Relating *In Situ* Shear Wave Velocity to Void Ratio and Grain Size for Unconsolidated Marine Sediments

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Abstract

Recent advances in field hardware have meant that it has become possible to measure in situ shear wave velocity in the upper few decimetres of sea floor sediment in a routine manner. It is known that shear wave velocity can be primarily related to overburden depth and void ratio. Field-derived empirical relationships have previously been formulated so that it is now feasible to assess the suitability of shear wave data as a means of predicting in situ void ratio. Field measurements performed on the northern Californian shelf are presented which reveal good agreement between predicted and control data.

1. Introduction

The dynamic rigidity of unconsolidated marine sediments controls a whole range of acoustic transmission and geotechnical behaviour which are of relevance to defence applications in the littoral and near-coast zone. Although it is difficult to directly measure rigidity in the field, it has become possible, over recent years, to measure *in situ* shear wave velocity (Vs) - a property directly related to rigidity via the solution to the general wave equation. Whilst Vs is an important measure in itself, it also has the potential to be related to other, more familiar, sediment properties, most notably void ratio (e) or porosity (n) (where $n = e / (1+e)$).

The hypothesis to be tested herein is that field measurement of *in situ* shear wave velocity can be used as a reliable technique for predicting void ratio, and that it can be demonstrated that grain size dependencies observed in previously acquired laboratory and field data can be related to changes in void ratio.

Given the aim of testing the hypothesis, the objectives of this study are to;

(i) acquire shear wave velocity - depth data along a survey profile,
(ii) acquire and process grab sample data for delineation of grain size changes,
(iii) predict void ratio and/or grain size variation along the profile and assess the predictions by comparison with control data,
(iv) assess previous velocity - grain size - void ratio data in terms of expected velocity changes.

2. Data Acquisition

There are many ways in which to measure shear wave velocity in the field. The approach taken in this study is to directly measure transversely polarised, refracted shear waves using a sea floor -dragged sled system along a survey profile.

2.1. Hardware and Deployment

The hardware and deployment techniques are described in detail in previous publications [1,2] so that only a brief overview is presented here.

The system comprises a sled on which is mounted an electro-magnetic hammer-impact seismic source, the firing being controlled via a direct link to the survey vessel. Transversely polarised shear waves are thus produced and detected by a series of six horizontally gimbaled geophones, towed behind the sled at discrete intervals, to a maximum source-receiver separation of 12.35 m. Received signals are then transferred in real-time via a multi-core cable to a ship-board seismograph for display, quality control and recording. Data are only acquired when the complete sea floor system is made stationary by excessive release of the main towing cable for a short period of time. Having completed a measurement, the cable is taken-up to its original towing point in anticipation of the next repetition of the process. In this way, it has been found that rapid shear wave data acquisition over relatively large survey areas is possible, making the system ideal for delineating subtle variation in shear wave velocity, as well as for general velocity mapping purposes [2,3].

2.2 Location of acquired data

The data were acquired along a profile off the northern Californian coast, running in a North Easterly direction from a starting point c. 5km offshore from Humboldt Bay, Eureka. Figure 1 shows the locations of all shear wave measurement points along the profile. Reference positions 'S40' to 'S70' correspond to bathymetric depth (in metres). Note that deviation away from the intended straight line profile was incurred due to the presence of sea floor obstructions.

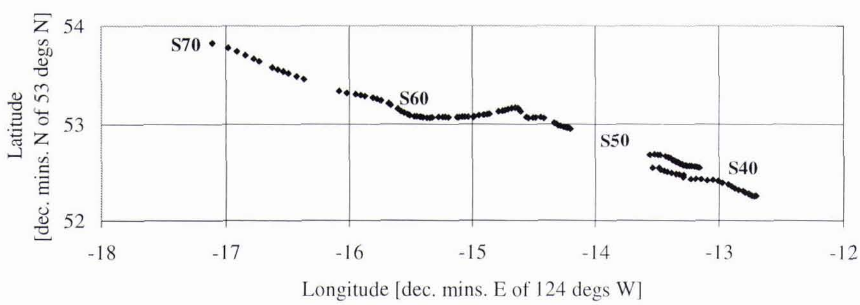

Figure 1. Location of shear wave data acquisition points

Grab samples were collected from a point on the profile at S40 and subsequently at 5m. water depth intervals to S70.

3. Data Processing and interpretation

3.1. Shear wave data

The data are processed in terms of horizontal plane layer refraction events. Thus, interpretations are limited in areas where 'low velocity' layers are present, or on occasions where the subsurface is composed of dipping layers.

Since shear wave velocity is known to be dependent upon, amongst other parameters, effective confining stress [4], it is generally expected that high velocity-depth gradients are present in the near surface. Thus, the idea of a 'direct' wave, traveling along the surface to the nearest receiver may be misplaced during shear wave analysis of unconsolidated marine sediments. The velocity represented by the time delay between firing of the source and arrival at the first geophone is merely an apparent velocity from an unknown and unmeasureable depth. Velocities can only be ascribed a representative depth between subsequent geophones. The interpreted travel-time data are shown in figure 2. Unlike systems which measure time-of-flight between two sub-surface transducers buried at known depth (e.g. the ISSAMS system [5]), the penetration depth of the sled data is determined by the source-receiver spacing on the sea floor and the velocity-depth structure at the measurement point. The data are presented as they occurred between the bathymetric intervals as shown in the accompanying legend.

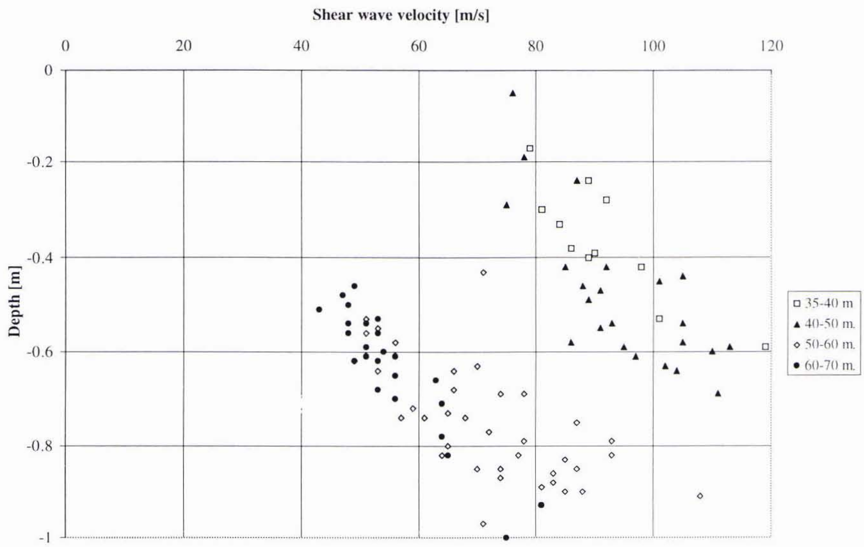

Figure 2. Interpreted shear wave velocity - depth data along the profile

It apparent that shear wave velocity generally decreases with increasing bathymetric depth. In order to clearly delineate the variation of shear wave velocity along the profile, it is necessary to normalise the data to a fixed sediment depth. Previous work has shown that that shear wave velocity is proportional to depth (confining pressure) raised to a power generally in the range 0.28 - 0.32 [5,6,7]. A value of 0.3 is assumed in this study such that the equivalent velocity at a depth of 10 cms below sea floor ($V_{0.1}$) may be calculated from:

$$V_{0.1} = V_z \ (0.1/z)^{0.3} \tag{1}$$

where V_z = shear wave velocity at measurement point
z = depth of shear wave measurement [m]

Velocity data normalised in this way are shown in figure 3.

The normalised data reveal a marked variation along the profile - changing from 55-70 m/s in water depths of up to 50 m., to 25-35 m/s at 70 m. Velocity is relatively constant within the water depth ranges 37 m. - 44 m. and 55 m. - 70 m. The greatest change in velocity is observed by inference to occur between the 44 m. and 55 m. isobath. Shear wave velocity data acquired via the ISSAMS probe during the same survey agree very well with the presented data [8].

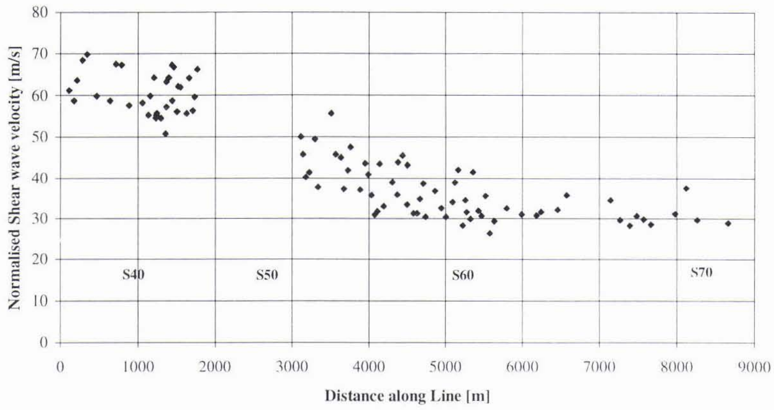

Figure 3. Normalised shear wave velocity along profile

3.2 Grab sample data

Data of sieve and hydrometer particle size analysis are shown in table 1.

Water depth of sample [m]	Mean Diameter [phi units]	Mean Diameter [mm]
40	2.96	0.129
45	2.98	0.127
50	2.79	0.145
55	6.53	0.011
60	7.84	0.004
65	7.27	0.006
70	7.82	0.004

Table 1. Results of particle size analysis (phi dia. = - $\log_2$ [dia. mm.])

It can be seen that mean grain size decreases with increasing water depth and that the largest change is observed between the samples acquired at 50 m. and 55m. (cf. Figure 3)

4. Predictions from shear wave velocity - depth data

4.1 Void ratio (porosity)

It has been established, either quantitatively or qualitatively, that shear wave velocity (or shear modulus) varies with a whole range of physical properties and conditions for sediments (unconsolidated or otherwise) [9, 10]. However, it is generally accepted that the two most important parameters that can be used to simply model the variation in velocity are effective confining pressure and void ratio. The first investigators of this link were Hardin and Richart [4]. They performed a series of resonant column experiments on Ottowa Sand and derived empirical relationships between shear modulus, effective confining pressure and void ratio within a specific range of void ratio and pressure. Subsequently, Bryan and Stoll [6] measured shear wave velocity whilst monitoring void ratio and effective confining pressure for 493 samples in the laboratory, with the intention of deriving as universal a relationship as possible. Whilst the confining pressure range was between 24 to 700 kPa, the data shown in their paper would suggest that the empirical relationship derived should function reasonably at the lower pressures involved in this study.

The relationship of Bryan and Stoll [6] for sands is given as:

$$G/p_a = 2526\, exp^{-1.5e}\, (s_0/\, p_a)^{0.45} \tag{2}$$

where: G = dynamic shear modulus (G = bulk density * $(Vs)^2$)
p_a = atmospheric pressure
e = void ratio
s_0 = overburden pressure

Similarly, Richardson et al. [5] derived an empirical relationship relating shear wave velocity to void ratio and depth:

$$Vs = (85/e)\, z^{0.3} \tag{3}$$

where: z = depth below seafloor

Given the *in situ* velocity-depth data acquired as part of this study, it would appear possible to predict void ratio either indirectly by applying equation (2), or by the direct application of equation (2). Plotted on figure 4 are the data of figure 2, superimposed on which are the velocity-depth trends of the two relationships for a range of void ratio (e) values - here plotted as porosity.

It would appear that there are quite large disparities between the two models, the differences being most accentuated at porosity values of 50% and at shallower depths.

Based upon ISSAMS data acquired over the last five years, equation (3) would appear to be valid for a range of siliclastic sediment types over the depth ranges for which *in situ* data are available in this study [8]. It should be noted that implicit in the application of this formula is the assumption that void ratio does not vary with depth.

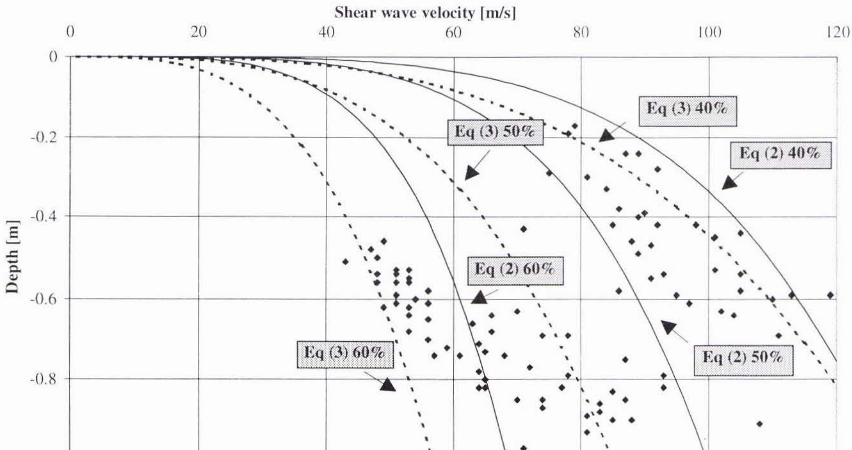

Figure 5. Velocity-depth data along S-line compared to empirical model data for a range of porosities.

The velocity-predicted void ratio data calculated from both (2) and (3) are plotted as porosity against 'distance along survey line' in figure 6. Comparison with porosity data acquired from subsampled box-core data (*pers. comm.* Briggs, 1996) would appear to show very good agreement with the values predicted by (3).

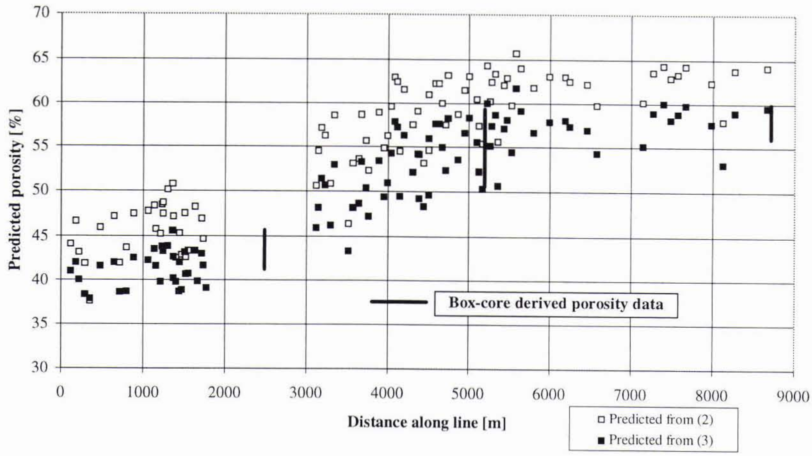

Figure 6 Porosity predicted by empirical relationships

4.2 Mean Grain Size

The causal link between void ratio and shear wave velocity is indirect since it lies in the association between the amount of void space in a sediment and the number (per unit volume) and nature of inter-particle contacts within the fabric. Studies have shown that shear wave velocity would appear to correlate, to some extent, with mean grain size [2,12,13]. However, like void ratio, this link cannot be made directly from velocity. If one considers an ideal case of perfect packing of spherical grains, grain size is a geometrical factor [12] so that there should be no causal link and no correlation between shear wave velocity and mean grain size. Equally, under such artificial circumstances, no correlation should be expected between grain size and void ratio. Empirical studies have shown that there is a link between the latter parameters [14], illustrating that the fabric of natural sediments differ substantially from the perfect case.

Previously published data are presented in figure 7 which reveal how shear wave velocity is observed to decrease with decreasing grain size. Three data sets are given: laboratory derived data [12] show the greatest variation for a given grain size, whereas the field data [2,13] reveal slightly less variability. The data presented have been normalised to a constant overburden depth, but have not been normalised to a constant void ratio. Using the empirical relationship between grain size and void ratio [14], it becomes possible to predict a range of expected void ratios for a given grain size, thus allowing a range of values for shear wave velocity for a given mean grain size to be predicted using (3). These are plotted on figure 7. They reveal that the trends between grain size and shear wave velocity are consistent with the correlation between grain size and void ratio. A logical adaptation of the method of predicting void ratio would be to use velocity as a predictor of mean grain size. Unfortunately, in this study, disparity results from the different effective measurement depth of the seismic and grab sample information (0.2 - 1.0 m and <0.1 m respectively). It should be noted that the laboratory data were acquired over a range from 'loosest packing' by underwater déposition to 'closest packing' achieved by impact invoked settling and are therefore likely to show an artificially high range of shear wave velocities compared with *in situ* data.

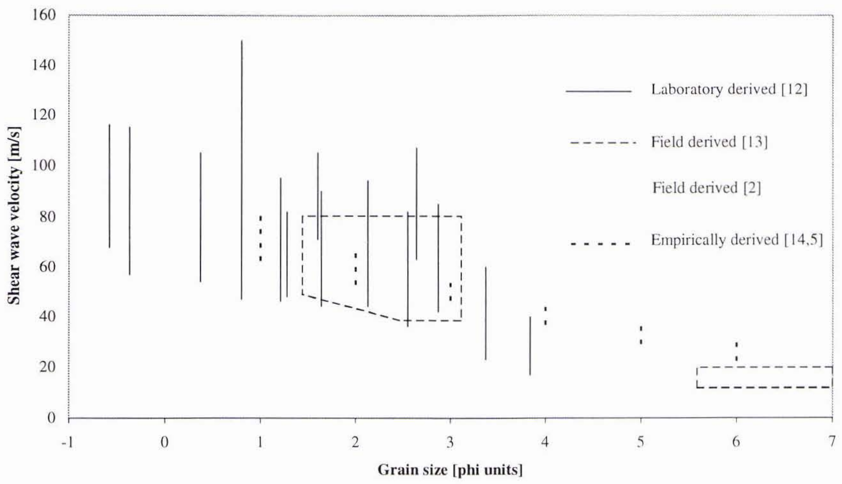

Figure 7. Normalised shear wave velocity versus mean grain size

5. Conclusions

Shear wave velocity - depth data have been successfully acquired and processed along the survey profile. The seismic (figure 3) and grab sample (table 1) data reveal that velocity is sensitive to changes in mean grain size - significant changes in grain size being reflected in the normalised shear wave velocity data. Two empirical relationships have been tested in order to use the velocity-depth data to predict *in situ* void ratio. It has been found that the equation derived by Richardson *et al.* [5] gives excellent agreement with box-core derived control data. Previously published relationships between grain size and void ratio have the potential to adapt the technique to predicting changes in mean grain size although prudence would be required during such procedures since it is known that the nature of the grain size - void ratio relationship varies with sediment type [14]. The implication of this work in the context of sediment classification studies is that the ability to map the shear wave velocity of marine sediments can reliably assist in the truthing of acoustic classification data sets. Other applications arise within the field of mine burial problems.

6. Acknowledgments

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7. References

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