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Influences of Penetrometer Probe Tip Geometry on Bearing Strength Estimates for Mine Burial Prediction

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P.J. Mulhearn

Maritime Operations Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

An important parameter for the prediction of mine burial on impact, when a mine is first laid, is the sediment bearing strength profile. A number of nations have been developing easily deployable penetrometers for measuring bearing strength relatively quickly. The plan would be to use these in route survey operations. Previous joint experiments by TTCP (The Technical Coperation Program) nations have found that the measured bearing strength decreases as the diameter of a penetrometer increases. This effect is not currently understood, but in this report it is shown, with the help of some new experiments, that with the right penetrometer design it is possible to obtain bearing strength profiles which can be validly used for mine burial prediction. Finally a particular penetrometer configuration is recommended for navy use.

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Executive Summary

For Mine Countermeasures Route Survey operations it would be advantageous to have a simple and reliable means of determining seabed bearing strength, so as to predict the depth of burial of mines, on impact with the sea floor. For this reason a number of TTCP nations have been developing easily deployable, internally recording penetrometers to provide sediment bearing strength profiles. Previous trials have taken place in Australian, Canadian and United States waters, but some results remained unexplained especially the fact that thinner penetrometers gave higher bearing strength values than thicker ones.

Combining results from past and some new experiments, it is shown that as the penetrometer tip-diameter increases the measured bearing strength decreases less rapidly, so that for tip diameters greater than approximately 70 mm the change becomes unimportant for the purposes of mine burial prediction. It is also found that the bearing strength values obtained by the larger diameter penetrometers provide data which is valid for mine burial prediction. Finally a particular penetrometer configuration is recommended for route survey operations.

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1. Introduction

For efficient planning and conduct of mine counter-measures (MCM) operations there is a need for good information on the distribution of those sediment properties which are relevant to mine warfare. Because knowledge is required on quite fine scales over considerable areas, remote sensing methods, particularly acoustic, are being investigated. The potential benefit of acoustic seabed classification systems is that they would be able to determine seabed characteristics continuously with a ship underway, as against the conventional approach of stopping at regular intervals to obtain bottom samples. Without some ground truthing however, it is still difficult to relate sediment properties to acoustic returns, and this is particularly true for sediment bearing strength, which is the main sediment property controlling mine burial on impact (Satkowiak, 1988; Rumball and Kitchings, 1989, Chu et al., 2000). To obtain sediment strength values quickly and easily, a number of free fall penetrometers have been developed (e.g., Beard, 1975 and 1984; Crook et al., 1995) and tested side by side in a number of trials (Hurst et al., 1996; Poeckert et al., 1996; Lott et al., 1996; Tooma et al, 1996, Mulhearn et al., 1998 and 1999).

The last series of trials, which took place in Sydney Harbour, (Mulhearn et al., 1999) found that as penetrometer diameter increased the measured bearing strength values decreased, as had been found in previous trials, but they appeared to decrease towards values which agreed with those obtained with more conventional apparatus (i.e. a vane-shear device). However more data were still required to verify this. It had previously been found that bearing strength values obtained with a vane-shear device provided good predictions of mine burial on impact using the IMPACT 25 model (Mulhearn, 1993). IMPACT 25 is regarded as the standard amongst TTCP nations (USA, UK, Canada, Australia and New Zealand). See Hurst (1992) for a description of the model.

The past trials had also found that larger diameter penetrometers slowed down, before they impacted the seabed, when they were within a distance of order one diameter above the seabed. In the trials reported here various sizes and shapes of penetrometer tips were tested to see which would minimise this deceleration and if it was significant for the range of tip diameters tested. More importantly bearing strength values were obtained with a range of tip diameters to determine more clearly how bearing strength values varied with tip diameter and if values plateaued out as diameter increased.

2. Equipment and Procedures

Work was carried out from a 12.2 m (40ft) workboat, AWB 440 at various locations in Sydney Harbour, as shown in Figure 1 and listed in Table 1. Differential GPS navigation was used. The DGPS reference station was a MX9250 Leica. Navigation accuracy is estimated as ± 5m. The STING (Seabed Terminal Impact Naval Gauge)

penetrometer, used for all these tests, was purchased by the RAN from JASCO Research Ltd of Victoria, British Columbia, Canada.

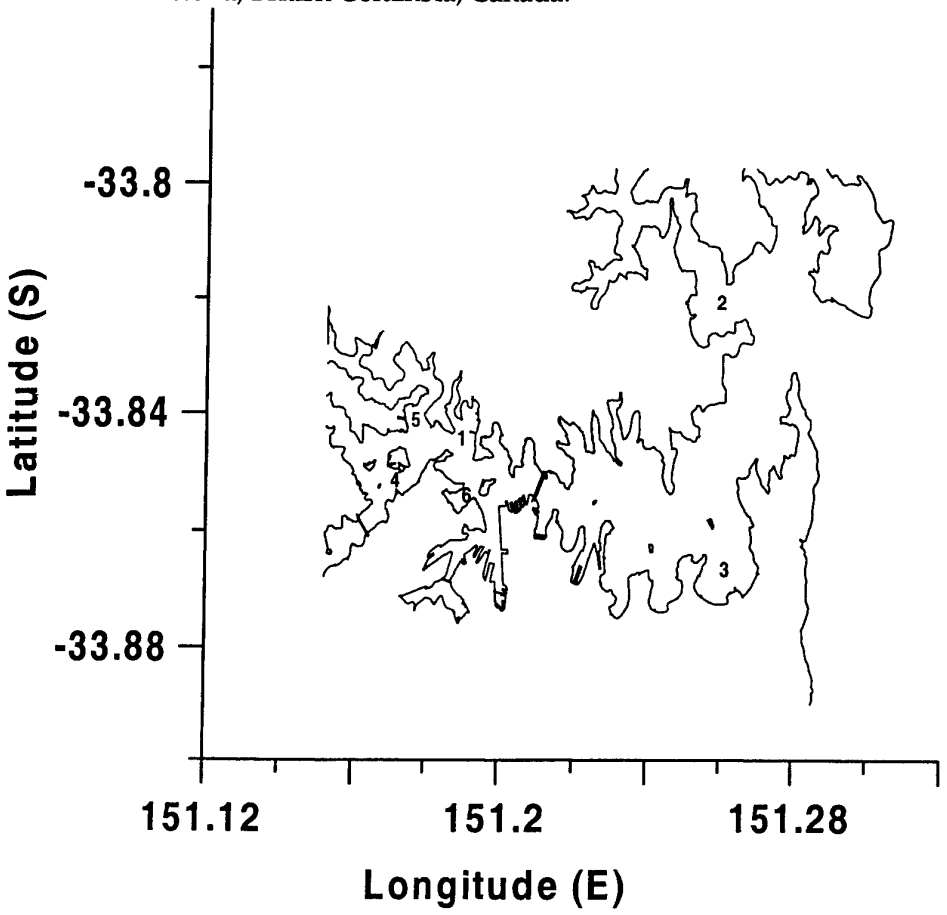

Figure 1 Station positions in Sydney Harbour.

Table 1. List of Stations

Station No.	Date	Site	Latitude (°S)	Longitude (°E)	Depth (m)
1	25 June 2001	Coal Jetty	33° 50.696′	151° 11.527′	15.5
2	"	Hunters Bay	33° 49.285′	151° 15.862′	10.0
3	"	Rose Bay	33° 51.921′	151° 15.776′	9.8
4	23 August 2001	Balmain	33° 51.047′	151° 10.471′	11.5
1	6 September 2001	Coal Jetty	33° 50.519′	151° 11.512′	9.0
5	"	Woolwich	33° 50.543′	151° 10.556′	10.8
6	"	Morts Bay	33° 51.224′	151° 11.526′	8.0

The STING penetrometer consists of a finned pressure case which contains the sensors and data logging electronics, a 1 m long 19 mm diameter steel rod and tips of various sizes and shapes to be attached to the rod. The tips used in the trials had base diameters of 25, 35, 50 and 70 mm. The shapes used were a flat disc, a hemisphere and a cone, with an apex angle of 90°. The STING is described in detail by Poeckert et al (1997) and is shown in Figure 2. It is essentially an instrumented javelin which, although tethered, is allowed to free-fall to the seabed. The deceleration of the penetrometer as it impacts the seabed is measured and the force exerted by the sediment can then be estimated. The tether is used to recover the penetrometer. The internal data-logger records for two minutes, so that a number of seabed impacts can be obtained at one place, allowing better statistics to be calculated.

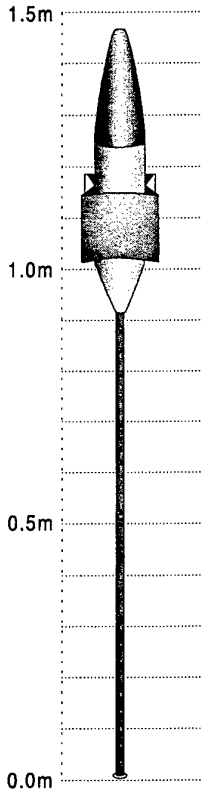

Figure 2. STING .

At each station the boat was anchored from the bow. After it had come to a stable orientation under the influence of the prevailing wind and sea, the penetrometer was deployed by hand over the side, slightly aft of midship. Because the boat was only anchored at the bow the impact point would have varied slightly due to the movement of the stern. At each deployment station as many impact events as possible were recorded within the two minutes of recording time available. The STING was raised approximately 5 m between impacts. At the conclusion of each recording period the STING was recovered on board and the data downloaded to a laptop computer, using the STING's data communication software. The STING penetrometer also comes with data analysis software which converts the raw data of deceleration versus time to bearing strength versus depth.

Tests with different tip shapes only occurred on the 25 June 2001. Tests with different tip diameters occurred on all three days.

3. Results

3.1 Decelerations close to the seabed, but before impact

The analyses showed that changing the shape or size of the probe tip made little difference to the deceleration of the probe immediately before impact. Even for the 70 mm diameter tips the decelerations before impact only occurred over, at most, the last 23 mm above the bottom, and so can be ignored in practice. (In the March 1998 trials (Mulhearn et al., 1999) decelerations before impact were observed over 60 mm for a 0.19 m diameter penetrometer, and over approximately 0.5 m for a 0.51 m diameter penetrometer).

Comparing bearing strength profiles obtained with probe tips with different shapes, but the same diameter, showed that tip shape has little effect on bearing strength values. This confirms earlier results of Mulhearn et al. (1999), and was not unexpected.

3.2 Tests with different diameters

The majority of tests on the influence of tip diameter were conducted with the flat disk shaped tips and only these will be discussed here. Figure 3 shows a typical series of analysed impacts from one site. Averaged profiles from a range of sites in Sydney Harbour can be seen in Mulhearn et al. (1999).

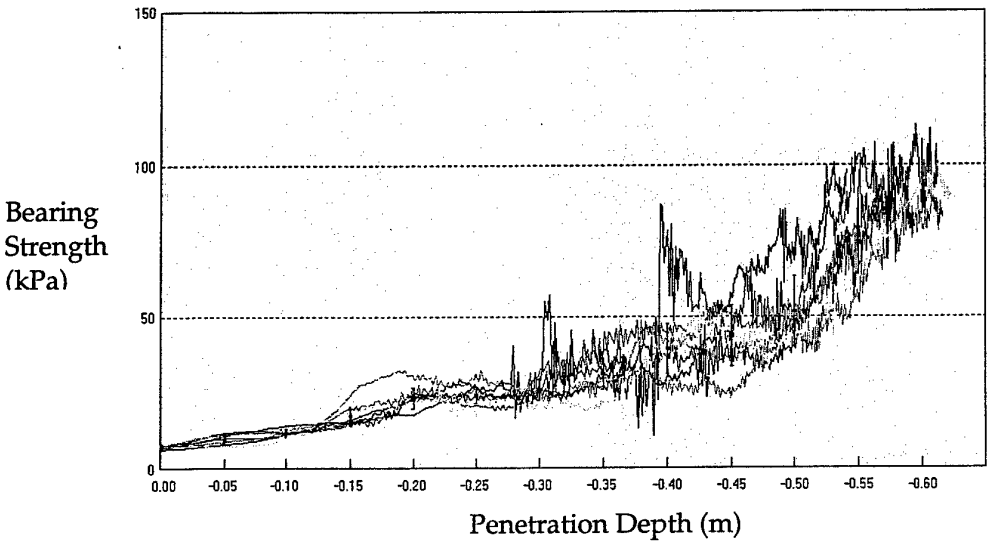

Figure 3. Frame grab from STING software of analysed impacts at station 5, 6 September 2001.

Comparing bearing strength values obtained at any one depth at any one site, correlations were obtained between values obtained with the 25 mm, 35 mm, 50 mm and 70 mm flat probe tips. The correlations were all constrained to pass through the origin. The regression lines for values from the 25, 50 and 70 mm tips, versus those from the 35 mm tip, are shown in Figures 4 to 6, respectively. Comparisons are made with the 35 mm tip values to allow comparisons with earlier results, as is explained in the next section.

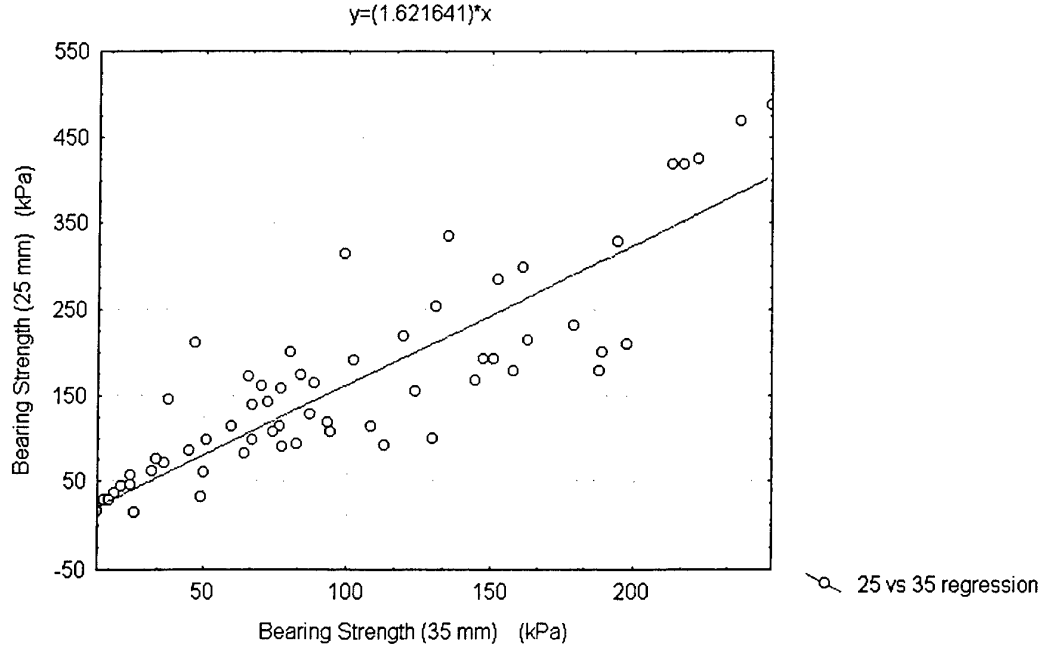

Figure 4. Regression line between bearing strength values obtained with 25 mm flat tip versus those obtained with a 35 mm tip. (Regression coefficient)² = 0.731.

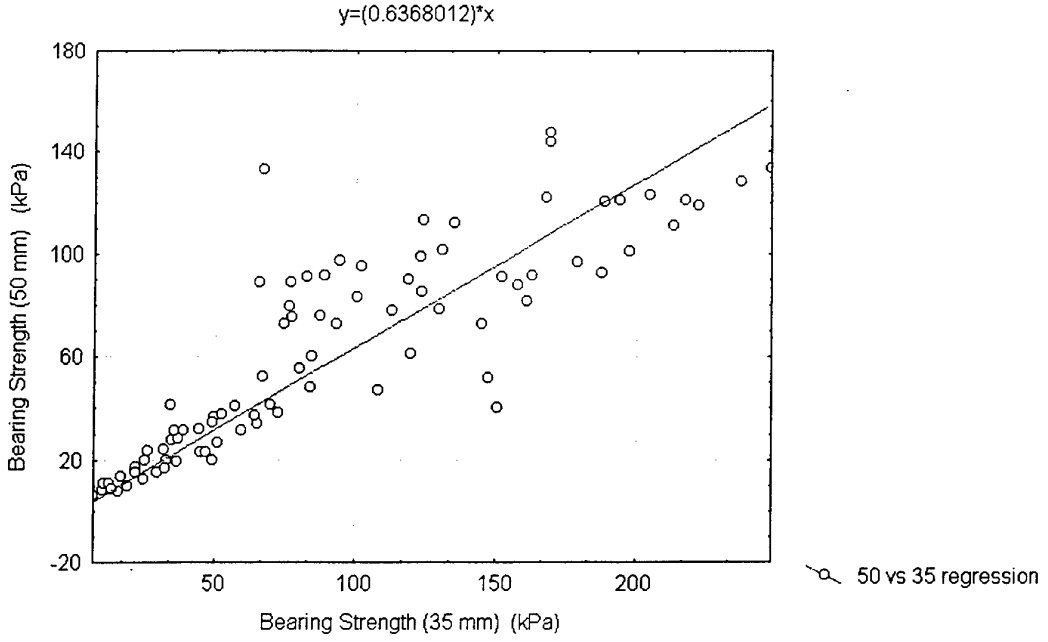

Figure 5. Regression line between bearing strength values obtained with 50 mm flat tip versus those obtained with a 35 mm tip. (Regression coefficient)² = 0.746.

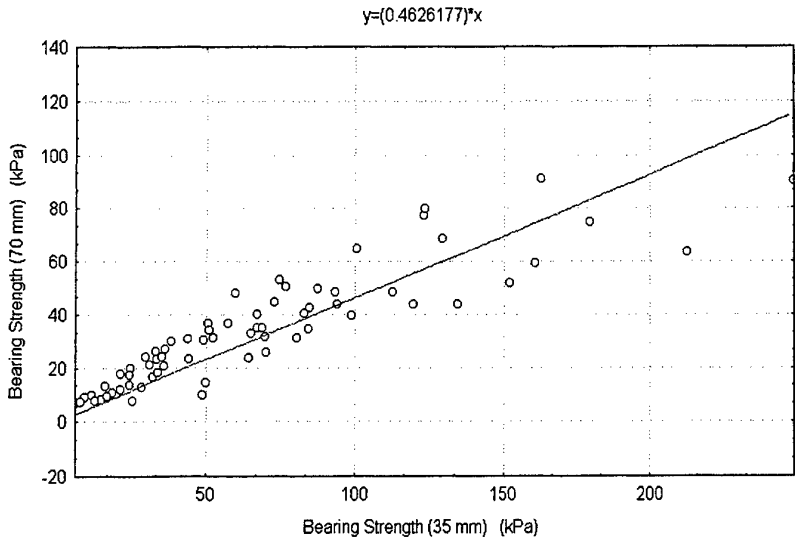

Figure 6. Regression line between bearing strength values obtained with 70 mm flat tip versus those obtained with a 35 mm tip. (Regression coefficient)² = 0.712.

Values of β, the slope of the regression line, and of r^2, the square of the regression coefficient, are shown in Table 2. (r^2 is a measure of the percent of variation in the ordinate variable explained by the regression. It is only presented here to provide a measure of goodness of fit). A regression line of values, obtained using the 35 mm tip, versus themselves would yield an r^2 of 1.0 and a slope, β, of 1.0. 95% confidence limits for β were obtained using standard statistical techniques, adapted for a regression through the origin (Draper and Smith, 1966).

Table 2. Regression coefficients squared, slopes (β) of the regression lines, and 95% confidence limits for β for bearing strength values obtained using 25, 50 and 70 mm tips versus those obtained with a 35 mm tip.

Regression relation	**r^2**	**β**	**95% confidence limits on β**
25 mm vs. 35 mm	0.73	1.62	1.38 to 1.86
50 mm vs. 35 mm	0.75	0.64	0.57 to 0.71
70 mm vs. 35 mm	0.71	0.46	0.40 to 0.52

4. Comparison with Previous Results

In the earlier experiments of Mulhearn et al. (1998 and 1999) measurements were obtained with a STING penetrometer and also with two other types of penetrometer - an ESP (Electronic Sediment Strength Probe) and an AUSSI (Australian Sediment Strength Instrument). These are shown in Figures 7 and 8, respectively. Descriptions of these are given in Appendix A. The ESP has a flat end and can have a diameter of either 22 or 33 mm. The AUSSI has a hemispherical nose, the hemisphere having a diameter of 190 mm. ESPs with both diameters were used in experiments off Cairns in 1997 (Mulhearn et al., 1998), while a 33 mm diameter ESP and the AUSSI were used in experiments in Sydney Harbour in 1998 (Mulhearn et al., 1999).

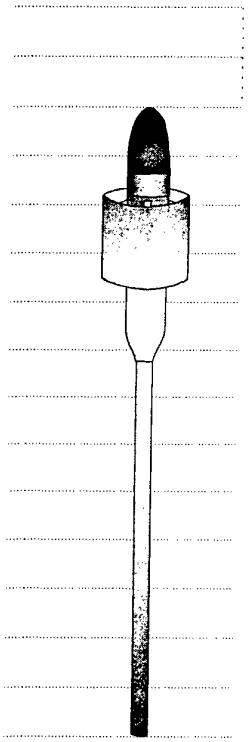

Figure 7. ESP probe

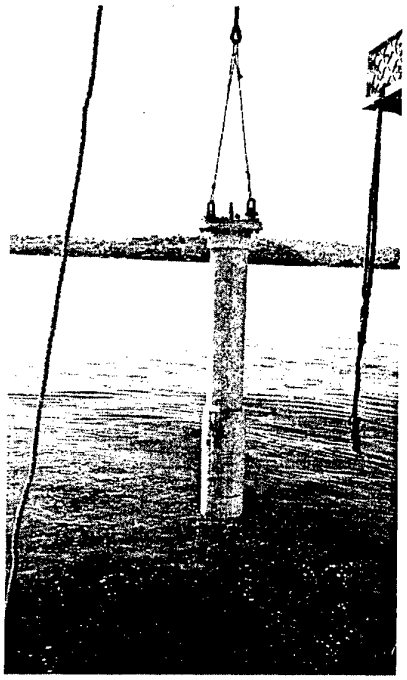

Figure 8. AUSSI probe ready to be launched.

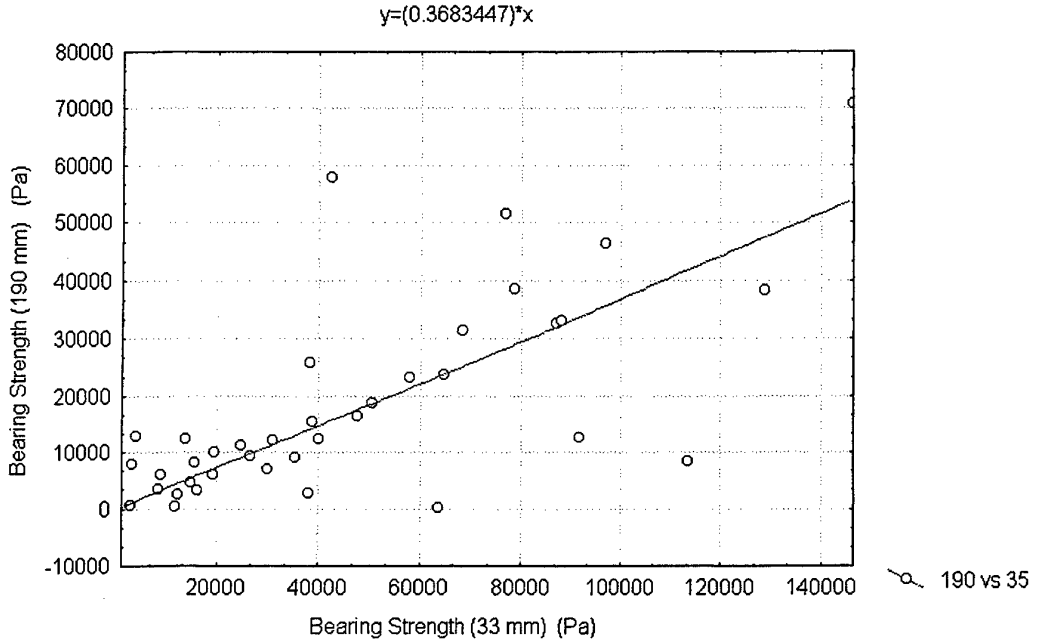

Figure 9. Regression line between bearing strength values obtained with the 190 mm AUSSI penetrometer versus those obtained with a 33 mm diameter ESP penetrometer. (Regression coefficient)² = 0.524.

Regression relations were obtained between the bearing strength values obtained with the AUSSI probe and a 33 mm ESP, between values obtained with 22 mm and 33 mm ESPs, and between values obtained with a 25 mm tipped STING and a 33 mm ESP. The AUSSI versus 33 mm ESP data are shown in Figure 9, while r^2 and regression slope results are presented in Table 3. Regressions are made here with results from the 33 mm diameter ESP so as to aid comparison with the new Sydney Harbour results. Confidence limits could not be calculated for the 22 mm versus 33 mm and the 25 mm versus 33 mm regression lines because the original data from these older experiments are no longer available.

Table 3. Regression coefficients squared, slopes (β) of the regression lines, and 95% confidence limits for β for bearing strength values obtained using 22, 25 and 190 mm diameter probes versus those obtained with a 33 mm diameter ESP.

Regression relation	r^2	β	95% confidence limits on β
22 mm vs. 33 mm	0.77	1.99	
25 mm vs. 33mm	0.71	1.57	
190 mm vs. 33 mm	0.52	0.37	0.28 to 0.46

The values of β, from Tables 2 and 3 are plotted in Figure 10. The regressions are all made between data from a penetrometer with a diameter, d, and that from a

penetrometer with a diameter of 33 mm or 35 mm. The abscissa in Figure 10 is the diameter d. It has been found previously that measured bearing strength decreases as probe diameter increases (Poeckert et al., 1996, Mulhearn et al., 1998 and 1999) and Figure 10 clearly shows this trend. What is useful here is that as tip diameter increases the curve appears to be flattening out. Although the average value at 190 mm is less than that at 70 mm there is considerable overlap in their 95% confidence limits. In a normal field situation, without large data samples, values from penetrometers with 70 mm and 190 mm diameters would be little different. It is still unknown why measured bearing strength decreases with penetrometer diameter, but it does not appear to be due to side friction effects on the penetrometer shafts.

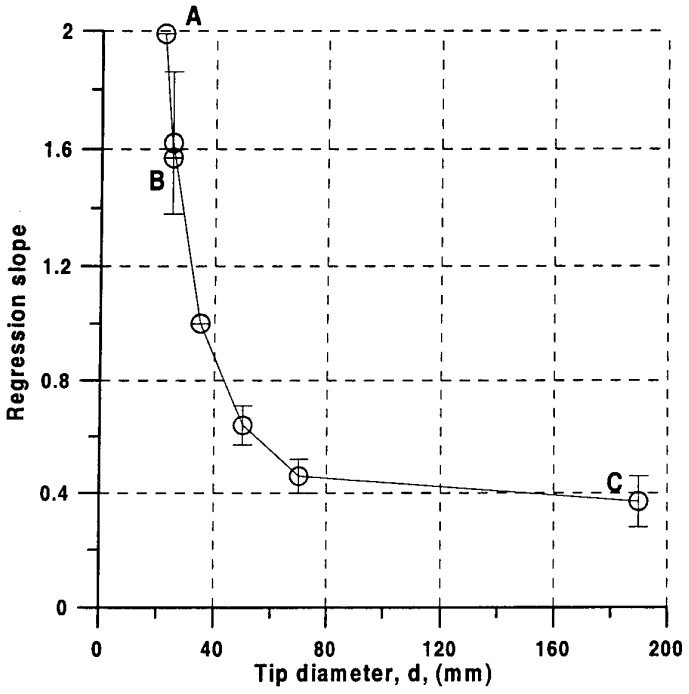

Figure 10. Slope of regression line versus penetrometer tip diameter. Point labelled A is for 22mm ESP versus 33 mm ESP. Point labelled B is for 25 mm STING versus 33 mm ESP. Pont labelled C is for AUSSI versus 33 mm ESP. Other ponts are for various STINGs of diameter, d, versus 35 mm STING. (Error bars, where shown, show 95% confidence limits for regression slope values)

Note that the β values from the 25 mm versus 33 mm regression and the 25 mm versus 35 mm are very close. One would not expect the difference between 33 mm and 35 mm to have much effect, but the 33 mm ESP and the 35 mm STING have quite different geometries. The ESP is a straight 33 mm cylinder with no larger diameter tip, while the STING has a 35 mm diameter tip and a 19 mm shaft. One would expect friction on the shaft of the ESP to have a much greater effect than shaft friction on the STING. This is

not apparent. Poeckert (1998, private communication) has also carried out some experiments that showed that shaft friction had a minimal effect. Using a STING penetrometer he took bearing strength measurements with different size tips using both the standard 19 mm shaft and a thicker 33 mm shaft. He found that using the thicker shaft changed the bearing strength measurements by less than 5% with a 35 mm tip, and a negligible amount with the larger tips.

In Mulhearn et al. (1999) a regression was obtained between bearing strengths obtained with the AUSSI penetrometer and a vane-shear device. As can be seen in Figure 11, acceptable agreement was found between the two. The regression line has a slope of 1.01. In an earlier study (Mulhearn, 1993) it was found that good mine burial predictions, illustrated in Figure 12, were obtained using bearing strengths obtained with a vane-shear device. Burial predictions were generally correct within ± 0.1 m.

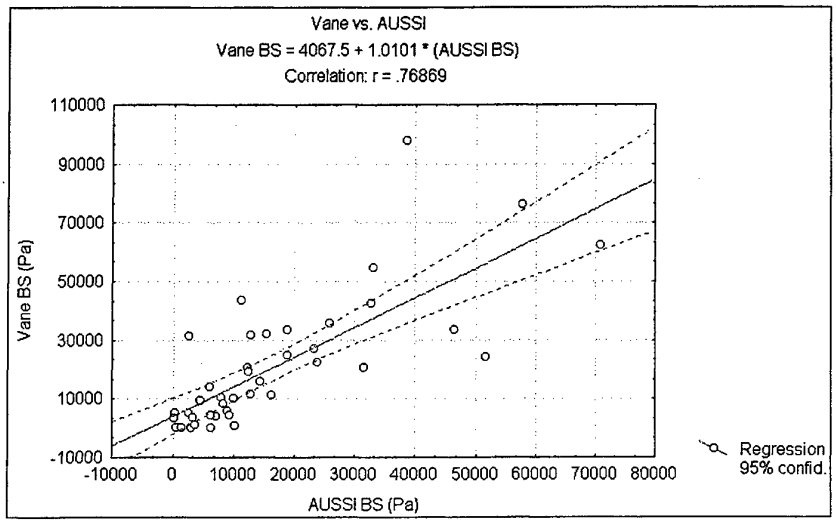

Figure 11. Linear regression between bearing strength values from vane-shear device and AUSSI (from Mulhearn et al., 1999). (Regression coefficient)² = 0.59.

So if bearing strengths from vane-shear data can be used to give good mine burial predictions and bearing strength values from a vane-shear device, the AUSSI and a 70 mm STING closely agree, then any of these devices can provide valid bearing strength values for mine burial prediction[1]. With a large enough sample, as shown in Figure 10,

[1] In general one would not expect bearing strength values from a vane-shear device and a penetrometer to agree. Because of the high strain-rate occurring in a penetrometer impact the sediment would be in an "undrained" condition, while in a coarse sediment the water could drain away in the course of a vane-shear measurement. Most of the Sydney Harbour experiments occurred in silt or sandy silt seabeds, so that one might expect some drainage to

the 70 mm STING values appear to be slightly higher than those from the 190 mm AUSSI, but given the normal variability found in soil properties this difference will not be significant. Given that it is far easier to obtain data with a 70 mm STING than with the other two devices, it is the preferred option.

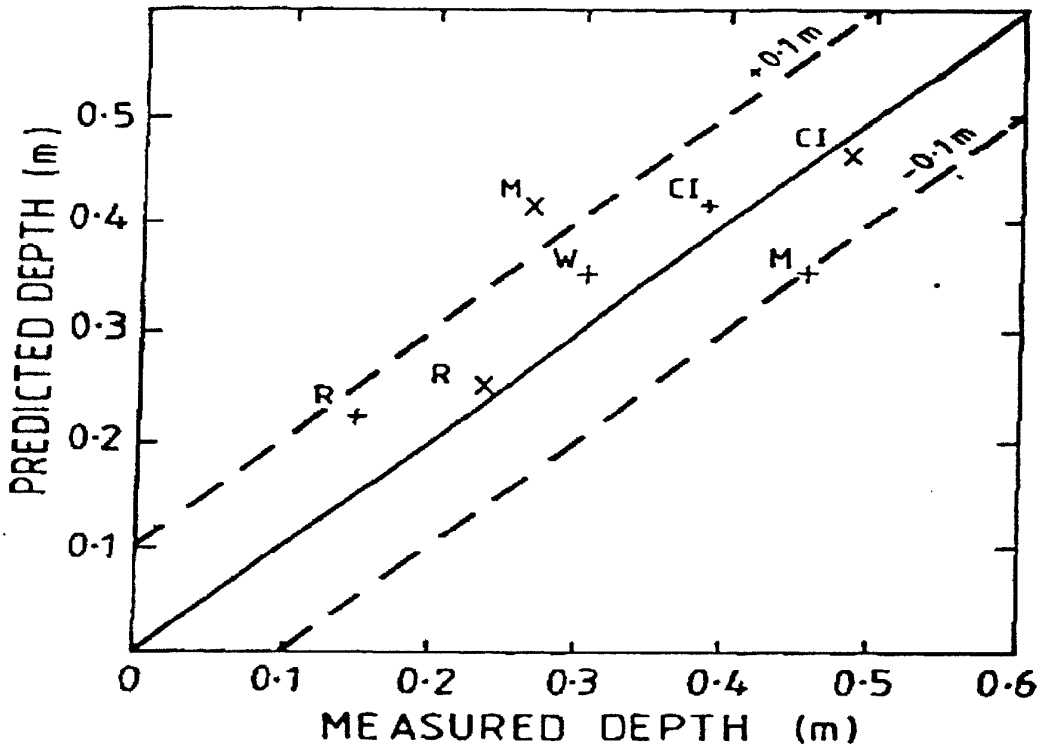

Figure 12. Comparison of predicted versus measured mine burial depth from Mulhearn (1993). Predictions were based on sediment shear strength data obtained with a vane-shear device.

5. Conclusions

It has been found that of the free-fall penetrometers the 190 mm AUSSI (Australian Sediment Strength Instrument) and the STING (Seabed Terminal Impact Naval Gauge), with a 70 mm tip, give valid bearing strength values for mine burial prediction. Of these the latter is, by far, the easier to handle and is recommended for RAN use.

occur. (See sediment properties in Appendix A3). However it seems to have had an insignificant effect.

6. Acknowledgements

People who helped with these trials were Mr Wayne Dunn of HMAS Waterhen, who approved the loan of the STING penetrometer to DSTO, LT Aaron Hershaw and the other men of the Navy Reserve Mine Warfare Group 50 (MWG50), and the following from DSTO's Maritime Operations Division, Pyrmont: Messrs Les Hamilton, Angus MacInnes, Tony White, Colin Mason and Colin Andrew. Hauling the STING up and down many times at each station required a lot of manual effort, which is why so many people were involved. Not all were present on any one day.

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Appendix A: ESP and AUSSI Penetrometers

A.1 ESP

The ESP (Electronic Sediment Strength Probe) has been described extensively elsewhere (Crook et al., 1995; Hurst and Murdoch, 1991; Hurst et al., 1996; Mulhearn et al., 1998). Briefly the instrument consists of a long thin shaft with an electronics housing on its upper end. The tethered probe is dropped over the side of the ship, free falls through the water surface and plunges into the seabed. An ESP is shown in Figure 7. Data on various models of ESP are shown in Table A1. Within the electronics package acceleration versus time is recorded. From the ESP's acceleration signals, velocities and depths into the sediment can be obtained by integration. At each station the probe is dropped and raised a number of times to record multiple impacts. Once the probe is recovered, the recorded data is downloaded to a computer for the calculation of bearing strength versus depth profiles.

The forces acting on a probe during its deployment are its weight, buoyancy, hydrodynamic drag and force due to the sediment. All except the last are known or can be calculated, knowing the probe's velocity, so that the sediment force, F, can be found by subtraction, knowing the probe's acceleration. Bearing strength, B, is then given by:

$$B = F/(\pi r^2 s),$$

where r = penetrometer tip radius and
s = a strain rate factor (See Hurst and Murdoch, 1991)
$= (2v/r)^{0.15}$, and
v = penetrometer velocity.

Table A1. Data on various ESP models

Model No.	Shaft Diameter (mm)	Mass (kg)	Weight in Water (N)	Location used
ESP 1a	33	5.34	27.17	Cairns '97
ESP 2a	33	5.24	26.66	Sydney '98
ESP 2b	22	6.65	42.21	Cairns '97

A.2 Australian Sediment Strength Instrument (AUSSI)

The AUSSI, shown in Figure 8, has a mass of 61.25 kg and a weight in water of 272.2 N. It is 1.33 m long and has a diameter, at the wider section near its nose, of 0.19 m. The diameter of the top flange is 0.28 m. The probe has a terminal velocity of approximately 2.89 m/s. The wider section, near the AUSSI's nose, is filled with lead shot, contained in resin. Acceleration and pressure are logged internally, and a sampling rate of 200 Hz was used in the trials. Velocities and depths were calculated by integration from the acceleration signal, and bearing strength profiles were then calculated using a suitably modified version of the ESP software.

Diver observations of the actual depth of penetration of the AUSSI were obtained at some sites. From the accelerometer records at both these sites and sites which were too hard for the AUSSI to penetrate (i. e. rock or compact sand), it was found that the AUSSI began to decelerate between 0 and 6 cm above the seabed. This distance is significantly less than the AUSSI's diameter. This small offset in locating the point of bottom impact was ignored in subsequent analyses.

It is likely that all penetrometers decelerate before actually impacting the seabed but, as the height over which this occurs would be of the order of a probe diameter or less, this would be very hard to detect for the slimmer penetrometers.

A.3 Sediment properties at stations used for AUSSI versus vane-shear comparisons.

Table A2. List of stations

Station No.	Date	Site	Latitude (S)	Longitude (E)	Depth (m)
2	2 Mar 98	Castle Cove	33 47.565	151 13.053	7
3		Off Sugar Loaf Point	33 47.981	151 13.825	24
9	3 Mar 98	Rose Bay	33 52.112	151 15.710	8
12		Taylors Bay	33 50.749	151 14.842	10
10		Mosman Bay (drifting)	33 50.898 to 33 50.940	151 13.927 151 13.895	14 13
11		Fort Denison	33 51.416	151 13.567	14
17	4 Mar 98	White Horse Point	33 51.180 33 51.188	151 10.465 151 10.451	9 8
16		Woolwich	33 50.553	151 10.541	9
14		Coal Jetty 2	33 50.704	151 11.371	15
13		Coal Jetty 1	33 50.577	151 11.308	8
15		Coal Jetty 3	33 50.831	151 11.484	16

Table A3. Sediment properties

Station No.	Location	Depth in core (m)	%gravel	%sand	%mud	% clay in mud fraction	%carb in sand	%carb in mud	Grain Specific Gravity	Porosity (%)	Lab. wet bulk density (gm/cm^3)
14	Coal Jetty 2	0	0.00	10.27	89.73	8.17	27.7	8.1	3.378	0.735	1.134
14		0.26	0.00	16.86	83.14	8.44	24.6	8.2	2.869	0.634	1.238
16	Woolwich	0	0.00	6.05	93.95	6.99	35.9	6.8	2.866	0.686	1.141
16		0.27	0.00	6.25	93.75	8.43	38.0	7.1	2.732	0.600	1.273
17	White Horse Pt	0	0.00	2.45	97.55	8.41	32.5	tr	3.109	0.730	1.113
17		0.21	0.00	2.53	97.47	6.34	32.8	6.1	2.841	0.651	1.219
3	Sugar Loaf Pt	0	0.38	7.07	92.55	1.63	37.7	10.2	3.344	0.729	1.127
3		0.20	0.07	12.52	87.41	11.61	40.3	10.4	2.668	0.644	1.202
12	Taylor's Bay	0	0.59	76.39	23.01	5.39	19.0	15.5	2.669	0.494	1.484
12		0.16	1.00	79.90	19.10	6.00	17.6	20.8	2.462	0.352	1.744
2	Castle Cove	0	1.57	15.14	83.29	2.68	0.0	0.0	2.679	0.690	1.014
2		0.19	0.00	36.88	63.12	6.26	0.0	0.0			
13	Coal Jetty 1	0	0.46	91.75	7.79	11.77	7.8	7.3	2.750	0.439	1.611
13		0.16	1.40	89.02	9.58	6.58	12.8	9.3	2.689	0.336	1.657
9	Rose Bay	0	0.12	96.30	3.58	19.08	3.7	12.7	2.699	0.348	1.803
9		0.25	0.67	91.52	7.81	13.44	5.1	13.4	2.731	0.313	1.753
15	Coal Jetty 3	0	14.41	14.52	71.07	6.50	30.0	6.6	2.368	0.631	1.125
15		0.25	0.64	46.09	53.27	14.42	22.9	7.5	2.635	0.524	1.416
10	Mosman Bay	0	0.00	13.19	86.81	5.46	58.6	16.6	2.721	0.666	1.185
10		0.19	4.41	23.04	72.55	5.78	61.4	17.5	2.558	0.533	1.371
11	Fort Denison	0	1.33	49.43	49.24	8.32	35.6	9.6	2.774	0.635	1.293
11		0.18	7.02	76.20	16.78	6.68	36.7	11.4	2.752	0.417	1.630
12 (duplicate)	Taylors Bay	0							2.687	0.496	
11 (duplicate)	Fort Denison	0.18							2.807	0.422	
17 (duplicate)	White Horse Pt	0							3.185	0.878	

Table A4. Liquid limits, LL, plastic limits, PL, and plasticity indices, PI =LL - PL.

Station No.	Station Name	LL (%)	PL (%)	PI (%)	British Plasticity Chart System	Unified System	Average Bulk Density from core (kg/m^3)
2	Castle Cove	67	43	24	MH	MH or OH	1249
3	Sugar Loaf Pt	83	36	47	On the MV CV boundary	MH or OH	1266
9	Rose Bay						1889
10	Mosman Bay	60	25	35	CH	CH	1351
11	Ft Denison	34	21	13	CL	CL	1551
12	Taylors Bay						
13	Coal Jetty 1						1789
14	Coal Jetty2	70	30	40	CH to CV, but just not M	CH	1260
15	Coal Jetty3	56	22	34	CH	CH	1330
16	Woolwich	75	35	40	On the CV MV boundary	On the CH - (MH or OH) boundary	1298
17	White Horse Pt	77	32	45	CV	CH	1240

British System
C = Clay
M = Silt
L = Low Plasticity
H = high Plasticity
V=Very high Plasticity

Unified System
MH = Inorganic silts of high plasticity
CH = Inorganic clays of high plasticity
OH = Organic clays of high plasticity
CL = Inorganic or silty or sandy clays of low plasticity

It is interesting that some sediments are classified as clays on the basis of liquid and plastic limits, but from grain size analyses, the percentage of clay size particles in their mud fractions is at most 14.42%, i.e. the mud is at least 85.58% silt

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P.J. Mulhearn

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19. ABSTRACT

An important parameter for the prediction of mine burial on impact, when a mine is first laid, is the sediment bearing strength profile. A number of nations have been developing easily deployable penetrometers for measuring bearing strength relatively quickly. The plan would be to use these in route survey operations. Previous joint experiments by TTCP (The Technical Coperation Program) nations have found that the measured bearing strength decreases as the diameter of a penetrometer increases. This effect is not currently understood, but in this report it is shown, with the help of some new experiments, that with the right penetrometer design it is possible to obtain bearing strength profiles which can be validly used for mine burial prediction. Finally a particular penetrometer configuration is recommended for navy use.

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