THE STRENGTH OF CORRELATIONS BETWEEN GEOTECHNICAL VARIABLES AND ACOUSTIC CLASSIFICATIONS

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Abstract – Seabed grain size, shear strength, bearing strength, and porosity were measured at 15 sites, all in bays and harbours around southern Vancouver Island. Sounder echoes at 38 and 200 kHz from the same sites were classified using the QTC VIEW™ technology. This approach uses a feature set generated from the direct echoes by a set of algorithms and then reduced by multivariate analysis, with similar acoustic responses put into the same class. Canonical correlation analysis was used to uncover correlations between two data sets: the frequency of occurrence of each acoustic class, and the four geotechnical variables. Bearing strength was found to be the major contributor to the first geotechnical canonical variable, which correlated with classes from the 38-kHz echoes with a coefficient of 0.94.

I. INTRODUCTION

Estimating shear strength, grain size, and other geotechnical variables of the seabed from a vessel underway could give much better coverage, and be quicker and cheaper, than using seabed probes or collecting samples. Calculating geotechnical variables from acoustic data is practically impossible, because there are no direct theoretical or empirical connections between acoustic vibrations and large-scale inelastic concepts such as bearing strength. In the absence of direct acoustic-geotechnical connections, these relationships can only be statistical.

This paper explores the strength of correlations between sediment geotechnical properties and characteristics of acoustic signatures in soft seabeds. Our motivation is that if correlations are strong, they could be used to estimate geotechnical variables in areas that have been surveyed only acoustically. While the estimates would have only a statistical basis, this may be a useful empirical technique for area surveys.

The acoustic data for this paper had higher signal-to-noise ratios than that used in a previous study [1], and stronger correlations were found. The basic theory of canonical analysis is summarized in [1], and is not repeated here.

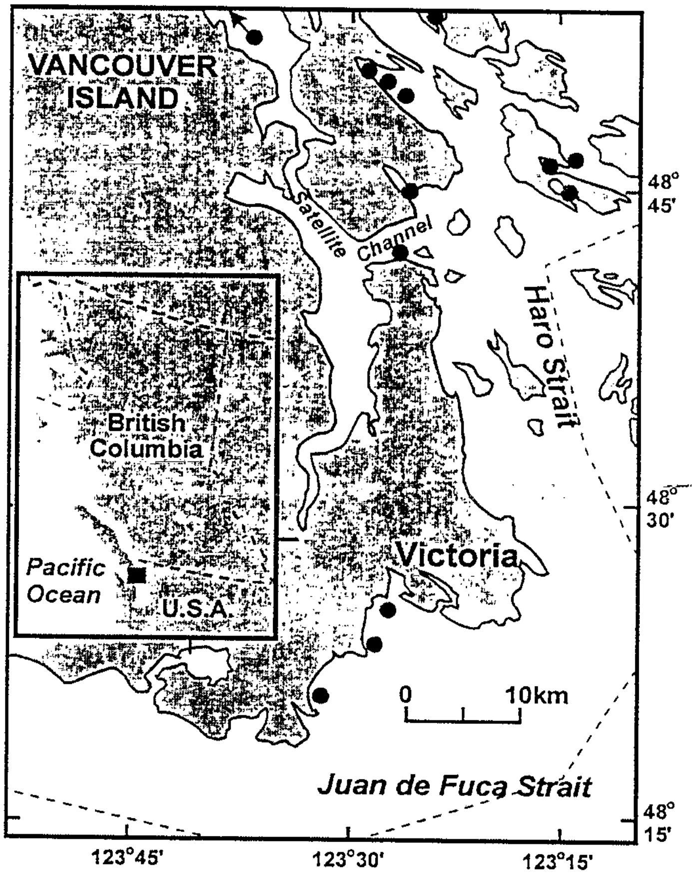

Fig. 1. Locations of 13 of the 15 sites, indicated by circles. The other two were in Nanoose Bay, 41 km north of the northwest corner of this chart.

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* JMP, RHP and RHK were with the Esquimalt Defence Research Detachment of Defence Research Establishment Atlantic when this work was done.

II. LOCATION

The 15 sites were in bays and harbours on the east (sheltered) side of Vancouver Island, as shown in Fig. 1. The sediments were generally non-cohesive and composed primarily of different classes of sand with varying amounts of silt and clay. All sites had soft sediments; the highest shear strength observed was only 10 kPa. Hard substrates were excluded because the overall aim was to study the ability of the bottom to support a naval mine dropped onto it.

III. GEOTECHNICAL DATA

The geotechnical variables used in this statistical work were mean grain size at the surface and at 10–15 cm depth, shear strength and porosity at the same depth, and dynamic bearing strength as measured by a free-fall penetrometer. There are some strong correlations among these data, particularly between the two grain size measurements, and between porosity and bearing strength.

Seabed grain-size distributions were measured using ASTM Procedure D422. Surface data are from grab samples. Core samples were analyzed to determine the grain-size distribution, porosity, and shear strength, at 5-cm depth intervals in the top 20 cm and at 10-cm intervals below that. Mean specific gravity for dried sediment, following ASTM D854, was found to be 2.721 ± 0.017, and this value was used to convert aliquot weights and volumes to porosity [2]. Shear strength was measured on the intact core with a laboratory Torvane [3]. The choice of a 7.5-cm gravity core lowered rapidly into the bottom caused some sample disturbance, particularly near the sediment-water interface

A free-fall penetrometer, STING [4, 5] was used to measure dynamic bearing strength. STING consists of a 1-m long, 19-mm shaft with a replaceable foot wider than the shaft (typically 25 or 35 mm), topped by an instrument housing and tail fins. The foot diameter can be changed to match the anticipated bearing strength. The only important sensor was an accelerometer to record the deceleration as the shaft enters the bottom. STING's mass was 9.5 kg, and it weighed 69 N in water. Dragging a thin recovery line, its terminal velocity was 5–6 m/s in the water depths at these sites. Since data were logged for up to 2 min, as many as six impacts could be recorded in sequence by pulling STING up a few meters and releasing. For each impact, the deceleration was compared with the buoyancy, body drag, and tether drag to extract the sediment force. The dynamic bearing strength is the sediment force per unit area of the foot divided by the strain rate, which is the 0.15 power of the inverse of the time to penetrate a distance equal to the diameter of the foot. Bearing strength was calculated at 5-cm depth intervals.

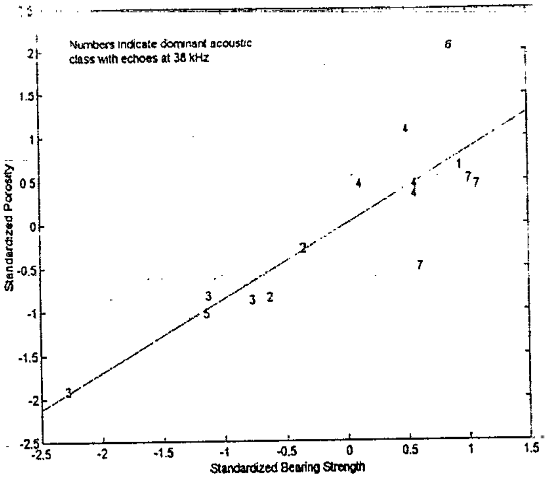

Fig. 2. Porosity and bearing strength, both reduced to zero mean and unit variance, for the 15 sites. Symbols indicate the acoustic class from the 38-kHz data set.

As shown in Table 1, there were strong correlations among the geotechnical variables, particularly between grain size, bearing strength, and porosity. Fig. 2 illustrates one of these correlations. In a sand-to-silt transition (increasing bearing strength implies decreasing mean grain size) bearing strength and porosity both increase, and the acoustic classes appear to reflect a combination of these variables plus some additional details. Results such as these suggest that there are indeed underlying correlations to be found by canonical analysis.

In preparation for canonical correlation analysis, it is important to prune the set of geotechnical variables to those that are largely independent of each other. Grain size at depth is redundant beside surface grain size, so was not used. This left four geotechnical variables. All were used, since a prime purpose of this work was to investigate which of these variables correlated with acoustic classes in various situations.

Table 1. Correlations of the initial geotechnical data set.

—	Mean Grain Size		Shear Strength	Bearing Strength	Porosity
	Surface	10 – 15 cm			
MGS surf	1	0.97	0.08	-0.78	-0.67
MGS deep	0.97	1	-0.06	-0.70	-0.59
Shear Str.	0.08	-0.06	1	-0.24	-0.39
Bear. Str.	-0.78	-0.70	-0.24	1	0.85
Porosity	-0.67	-0.59	-0.39	0.85	1

IV. ACOUSTIC DATA ACQUISITION AND PROCESSING

A hull-mounted Knudsen 38/200 Echo Sounder, operating at both frequencies at 250 W with a pulse length of 0.25 ms, was used to produce the echoes. Beam widths were 6° at 200 kHz and 19° at 38 kHz. The echo envelopes, after TVG, bandpass filtering, and sampling at 20 kHz, were stored on Exabyte tapes.

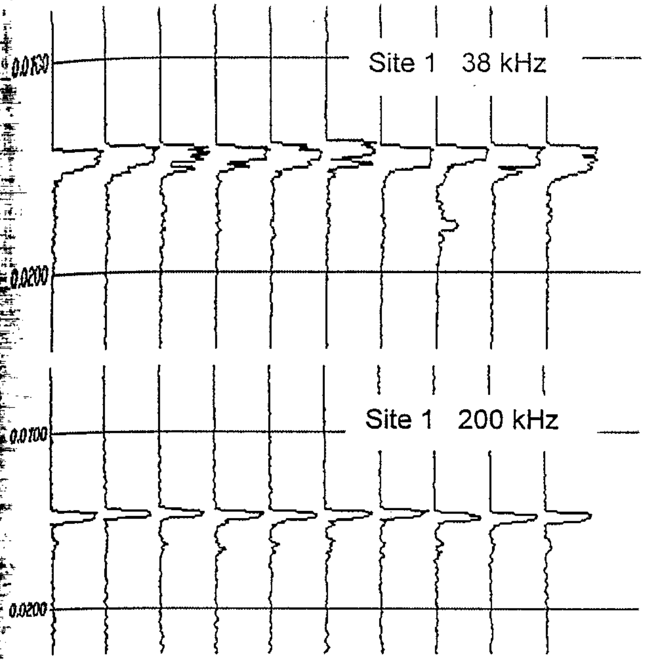

Fig 3. Echoes from site 1. The vertical axis is two-way travel time in seconds. At 38 kHz this site was classified as 89% class 2 and 9% class 7. The 200-kHz classes are a distinct set, and at 200 kHz this site was 99% class 1 of that set.

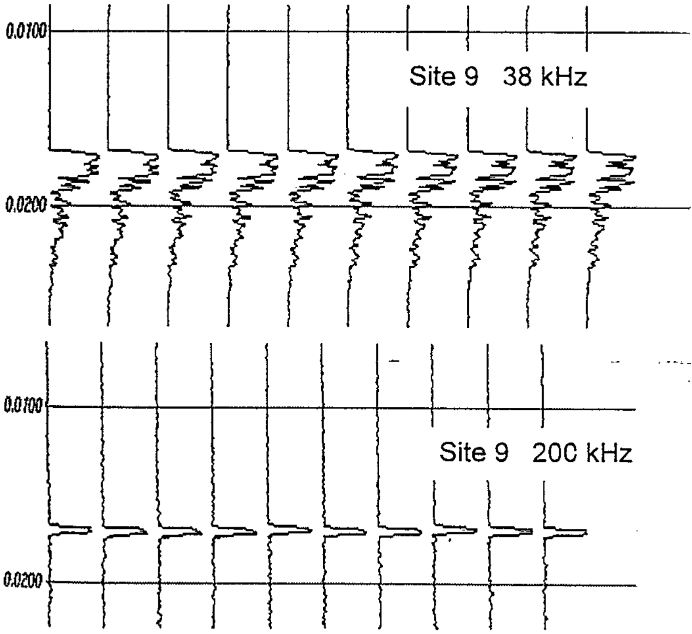

Fig. 4. Echoes from site 9. At 38 kHz this site was classified as 100% class 1, while at 200 kHz it was 57% class 4, 25% class 7, 11% class 8, and 5% class 5.

The QTC VIEW™ technique for bottom classification is based on the shape of the direct echo (no multipath echo is used). Figs. 3 and 4 show stacks of echoes from sites 1 and 9. Site 1 has twice the mean grain size and about one-half the shear strength and bearing strength of site 9.

The echoes were processed using QTC VIEW™ technology [6]. After picking the bottom, aligning with respect to the bottom pick, and stacking to reduce noise, a suite of algorithms was employed to extract features from the echoes. The many features are descriptors of echo shape, including the distribution of energy between the specular and scattered portions. Each feature value was normalized across all the echoes to zero mean and unity variance. Multivariate statistics were used to reduce the large number of features to the three linear combinations responsible for as much variance as possible. These three values, called Q-coordinates, were used to cluster the echoes into classes. In this unsupervised approach, the 38-kHz echoes formed seven classes (Fig. 5) and the 200-kHz echoes eight classes (Fig. 6). Most of the sites were acoustically uniform at both frequencies, which is one indication of successful and useful classification. These figures indicate classes and composition at each site, for example, at 38 kHz, site 7 was 85% class 6, 13% class 7, and 2% other classes.

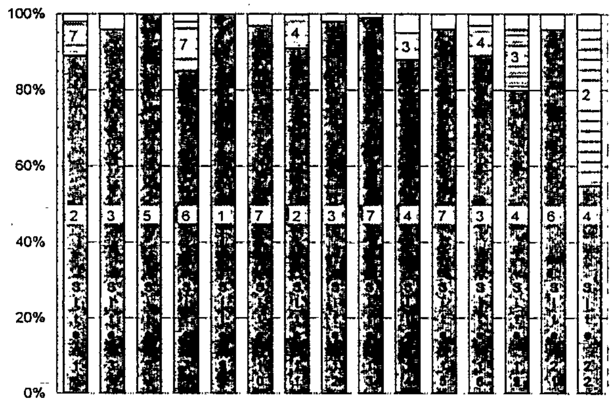

Fig. 5. Acoustic classes and proportional composition of the test sites at 38 kHz. Classes representing less than 4% have been suppressed.

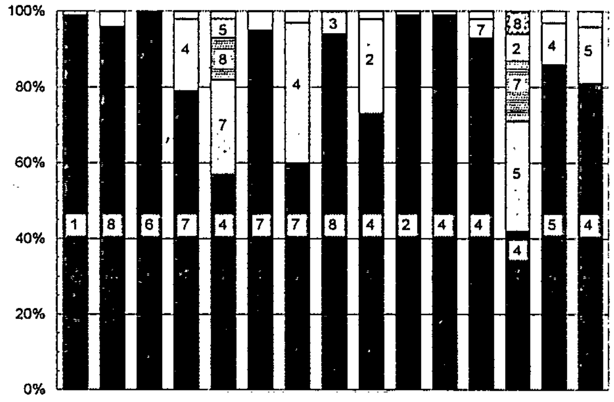

Fig. 6. Acoustic classes and proportional composition of the test sites at 200 kHz. Classes representing less than 4% have been suppressed.

resampled, with replacement, to generate many data sets [9]. Bootstrap is particularly useful for estimating confidence intervals of parameter (e.g. mean or variance) estimates. Here, it was used to estimate errors in the correlation coefficients among the variables of the data sets. Using standardized (zero mean, unit variance) values, the correlation coefficients calculated assuming Gaussian distributions and by bootstrap differed by no more than 0.02, small compared to their range of values: 0.60 to –0.73. Also, the bootstrap analysis gave small errors in these coefficients, typically 0.04 to 0.07. These results suggest that treating these data sets as if they were Gaussian had small effects on the correlation results, a conclusion that is supported by the strong canonical correlations and the Bartlett test.

VI. CONCLUSIONS

Acoustic classifications and geotechnical data were obtained for 15 sites in sheltered embayments near Vancouver Island. The seabeds in all sites had low shear strengths and grain sizes from silts to sands. The acoustic data were high quality and clustering was good, as shown by nearly homogeneous classification results at each site. Four geotechnical variables were selected: surface grain size, porosity, shear strength, and bearing strength. Some of these were strongly correlated, and acoustic classifications appeared to fit sensibly with these correlations.

Canonical correlation analysis was used to quantify the extent of the correlation between the acoustic and geotechnical data sets, and to identify the geotechnical variables most responsible. At least one canonical correlation was statistically significant at each sonar frequency. At 38 kHz, the strength-related variables had the highest factor loadings, that is, contributed most heavily to the linear combinations of geophysical variables that correlated with the acoustic set. Sonar at 200 kHz penetrates less, and the highest loading factors in this case were for porosity and grain size. Of the four geotechnical variables, porosity and grain size are the better descriptors of surface properties.

All 15 sites had soft substrates because they had been selected for studies of mine burial on impact. Whether or not mines would bury at each site is not the subject of this paper, but hard sites at which impact was clearly precluded were not studied. Of all our measurements of shear strength at all depths, only a few were over 10 kPa, which is below the range of most literature studies of correlations involving shear strength (an exception is [10]). In spite of using such a limited range, the classifications and correlation results were convincing. Extending this work to stiffer substrates would be of considerable interest.

Canonical analysis does not lead to estimates of a particular geophysical variable, but rather to estimates of linear combinations. For these data sets, it has been shown that combinations of geotechnical variables are strongly correlated with combinations of acoustic classifications. In particular, strength-related variables are highly correlated with classes from 38 kHz data, while 200-kHz echoes seem to relate more to surface character.

With the strength of these correlations established and with guidance as to which geotechnical variables are the more pertinent, a basis has been established for predicting geotechnical variables from acoustic classifications, using other correlation techniques such as multivariate analysis.

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Dr. Jon Preston, Senior Scientist, Quester Tangent Corporation, has twelve years experience as a research scientist with the Department of National Defence, Canada. At Defence Research Establishment Pacific, Victoria, BC, he developed mine countermeasures technology, particularly processing of high-frequency imagery, and towfish altitude and position measurement and control. Much of the work done by the DREP mine countermeasures group can be seen in the route survey payload of the 12 Maritime Coastal Defence Vessels recently acquired by the Canadian Navy. Starting about 1996, his research interests broadened to include both acoustic and invasive sensing of sediments, and he lead several multi-faceted research cruises focussing on sediments. During his years at DREP he published over 20 internal reports and 10 papers in conference proceedings. He was technical chairman of the IEEE Oceans '93 conference.

Dr. Preston's BSc is from McMaster University, 1970. His PhD work, in the plasma physics group at the University of British Columbia, dealt mostly with sensors, diagnostic equipment, and signal processing. Between graduation from UBC in 1974 and moving to DREP, he was responsible for Canada's R&D program in automatic detection of chemical warfare compounds. This work lead to a family of new detectors used in many NATO armies, 25 internal reports, 4 journal papers, and 2 patents.

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