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A novel shear vane used to determine the evolution of hydraulic dredge tracks in sub-tidal marine sediments

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Abstract

A novel shear vane is described which can be used to record the shear strength of discrete depth horizons of a variety of marine sediment types in situ. This vane, or modifications of it, has great potential in allowing measurement of in situ shear strength without requiring any samples to be removed from the sea bed, a process which can often destroy the fine structure of the sediment. The vane was used to monitor the change in sediment shear strength caused by a hydraulic dredge, which was used to fish razor clams (*Ensis arcuatus*) in a sheltered bay within the Clyde Sea area, Scotland. Data collected using this apparatus provided valuable and immediate information on the stratification of the sea bed post-dredging and allowed the evolution of the dredge track to be regularly monitored by divers over a period of 100 d.

Keywords: shear vane; shear strength; hydraulic dredging; razor clams; *Ensis*

1. Introduction

All mobile benthic fishing gears alter the physical characteristics of sediments and many of these environmental effects have been documented (Caddy, 1973; Fonteyne, 2000; Hall, Basford, & Robertson, 1990; Kaiser, Ramsay, Richardson, Spence, & Brand, 2000; Lindeboom & de Groot, 1998). In particular, shellfish dredges, such as scallop and cockle dredges, have been shown to abrade natural topographies and suspend fine sediments into the water column which later settle, blanketing the sea bed at some distance from the initial impact site (Eleftheriou & Roberston, 1992; Hall-Spencer & Moore, 2000; Thrush, Hewitt, Cummings, & Dayton, 1995).

Hydraulic dredges, used to harvest razor clams (*Ensis* spp.) and surf clams (*Spisula* spp.) in Scotland, Italy, Portugal and the USA, have the potential to cause great modification to the physical structure of the sea bed. They use blades or water jets to penetrate the sea bed to a depth of over 30 cm and use large quantities of sea water (≥3000 l min^{-1}) to fluidise the substratum (Meyer, Cooper, & Pecci, 1981; Tuck et al., 2000). While it has been shown that the physical disturbance caused by these dredges recovers with time (Hall et al., 1990; Hall & Harding, 1997) concerns have been expressed regarding the long-term impact of this regular disruption on the resident biological community (Hall et al., 1990). The predicted impacts of sea-bed fluidisation by hydraulic dredges range from reduced larval settlement and recruitment (Hall, 1994), causing a reduction in size of future bivalve populations, to a situation where the sea bed becomes so fluidised that large burrowing bivalves, which require a certain degree of sediment compaction to anchor themselves, can no longer burrow effectively.

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Shallow waters in which the hydraulic fisheries operate are amenable to the use of scientific divers to monitor the extent of any physical disruption and habitat modification. To date, however, the use of divers has been limited mainly to habitat mapping and the collection of faunal and sediment samples for ex situ analysis (Brazier, 1998; Eleftheriou & Robertson, 1992; Gamble, 1984; Hall et al., 1990; Hall, Robertson, Basford, & Heaney, 1993). While the recovery of cores for laboratory analysis is a long established practice, the act of removing a core from the sediment destroys the fine-scale structure and stratification of the sample being collected (Tolhurst, Riethmüller, & Paterson, 2000). In addition, the act of removing core samples from the sea bed and bringing them to the surface for analysis inevitably causes sediment decompression giving rise to erroneous fine-scale structural data (Briggs & Richardson, 1996). Core transportation can also lead to further conformational changes (Tolhurst et al., 2000).

As a result of these issues, and in response to a pressing need to quantify the physical impact to the sea bed caused by hydraulic dredges, an alternative means of recording sediment characteristics in situ was sought. A review of the literature indicated that sediment shear strength, a measure of the resistance of the sediment to torque, could be used as an indicator of sediment stratification and compaction and could be used to quantify the physical impacts of hydraulic dredges in situ (Underwood & Paterson, 1993). A common problem, however, was that the majority of methods used to measure the shear strength of soils and sediments relied on instruments that could not be submerged in sea water (Underwood & Paterson, 1993). Consequently, an alternative and more appropriate instrument was developed.

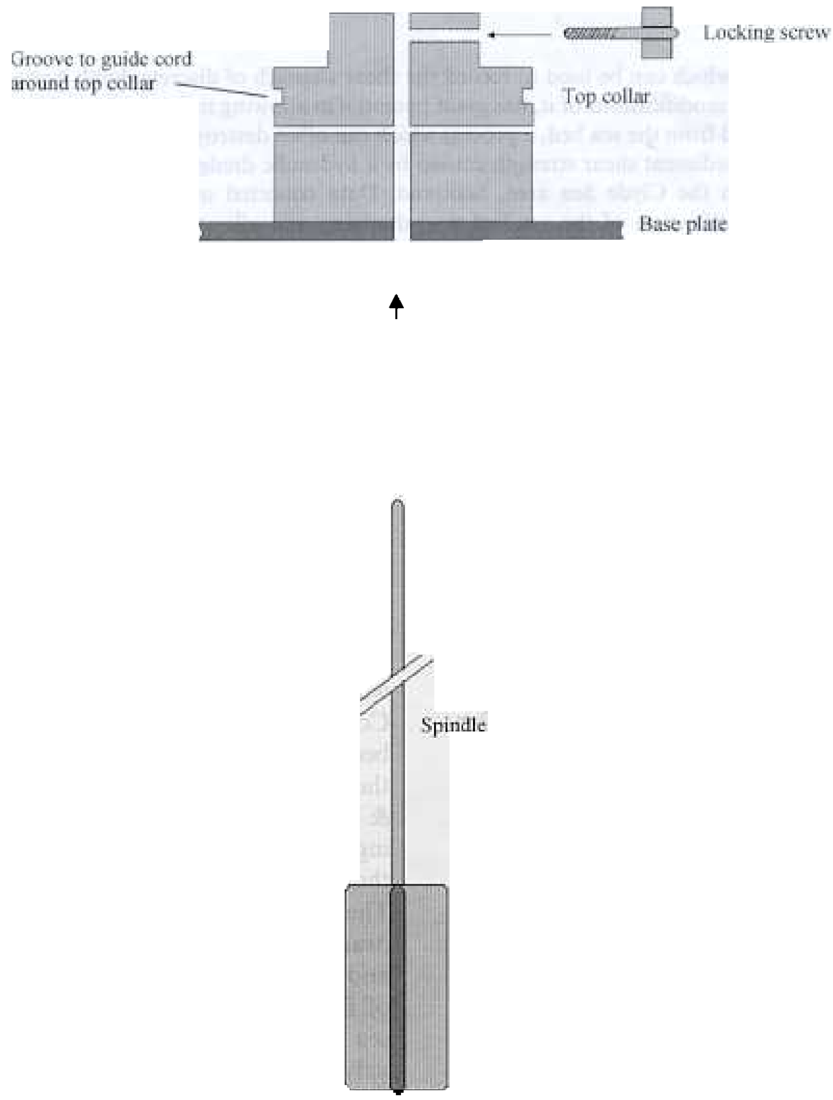


Fig. 1. Cross-section of the component parts of the shear vane. Not to scale.

2. Material and methods

2.1. Shear vane design

The design of the shear vane was constrained by the requirement for it to be used underwater by divers wearing thick (≤5 mm) neoprene gloves. A simple and robust design was needed to facilitate its assembly and use underwater. Additionally, an instrument that could measure the shear strength of discrete horizons beneath the surface of the sea bed was needed to record stratification with depth. The shear vane was constructed as shown in Figs. 1 and 2. The vane was made from marine-grade stainless steel and the cylindrical top collar and base plate mounting were machined from a single bar of steel, 6 cm in diameter.

Two vanes were produced to accommodate sediments of different shear strength. The spindle length of both vanes was 30 cm to allow measurements to be taken at different depth horizons within the sediment. The vanes were held in place by a stainless steel locking screw that was tightened through the top collar against the vane spindle (Fig. 1).

The shear vane was positioned on the sediment and spring balances (Salter Abbey™ spring balances: 0–500, 0–1000, 0–3000, and 0–10000 g) were used to apply a force to the top collar via the attached cord, which in turn created an angular force on the vane. The maximum force required to shear the sediment was recorded by divers using the scale on the face of the spring balance. The depth of the vane was adjusted by releasing the locking screw and pushing the vane deeper into the sediment. This allowed a series of measurements to be recorded at discrete horizons within the sea bed. Both vanes were calibrated according to British Standard BS 1377-7 (1990) using a variety of natural and artificial sediments including mud and wet and dry coarse and fine sands (Fig. 3).

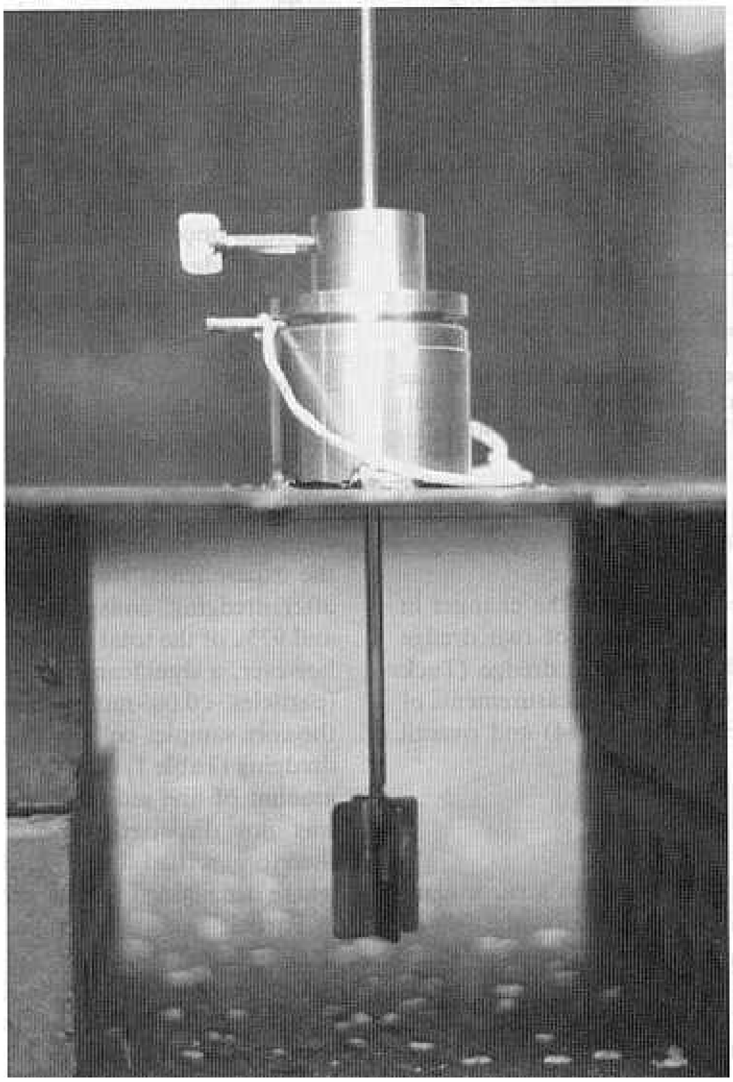
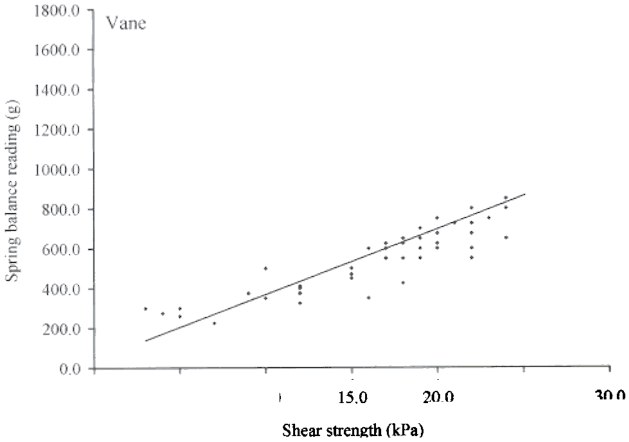


Fig. 2. The in situ shear vane as it would be deployed on the sea bed showing the cord used to apply the rotational force to the top collar.



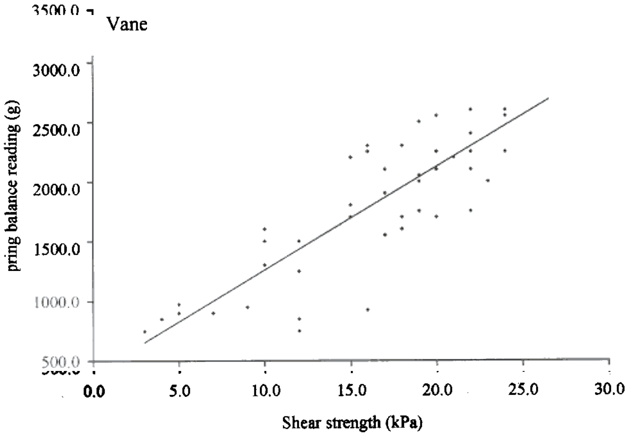


Fig. 3. Calibration curves for the two shear vanes. Vane 1: balance reading = 40.392 + (32.838 × shear strength); $r = 0.791$, $P < 0.001$. Vane 2: balance reading = 397.029 + (86.309 × shear strength); $r = 0.844$, $P < 0.001$.

2.2. Field experiment design

The shear vane was used to monitor the changes in shear strength during the development of two dredge tracks created using a hydraulic bivalve dredge (Tuck et al., 2000) as an addition to standard measurements of particle-size distribution (Buchanan, 1984) and overall dredge track dimensions.

2.3. Field measurements

Four sites were marked with buoys on a razor clam *Ensis arcuatus* bed in Lamlash Harbour on the Isle of Arran, Scotland (55.50°N, 05.10°W). The razor-clam bed was located at the northern end of Lamlash Harbour at a depth of between 4 and 6 m below chart datum (CD). Two sites were designated as control sites (c1 and c2) and two as impacted sites (i1 and i2) and all four sites were sufficiently far apart to avoid pseudo-replication (Hurlbert, 1984). Before dredging the two impacted sites, all four sites were surveyed on four occasions during the period October 2000 to March 2001. The two impacted sites were dredged using a single tow of the University Marine Biological Station (UMBSM) hydraulic dredge on the 30 April 2001. All four sites were re-visited on four occasions during the period May–August 2001 to quantify the extent of any recovery of the impacted sites, relative to the control sites.

On each occasion, one core sample (0.1 m^2, core depth 20 cm) was collected from each site and stored at −20 °C for particle-size analysis using a Malvern™ Mastersizer E laser particle counter (undertaken by Fisheries Research Services, Marine Laboratory Aberdeen). On each of the post-dredge surveys divers also used a tape measure to record the mean width and depth of the track (five replicate readings for each track).

2.4. Shear vane measurements

The shear vane was used to record the shear strength at two horizons: 'top' (−4 cm) and 'bottom' (−20 cm) for each site. Five replicate measurements of shear strength were made for each horizon at each site on every visit. Because of the time that was taken to develop and calibrate the shear vane, it was not available for use throughout the study. Shear vane measurements were recorded once before dredging (11 March 2001), on the day of dredging (30 April 2001), and then on every post-dredge survey during the period May–August 2001.

3. Results

3.1. Sediment granulometry

Sand fractions (2 → 0.063 mm, −1.0 → +3.5 Φ; Buchanan, 1984) dominated the core samples collected at the experimental site in Lamlash Harbour before and after dredging, constituting approximately between 89 and 97% of the total dry weight in each core. There was, however, a significant increase in the proportion of silt (particles <0.063 mm in diameter; Buchanan, 1984) in the core samples collected from the impacted sites after dredging (Table 1, Fig. 4). The dredge suspended a large amount of fine sediment into the water column, which was not dispersed by any appreciable current and therefore settled back down onto the dredge track, where it remained for the rest of the experiment (100 d).

Particle-size analysis and classification according to the Phi scale (Buchanan, 1984) allowed cumulative curves to be plotted for each of the 32 core samples (not shown), from which the inclusive graphic standard deviation (σ_1) was determined according to Folk (1974). The hydraulic dredge reduced the sediment from 'moderately sorted' to 'poorly sorted' within the dredge tracks (Table 2).

3.2. Track dimensions

The UMBSM dredge left 13.9 cm deep tracks in the sea bed at the impacted sites (i1 and i2). Wave action and bioturbation reduced the depth of these two tracks to 2.9 cm after nearly 100 d (Fig. 5). By this time, the tracks appeared as shallow furrows in the sea bed and were usually discernible from an accumulation of shells with adherent seaweed lying along the axis of the furrow. The dredge created straight tracks that were initially demarcated by parallel embankments caused by the 'snow-plough' effect of the base of the dredge and stabilising runners. The mean width of the dredge tracks between the parallel embankments increased from approximately 100 cm immediately after dredging, to 115 cm after 100 d (Fig. 6). This small increase was attributed to a gradual erosion of the embankments by wave action, which caused the apices to be flattened and broadened.

3.3. In situ shear strength

The sea bed in Lamlash Harbour was vertically stratified before dredging such that there was a significant difference (t test, $P < 0.01$) between the in situ shear strength recorded for the top (−4 cm) and the bottom horizon (−20 cm). At the start of the study the mean shear strength of the top horizon was 15.7 kPa while that of the bottom horizon was 72.6 kPa. The hydraulic dredge completely homogenised this vertical structure, reducing the shear strength to approximately 5 kPa to a depth of at least −20 cm (Fig. 7). During the post-dredge survey, the shear strength of the bottom horizon began to increase, although even after 100 d there was no significant difference (t test, $P > 0.05$) between the shear strength of the top and bottom horizons at sites i1 and i2 (Fig. 7).

Table 1
Summary of the two-factor orthogonal ANOVA comparing the percentage of silt in cores before and after dredging between control and impacted sites

Source of variation	SS	df	MS	F (versus residual)	$P = 0.01$
Sampling interval (Ti)	0.0063	1	0.0063		
Sand type (Dr)	0.0282	1	0.0282		
Interaction (Ti × Dr)	0.0215	1	0.0215		
Residual	0.0205	28	0.0007		
Total	0.0766	31			

Balanced ANOVA performed using GMAV5 statistical software (Underwood, 1997). Significantly different groups isolated using an a posteriori Student–Newman–Keuls analysis (SNK). Percentage data were arcsine square root transformed before analysis. SS, sum of squares; MS, mean square; df, degrees of freedom; s, significant.

4. Discussion

This article has described the design and in situ use of a simple shear vane, which was developed to allow scientific divers to record additional data on the mechanical properties of the sediment within the tracks created by a hydraulic dredge. This shear vane has great potential for monitoring sediment changes in situ without requiring samples to be removed for later

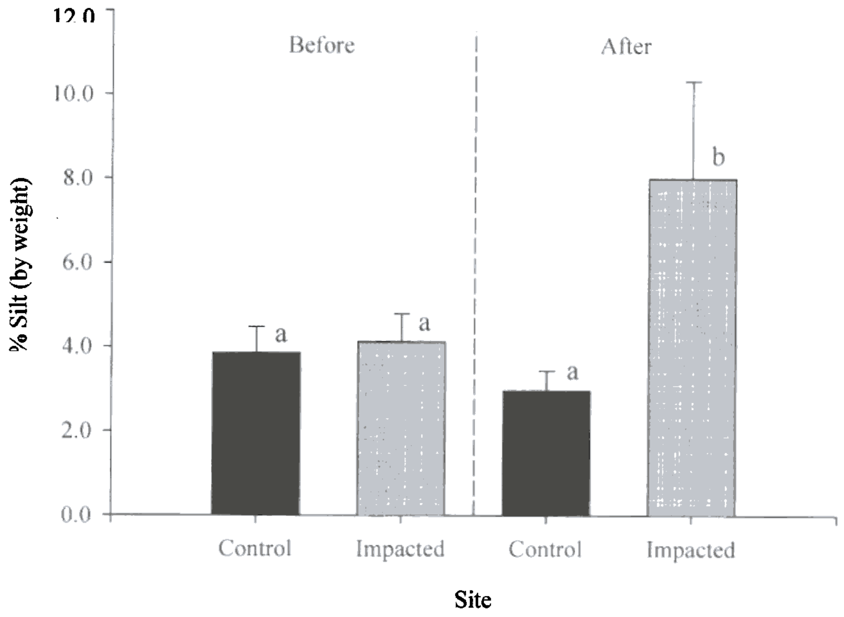


Fig. 4. Increase in percentage silt in the core samples collected from the impacted sites after dredging, showing the mean + SD ($n = 8$). Lower case letters denote significantly different groups (two factor orthogonal ANOVA and a posteriori Student–Newman–Keuls multiple comparison ((Underwood, 1997), $P < 0.01$, arcsine square root transformed data).

Table 2
Summary of the inclusive graphic standard deviations (σ_1) calculated according to Folk (1974) for the sediment cores collected at the experimental site

Sampling interval	Site	Mean σ_1 (Φ)	SD (Φ)	n	Classification
Before	Control	0.91	0.09	8	Moderately sorted
	Impacted	0.88	0.04	8	Moderately sorted
After	Control	0.87	0.04	8	Moderately sorted
	Impacted	1.42	0.36	8	Poorly sorted

analysis in a laboratory. Indeed, preliminary studies (data not shown) demonstrated that the fluidised structure of the sediment within a dredge track was totally changed by the process of removing a core sample. This ruled out any ex situ analysis of the sediment from a dredge track using instruments such as the Geonor Fall Cone apparatus (Meadows & Meadows, 1991; Meadows, Reichelt, Meadows, & Waterworth, 1994; Meadows & Tait, 1985, 1989) or load resistance penetrometers (Meadows, Murray, Meadows, Muir Wood, & West, 1998; Murray, Meadows, Meadows, West, & Muir Wood, 2000). Medium-scale changes in the vertical stratification of the sediment were measured using the in situ shear vane, providing valuable additional data to augment routine measurements of particle-size analysis. Shear vanes of similar design have been described previously (Briggs & Richardson, 1996; Underwood & Paterson, 1993). The instrument described herein, however, represents two advances on earlier designs because it can be used underwater and it does not require the operator to hold the vane spindle normal to the sediment surface as the integral base plate supports the spindle. This second feature means that the instrument is more stable and is not as prone to operator error as are previously described submersible torque vane meters (Briggs & Richardson, 1996).

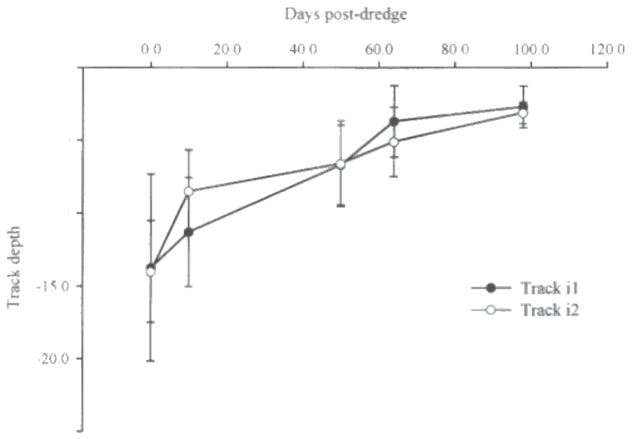


Fig. 5. Reduction in depth of the two dredge tracks created in Lamlash Harbour on 30 April 2001 (mean ± SD, $n = 5$).

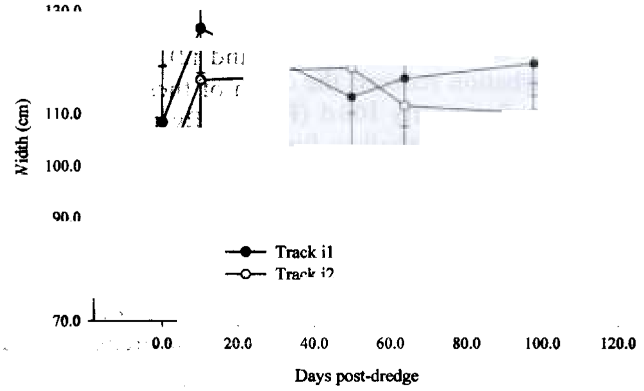


Fig. 6. Increase in linear distance between the embankments of both dredge tracks created in Lamlash Harbour (mean ± SD, $n = 5$).

Beyond the immediate issue of hydraulic dredge impacts, the scope for using divers to make in situ measurements is limited by the depth to which they can safely operate, essentially less than 30 m, as well as by underwater visibility. With modification, this vane could be used to record shear strength remotely, using the manipulator arm of a remotely operated vehicle (ROV) to provide a calibrated rotational force on the top collar. Furthermore, the length of the vane could be reduced to allow for stratified sampling of different depth horizons to be made at a higher resolution than reported in this study. Clearly, with some modifications, this device could have a wide application as a cheap and robust instrument for use in deep waters.

It is clear that the UMBSM hydraulic blade dredge significantly altered the physical nature of the sea bed, creating linear tracks of fluidised sand as well as suspending a large amount of silt into the water column which subsequently settled out onto the surface of the sea bed. The dredge removed all measurable sediment stratification and created a vertically homogenous bed to a depth of at least 20 cm. The tracks created in Lamlash Harbour existed for over twice as long as the 40-d period recorded in a previous study of hydraulic dredging (Tuck et al., 2000). The persistence of any dredge track depends upon how exposed a particular site is to wave action, currents and storm events. The site used for this work was sheltered from the prevailing south-westerly wind direction by hills rising to over 500 m. In addition, the tidal currents across this bed never exceeded $0.5\,m\,s^{-1}$ (Admiralty Chart # 2126). In earlier studies of hydraulic dredging, the experimental sites were located in the more exposed sound of Ronay near the island of Grimsay in Scotland (57.45°N, 7.25°W), subject to current speeds in excess of $1.5\,m\,s^{-1}$ (Tuck et al., 2000). As a result the dredge track features would have been eroded more quickly in the higher energy environment around Grimsay than in the sheltered bay used in this study. Frequent return visits by dredge fishers to dredge

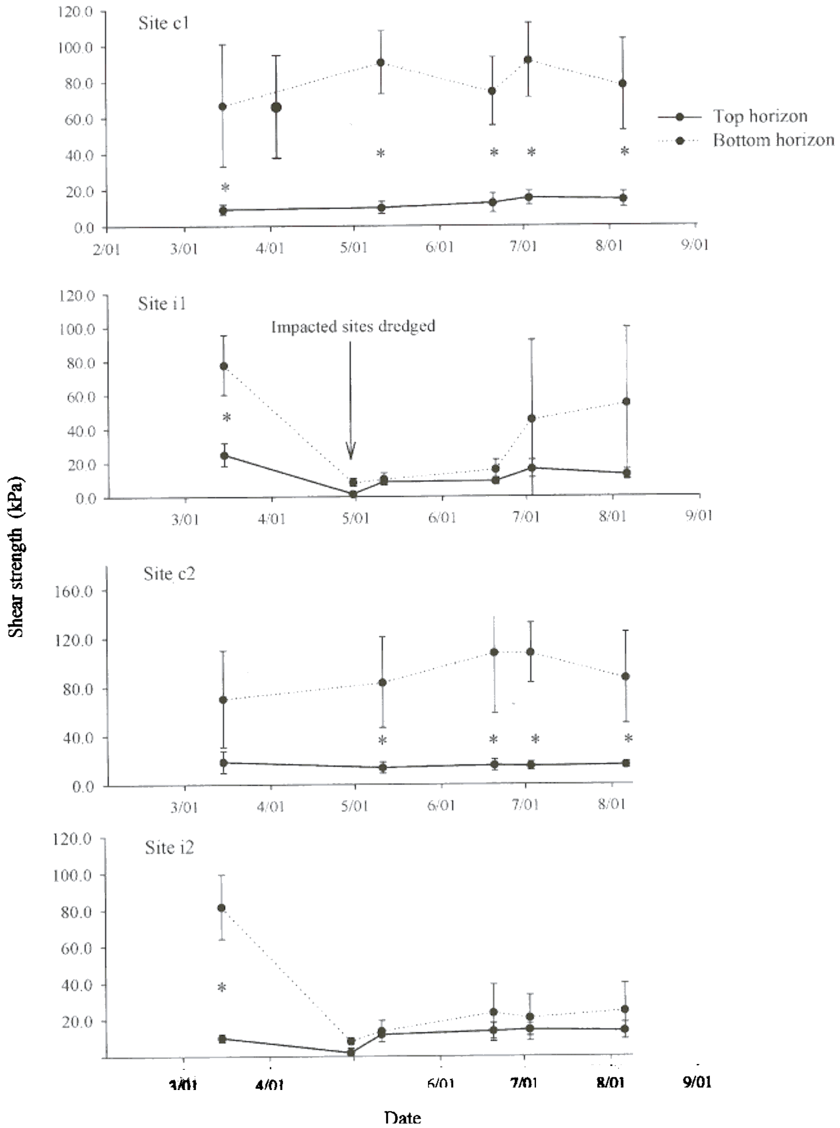


Fig. 7. Changes in the in situ sediment shear strength caused by a single pass of the UMBSM dredge (mean ± SD, $n = 5$). Asterisks indicate significant differences between the shear strength of the top (−4 cm) and bottom (−20 cm) horizons (t tests, $P < 0.01$).

sheltered sites may have a significant impact on biological recruitment, productivity and ultimately benthic community structure. The persistence and ultimate consequence of these impacts in sheltered environments, especially in areas regularly fished by hydraulic gear, should be carefully considered by fisheries managers and conservationists alike, as an integral part of any long-term ecosystem management strategy.

In summary, the shear vane described here represents a valuable new tool for the analysis of sediment structure in situ, which will allow detailed quantification of the impact of fishing gears on soft sediments, an area of research which to date has often been over-looked (Riemann & Hoffman, 1991; Palanques, Guillén, & Puig, 2001).

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