth the silt and clay component was 12% and the d50 was 100 µm.

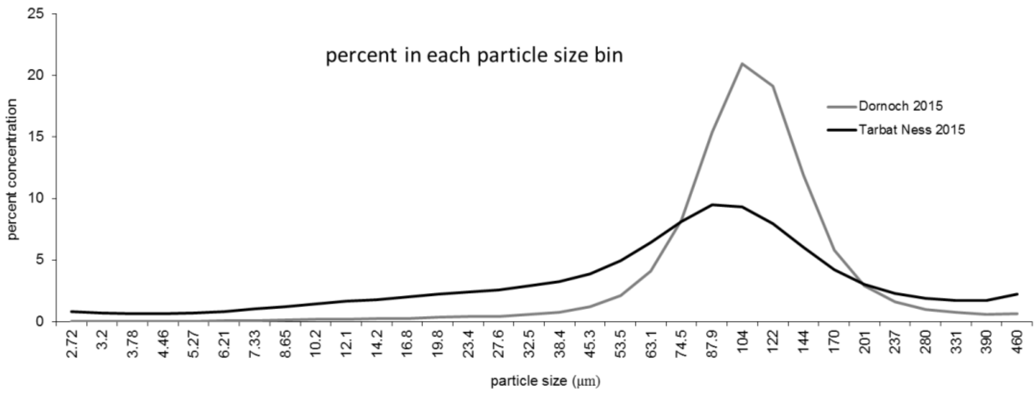

Figure 10. The percent concentration of sediment in each of the 32 logarithmically increasing particle size bins at the two sites where the sledge was towed.

The c_{cyl} and c_{axle} hydrodynamic coefficients for the cylinders and axle were estimated to be 0.87 and 0.72 respectively. These are consistent with estimates calculated from previous trials and hence the data was combined with these other data sets and reanalysed together. The resulting c_{cyl} and c_{axle} estimates were 0.78 and 0.77. The advantage of reanalysing the data in this way is that it also permitted us to estimate c_{disk} which had a value of 0.96.

The geotechnical drag measurements for the gear elements are presented in figure 11. The blue diamonds are the data from the softer sediment east north east of Tarbat Ness and the green triangles are from the sandier sediment in the Dornach Firth. These figures plot the drag per unit area data in terms of weight per unit area and for each of the d/b categories. The lines on each plot are the regression curves to the data collected in the softer sediment site (42% silt and clay fraction) and estimated at a towing speed of U = 1.54 ms-1 (the average value across the trials) and for each of the d/b values. A lot of the variation in the data is due to the additional dependency on towing speed. The plots also demonstrate that the geotechnical drag is greater on the softer sediment than on the harder, sandier sediment.

Figure 12 plots the model predictions for each of the d/b values and demonstrates that there is no real difference between any of the cylinders; however, there is a difference between the cylinders and the separated disks.

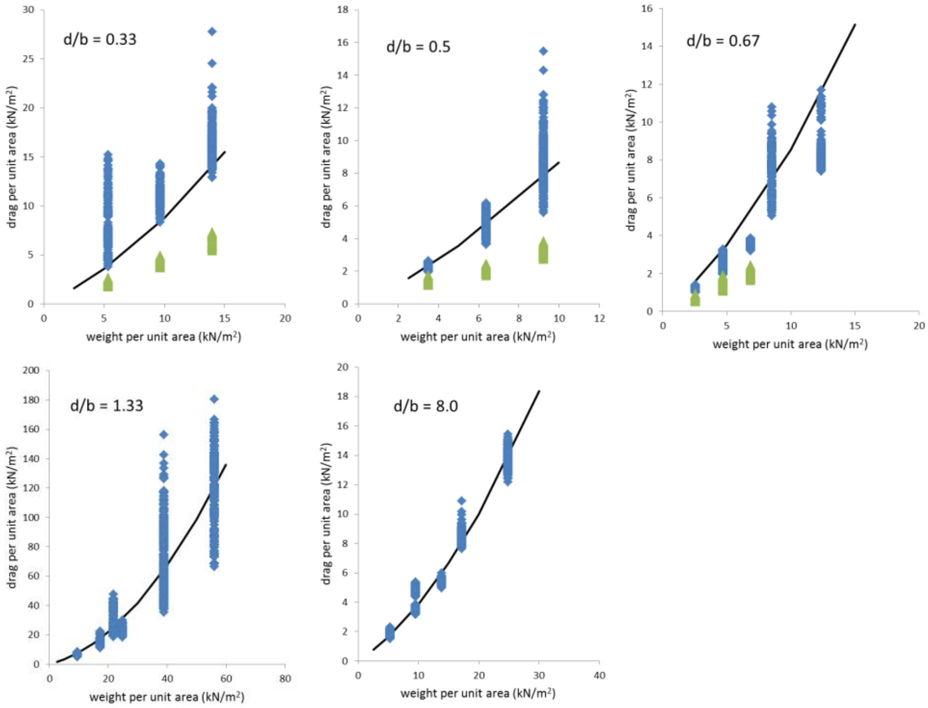

Figure 11. The geotechnical drag measurements where the blue diamonds are the data from the softer sediment east north east of Tarbat Ness and the green triangles are from the sandier sediment in the Dornach Firth. The black lines are the regression curves to the data collected in the softer sediment site estimated at a towing speed of U = 1.54 ms-1.

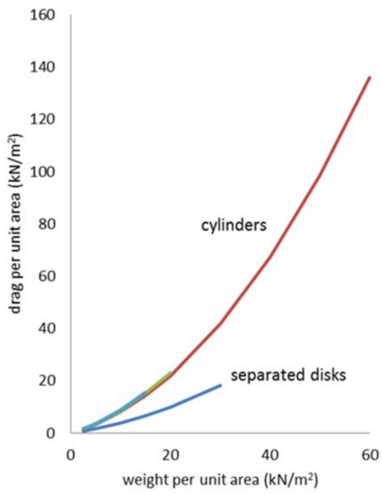

Figure 12. The regression lines to the cylindrical element data on the soft sediment are almost indistinguishable for each of the d/b categories. However, there is a difference between the cylinders and the separated disks.

Objective 3

In order to fulfil objective 3 the sediment used as part of Marine Scotland sea trials was simulated in the numerical model using the following parameters.

Table 5

specific weight	Young's modulus	Poisson's ratio	Cohesion	angle of friction
γ (kN/m^3)	E (MPa)	υ (-)	c (kPa)	φ (◦)
19.6	10	0.3	0.5	26

Simulations on the softer sediment resulted in a very similar trend as those obtained by Marine Scotland Science as shown in Figure 13.

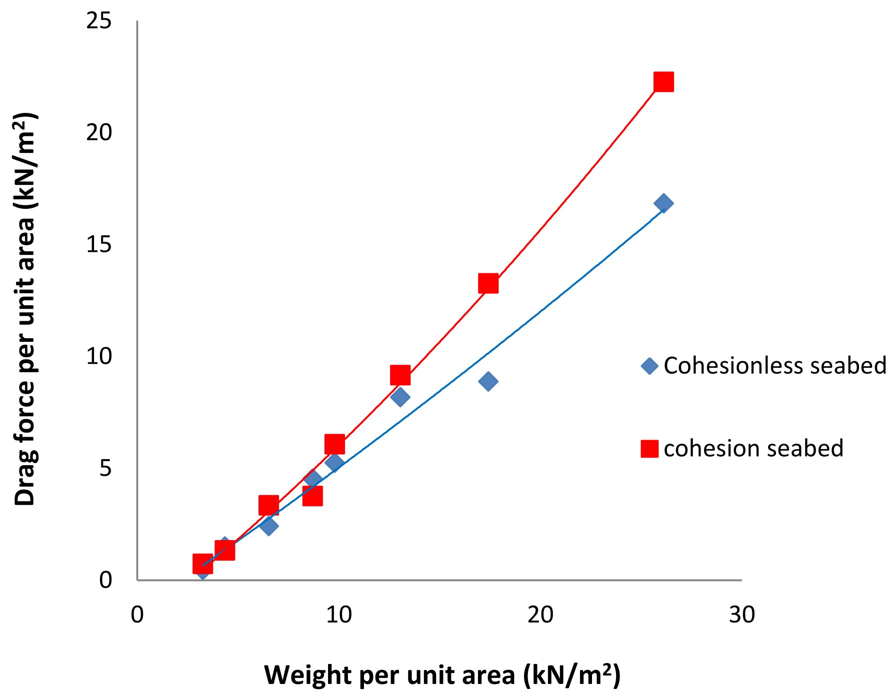

Figure 13 Comparison between cohesive and non-cohesive soil

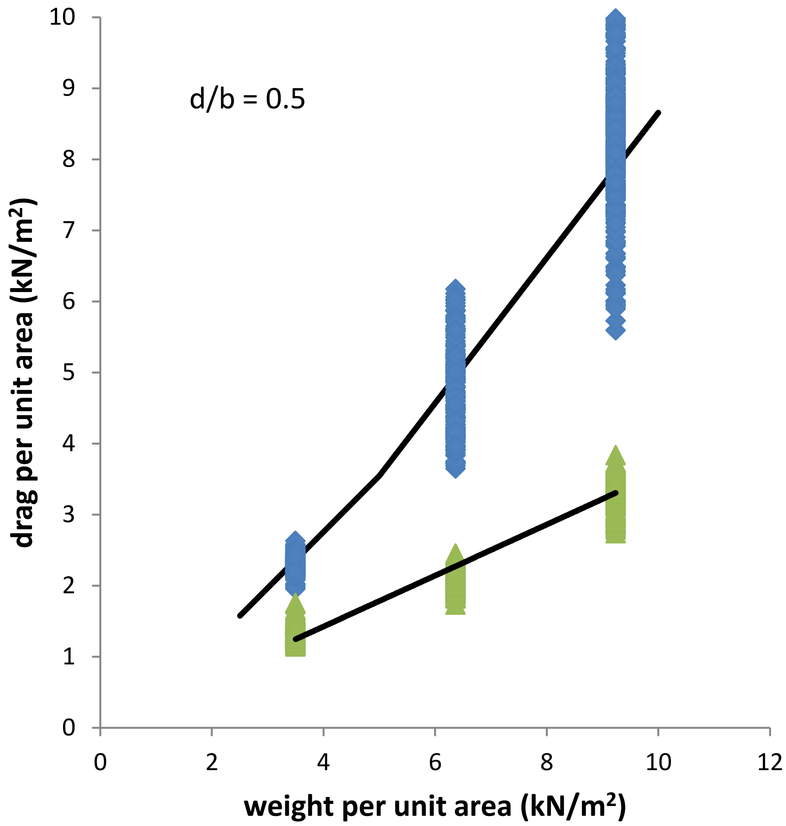

Figure 14 Comparison between cohesive and non-cohesive soils

These results demonstrate that the drag force is larger on the more cohesive sediment, which is what would be expected as components tend to penetrate more into cohesive sediments and cohesive sediments do not tend to flow around the object the way less cohesive, sandier sediments do.

Due to the computing problems encountered during the last part of the project the number of simulations initially planned for this type of sediment were not able to be undertaken but the results shown in Figure 13 and 14 show a very good comparison and therefore give encouragement that the chosen constitutive model for this, different type of soil is able to be modelled by using this approach.

The results indicate that the model has a potential to simulate different types of sediment other than purely frictional (clean sand) or purely cohesive (clay/mud) which is indeed commonly found on the seabed floor trawled around Scotland.

Conclusions

This study has extended the range of sediments on which we can model the physical impact of towed fishing gears.

The investigation of the geotechnical processes is an active area of research both within fisheries and in related engineering areas and it is important to keep up to date with developments as it is clear that some of the techniques and approaches being applied elsewhere could also be applied directly to the problems examined here. Different constitutive stress/strain relationships are being explored to characterize the geotechnical response of a broader range of sediment types which in relation to the impact of towed gears need to include both sandier and more clay-like sediments. Improvements to the accuracy and efficiency of the numerical methods are also being investigated. There are also difficulties in measuring the mechanical parameters used to characterize the geotechnical response of sediments which need to be resolved. These parameters are difficult to measure in-situ, and those measured from samples taken from the seabed do not always reflect their in-situ response.

There is also a need to be able to develop further the predictive models of the hydrodynamic processes and the resultant mobilisation of sediment. The existing empirical model will need to be updated and possibly reassessed as new experimental data are collected. Furthermore, there is particular scope for using experimental methods such as particle image velocimetry (PIV) to gain a more detailed description of the mechanisms governing sediment mobilization and computational fluid dynamic (CFD) modelling to develop deterministic models of this process. The mobilisation of sediment by turbulent flows is an important topic in many other environmental and engineering contexts and there has been a great deal of research directed at the transport of sediment by current flows and waves and the scouring and removal of sediment behind static objects such as pipelines, vertical cylinders, bridges and piers which will improve our understanding of how towed fishing gears mobilise sediment.

The longer term aim of developing models to predict the physical impact on soft sediments is to be able to assess and quantify the environmental and ecological impact of towed gears. To achieve this, the physical impacts need to be related directly to the resulting geochemical, biological and environmental effects such as nutrient enhancement and benthic mortality. A few studies have investigated some of these relationships. The rate of dissolved and particulate nutrient release behind groundropes has been measured by Dounas et al. (2007). The damage to infaunal bivalves from a trawl door have been examined by Gilkinson et al. (1998) and the mobilisation of phytoplankton cysts and copepods eggs behind gear components and of inhabiting infauna behind scallop dredges have been studied by Brown et al., (2013), Drillet et al., (2014) and O'Neill et al., (2013). Meta-analysis of studies undertaken into the mortality of benthos in the passage of towed gears (Kaiser et al., 2006) have related mortality by different fishing gears to biological characteristics and research is on-going to further refine these models to relate mortality with biological traits, such as life history, morphology and behavioural characteristics.

The development of such a hierarchy of models would provide management tools to direct fishing effort, identify and establish closed areas and develop environmentally friendly fishing techniques. With sufficient spatially and temporally refined fishing effort data and spatially refined data on sea bed typology it will be possible to assess the impact of fishing at the fleet level and hence permit a comparison with the environmental and ecological impact of other anthropogenic activities or naturally occurring events such as storms and tidal currents.

Recommendations

In order to achieve the longer term aim of developing models to assess and quantify the environmental and ecological impact of towed gears on soft sediments future research needs to take place at a number of levels.

At a fundamental level, in order to validate and ensure their accuracy and to ensure comprehensive coverage of the range of sediments on which fishing takes place there needs to be

> **(R1) further development of geotechnical models and**
>
> **(R2) further development of hydrodynamic / sediment mobilisation models**

Following on from this there is a need to

> **(R3) raise the effect at gear component and fishing gear level to the fishery/fleet level**

which will have to take into account the variation that exists in gear design between vessels and also account for the spatial and temporal variation in fishing effort and the spatial variation of sediment type.

To develop predictive models of the ecological and environmental impact of towed gears

> **(R4) the physical impacts need to be related directly to the resulting geochemical, biological and environmental effects.**

This is a growing area of research and approaches being explored utilise biological traits to assess the vulnerability of benthic species to trawling and to quantify their mortality; and laboratory mesocosm experiments and sea trials to investigate oxygen demand and the rate of dissolved and particulate nutrient release behind fishing gears.

Ultimately

> **(R5) these results should be incorporated into ecosystem models such as ERSEM to assess the broader effects of towed demersal fishing gears (eg on benthic-pelagic nutrient and carbon fluxes)**

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