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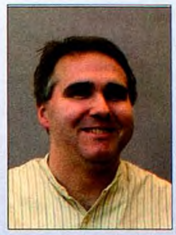

The Integration of the Free Fall Cone Penetrometer (FFCPT) with the Moving Vessel Profiler (MVP) for the Rapid Assessment of Seabed Characteristics

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Abstract

The Free-Fall Cone Penetrometer (FFCPT) is an instrument for the rapid assessment of seabed characteristics, such as grain size and shear strength. The FFCPT also acquires water column sound speed data during its descent to the seabed. The data collection process is very efficient when the FFCPT is deployed by an automated winch system, the Moving Vessel Profiler (MVP). This paper presents engineering, seabed, and SVP data that have been collected from a vessel moving at speeds from 4 to 8 knots.

Résumé

Le pénétromètre à cône à chute libre (FFCPT) est un instrument d'évaluation rapide des caractéristiques des fonds marins, comme par exemple la dimension prédominante des grains des sédiments et la résistance du sol non drainé au cisaillement. Le FFCPT procède également à l'acquisition des données sur la vitesse du son et la pression (SVP) dans la colonne d'eau lors de sa descente vers le fond de la mer. Le processus de collecte des données est très efficace lorsque le FFCPT est utilisé avec un système de treuil automatisé, le profileur de bâtiment en mouvement (MVP). L'article qui suit traite de l'ingénierie, du fond de la mer et des données SVP qui ont été collectées à l'aide d'un pénétromètre FFCPT intégré dans un profileur MVP, à partir d'un bâtiment se déplaçant à des vitesses allant de 4 à 8 nœuds.

Resumen

El Perfilador-Registrador Cónico de Caída Libre ('Free-Fall Cone Penetrometer – FFCPT') es un instrumento que se usa para la rápida evaluación de características del fondo marino, como el tamaño predominante de los granos de los sedimentos y la resistencia al corte. El FFCPT adquiere también datos sobre la velocidad y la presión (SVP) de la columna de agua durante su descenso al fondo marino. El proceso de recogida de datos es muy eficaz cuando el FFCPT se despliega mediante un sistema de guinche automatizado, el Perfilador para Buque en Movimiento ('Moving Vessel Profiler – MVP'). Este artículo presenta datos de ingeniería, del fondo marino y de SVP, que han sido recogidos utilizando un FFCPT integrado a un MVP, a partir de un buque que navegaba a velocidades que oscilaban entre 4 y 8 nudos.

1. Introduction

The Free-Fall Cone Penetrometer (FFCPT) has been developed as a tool for the rapid environmental assessment (REA) of seabed and water column properties for anti-submarine warfare (ASW) and mine counter measure (MCM) operations [1, 2]. REA involves the collection and dissemination of environmental information in a tactically relevant time frame. The integration of the FFCPT with the Moving Vessel Profiler (MVP) provides a means for obtaining seabed parameters from a vessel that is underway with minimal impact on other operations. Relative to traditional methods of making *in situ* seabed measurements from a stationary vessel, such as cores or conventional cone penetrometer tests, this integration offers an order of magnitude increase (or better) in the rate of seabed data collection. DRDC (Defence Research Development Canada) Atlantic is pursuing this development to enhance the predictions from numerical models of sonar performance and the impact burial of seamines. However, numerous scientific and commercial applications for the MVP with an FFCPT as the payload are also foreseen, for example: ground-truth for acoustic seabed classification systems, pipeline and cable route surveys, benthic habitat surveys, and dredge site surveys. This paper describes the MVP and FFCPT equipment, reports engineering data from moving vessel deployments of the FFCPT, and presents an initial comparison of FFCPT measurements with acoustically defined sediment classes.

Figure 1. Photograph of the FFCPT and MVP installed on CCGS Matthew in preparation for field trials in November, 2005.

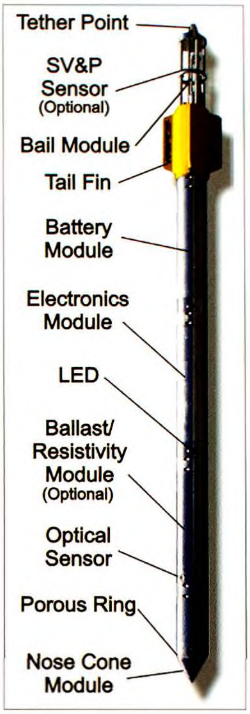

Figure 2. Diagram indicating the contents of the different modules and sensor positions in the FFCPT.

2. Equipment

a. Moving Vessel Profiler (MVP)

The MVP is an automatic winch system (Figure 1) that is used to collect water profile characteristics by deploying a free-fall fish that carries a baseline instrument such as a conductivity-temperature-depth (CTD) sensor, or a direct reading sound velocity and pressure (SVP) sensor [3]. The MVP is integrated with the ship's echosounder in order to apply the brake and stop the descent of the SVP or CTD sensor at some preset height above the seabed. The MVP has been found to be quite efficient at collecting data to calibrate multibeam mapping systems and to correct for refraction effects without having to stop the vessel and disrupt survey operations [4].

b. Free-Fall Cone Penetrometer Test (FFCPT)

The FFCPT makes direct measurements of geotechnical (large strain) properties of the seabed. It has the same scaling factors as a conventional pushed cone penetrometer, but with a larger diameter to house the instrumentation and power supply (nine 'D' cell batteries). It is designed to free-fall into the seabed and to survive impacts with rock, if and when that happens. It consists of a nose cone instrumented with geotechnical sensors, power supply, electronics, and tail pressure sensor (Figure 2). It measures acceleration and dynamic sediment pore pressure as a function of depth of penetration into the seafloor. The FFCPT also records hydrostatic pressure, to monitor its descent velocity during free-fall, and optical backscatter for the detection of the water-sediment interface (or 'mudline') which is particularly helpful on high porosity fluid-mud seabeds. When fitted with the optional electrical resistivity module (Figure 2), the FFCPT can also obtain geoacoustic (small strain)

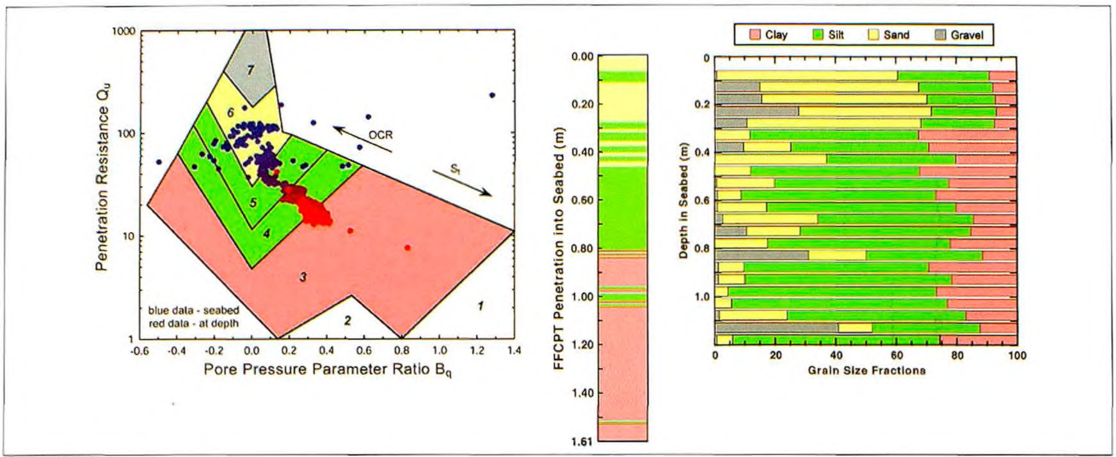

Figure 3. Left: Sediment behaviour type of an FFCPT drop at a site in St. Margaret's Bay, Nova Scotia (Site 3 in Table 2). Middle: "Pseudo-core" of the dominant sediment behaviour type measured by the FFCPT. Right: Grain size analysis of a co-located sediment core, collected by the NRV Alliance. The seabed has a surficial layer of sand underlain by finer grained material.

properties of the seabed by relating resistivity to porosity and other parameters [1,6].

The FFCPT provides two independent means of calculating the undrained shear strength. The first technique uses the acceleration to calculate the dynamic penetration resistance. The second technique uses the dynamic pore pressure measured by a sensor in the nose cone of the FFCPT. The pressure signal passes through a porous hydrophilic ring to the pressure sensor inside a cavity in the nose cone that is filled with mineral oil. Before conducting experiments, steps are taken to ensure that the cavity does not contain any air and that the pressure transducer has reached thermal equilibrium.

Normalized values of the dynamic penetration resistance and dynamic pore pressure are used in a qualitative determination of the sediment behaviour type (e.g. clay, silt, sand, or gravel) by the direct application of geotechnical analysis methods and parametric-based correlations already long established in engineering practice [5]. When plotted against each other, these parameters yield an empirical measure of sediment type (Figure 3), based on the zone in which the data lie (Table 1). Discrete measurements at different depths are plotted as dots, colour coded as a function of depth from the seabed to the depth of penetration of the FFCPT into the seabed. The FFCPT sediment behaviour type may also be presented as a colour coded 'pseudo-core' (Figures 3 and 8). Through comparison of FFCPT results with independent measurements of sediment grain size and porosity for clay, silt, and sand seabeds, Osler et al. [1] confirmed that the FFCPT accurately characterizes a diverse range of marine sediments. Figure 3 provides a sample comparison of an FFCPT pseudo-core with grain size measurements from an actual core at the same location (Site 3 in Table 2). (To permit a comparison with the four grain size fractions in the actual core, note that two of the five FFCPT sediment behaviour types have been colour-coded identically).

The inclusion of an optional SVP sensor in the tail of the FFCPT (Figure 2) permits the acquisition of

FFCPT Zone	Sediment Behaviour Type
1	Sensitive, fine-grained
2	Organic sediments: wood waste, peats
3	Clays: clay to silty clay
4	Silt mixtures: clayey silt to silty clay
5	Sand mixtures: silty sand to sandy silt
6	Sands: clean sands to silty sands
7	Gravelly sand to sand

Table 1. Description of FFCPT sediment behaviour types (after [5]).

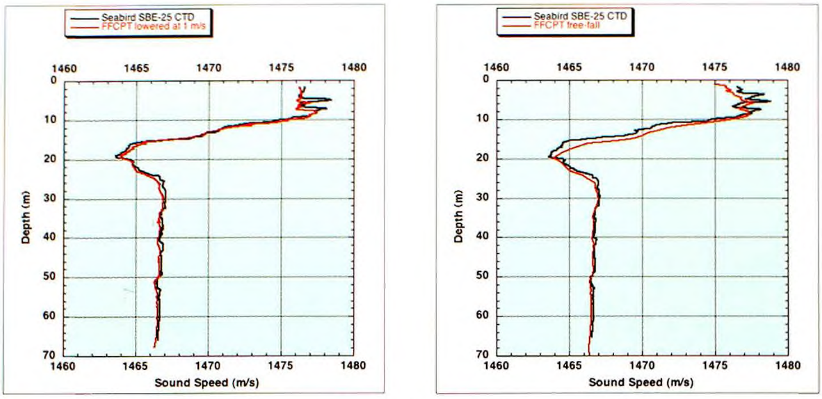

Figure 4. Comparison of sound velocity profiles calculated from CTD measurements with the direct reading SVP sensor in the FFCPT. Left: The FFCPT is lowered at the same speed as the CTD, approximately 1 m/s. Right: The FFCPT is in free-fall at approximately 8 m/s.

water column sound speed data during each deployment. This makes the data set more comprehensive for REA applications, and also to mapping systems that have a basic requirement for water column sound speed data. To determine if the free-fall velocity of the FFCPT or the position of the SVP sensor adversely affect the FFCPT sound speed measurements, two tests were conducted from a stationary research vessel. In the first test, the FFCPT and a Seabird SBE-25 CTD were lowered simultaneously at a rate of approximately 1m/s. In the second test, the FFCPT was allowed to free-fall at approximately 8m/s while the CTD was once again lowered at approximately 1m/s. When the FFCPT is in free-fall, some minor differences in the sound speed data are apparent (Figure 4), especially in the region of the thermocline where the FFCPT curve has the correct shape but is slightly offset (by up to 2 m) in depth. The differences may be attributable to the reduced number of FFCPT SVP samples (by a factor of approximately 8) and/or the advection of some water in the tail zone of the FFCPT. For the REA applications that DRDC Atlantic envisions, these discrepancies are considered minor and acceptable.

c. Integration of the FFCPT and MVP

The FFCPT payload has been integrated with the MVP to permit the assessment of seabed characteristics from a vessel that is underway (Figure 1). Rather than having the MVP winch apply its brake to stop the descent of an SVP or CTD payload at a preset height above the seabed, the FFCPT payload is intentionally allowed to impact the seabed. To prevent slack cable on the drum when the FFCPT impacts the seabed, a line puller replaces the standard over-boarding sheave (Figure 5). It is hydraulically driven and incorporates a clutch bearing to allow the sheave to freewheel during free-fall yet be driven once tension is removed from the cable. The line puller may remain in place (in a deactivated mode) for operations with the SVP and CTD payloads. (The MVP installed on the CCGS *Matthew* was fitted with a line puller for the 2005 field season and no unusual cable wear was detected). Additional modifications to the MVP for FFCPT operations included some supplemental bracing to the frame, a clevis pin load cell installed in the inner sheave to monitor pull-out loads, and modifications to the winch control algorithm to prevent damage to the winch motor in the event that the brake slips – if the load exceeds 1000 lbs. Note that the system is intentionally designed such that the brake will slip before any other point of failure is encountered (such as cable break strength or mechanical load on the superstructure).

Two modifications were required to the design of the FFCPT for use with the MVP. Previous testing

Figure 5. Photograph of the line puller that replaces the normal over-boarding sheave on the MVP to prevent the cable drum from over-rotating when the FFCPT impacts the seabed.

	Latitude	Longitude	Anticipated Penetration (m)	Depth (m)	Sediment Type
Site 1	44°36.958'N	063°59.794'W	0.5	40	Sand and gravel
Site 2	44°36.601'N	064°00.629'W	1	39	Sand
Site 3	44°36.436'N	064°00.557'W	1.5	43	Sand over silt and clay
Site 4	44°34.972'N	063°59.244'W	2.5	58	Clay

Table 2: Underway drop test locations in St. Margaret's Bay

during the development of the FFCPT established a requirement for tail fins (Figure 2) to ensure that the FFCPT impacts the seabed at a near-vertical angle. To prevent rotation of the FFCPT when it is being towed behind the vessel (and potential damage to the electro-mechanical tow cable), two of the adjacent fins were enlarged. The modified fins provide a stable tow with no adverse effect on its angle of impact with the seabed. The second modification was the introduction of a 2ft wire rope extension between the probe and cable to act as a 'standoff', preventing the cable from coiling around the tail fins.

3. Field Testing

The FFCPT has been deployed from MVP200 winch systems installed on the CFAV *Quest* in October 2005 and CCGS *Matthew* in November 2005. Seabed and SVP data have been collected from these vessels while underway in Bedford Basin, the approaches to Halifax Harbour, and in St. Margaret's Bay at speeds ranging from 4 to 8 knots. Four sites in St. Margaret's Bay, Nova Scotia (Figure 6 and Table 2) were selected for underway drop testing based on the diversity of sediment types and expected penetration of the FFCPT (from previous sea-trials with FFCPT drops from a stationary vessel [1]). Sites 1-3 are in an area with extensive survey information: four swath bathymetry systems (Atlas Hydrosweep MD50, Simrad EM3000 and EM710, and Reson 8125); side-scan sonar (Klein 5500); sediment cores with grain size analysis and multi-sensor core logging of physical properties (porosity and compressional wave sound speed); stereo photographs; high resolution seismic profiles (EdgeTech X-Star chirp system and GeoAcoustics Boomer impulsive system); scientific [7] and commercial seabed classification systems– Roxann; grab samples [8]; and sediment probe drops (FFCPT, STING, and XBP) [7].

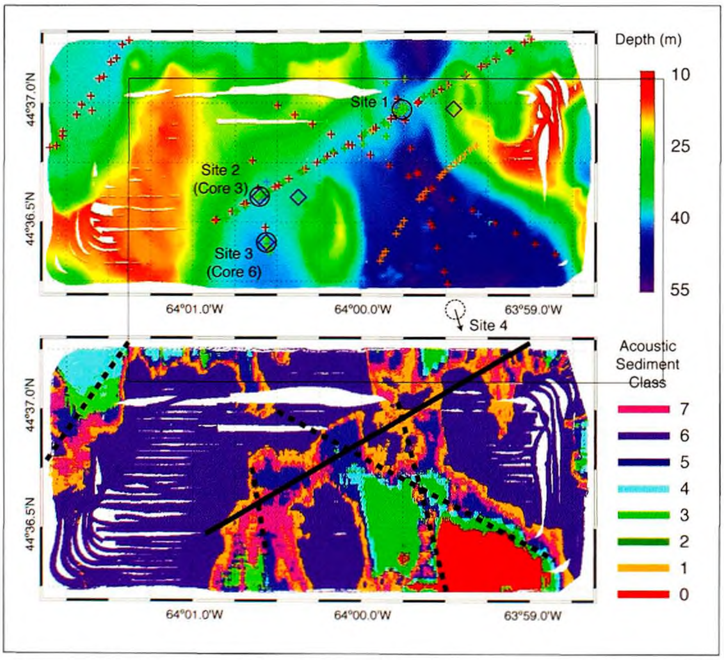

Figure 6. Top: Location of FFCPT drops ('+' symbols, coloured to represent different sea-trials) in St. Margaret's Bay are superimposed on a swath bathymetry image [7]. Diamonds are the locations of cores. Circles denote the locations of the underway drops repeated at different vessel speeds (Table 1). Bottom: Survey transects with consecutive FFCPT drops from a moving vessel are superimposed on an acoustic sediment classification map [7]. The solid line is the survey transect conducted by CFAV Quest and shown in Figure 8. Dashed lines are survey transects conducted by CCGS Matthew.

a. Underway drop testing

Underway drop testing progressed from Sites 1 through 4, with the expectation that pull-out loads would increase at the progressively softer sites as the depth of FFCPT penetration increases. To eliminate the possibility of damaging the electro-mechanical cable on the MVP200 during the initial tests conducted aboard CFAV *Quest*, the electro-mechanical cable was replaced with a mechanical rope (ø1/4", 5000lbs break strength). For the November 2005 FFCPT transects aboard CCGS *Matthew*, the standard electro-mechanical cable for MVP operations was used and the 'slow' data from the FFCPT, decimated to 1 Hz, was telemetered up the tow cable. To minimize the risk of damaging equipment, the initial underway drops at Sites 1-4 were conducted with a 'dummy' probe whose geometric and mass properties are identical to the FFCPT. Underway drops with the actual FFCPT were then conducted at speeds of 6, 5, 4, and 3.5 knots.

A fundamental objective of the underway drop testing was to establish that the FFCPT could be extracted from the seabed regardless of seabed type and for a reasonable range of vessel speeds. Measured peak pull-out loads at Sites 1 to 4 were less than 275 kg, and well within the capacity of the brake on the cable drum of the MVP200 (Figure 7). (For the purposes of this paper, the measured pull-out forces in Newtons have been normalized by the acceleration due to gravity to provide pull-out 'loads' in units of kilograms). There was some unexpected behaviour as the pull-out loads at Site 2 were consistently higher than Sites 3 and 4. A detailed examination of the load cell time series has revealed that the extraction from the softer sites (3 and 4) is more gradual (~ 4 to 5 s duration) whereas the extraction from the harder sites (1 and 2) is faster (~2 to 3 s duration). There is some evidence that the pull-out load decreases as vessel speed increases (Figure 7) due to the near-vertical force exerted by the catenary that the tow

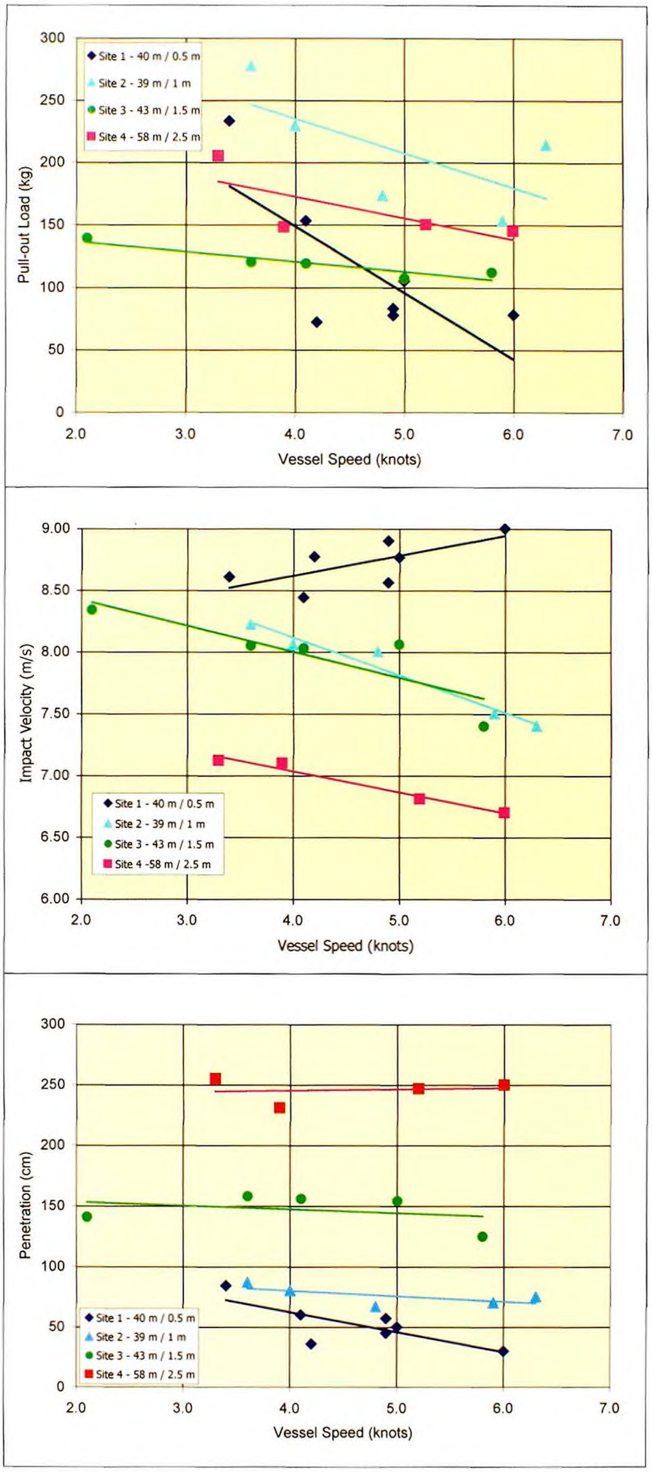

Figure 7. Top: Pull-out loads as a function of vessel speed at the four Sites listed in Table 2 (the legends include water depth and the anticipated FFCPT penetration). Middle: Impact velocity of the FFCPT with the seabed as a function of vessel speed. Bottom: Actual depth of FFCPT penetration as a function of vessel speed.

cable forms in the water column, though this effect is not as pronounced as expected. Another metric to examine underway drop behaviour is the impact velocity of the FFCPT when it strikes the seabed (Figure 4). The impact velocity may be determined by measuring the rate of change of the hydrostatic pressure and/or by integration of accelerometer signals during the impact event. (The two should agree and this is a useful sanity check in the analysis). In this case, the latter is plotted versus vessel speed and there appears to be a trend (at 3 of 4 Sites) for the impact velocity to decrease as vessel speed increases. It is suspected that this is a consequence of additional cable being in the water at higher vessel speeds. This explanation would be consistent with an analysis of FFCPT drops from a stationary vessel that indicates that the impact velocity decreases as water depth (and hence cable drag) increases. The depth of penetration of the FFCPT into the seabed depends upon the Site, from approximately 250 cm for a soft clay seabed (Site 4 in Figure 7) to less than 50 cm for a sand and gravel seabed (Site 1 in Figure 7). The depth of penetration is quite consistent at all vessel speeds (Figure 7), as are the sediment behaviour types in the respective pseudo-cores (not shown). These observations suggest that the performance of the FFCPT does not depend on vessel speed (or impact velocity).

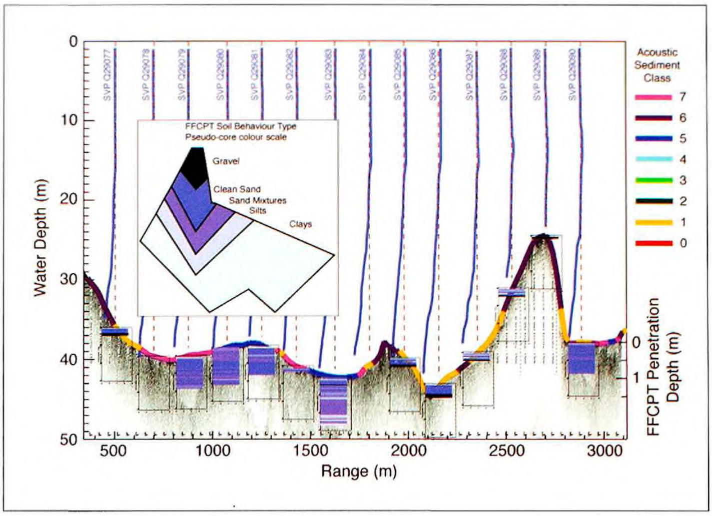

Figure 8. A combination of FFCPT results with different survey information. Thin vertical red lines are FFCPT drop locations and represent a value of 1485 m/s for the SVP measurements (thick blue lines). The thick coloured lines that follow the seabed denote acoustic sediment classes (legend to right of the plot, see text for additional details). The image below the seabed is from an X-star sub-bottom profiler. Pseudo-cores of sediment behaviour type as a function of depth are plotted at each FFCPT drop location (colour scale in inset as per Figure 3 and Table 1).

b. Multiple underway drop survey transects

Having established confidence that the FFCPT could be deployed on a wide range of seabed types at different vessel speeds, underway testing progressed to conducting a series of drops in succession as the vessel maintained course and speed. Multiple drop survey transects were conducted by CFAV *Quest* passing through Sites 1 and 2 at 4 and 6 knots (Figure 6). Three weeks later, multiple drop survey transects were conducted by CCGS *Matthew* in Halifax Harbour and its approaches, and in St. Margaret's Bay. At the latter location, CCGS *Matthew* repeated the CFAV *Quest* transects and then progressed along four additional transects (Figure 6) designed to pass through Sites 2 and 3 and areas identified as being distinct sediment classes (based on the angular backscatter response of EM3000 swath bathymetry data [7]). The cycle time per drop is presently dictated by the time required for the FFCPT to write data to its Compact Flash card and re-arm. However, this is also the approximate time required for a complete drop cycle (free-fall, impact, and winch back) in 50 m of water. The survey transects conducted with CFAV *Quest* used a time interval of 90 s between successive drops (180 m at a vessel speed of 4 knots); those conducted from CCGS *Matthew* used a time interval of 75 s (with probe re-arming confirmed by monitoring the 'slow' data telemetry).

An ongoing goal of this research is to study the relationship between acoustic techniques for seabed classification and *in situ* measurements that are made by the FFCPT. The acoustic techniques have the advantage of providing broad area coverage for REA applications and they are generally able to successfully distinguish regions of the seabed that are distinct from one another. However, they are generally unable to indicate the physical properties of the seabed that are responsible for the distinct regions. One could envision a survey strategy that combines the broad area coverage of the acoustic techniques with the *in situ* measurements made by the FFCPT. This would allow confirmation that different seabed classes are indeed distinct and to determine their composition. The authors note that backscatter intensity (as used for the seabed classification results presented in this paper) is a function of both the 'hardness' and the 'roughness' of the seabed. Further, there may be contributions from both interface and volume scattering depending on the frequency of mapping system and composition of the seabed. Seabed characterization with the FFCPT should permit the hardness to be characterized and may be able to indicate the likelihood of contributions from volume scattering mechanisms.

Figure 8 provides an initial demonstration of this approach. It is a combination of SVP profiles and pseudo-cores measured by the FFCPT, a sub-bottom profiler image, and seabed classification from EM3000 swath bathymetry angular backscatter analysis [7,8]. FFCPT drops in acoustic classes 1, 6, and 7 generally have limited penetration (less than 0.5 m) and report seabed compositions of gravel and sand. This is consistent with the grain size information (Table 3) available from grab samples [8]. The FFCPT indicates that Class 1 has a thin surficial layer of sandy-silt. FFCPT drops in Class 5 have deeper penetration (1 to 1.5 m) and indicate a sandy-silt to silty-sand composition. There are FFCPT drops in the other sediment classes on different transects (Figure 6) that will be examined as part of the ongoing analysis of this data set.

4. Summary

The FFCPT is a tool for the rapid assessment of water column and seabed properties (undrained shear strength and sediment behaviour type). The integration of the FFCPT with the MVP automated winch system provides a means to assess the seabed from a vessel that is underway with little or no impact on other operations. A wide range of military, commercial, and scientific applications are foreseen for this technology. Underway profiling with the FFCPT has been demonstrated for a range of vessel speeds and sediment types. Measured peak pull-out loads are less than 275 kg, well within the capacity of the brake on the cable drum of the MVP200. At most Sites, pull-out load decreases moderately as vessel speed increases due to the force formed by the catenary of the electro-mechanical cable in the water column.

5. Future Work

Several instrument developments are planned or already underway. These include the high speed, real-time or near real-time, telemetry of FFCPT and SVP data. (At present, the instrument records internally for later download and only telemeters data that has been decimated to 1 Hz sampling rate to monitor probe depth and status). Software developments will further improve and automate the data processing and display, including options to filter the accelerometer signals and a 'vehicle dynamics' panel to permit a detailed analysis of the FFCPT free-fall and impact with the seabed. In

Class	**Grab Sample Grain Size Fractions**					**Visual Description**
	gravel	**sand**	**silt**	**clay**	ϕ	
0	0%	3%	48%	49%	8.3	Mud
1	4–31%	43–71%	10–35%	6–12%	0.9–4.1	Silt, shells and stones
2						No sample
3	0%	12–20%	43–46%	29–42%	7.3–7.8	Mud
4						No sample
5	1–2%	57–62%	25%	12–15%	4.2–4.5	Silt
6	17–36%	51–83%	0–7%	0–6%	-0.1–0.6	Gravel, sand, shells
7	2–3%	61–64%	23–27%	9–11%	3.9–4.3	Silt

Table 3: Acoustic sediment classes in St. Margaret's Bay and grain size information from grab samples (after [8]). Note that ϕ = –log2(mean grain diameter in mm)

St. Margaret's Bay, the authors plan to continue investigating the relationship between measurements made by the FFCPT and other survey data and techniques that are used for seabed classification (swath bathymetry, sidescan sonar, and high resolution seismic profiles).

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Biographies of the authors

Dr. John Osler is a scientist with Defence Research and Development Canada–Atlantic and Leader of the Maritime Environmental Awareness Group since 2004. He graduated with an Honours B.Sc. degree in Geophysics from McGill University in 1986 and received a Ph.D. from Dalhousie University in Geological Oceanography in 1993. He was a scientist at the NATO Undersea Research Centre in La Spezia, Italy from 1996 to 1999. His research focuses on seabed-interacting acoustics and techniques for the rapid environmental assessment of oceanographic and seabed conditions.

Arnold Furlong is a partner at Brooke Ocean Technology Ltd. and a Senior Engineer specializing in the development and application of ocean profiling tools and payloads. These tools include the Moving Vessel Profiler (MVP) and the integrated Free Fall Cone Penetrometer (FFCPT). This work has included trials with these tools during field operations. Mr. Furlong is presently focusing his efforts on the continued development of payloads for the MVP and the commercialization of these innovative technologies.

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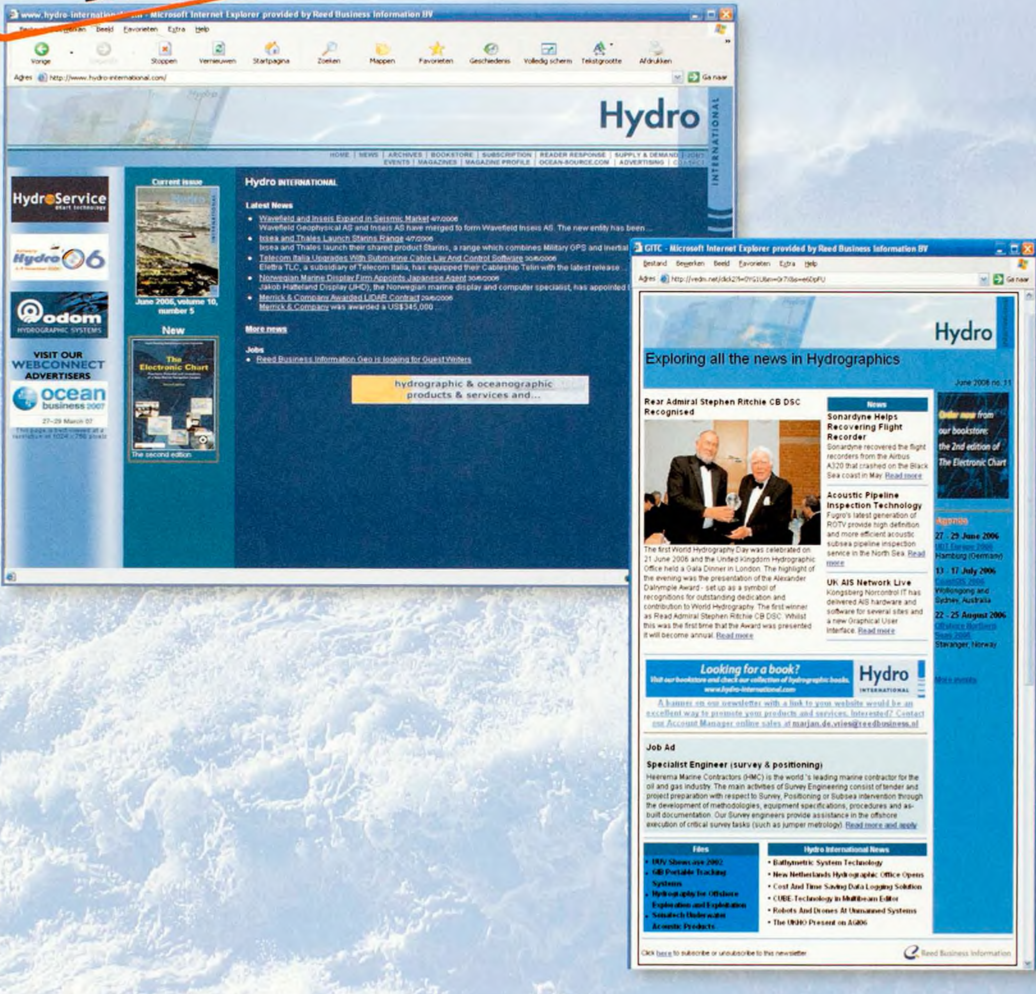

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