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Acquisition and inversion of Love wave data to measure the lateral variability of geo-acoustic properties of marine sediments

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Abstract

A towed sledge system has been utilised to generate and receive Love waves at the seabed. Due to unique deployment procedures, the system is capable of acquiring data both rapidly and efficiently over an extensive area. An experiment was undertaken to assess the capability of the system to measure the lateral variation of the shear wave velocity in unconsolidated near-surface sediments along a 4-km survey line. The site chosen was known to display significant variations in sediment characteristics over relatively short distances and could therefore provide a suitable test. A parametric approach was used to obtain phase-velocity dispersion curves from the Love wave data sets. This approach enabled the *fk*-spectra to be resolved to a sufficiently high level using a limited number of receivers. Finally, the shear wave velocity profile for each record was estimated with respect to a reference model using a non-linear least squares inversion algorithm. Results indicated that the shear wave velocity field varied significantly along the survey line. The shear wave velocity at a depth of 30 cm below the seabed changed from 30 to 55 m/s over the length of the survey line. The velocity variations correlated well to geotechnical data acquired from the area, suggesting that Love waves acquired from only five seafloor receivers can successfully be used to construct near-surface models of seafloor shear wave velocity in unconsolidated near-surface sediments, with a lateral resolution of up to 25 m and a depth measurement range of up to 4 m.

Keywords: Love; Near-surface; Shear wave; Velocity; Inversion

1. Introduction

In the marine environment, the geo-acoustic properties of near-surface unconsolidated sediments play a key role in predicting a number of physical properties. More specifically, the knowledge of near-surface shear wave velocity (V_s) values are of great importance in both geophysical and geotechnical applications. The shear wave velocity in unconsolidated sediments is primarily a function of the number and area of grain-to-grain contacts and the effective stress, σ, across those contacts. As such, it is a sensitive measure of the fabric of the sediment and thus can be used in the prediction of geotechnical parameters. A number of empirical relationships have been formulated linking V_s to σ and the void ratio (e) (Hardin and Richart, 1963; Hamilton, 1976; Bryan and Stoll, 1989). Being empirical, such relationships have not

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proven universally applicable. However, these relationships can be used to predict void ratio from in situ shear wave velocity–depth data (Huws et al., 2000). The void ratio is defined as the ratio of pore space volume to solid grain volume and is, by proxy, a measure of the nature of the particle contacts and it, in turn, can be used to predict an approximate mean grain size (Hamilton, 1974). Knowledge of the shear wave velocity field has also been useful in the areas of sediment liquefaction-potential studies (Robertson et al., 1992; Pyrah et al., 1998) and seafloor classification (Davis et al., 1997). On a larger scale, it is likely that the near-surface shear wave velocity field, if accurately modelled, could be used in the prediction of shear wave statics in commercial shear wave data.

Since the shear wave velocity is essentially a sensitive measure of the fabric of the sediment, any minor variation within the sediment fabric may result in a significant change in V_s. In near-surface marine sediments, the shear wave velocity can therefore vary significantly both vertically and laterally. In situ shear wave velocities of less than 20 m/s at depths of around 30 cm have been reported for silty-clays (Richardson et al., 1991), but for sands at similar confining stresses, the velocity can be higher than 100 m/s. Variability of this scale is large when compared to equivalent change in compressional wave velocity. A transition from silty-clays to sands on the continental shelf can occur over a relatively short distance (< 1 km). In engineering terms, a transition of this magnitude would correspond to a significant change in the geotechnical properties of the sediments. In geophysical terms, the combination of low V_s and high variability associated with such a transition would result in large static errors in mode converted shear wave data. Thus, measuring the lateral variability of shear wave velocity in near-surface sediments has potentially very important and obvious applications.

The measurement of the shear wave velocity profile in marine sediments is often logistically difficult due to the nature of shear waves but a number of studies have succeeded in accurately measuring near-surface velocity profiles through various techniques. Richardson et al. (1991) used an approach whereby bender elements were directly inserted into soft sediment to measure the shear wave velocity between transmitter and receiver probes. Davis et al. (1989) describes the development of a seafloor shear wave refraction system capable of acquiring refraction profiles at discrete points along a survey line. Unlike alternative systems, it was able to measure the lateral variability in the topmost sediments over large distances. However, depending on the velocity–depth structure of the sediment, the system could exhibit limited vertical penetration. An extensive number of studies have concentrated on indirectly measuring the shear wave velocity profile by the inversion of interface waves of both the Scholte and Love type (Caiti et al., 1994; Bautista and Stoll, 1995). The inversion of interface wave data as a method of estimating the shear wave velocity profile has the advantage over other approaches that it is able to obtain shear wave data in areas of velocity inversion and potentially to greater depths. Stoll and Bautista (1994) developed a source–receiver system designed to generate S_h waves and Love waves at the seabed. This source was deployed on the seafloor with a large receiver array from a ship at anchor and was used to collect a single Love wave data set. Using an individual seismic trace, the multiple filter technique was used to derive the average shear wave velocity profile between the source and the receiver. By repeating this procedure for each receiver, an indication of the lateral variability of the sediment could be made.

This paper describes the development of new bottom dragged instrumentation capable of acquiring Love wave data both rapidly and efficiently over large distances. In addition, it tests the feasibility of the system as a tool for observing the variation of shear wave velocity both with depth and distance in marine sediments. The technique is based on the estimation of the shear wave velocity profile from Love wave dispersion characteristics using a non-linear least squares inversion algorithm. Previous shear wave velocity values using this technique in land based experiments have proven reliable when compared with additional measurements.

2. System design

2.1. Source

In collaboration with the British Geological Survey, a sledge mounted shear wave source was designed to excite S_h and Love waves in the seafloor as a result of a horizontal pulse applied to the sledge frame. The source is a refinement of a simple operating principle originally used by Schwarz and Conwell (1974) and then subsequently developed by the University of Wales, Bangor (Davis et al., 1989) whereby a high voltage electromagnetic hammer imparts a horizontal force relative to the seabed. The use of impulsive sources such as a sledge mounted airgun (Ewing et al., 1992) to generate S_h waves was found to also produce significant S_v and P wave energy. The operating principle and the configuration of the electromagnetic hammer source greatly reduce the proportion of energy converted to P and S_v waves. The new source consists of two low resistance coils positioned over either end of a free-moving central axle and separated by a brass centre-plate (Fig. 1(a)). Mounted on the axle between each coil and the centre-plate is a steel hammer. A current is discharged alternately across each coil at a given firing frequency. This current induces an electromotive force on the central axle and the hammer causing the hammer to accelerate until it impacts against the central brass plate, thus producing a horizontal shearing force. The use of low resistance coils removes the need for an on-ship high voltage power supply since high current can be drawn from a low voltage battery pack incorporated in the sledge frame (Fig. 1(b)).

The electromagnetic hammer is housed within a watertight brass tube mounted horizontally on a sledge frame. The tubes containing the system electronics and the batteries are mounted on the sledge frame either side of the source (Fig. 1(b)). The sledge frame itself weighs approximately 50 kg but combined with the weight of the source and the power-supply, there is sufficient coupling with the seabed without the use of fins beneath the frame. Side-scan-sonar images acquired over test sites where the system has been deployed indicate that physical disturbance to the sediment is very minor, being either barely detectable or undetectable. Within the context of the resolution of the velocity–depth profiles to be presented in this study, the physical effect of the sledge system on the sediment is not considered to be significant in altering the natural velocity profile of the seafloor material. The firing of the source is carried out remotely from aboard the ship by sending a 9-V trigger pulse down to the source at a chosen repetition rate. Depending on the ground type surveyed, the frequency content of shear waves produced by the source is typically in the range of 5 to 15 Hz.

2.2. The receiver array

A series of nine, three-component gimbal-mounted geophones are attached behind the sledge frame. Each of the geophones are housed in water-sealed chambers and mounted on free-flooding stainless steel trays designed to be robust enough to be dragged along the seafloor. The trays each have attachment points on both edges to provide greater stability during towing. Lengths of metal chain attached to the steel housings are used to join the receivers in a linear array and to maintain a fixed source–receiver geometry when under the tension of towing. The receivers are spaced at 3 m intervals out to a maximum offset of 27 m. Synthetic modelling suggested that 3 m spacing between receivers would be sufficient to avoid spatial aliasing. The approach used to estimate the dispersion characteristics from the data only requires the use of five traces so the shear wave velocity–depth profile was effectively an average across a 12-m distance of sediment.

The receivers are linked to the seismograph aboard the ship through a multi-core cable. Thus, noise levels and the quality of the data can be monitored in real time.

2.3. Deployment procedure

The deployment technique is fundamental to the successful acquisition of data. The sledge system is operated in a pseudo-underway manner which allows large distances to be profiled by making a number of measurements at discrete points along a given survey line. The principle of deployment is simple although it requires smooth co-ordination between crewmembers. The ship travels at a minimum speed whilst towing the sledge. Before a shot, the towing cable is wound in so that the sledge is relatively close to the stern of the ship. The winch is then released causing the sledge to be momentarily stationary on the seabed. The source can then be fired once noise levels are seen to have reached an acceptable min-

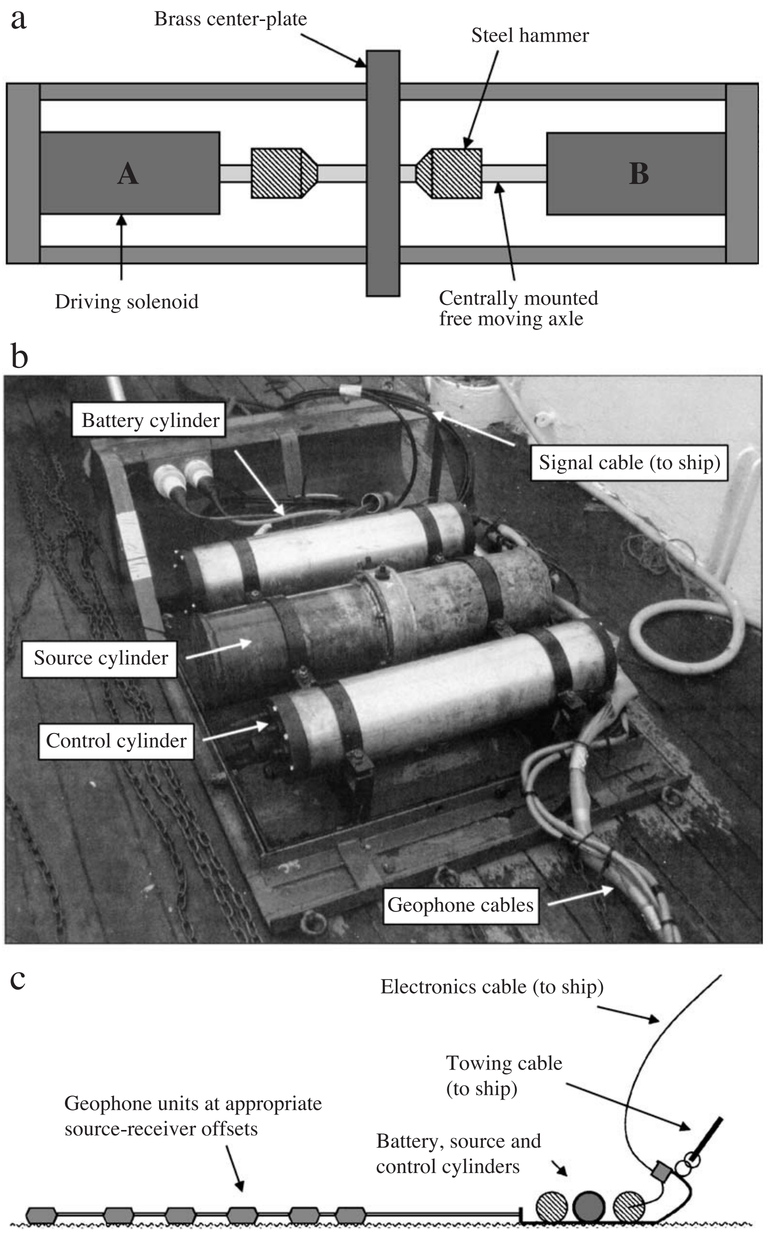

Fig. 1. The acquisition system. (a) The low-voltage electromagnetic S_h and Love wave source. A and B are the low resistance solenoids; (b) the sledge mounted source, power supply and system electronics; (c) illustration of the towing configuration during sledge deployment.

imum. This procedure can be repeated up to once a minute which results in sampling distances of approximately 25 m. A diagram showing the configuration of the Love wave system on the seafloor can be seen in Fig. 1(c).

3. Description of experiment

An assessment of the capability of the system to detect lateral variations in shear wave velocity was made by means of a field survey. A site approximately

1 km offshore at Red Wharf Bay, Anglesey, UK (Fig. 2), was chosen since it was known to have a sand bank in the middle of the bay which provided a marked lithological transition from the surrounding silts over a relatively short distance. Specifically, the survey line, measuring approximately 4 km long, crossed from a sandy-silt facies into a sand facies (sandbank) and back to a silt facies. The classification of these facies was made according to the mean grain size (M_z) of grab samples additionally acquired along the survey line. The term sandy-silt facies was used since sediment within this area although classified as silt according to the mean grain size (Wentworth, 1922), was still composed of approximately 75% fine sand. Other facies classification as either silt or sand was justified due to the M_z value falling near the mid-point of their respective boundaries.

The profiling system was used to acquire Love wave records at 56 discrete points along the survey line. Although some survey time was lost to poor weather, the dataset used in this study was acquired over the period of 4 h.

It is apparent from a cursory glance at the raw data (Fig. 3) that there is a difference in the frequency content and the dispersion characteristics of Love waves recorded in the silty zone as compared to those recorded on the sandbank. It is also apparent that the dispersion is less pronounced in the silt, which suggests the presence of a lower velocity–depth gradient than in the sand.

4. Interpretation of data

4.1. Dispersion analysis

One of the most common approaches to measuring the dispersion characteristics of surface wave data is the *fk*-spectrum method (e.g. Gabriels et al., 1987). The analysis involves the transformation of surface wave data to the *fk*-domain. The data can then be used to create a phase-velocity-frequency spectrum using a simple relationship between the frequency (f), the wavenumber (k) and the phase-velocity (c) ($c = 2\pi f/k$).

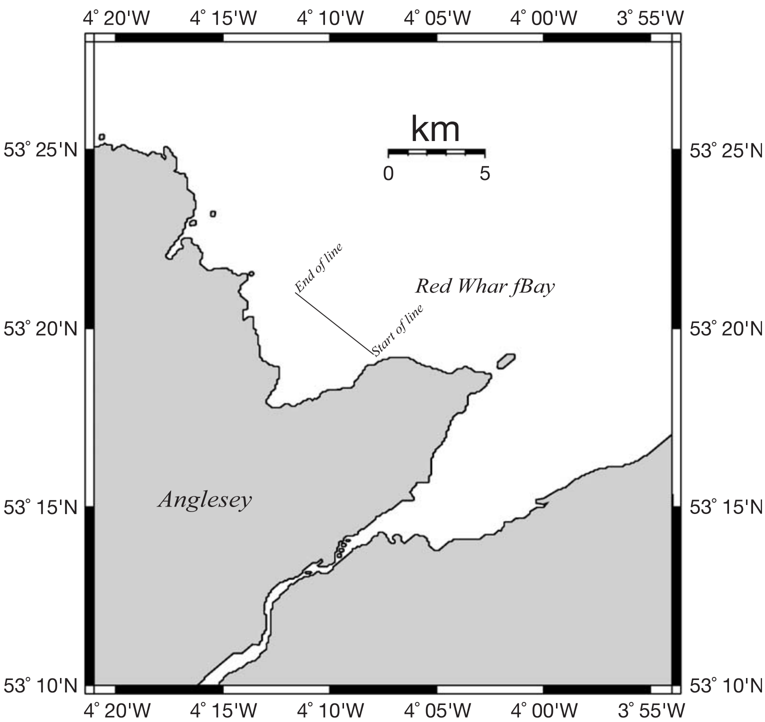

Fig. 2. The location of the designated survey line. From the SE end of the survey line the sediment grades from sandy-silt, to sand, to silt.

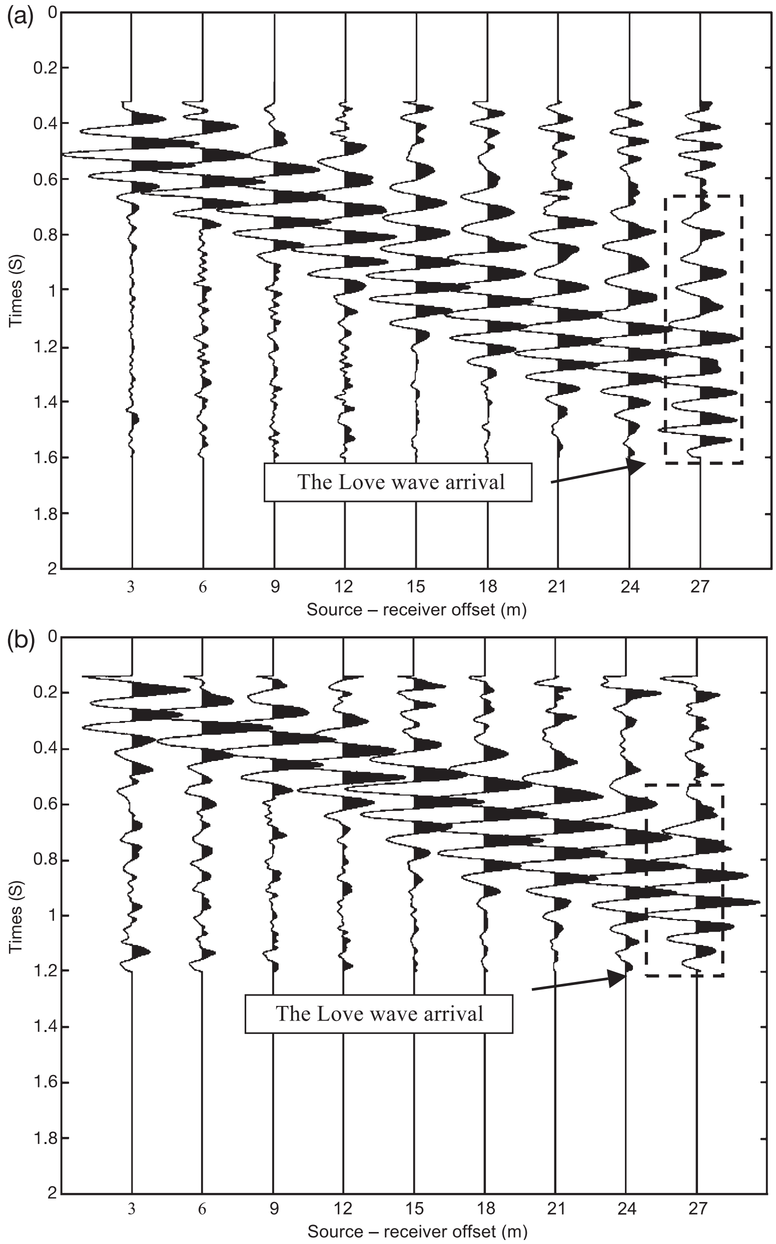

Fig. 3. Examples of Love wave data collected in (a) the sand facies, and (b) in the silt facies. Note how the dispersion is less pronounced in the silt facies, implying a lower velocity–depth gradient than in the sand.

However, tests have shown that the performance of this method is reduced in situations where the number of receivers present is decreased.

A new method for calculating high resolution *fk*-spectra requiring significantly less spatial sampling has been developed by Iranpour et al. (2002). The method is an adaptation of the parametric signal processing method MUSIC, multiple signal classification (Kay, 1988; Krim and Viberg, 1996). Parametric methods are based on the properties of the autocorrelation matrix of the sampled series. It differs from other Direction of Arrival (DOA) applications since the steering vector sweeps only for the wavenumber rather than the angle of arrival. The correlation matrix can be divided into a signal subspace and a noise subspace. The signal propagation is ideally orthogonal to the noise subspace. The noise subspace can be whitened, by replacing all the eigenvalues with the value 1. This forms the principal behind the MUSIC technique. A full description of the *fk*-MUSIC method is presented by Iranpour et al. (2002).

The authors have conducted tests to evaluate the performance of the MUSIC method for the processing of Love wave data. Comparisons between spectra calculated using 140 traces and spectra calculated using five traces have shown that the resolution of the spectra are not significantly reduced by limiting the number of receivers. Tests also revealed that for large numbers of traces, the MUSIC algorithm produced a more extensive frequency range for the calculation of the phase-velocity dispersion characteristics when compared to methods using a Fourier transform (e.g. Gabriels et al., 1987). The dispersion analysis of surface wave data using the MUSIC method is especially suited to data acquired using the sledge system. Practical limitations dictate that only a small receiver array can be deployed in the 'pseudo-underway' manner previously described. It was found that the *fk*-spectrum obtained from the Love wave data using the MUSIC approach could be calculated to a high resolution using the five traces recorded at the furthest source-offsets. The addition of traces recorded at smaller offsets did not significantly improve the resolution of the *fk*-spectrum since dispersion was less evident at these offsets. In using fewer traces in the dispersion analysis, the shear wave velocity profile is averaged over a shorter distance and therefore more sensitive to lateral variations within the sediment. An example of the *fk*-spectrum calculated for one of the Love wave records using the MUSIC method acquired over the sand facies is shown in Fig. 4. A well-defined energy band corresponding to the

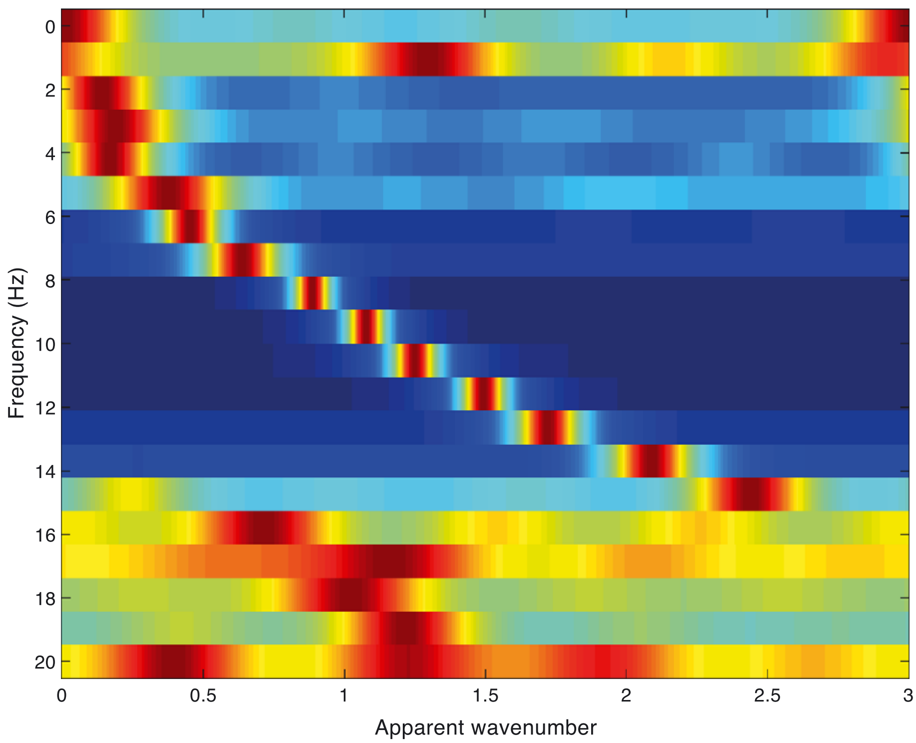

Fig. 4. The MUSIC *fk*-spectrum. Energy peaks can be used to define the phase-velocity dispersion curve. For the illustrated spectrum, phase-velocities calculated from frequencies ranging from 6.5 to 14.5 Hz were used in the inversion.

frequency content of the Love wave arrival is clearly evident. In the context of this study, it was stipulated that the peak wavenumber be definable to ± 0.001 m^{-1} for the frequency range used in the inversion. The dispersion curve can be estimated by picking peak energy values from the *fk*-spectrum and using them to calculate *c*, the phase-velocity. Comparisons with alternative methods show that the MUSIC method is capable of providing phase-velocity values over a greater frequency range.

5. The inversion algorithm

The final step in estimating the shear wave velocity profile is to invert the phase-velocity dispersion curve with respect to a reference model. The reference model consists of a number of layers each with specified shear wave velocity, compressional wave velocity, V_p, density, ρ, and thickness, d*z*. Synthetic phase-velocity values, calculated for the reference model, are used to invert the field Love wave dispersion curves. The inversion process is least sensitive to ρ and V_p. Nevertheless, realistic values were chosen. The sensitivity of the phase-velocity to the compressional wave velocity is small since Love waves are essentially guided horizontally polarised shear waves. The values of V_p and ρ were obtained from a previous survey at a nearby site (Jones, 2000, unpublished) ($V_p = 1650$ m/s, $\rho = 2000$ kg/m^3). Under normal circumstances, the inversion procedure is robust. However, the reliability of the inversion procedure is reduced if the reference model bears little resemblance to the actual shear wave velocity profile. It is therefore important to define a sensible reference model and, where possible, use existing data to construct the reference model. Plane layer analysis of single ended shear wave refraction data acquired at a nearby intertidal site provided a number of velocity–depth values. The following power law relationship between shear wave velocity and depth, *z*, was derived for these values:

$$V_s = 69z^{0.46} \tag{1}$$

The partial derivatives of the phase-velocity with respect to the model parameters were calculated as follows (see Takeuchi and Saito, 1972). The change in phase-velocity for each mode and frequency due to the variation of *S*-wave velocity as a function of depth is given by Eq. (2):

$$\mathrm{d}c = \int_{z=0}^{z} \left[\frac{\delta c}{\delta V_s}\right] \frac{\mathrm{d}V_s(z)}{\mathrm{d}z}\,\mathrm{d}z \tag{2}$$

where $c =$ phase-velocity (m/s).

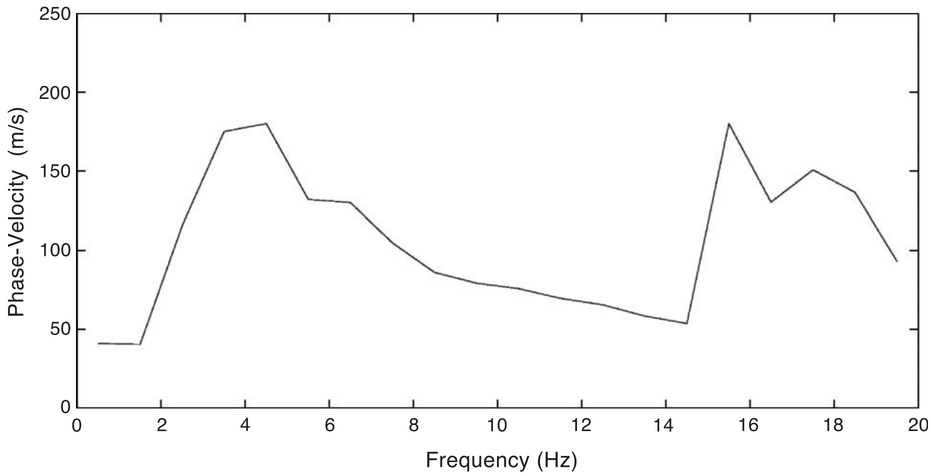

Fig. 5. The phase-velocity dispersion curve calculated from the spectrum shown in Fig. 4. The most coherent region of data lies between 6.5 – 14.5 Hz and this was the frequency band used for the subsequent inversion.

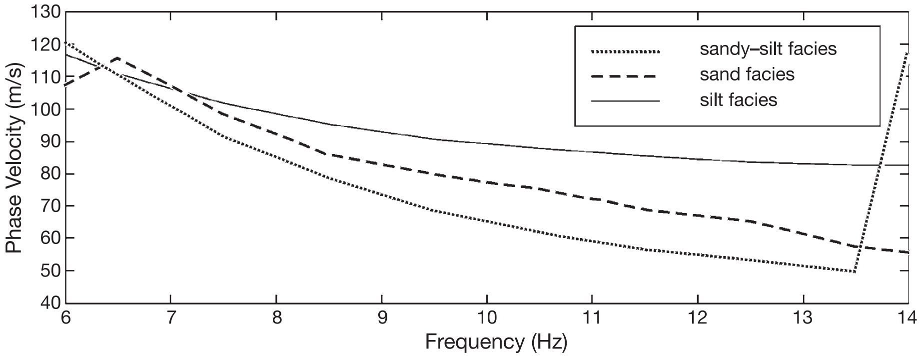

Fig. 6. Examples of the phase-velocity dispersion curves calculated from each of the sediment facies. The frequency range used in the inversion is restricted to values whose peak wavenumber can be defined to $\pm 0.001\ m^{-1}$ from the *fk*-spectrum.

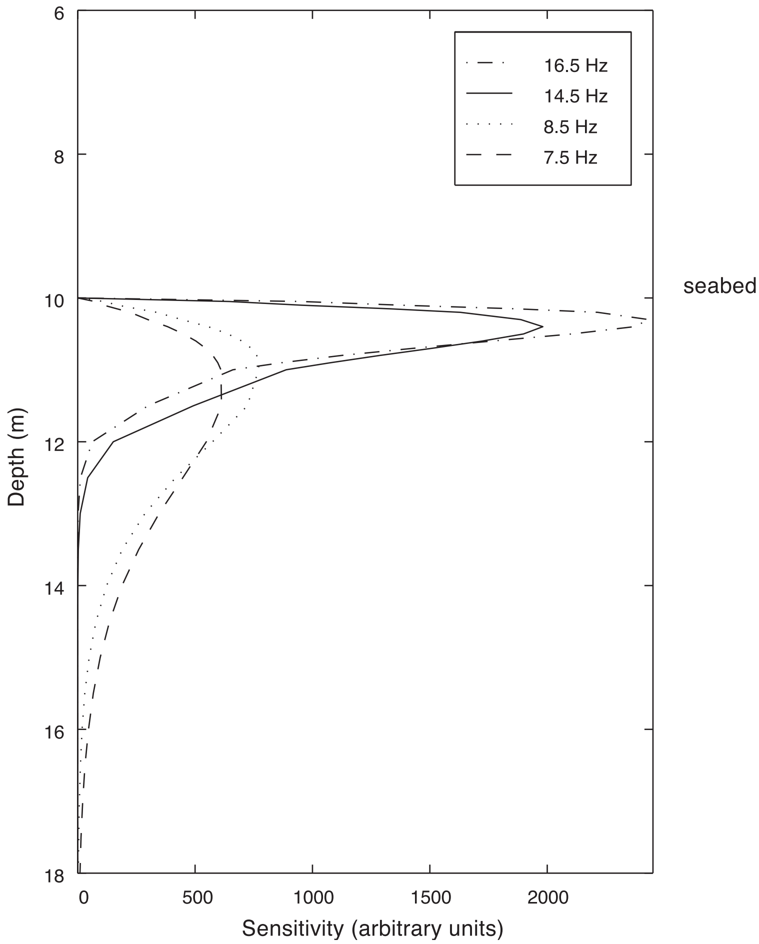

Fig. 7. A plot of the depth sensitivity of the range of frequency components used in the inversion procedure. It assumes that a 10-m water layer overlies sediment. The limit of depth reliability for the data sets acquired is generally between 3 and 4 m, dependant on frequency content.

The model is defined as a series of parameterised layers, Z_i, each with constant dV_s and so the partial derivatives can then be integrated over each layer:

$$\left[\frac{\delta c}{\delta V_s}\right] = \int_{z=z_i}^{z_{i+1}} \left[\frac{\delta c}{\delta V_s}\right] \mathrm{d}z \tag{3}$$

Eq. (2) can be written as:

$$\mathrm{d}c = \sum_{i=1}^{1} \left[\frac{\delta c_{m,f}}{\delta V_s}\right] \mathrm{d}V_s(z)_i \tag{4}$$

where m = mode number, f = frequency (Hz).

Eq. (4) can now be used to form the linear matrix equation:

$$d = \mathbf{G}p \tag{5}$$

where d = vector containing the difference between measured c, and c calculated from the reference model, $\mathbf{G}$ = matrix of elements corresponding to the integrated partial derivatives for values of m and f, $p = V_s$ perturbation in each layer.

This equation can be solved by inversion using the algorithm defined by Tarantola and Valette (1982). The algorithm uses a least-squares approach in order to obtain a stable solution. The implementation of the inversion algorithm may require a number of iterations before the final shear wave velocity profile is attained. At the point where the measured phase-velocity dispersion curve and that computed for the inverted V_s profile display good agreement (maximum difference ~ 2 m/s), no further iterations are required.

6. Shear wave velocity profiles

The Love wave records acquired along the designated survey line displayed a relatively limited fre-

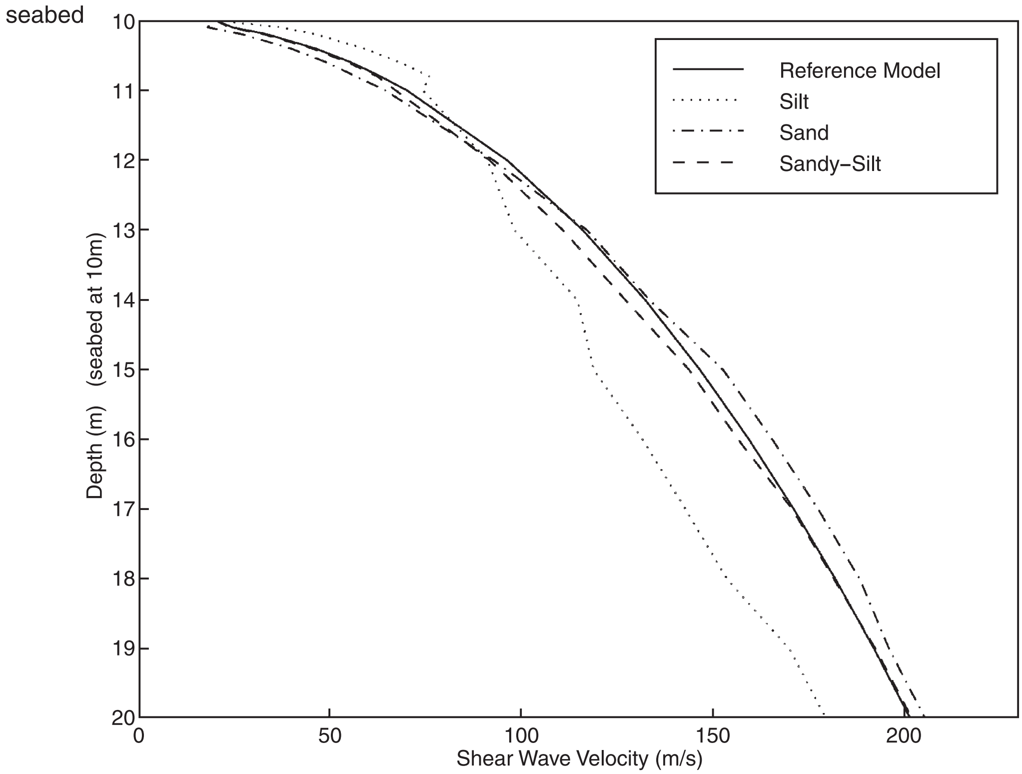

Fig. 8. Example shear wave velocity profiles estimated using the inversion procedure. It should be noted that frequency components used in the inversion restrict the reliability of the velocity values to a maximum depth of 4 m. Values beyond this depth cannot be considered as reliable, given the sensitivity of the frequency range used.

quency range. It is likely that a greater source–receiver offset combined with a greater number of receivers would have increased the frequency range for which phase-velocity values could be calculated. For each record, the frequency band of the phase-velocity dispersion curve that fulfils the criteria stated was used in the inversion. The phase-velocity dispersion curve calculated using values picked from Fig. 4 can be seen in Fig. 5. For those records collected over sandy facies, frequencies used for the inversion of the phase-velocity data generally ranged from 7.5 to 14.5 Hz. Records acquired from more fine-grained sediments appeared to have a marginally higher frequency content. The dispersion curves used in the inversions of these records extended from 8.5 to 16.5 Hz. Examples of phase-velocity dispersion curves from each of the sediment facies are shown in Fig. 6. The partial derivatives of the phase-velocity with respect to the shear wave velocity can be used as a measure of the sensitivity of a mode and its frequency components with depth (Takeuchi and Saito, 1972). Fig. 7 displays the sensitivities of the frequency components used in the inversion of the Love wave fundamental dispersion curves calculated using the reference model. From the sensitivity plot, it is apparent that the frequency range used in the inversion limits the reliability of the shear wave velocity profile obtained, at best, to the top 4 m of sediment at its maximum. The reliability of the shear wave velocity profile inverted from data acquired over the silt facies may, in some cases, be limited to the top 3 m due to its lesser low frequency content.

The phase-velocity dispersion curves obtained for each data set were inverted to obtain the shear wave velocity profile using a non-linear least squares technique as described. For all the data sets, only a single iteration was required due to the use of a realistic reference model. Examples of the shear wave velocity profiles derived from data from each of the sediment facies along the survey line can be seen in Fig. 8.

7. Discussion

From preliminary inspections it is apparent that there are differences in the shear wave velocity profiles obtained from each of the facies. Shear wave velocity profiles from the silt region display higher surface velocity values than those obtained from the areas with higher sand content. It would be expected that for a pure silt, the shear wave velocity would be lower than in sands since V_s is essentially a function of the void ratio (Richardson et al., 1991). Published inter-relationships (Richardson et al., 1991; Bryan and Stoll, 1989) all suggest decreasing V_s with increasing void ratio or porosity. Hamilton (1974) shows that porosity increases with decreasing grain size, thus V_s, and grain size can be linked. However, grain size analysis of samples from the silt region illustrates that there is a significant clay content ($\sim$18%) within the sediment. The influence of clay is rarely included in published empirical inter-relationships between V_s, stress and void ratio. Indeed, there is a paucity of published information regarding the shear wave velocity in mixed sediment types as seen in this study. It can be postulated that the addition of clay particles means that the shear wave velocity is dependent not only on the nature of the contacts and the stress across them, but also on the cohesion between particles. In near-surface sediments where the confining stress is small, it is plausible that cohesion between particles forms an important control on V_s. Cohesion at the surface may be sufficient to increase the rigidity of the sediment, and therefore V_s, compared with neighbouring facies which contain a smaller proportion of clay. The overall trend from the silt region illustrates that below the seabed V_s increases linearly with depth. Again, this linear increase may indicate that it is cohesion between particles which predominantly controls V_s in these near-surface sediments. This linear trend is in agreement with the empirical relationship linking V_s and depth in silts derived by Hamilton (1976). The exception to this linear form in the inverted V_s profiles can be seen in top 1 m of sediment. In this region V_s values are lower than if the linear silt V_s profile were extrapolated to the sediment surface. It has been observed by Jones and Jago (1992) that V_s in surface sediments can be strongly affected by biological activity. Depending on the nature of the activity, bioturbation can either reduce or increase the rigidity of sediments and hence correspondingly reduce or increase V_s. Such activity is most common in silt rich sediments where conditions favour the habitat of benthic burrowers. It is possible that bioturbation can be observed to depths of 1 m below the seabed which accounts for the deviation from the linear V_s profile seen over the top 1 m of sediment in the silt facies.

The V_s profiles inverted from Love wave data acquired in the sandy-silt region and over the sandbank display a power law relationship with depth as does the reference model. The power law relationship between V_s and depth is a function of the fundamental control provided by the confining stress on the friction between grains. Again, the form of these V_s profiles conforms to the pattern of the variation of V_s with depth in sands defined by Hamilton (1976). It is the high proportion of sand (~ 75%) and the reduced clay content (~ 10%) within the sandy-silt facies which is thought to produce this power law relationship as opposed to the linear relationship which might be expected for a silt as defined by Hamilton (1976). Modelled velocity–depth values are lower in the sandy-silt facies than those predicted in the sand facies, which concurs with the established trend of higher porosity values found in the finer sediment types, i.e. the sandy-silt facies.

The lateral variation of the shear wave velocity along the survey line can be seen in Fig. 9. Shear wave velocities are plotted to a depth of 3 m since this represents the limit of reliability for some of the data acquired over the finer sediments. The transitions from sandy-silt to sand and sand to silt are at approximately 1500 and 3500 m along the line, respectively. The shear wave velocity near the surface can be seen to progressively increase along the length of the line. Shear wave velocity values of as low as 17 m/s can be observed in the sandy-silt. Minor variations in values of V_s along the line, especially in this topmost layer, could result in large shear wave statics for exploration scale surveys. Beneath the surface layer, V_s can be seen to gradually increase as the proportion of sand within the sediment matrix increases although no clear boundary between the sandy silt and sand facies is evident. At the termination of the sandbank ~3500 m, the shear wave velocity significantly decreases laterally. This reflects the transition from a V_s–depth power law profile to a linear profile as defined by Hamilton (1976).

8. Conclusions

The Love wave profiling system developed by the University of Wales, Bangor has demonstrated that surface wave data can be collected both rapidly and

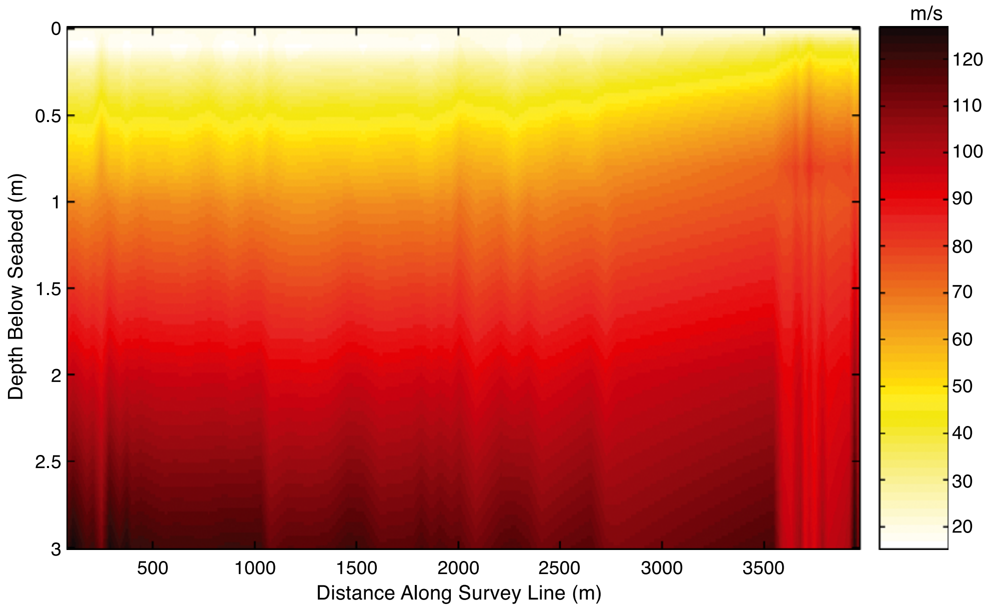

Fig. 9. The 2-D V_s field estimated from data acquired using the Love wave profiling system (0–1500 m sandy-silt facies; 1500–3400 m sand facies; 3400–4000 m silt facies).

efficiently due to its unique deployment procedure. The low voltage electromagnetic hammer has proved to be a suitable source for the acquisition of such data. The low voltage principal behind the development of the source has also removed the need for an on-board power supply thereby simplifying the operation of the system.

Experiments carried out to test the feasibility of such a system to measure the lateral variability of the shear wave velocity in unconsolidated marine sediments have proved successful. From the inversion of Love wave data acquired by the system using a non-linear least squares method, a two-dimensional near-surface V_s field can be obtained. Any lateral variation in the shear wave velocity can then be easily observed from the data. Geotechnical measurements of sediment samples collected along the survey line provide additional support for the applicability of the technique. However, successful implementation of the inversion algorithm to estimate the shear wave velocity profile requires the use of a realistic reference model in addition to the accurate estimation of the phase-velocity dispersion curve. The current system could be optimised by increasing the source–receiver offset. The greater dispersion associated with increased offset would improve the resolution of the dispersion curve and it would be expected that a larger frequency range could therefore be used in the inversion. At present, a combination of low shear wave velocities in near-surface sediments along the survey line and limited frequencies available for inversion has, realistically, limited the depth sensitivity of the technique to $\sim$ 4 m below the seabed.

The lateral variations measured by this technique provide a good illustration of the complex inter-relationships which define the shear wave velocity. In terms of the physical composition of the sediment, it can be seen that minor variations in composition, in particular fines, can have a large affect on the shear wave velocity.

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References

Bautista, E.O., Stoll, R.D., 1995. Remote determination of in situ sediment parameters using Love waves. Journal of the Acoustical Society of America 98, 1090–1096.

Bryan, G.M., Stoll, R.D., 1989. The dynamic shear modulus of marine sediments. Journal of the Acoustical Society of America 83, 2159–2164.

Caiti, A., Akal, T., Stoll, R.D., 1994. Estimation of shear wave velocity in shallow marine sediments. IEEE Journal of Oceanic Engineering 19, 58–72.

Davis, A.M., Huws, D.G., Bennell, J.D., Thomas, D., 1989. Development of a seafloor geophysical sledge. Marine Geotechnology 1, 91–115.

Davis, A.M., Haynes, R., Huws, D.G., 1997. Seabed sediment characteristics assessed geophysically: results of experiments in the Clyde Sea. In: Pace, N.G., Pouliquen, E., Bergen, O., Lyons, A.P. (Eds.), High Frequency Acoustics in Shallow Water. Conference Proceedings, SACLANT NATO Center, La Spezia, Italy, pp. 115–122.

Ewing, J., Carter, J.A., Sutton, G.H., Barstow, N., 1992. Shallow water sediment properties derived from high-frequency shear and interface waves. Journal of Geophysical Research 97, 4739–4762.

Gabriels, P., Snieder, R., Nolet, G., 1987. In situ measurements of shear-wave velocity in sediments with higher mode Rayleigh waves. Geophysical Prospecting 35, 187–196.

Hamilton, E.L., 1974. Prediction of deep-sea sediment properties: state of the art. In: Inderbitzen, A.L. (Ed.), Deep Sea Sediments: Physical and Mechanical Properties. Plenum, New York, pp. 1–44.

Hamilton, E.L., 1976. Shear-wave velocity versus depth in marine sediments, a review. Geophysics 41, 985–996.

Hardin, B.O., Richart, F.E., 1963. Elastic velocities in granular soils. Journal of the Soil Mechanics and Foundations Division, ASCE 89, 33–65.

Huws, D.G., Davis, A.M., Pyrah, J.R., 2000. A nondestructive technique for predicting the in situ void ratio for marine sediments. Marine Georesources and Geotechnology 18, 333–346.

Iranpour, K.E., Muyzert, E., Grion, S., 2002. Local velocity analysis by parametric wavenumber estimation in seismic (*fk*-MUSIC). 64th EAGE Conference Extended Abstracts. EAGE, Houten, Netherlands, p. 171.

Jones, S.E., Jago, C.F., 1992. In situ assessment of modification of sediment properties by burrowing invertebrates. Marine Biology 115, 133–142.

Kay, S.M., 1988. Modern Spectral Estimation. Prentice-Hall Signal Processing Series, Englewood Cliffs, NJ, p. 543.

Krim, H., Viberg, M., 1996. Two decades of array signal processing research. IEEE Signal Processing Magazine (July).

Pyrah, J.R., Davis, A.M., Huws, D.G., 1998. A combined geotechnical/geophysical method for the prediction of liquefaction with particular reference to the Fraser River Delta, British Columbia. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Engineering Geology Special Publications, vol. 15. Geological Society, London, pp. 11–23.

Richardson, M.D., Muzi, E., Miaschi, B., Turgutcan, F., 1991. Shear wave velocity gradients in near-surface marine sediment. In: Richardson, J.M., Hovem, M.D., Stoll, R.D. (Eds.), Shear Waves in Marine Sediments. Kluwer Academic Publishing, Dordrecht, pp. 295–304.

Robertson, P.K., Woeller, D.J., Kokan, D.J., Hunter, J., Luternauer, J., 1992. Seismic techniques to evaluate liquefaction potential. 45th Canadian Geotechnical Conference: Innovation, Conservation and Renovations, Toronto, Ontario.

Schwarz, S.D., Conwell, F.R., 1974. A technique for the in-situ measurement of shear wave velocity (V_s) for deep marine foundations. Offshore Technology Conference, OTC 2014, pp. 755–762.

Stoll, R.D., Bautista, E., 1994. New tools for studying seafloor geotechnical and geoacoustic properties. Journal of the Acoustical Society of America 96, 2937–2944.

Takeuchi, H., Saito, M., 1972. Seismic surface waves. In: Bolt, B.A. (Ed.), Methods in Computation Physics. Academic Press, New York, pp. 217–295.

Tarantola, A., Valette, B., 1982. Generalized non-linear inverse problems solved using the least squares criterion. Reviews of Geophysics 20, 219–232.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. Journal of Geology 30, 377–392.