

THE EXTRACTION OF GEOTECHNICAL INFORMATION FROM HIGH-RESOLUTION SEISMIC REFLECTION DATA

R. HAYNES

School of Ocean Sciences, University College of North Wales, Menai Bridge, Gwynedd, North Wales LL59 5EY and Applied Geology (NW) Ltd., Techbase 3, Newtech Square, Deeside, Clwyd, North Wales CH5 2NT

A. M. DAVIS

School of Ocean Sciences, University College of North Wales, Menai Bridge, Gwynedd, North Wales LL59 5EY

and

J. M. REYNOLDS and D. I. TAYLOR

Applied Geology (NW) Ltd., Techbase 3, Newtech Square, Deeside, Clwyd, North Wales CH5 2NT

Abstract. There are strong empirical and theoretical correlations between the geotechnical and seismic properties of a marine sediment. With the development of modern digital acquisition techniques, and the advent of PC/workstation-based data processing methods it is becoming possible to extract geotechnical information from seismic data in a cost-effective manner.

In a collaborative project between U.C.N.W., Bangor and Applied Geology (NW) Ltd., attempts are being made to develop improved capabilities in high-resolution seismic data acquisition and processing for geotechnical site investigation purposes. The ultimate objective is the creation of a rapid and cost-effective method by which the physical properties of seafloor materials can be determined. The potential users of such a method might include offshore contractors working within the hydrocarbon industry (for rig-site surveys, investigation of pipeline routes, etc.), coastal engineers, dredging companies, and river and harbour authorities.

It is envisaged that via the development of robust computer programmes designed to extract a number of different seismic parameters (velocity, acoustic impedance, attenuation) it will be possible to produce depth profiles (to 20–30 metres below seabed surface) of a marine soil's bulk properties (e.g. density, void ratio, moisture content and grain size). Given this information, it is then theoretically possible to calculate order-of-magnitude estimates of parameters such as shear strength and permeability. Ultimately, with a limited amount of borehole control, it should be possible to improve upon these initial estimates and provide information on the spatial variability of the *in situ* geotechnical properties.

1. Introduction

A joint project between UCNW, Bangor and Applied Geology (NW) Ltd., Deeside, Clwyd, has been established as part of a SERC Teaching Company Scheme. The objective of the project is to develop methods to extract geotechnical information from high-resolution seismo-acoustic data obtained from underway sub-bottom

profiling systems (for example, boomer, sparker, pinger systems). Such data are collected routinely, usually in the form of analogue paper records but increasingly in the form of digitally-stored records, during offshore site investigation studies.

The ultimate goal of the project is to create a rapid and moderately inexpensive methodology for investigating the physical properties of marine sediments. It is presently envisaged that such a method will be capable of investigating physical properties to depths of the order of 30–50 m and have a resolution of layer thickness to better than 0.5 m. The development of such a methodology offers large potential cost and technical benefits to the offshore industry.

To date, the major emphasis of the project has been on evaluating what is theoretically possible and what is presently technically feasible. This paper is a brief precis of what the authors believe can be expected realistically as regards the extraction of geotechnical information from seismo-acoustic data. The theoretical relationships between the geotechnical and acoustic properties of a marine sediment, and the strong empirical relationships between the two are discussed briefly. The important role of acoustic models is mentioned, before the implications of recent technological advances are discussed.

Recent developments in the processing of seismic data for the hydrocarbon industry and in the processing of basic sonar data have also led to methodologies which can be applied to the extraction of geotechnical information from acoustic data. However, one of the most important technological improvements has been the advent of moderately inexpensive but very powerful computers. This makes it possible (probably for the first time) to process the large amounts of acoustic data required to obtain useful geotechnical information quickly, cheaply and efficiently.

2. Geotechnical Relationships

The most important parameters that control the acoustic response of a marine sediment are given by Stoll (1989) as:

- i. porosity,
- ii. density,
- iii. overburden stress,
- iv. degree and type of lithification,
- v. grain size and distribution,
- vi. dynamic strain amplitude,
- vii. material property of grains,
- viii. sediment structure.

TABLE 1.

Problems associated with the acquisition of sub-bottom profiler data.

INSTRUMENTAL EFFECTS		
(i)	source	- repeatability - directionality - bandwidth
(ii)	receiver	- array directionality
(iii)	acquisition system	- dynamic range - sampling rate
ENVIRONMENTAL PROBLEMS		
(i)	noise	- self-induced - ship noise - electrical noise - hydrophone turbulence - ambient - cultural - natural
(ii)	waves	
GEOLOGICAL EFFECTS		
(i)	multiples	- water-bottom multiples
(ii)	diffractions	
(iii)	apparent attenuation	- peg-leg multiples

From the above list it can be seen that many of the properties that affect the acoustic response are of direct interest to geotechnical engineers (e.g. porosity, density, grain size and distribution). It is this inter-dependence between the acoustic and geotechnical properties of a marine sediment that theoretically allows the extraction of geotechnical information from sub-bottom profiler data.

The problem of deriving geotechnical information from seismo-acoustic data has been taxing geophysicists and engineers for at least the last thirty years and as yet there is no commercially available system that can extract meaningful results consistently. The measurements of seismic properties (e.g. velocity, acoustic impedance and attenuation) is not always straightforward and a number of intrinsic problems need to be addressed and overcome before any meaningful geotechnical parameters can be derived. These intrinsic problems can be split into three categories (Table 1), the first relating to instrumental effects, the second to environmental problems, and the third to geological effects.

When using analogue systems these problems cannot often be overcome. This results in a serious degradation of the quality of the output which renders the data difficult, if not impossible, to interpret adequately. In the light of recent technological advances, particularly in the digital recording of data, many of these problems can be eliminated, or substantially reduced, by careful design of the data

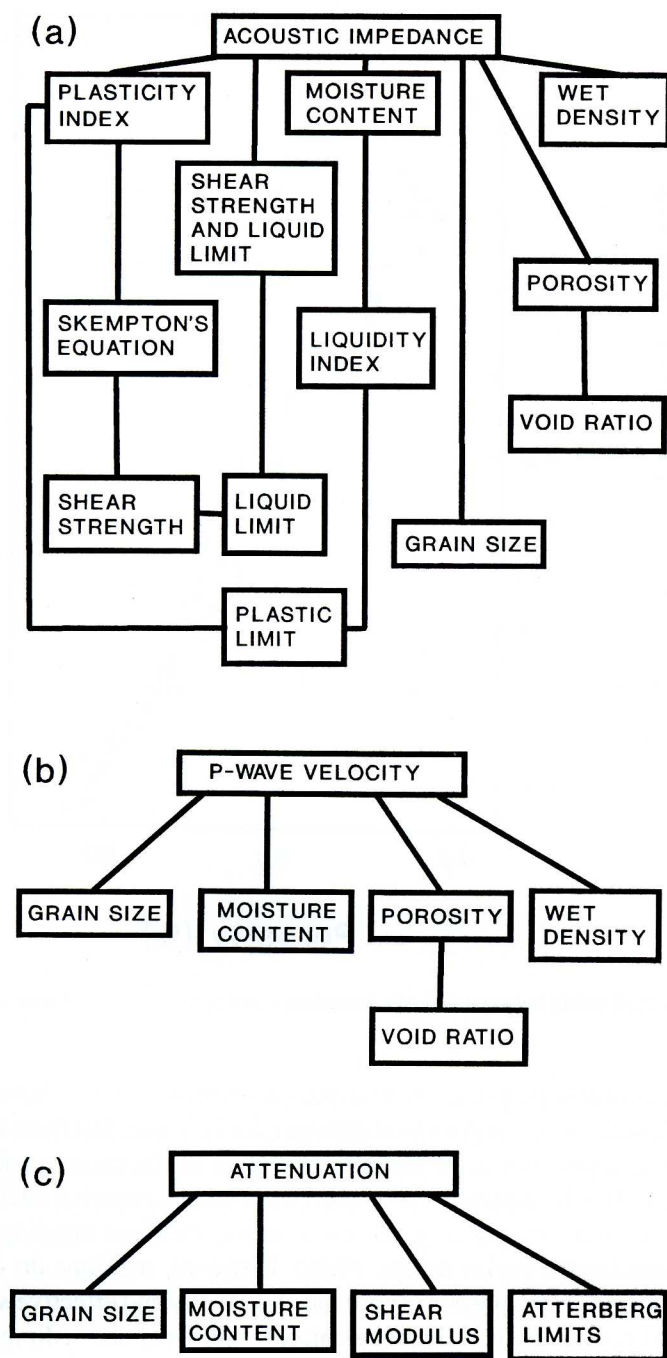


Fig. 1. Schematic diagrams showing the empirical inter-relationships between the geotechnical properties of a marine sediment and its seismo-acoustic properties ((a) acoustic impedance, (b) P-wave velocity, and (c) attenuation).

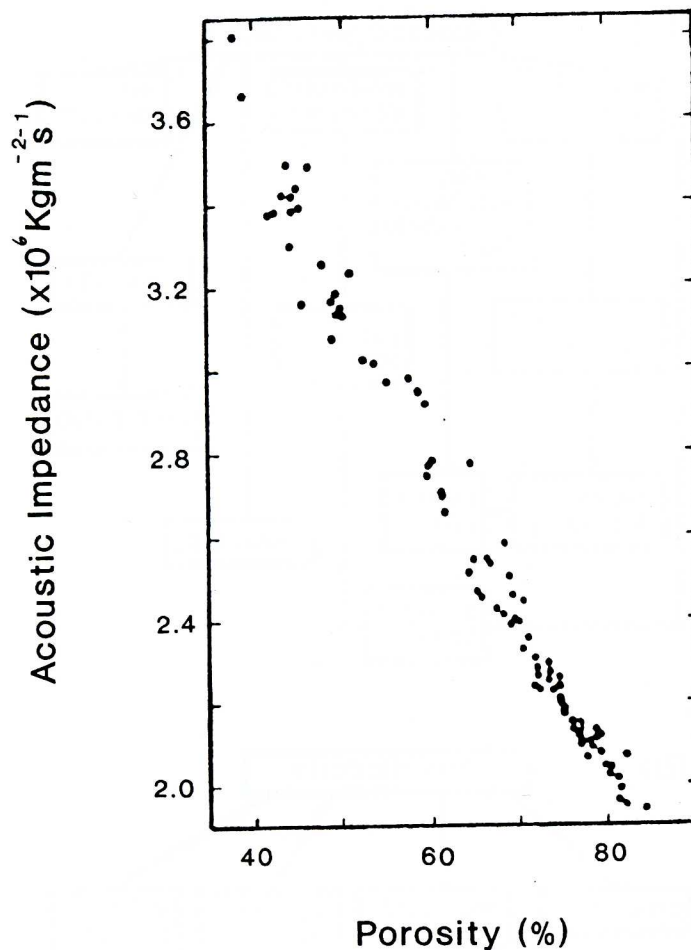


Fig. 2. Relationship between acoustic impedance and porosity (after Hamilton, 1970).

Variations of acoustic properties with depth (or effective stress), however, are not nearly so well understood. It is well established, for instance, that there is an increase in velocity with depth. This is primarily as a result of the increase in sediment frame stiffness (related to the number and length of the grain contacts); such an increase could be due to many factors, e.g. effective stress, chemical bonding, and maybe geological time itself (Taylor Smith, 1986). However, relations do exist (Taylor Smith, 1986) between the porosity (void ratio), velocity and effective stress (depth) such that it is theoretically possible to estimate the porosity and sediment type given the velocity and effective stress (depth) (Figure 3).

Many similar relations exist between other geotechnical and acoustic parameters. Given recent improvements in the processing of acoustic profiler data, it should be possible to extract estimates of the bulk geotechnical properties of ma-

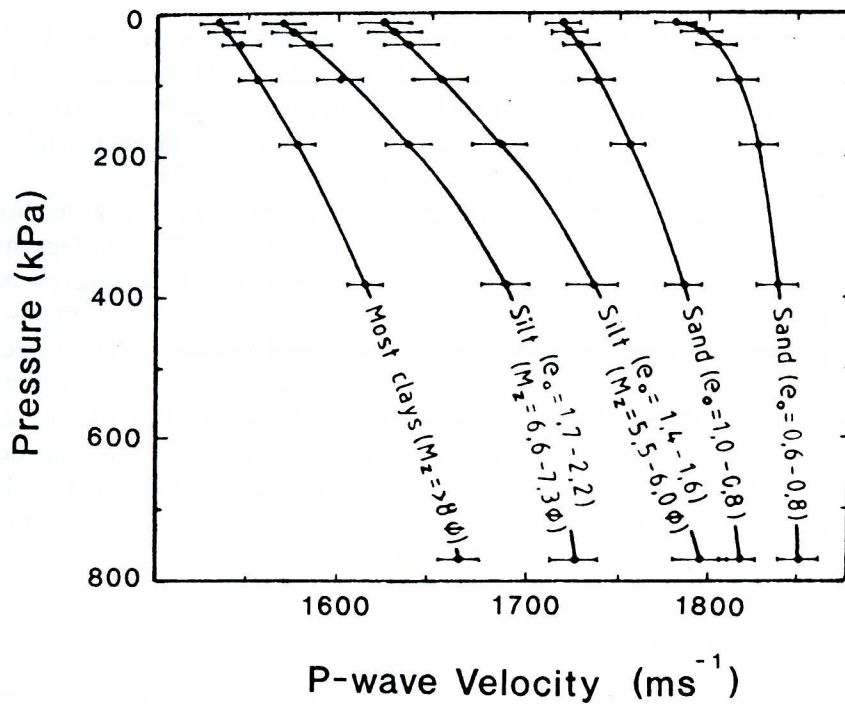


Fig. 3. Compressional wave velocity variations with effective stress and grain size (after Taylor Smith 1986).

rine sediments using data from underway continuous profiling systems.

3. Acoustic Models

The formulation and application of acoustic models of marine sediments, in particular the Biot-Stoll model (Biot, 1962, Stoll, 1989) has led to a much greater theoretical understanding of the inter-relationships between the acoustic and geotechnical parameters. The Biot-Stoll model enables the prediction of the acoustic properties of a sediment to be achieved almost entirely from geotechnical quantities. The model allows the geo-acoustic behaviour of a sediment to be unravelled. In particular, it predicts the velocity and attenuation of both compressional and shear waves.

The use of geo-acoustic models allows the relationships between the velocity and attenuation versus frequency of acoustic waves to be examined. At present there is a paucity of observational data relating to frequency dependence of velocity and attenuation. Potentially this represents one of the greatest sources of error in deriving geotechnical parameters from acoustic data. These errors may arise as many of the empirical relationships connecting geotechnical and acoustic properties are laboratory-derived using frequencies in the 100's kHz – 1 MHz range. It is

a matter of debate (Stoll, 1989) whether these relationships, particularly those involving attenuation, can be applied to the frequencies of interest for *in situ* geotechnical site investigations (1–10 kHz). Clearly, more studies need to be carried out to resolve this question and determine the precise frequency-dependent relations between the geotechnical and acoustic properties of marine sediments.

The use of models, such as the Biot-Stoll, represents one potential method to study these relations. A number of authors, notably Stoll (1989) and Ogushwitz (1985a, b, c), have started to address these issues. Their work is leading to a much better theoretical understanding of the acoustic response of marine sediments.

It is not possible at present, however, to use such models to derive the geotechnical parameters as many of the same parameters are required to solve the equations involved to form the model in the first instance. This means that whilst models allow us to study the effects of varying sediment properties on the acoustic response, the user must also supply meaningful geotechnical input to the model to obtain reasonable results. In other words there is a classic "Catch 22" situation if the Biot Stoll model is used as a predictive tool.

4. Technological Advances

Advances in the last few decades in the electronics field have had an immeasurable effect on many aspects of human life in the developed world; the field of geophysics is no exception. It is these technological advances that make it feasible, possibly for the first time, to attain the goal of determining the geotechnical parameters of a marine sediment from continuous acoustic sub-bottom profiling data.

Probably the two most important advances are (i) the development of fast A/D converters which can operate at the rates required for use with sub-bottom profiling systems (i.e. sampling rates well in excess of 10 kHz) (McGee, 1990), and (ii) the advent of relatively inexpensive, powerful computers, which enable the data acquisition, and more importantly, the data processing, to be fast, efficient and cost-effective (Hatton *et al*, 1986).

It should be noted that in nearly every aspect of shallow high-resolution marine seismo-acoustics there have been recent improvements in technology, from source and receiver design, digital data acquisition systems, to output (both hardcopy and digitally-recorded). The cumulative effect of all these advances is to enable high-quality digitally-recorded seismo-acoustic data to be more readily available. This availability of digitally-recorded data then enables subsequent post-processing to be undertaken thus facilitating the derivation of appropriate geotechnical parameters.

5. Data Processing

It is the application of data processing techniques which are already routinely employed in the processing of seismic data in the hydrocarbon exploration industry that will allow the geophysicist operating in the marine site investigation industry

to produce acoustic data in a form suitable for the subsequent derivation of geotechnical parameters. The three data processing procedures of most interest from this point of view are (i) velocity analysis, (ii) seismic inversion to determine acoustic impedance, and (iii) estimation/determination of attenuation.

All three data processing procedures are becoming increasingly sophisticated as the power of computers increases. In the case of velocity analysis, recent high-resolution techniques have emerged from the field of multi-channel sonar array processing which can be readily applied to seismic reflection data (Key and Smithson, 1990). These techniques provide results superior to the widely used semblance measure (Hatton *et al*, 1986) and offer a degree of resolution not previously attainable. This improved degree of resolution will be required if meaningful estimates of geotechnical parameters are to be made from the velocity determinations.

The recovery of acoustic impedance data from high-resolution reflection records is potentially the most rewarding and productive avenue of approach in determining the geotechnical parameters of a marine sediment. This requires that the 'seismic inverse problem' is solved. A large number of methods have and are being developed to solve this 'inverse' problem (Oldenburg *et al*, 1983; Berteussen and Ursin, 1983; Walker and Ulrych, 1983; Caulfield and Yim 1983) and it is presently an active area of research in the hydrocarbon exploration industry due to its potential value in reservoir studies.

The problem of determining attenuation from seismo-acoustic data is probably a much more exacting problem than the other two and it is likely that a number of methodologies will need to be developed to ascertain the most reliable techniques. Indeed it may prove to be the case that accurate determination of attenuation will be difficult to achieve *in situ* and only relative estimates will be able to be made (Janssen *et al*, 1985; Tarif and Bourbie, 1987; Tonn, 1991). However, even given estimates it should be possible to gain some useful information on the grain size of marine sediments (Hamilton, 1972).

6. Practical Aspects

The approach that the authors are pursuing towards the ultimate goal of this project, namely the extraction of useful geotechnical information from seismo-acoustic data obtained during continuous seismic profiling site investigation surveys, can be summarised as follows.

6.1. DATA ACQUISITION

The acquisition of high-quality digitally-recorded data is the basis on which the whole success, or failure, of the project will depend. Therefore, a lot of effort has been placed in these early stages of the project on designing optimum acquisition procedures. The source should have the broadest frequency bandwidth that the required depth of penetration to the investigation target will allow. If the depth

of interest is less than 30–50 m experiments undertaken in Lake Windermere, in conjunction with the Universities of Utrecht (Holland) and Århus (Denmark) and the British Geological Survey, indicate that a 'boomer'-type system is presently the best commercially available source type (McGee, 1992). The hydrophone streamer should be suitable for high-resolution work with a group length of the order of 1 m. There are presently few commercially available streamers that are suitable. Similarly, and probably most importantly, there are very few commercially available digital data acquisition systems that are suitable for very high-resolution work. Ideally such a system should have 10–12 channels capable of recording at sampling rates in excess of 25 kHz ($40\ \mu\text{s}$) with a dynamic range of at least 16 bit. At present such systems exist in research institutes only but commercial systems approaching this are appearing (e.g. GeoAcoustics Sonar Enhancement System and Elics – Delph 1). The system presently used at UCNW, Bangor, is a Carrack SAQ-V which is capable of sampling up to twelve channels with a total throughput of 48 kHz (i.e. 3 channels at 16 kHz, 12 channels at 4 kHz, etc.). This is a PC-based system which can be installed on small boats making it suitable for very shallow water work. An example of the quality of the data that can be acquired using this system is given in Figure 4, this shows that in ideal conditions it is possible to resolve reflectors to better than 20 cm down to sediment depths in excess of 15 m.

6.2. DATA PROCESSING

There are two avenues of approach to the processing of seismo-acoustic data for the extraction of geotechnical information. In the first, the data are digitally recorded and then post-processed at a later date. In the second, the data are processed in real-time using the acquisition computer. At UCNW the approach presently favoured is the first, the data being digitally recorded on magnetic tape and then processed using a commercial data processing package. The processing package used is the Sierra Geophysics ISX/SierraSeis system which is run on a Sun IPX workstation. The Sierra ISX system permits rapid processing of the acoustic data into a form suitable for the derivation of the geotechnical information. The type of processing that can be done includes: deconvolution, filtering, multiple suppression, velocity analysis, and pseudo-acoustic impedance inversion. Computer modules are presently being written that will derive geotechnical parameters from the processed seismo-acoustic data. It is possible that if some optimum processing parameters can be determined then some processing can be undertaken in real time, especially if multi-tasking computers are employed as acquisition systems.

7. Future Developments

From the above discussions it should be apparent that in the future there are likely to be:

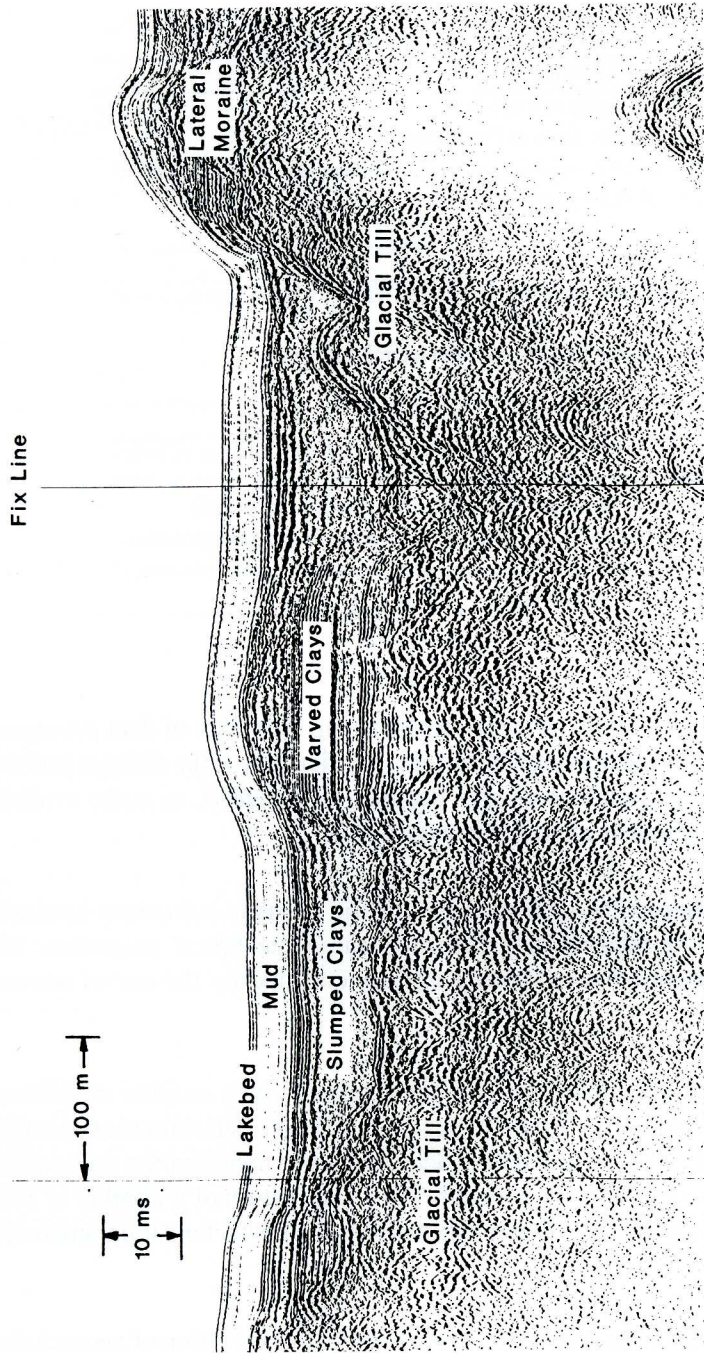


Fig. 4. An example of high-resolution seismic data obtained from Lake Windermere using a 'boomer'-type source. The actual source being an O.R.E. "Geopulse" Model 5810B, operated at 280 J with a trigger cycle length of 0.5 s, and a sweep length of 150 ms. The signals were received by an E.G.&G. Model 265 hydrophone streamer and recorded using a Dowty Waverley Model 3700 thermal linescan recorder.

TABLE 2.
Potential Benefits for offshore industries.

1. RECONNAISSANCE USE	
-	rapid surveying of large areas
-	gross interpretation of bulk properties
-	improved data quality leads to identification of difficult areas ⇒ better placement of boreholes
2. DETAILED SURVEY	
-	interpolation between boreholes leads to better geotechnical design
-	identification of areas of rapid lateral variation
LEADS TO:	
(i)	cost savings due to a possible reduction in the number of boreholes required and/or increased cost-effectiveness that a given number of boreholes are located with maximum benefit
(ii)	increased confidence in geological/geotechnical interpretations
(iii)	cost savings due to more appropriate and efficient geotechnical designs being produced

- a. Continued technical improvements especially in the fields of data processing techniques and data acquisition hardware. (Particularly if the defence industry under the changed political climate decides, or is forced, to make available for general use some of its acoustic expertise.)
- b. An improved theoretical understanding of the acoustic behaviour of marine sediments and the inter-relationships with the geotechnical properties. This should come about from laboratory experiments and by the use of acoustic models.
- c. The integration into intelligent computer systems of a number of different seismo-acoustic processing techniques (e.g. velocity determination, acoustic impedance analysis, and attenuation determination) to determine the geotechnical properties of a marine sediment. The combination of a number of techniques should enable much better estimates of the geotechnical parameters to be made.

These technological improvements should enable the derivation of geotechnical properties of marine sediments remotely using sub-bottom profiler data. Such a methodology offers large potential benefits for the offshore site investigation industry (Table 2).

8. Conclusions

It can be seen that the extraction of geotechnical parameters from seismo-acoustic data is possible theoretically, and with recent technological advances is, or is becoming, practically feasible. These recent improvements now make it possible to digitally record sub-bottom profiler data with enough signal fidelity and at the required sampling rates to enable digital seismic data processing techniques to be subsequently applied. The data processing of the seismo-acoustic data should then produce data of sufficiently high quality to enable the many empirical relationships that exists between geotechnical and acoustic properties to be used to extract geotechnical parameters. It is envisaged that it will be possible to produce depth profiles (to 20–30 metres below seabed) of a marine sediment's bulk properties (e.g. density, void ratio, moisture content and grain size). Given this information it is then theoretically possible to calculate order-of- magnitude estimates of parameters such as shear strength and permeability. Ultimately, with a limited amount of borehole control, it should be possible to improve upon these initial estimates and provide information on the spatial variability of the *in situ* geotechnical properties.

With the advent of powerful, but moderately inexpensive, computers it should be possible to extract this geotechnical information from seismo-acoustic data in a cost-effective manner. The derivation of geotechnical properties remotely and rapidly from sub-bottom profiler data offers large potential technical and cost benefits to the offshore site investigation industry.

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