GEOPHYSICAL-GEOTECHNICAL PREDICTIONS

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Abstract:- Civil engineering constructions generally rely on predicting the response of the foundation material to the load placed upon it, which may be static or dynamic or a combination of both. The prediction usually requires carrying out a number of *in situ* tests complemented by laboratory analysis of collected samples. Such a procedure for the sea floor, while not impossible, is inhibited by the extremely high costs involved. The fundamental geotechnical parameters required are the three elastic moduli (constrained, Young's and shear) at the appropriate strain levels and rates together with their directional variations, porosity, and permeability to assess fluid flow and the dissipation of pore fluid pressure. It is also necessary for vibrational considerations, such as in the assessment of seabed response to earthquakes, to determine energy attenuation. Much of the desired information can be obtained from electrical and seismo-acoustic sea floor observations, resonant column tests on samples, and a combination of empirical correlations associated with the use of a Biot porous medium model. Permeability, however, defies an overall sensible solution, often providing a value which can be several orders of magnitude higher than that obtained conventionally, particularly in clays and silts which sometimes have the effects of burrowing animals as an added complication. As permeability is, perhaps, the most important single sediment property of value to biologists, chemists, geologists, physicists and engineers alike, any acoustic classification of the seabed should take account of this parameter and prescribe methods of determining it.

1. INTRODUCTION

Von Karman, one of the engineering giants of the early part of this century and well-known for his epigrams, epitomised in one of them the difference between science and engineering while at the same time spelling out the fundamental problem in engineering: *Scientists explore what is; Engineers create what has never been.*. Predictions are at the heart of this process of creation.

Unfortunately for the civil engineer the foundation materials upon which the construction has to rest are highly variable: shear strength can vary from zero to around 100 megapascals; there are probably 10 orders of magnitude difference in permeability; even in areas of apparent homogeneity, variations in saturation - the replacement of some pore water by gas - and directional effects can lead to complex behaviour under load. The presence of thin bands of clay in otherwise competent foundations, and usually unseen in any conventional acoustic scan, can lead to slip failure while intercalations of sands and silts in clay formations produce such a complex permeability pattern, allowing a build-up of excess pore pressures, that a foundation failure results (Ardus [1]). Such unsympathetic geology can also present considerable alarm to the acoustic modeller through multi-path effects.

For the engineer the usual procedure is to carry out a number of *in situ* tests at the construction site and to collect samples, for subsequent laboratory testing, to depths within the foundation material appropriate to the size of the construction. From these data the prediction process begins. Conventionally there seems to be three streams of attack: there is the diagnostic approach (the experiential technique), there is the assessment of behaviour through the use of a physical model, such as in centrifuge tests, and then there is the use of finite element analysis (Zienkiewicz [2]).

While one or other or even a combination of all three predicting methods prove to be reasonably satisfactory for most civil engineering site investigations, when these are applied to the marine environment the difficulties of carrying out *in situ* tests and collecting undisturbed samples of the sea-floor material vastly increase the costs of the project. It is for such areas that the remote sensing capabilities of geophysical surveys are becoming important.

2. GEOPHYSICAL SENSING

Historically the geophysicist has had to endure a peculiar position in civil engineering site investigations. Of course there has always been an element of geophysics within the investigative programmes for large construction projects, such as motorways, dams and nuclear power stations, but in general the geophysical application has been a minor one largely involving seismic refraction and electrical resistivity techniques to assess depth to bedrock of the site in question. Up to relatively recent times little attempt has been made to make use of the geophysical quantities (e.g. seismic wave velocity, electrical resistivity) derived from the actual site investigation. There have been, of course, notable exceptions to this, such as the application of oilfield well-logging principles to water supply studies (e.g. Barker & Worthington [3]) and self-boring pressuremeter measurements (Windle & Wroth [4]) as well as the use of differences between compressional wave velocities measured in the field from those in the laboratory to give an indication of rock quality, particularly for dam site investigations. But, in general, the civil engineer has been reticent to accept geophysically-derived engineering parameters (such as the constrained modulus, permeability, and so on) for design purposes.

To a certain extent this reluctance is understandable in that much of the early geophysical-geotechnical were presented in an empirically-derived

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correlatable form which was plainly unacceptable (Fig.1). The last few years, however, have seen some remarkable changes in the geophysical-geotechnical prediction game. This has come about largely through naval defence requirements - the need to understand more about the responses of the sea floor to loads placed upon it, including seismo-acoustic loads - but has also been achieved through the need for improved design of large constructions such as nuclear power stations. The result has been the development of highly sophisticated seismo-acoustic surveying techniques which allow intense signal processing of the collected data on the one hand, and the enhanced use through microelectronic instrumentation of engineering laboratory testing equipment, such as the resonant column, on the other. Many fine examples of the various equipment and procedures are seen in the conference proceedings on shear waves held in La Spezia in 1990 (Hovem *et al* [5]).

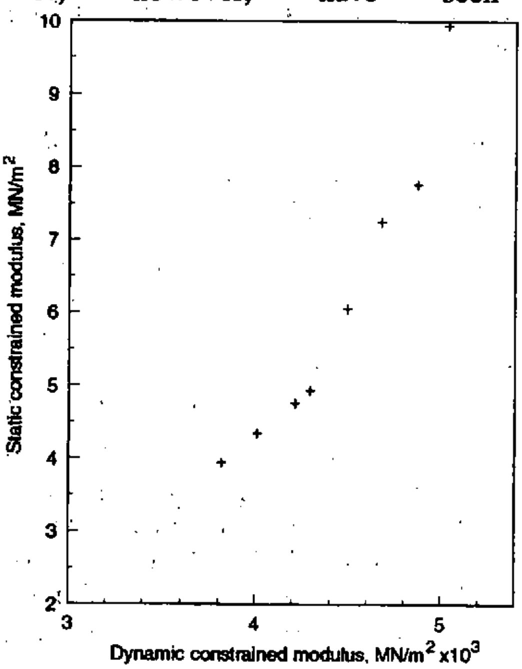

Fig. 1

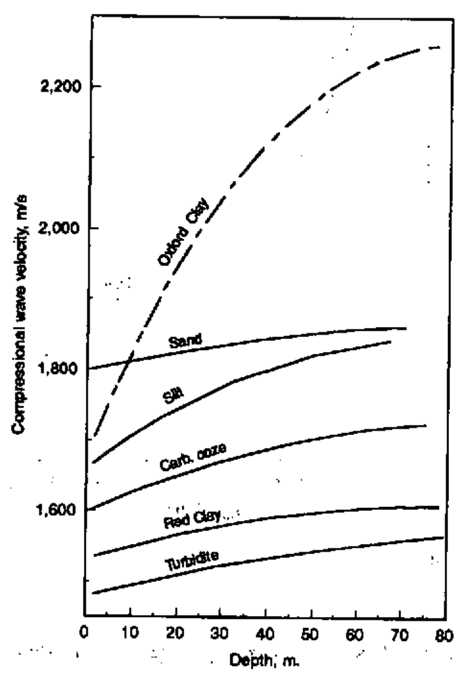

Fig. 2

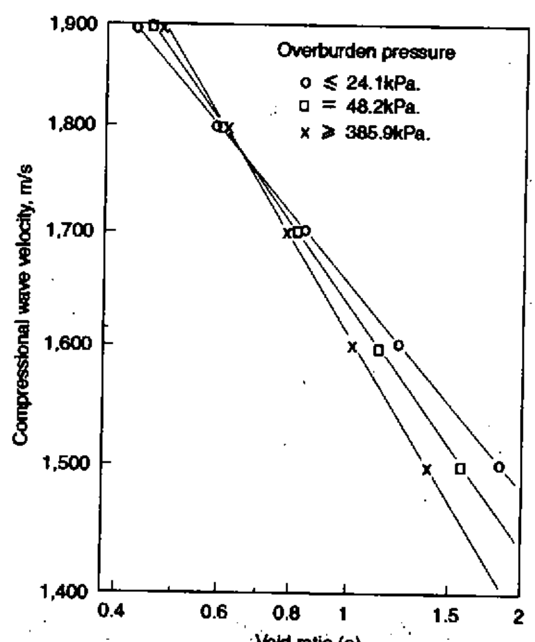

Fig. 3

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A good place to start in an assessment of geophysical predictions of geotechnical quantities, because of the apparent similarity with seismic velocity gradient with depth, is with sediment consolidation.

2.1 Consolidation

Consolidation in the geotechnical sense is the reduction in volume of a sediment under a compressive load. The load may be either produced by some engineering construction, or by the overburden pressure from the accumulating superincumbent material itself. In either case the end result is settlement. To provide a simple assessment of the effect for a homogeneous material requires some knowledge of the material properties (such as those provided by a grab sample), values of the *in situ* void ratio and uniaxial compressibility (the inverse of the constrained modulus), and knowledge of sediment permeability. As the reduction in void ratio with depth in a sediment produces an inverse effect on the seismic P wave velocity (Figs.2 & 3), it is a relatively simple matter to predict the required void ratio/pressure curve provided that the *in situ* void ratio is known (Fig.4). The last quantity, of course, can be obtained by a measurement of *in situ* electrical resistivity; a generalised plot of void ratio against electrical formation factor is shown in Fig.5. Proceeding

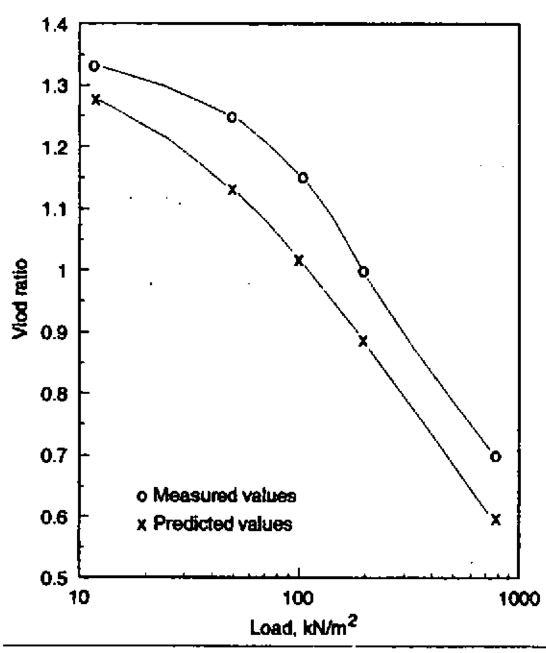

Fig. 4

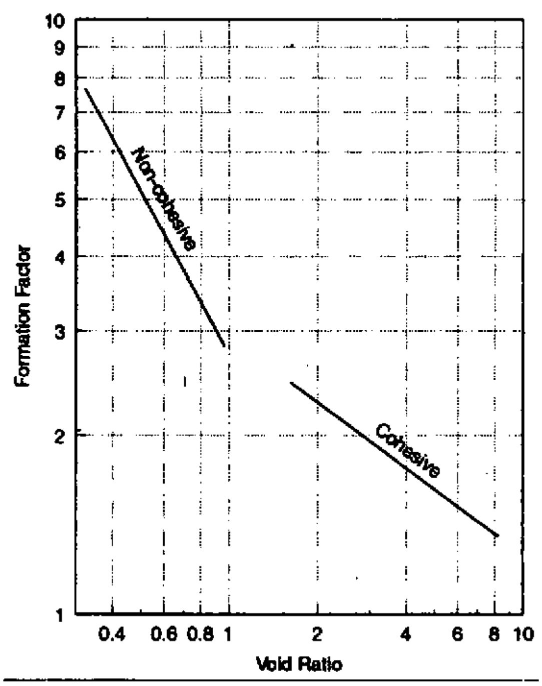

Fig. 5

further from this stage, so as to consider the time element in settlement, requires a value of the uniaxial compressibility (which can be obtained from Fig.4) and of the sediment permeability. But permeability measurement is a nebulous proposition and does require a study of its own.

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3. SEDIMENT PERMEABILITY

No discussion of permeability can be divorced from a consideration of excess pore fluid pressure. The interrelations are perhaps best seen in a simple model experiment of a building resting on a saturated sand (Fig.6a). At this stage the water pressure is hydrostatic and no flow takes place through the overflow pipe. The water pressure at the base of the tank is now increased by raising the auxiliary tank (Fig.6b); there is an upward flow of water which is dependent on the magnitude of the excess pressure and the permeability of the sediment, the greater the permeability the greater the flow of water. If the excess pressure is now increased further, movement occurs within the sand body and the structure topples over (Fig.6c).

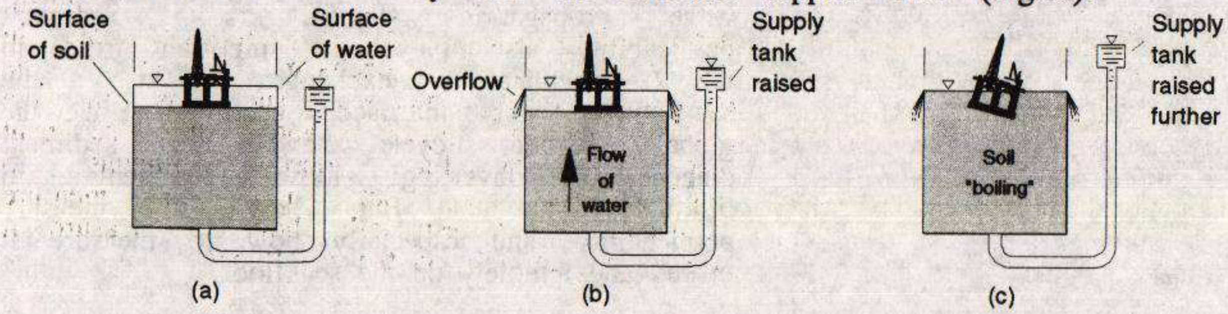

Fig. 6

Fig. 7

Compare this to the photograph of the Niigata disaster (Fig.7): the sand in the experimental tank has liquefied, as did the foundation material in Japan. Clearly in this experiment the rate of application of the excess pore pressure has been greater than the capability of the sediment permeability to dissipate it, thus forcing the sand grains apart and temporarily destroying the solid skeleton.

It follows that permeability is a much sought after sediment property; there can be no consolidation settlement if there is no drainage; and if there is no drainage any excess pore pressure can build up to a level where the effective stress is zero and the sediment skeleton collapses. Such a situation can destroy shear wave propagation (Fig.8). Sediment permeability also plays an important role in the chemical exchanges at the sea-floor/sea-water interface, such as in the global carbon cycle and in sediment diagenesis, converting loose sediments to lithified rock. But how to measure permeability, and especially how to measure it *in situ* and remotely on the sea floor?

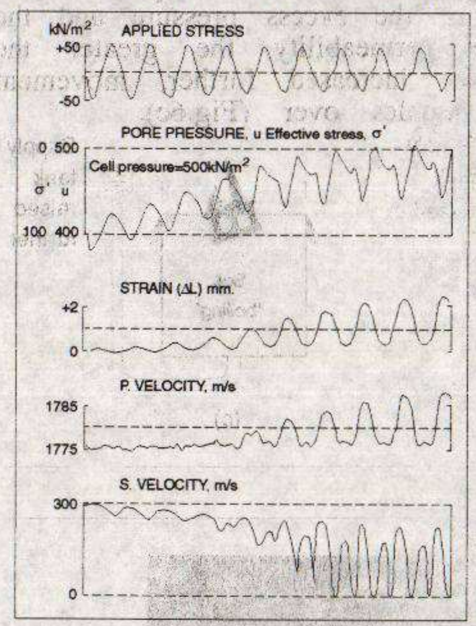

Fig. 8

3.1 Permeability measurement

Permeability can be measured in the laboratory by a variety of techniques many of which use flow/excess pore pressure methods, similar to the simple demonstration shown in Fig.6, but with some using more sophisticated apparatus, such as triaxial equipment where the cell can have its ambient pressure surrounding the sediment sample varied as well as the axially-directed pressure and the fluid pressure in the pore waters. Another laboratory method uses the consolidation experiment, carried out in the oedometer to obtain a value for the permeability in the sample. All of these methods are described in any standard text-book on soil mechanics (e.g Lambe & Whitman [6]) and will not be discussed further here except to use the results from such analyses to compare them to *in situ* data.

In situ tests depend very much on the volume of ground over which the water flow pattern is required. Thus large volumes can be examined using pumping tests where a central well is pumped out at a constant rate and the drawdown of the water table is measured in observation wells some distance from the pumped well. With some knowledge of the geology of the site it is possible from the obtained data to calculate permeability. However this technique is expensive and gives an average volume function for the permeability; it is of limited value in examining permeable properties near to an interface or where the water table is very near to that interface. For those conditions piezometers and permeameters may be used; Hurley & Schultheiss [7] describe a method to obtain permeability on the sea floor by measuring tidally-induced pore pressures in the sediment. Chandler *et al* [8] have carried out an interesting experiment in the London Clay at Bradwell in Essex where the results from a self-boring permeameter are compared to those from conventional borehole piezometer methods and to laboratory determinations of permeability from samples (Fig.9a). The data show that not only does the permeability decrease with depth, as might be expected in this overconsolidated clay, but also that there are directional properties and several orders of magnitude difference between the various methods of measurement. It is also interesting to compare the depth variations with the seismic shear wave velocity gradients collected by Davis [9] for the same site which illustrate also the anisotropic structure of the clay (Fig.9b). Is there also a geophysical model of permeability similar to that shown for consolidation earlier?

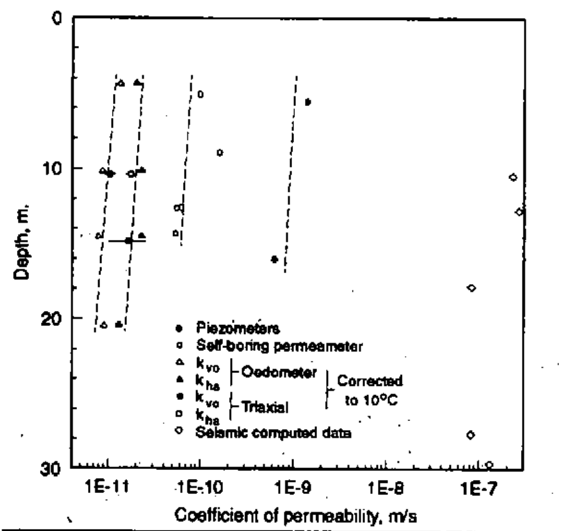

Fig. 9a

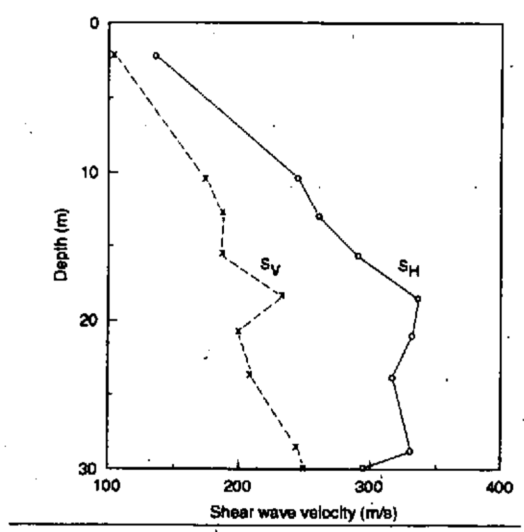

Fig. 9b

3.2 The search for a geophysical permeability model

The geotechnical literature abounds in empirical relationships between material properties and permeability. Some of these equate permeability to grain size, others to porosity or void ratio, some to combinations of grain size, pore space and its tortuosity, and so on. Perhaps the most successful has been the Kozeny-Carman equation based on the capillaric equation of Poiseuille, modifying it to account for the increased path length, or tortuosity of the flow path compared to the length of the sample:

$$k = \{D^2 n^3 . \gamma C\}/\{\mu (1 - n)^2\}$$

where k = permeability coefficient in velocity units
D = harmonic mean grain diameter
n = fractional porosity
γ = unit weight of fluid
C = grain shape tortuosity factor
μ = fluid viscosity

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As some geophysical parameters, particularly the compressional wave velocity and electrical formation factor, seem to vary with the material properties indicated above, many attempts have been made to develop empirical equations. The syllogism goes thus: *all deep-sea sediments have low permeabilities; all deep-sea sediments have low seismic velocities; hence all low permeabilities have low velocities.* But this is a nonsense as is seen by Fig.9. However graphs of the sort shown in Fig.10 do exist and serve a useful, though limited purpose. Clearly there is a need to produce a geophysical porous medium model.

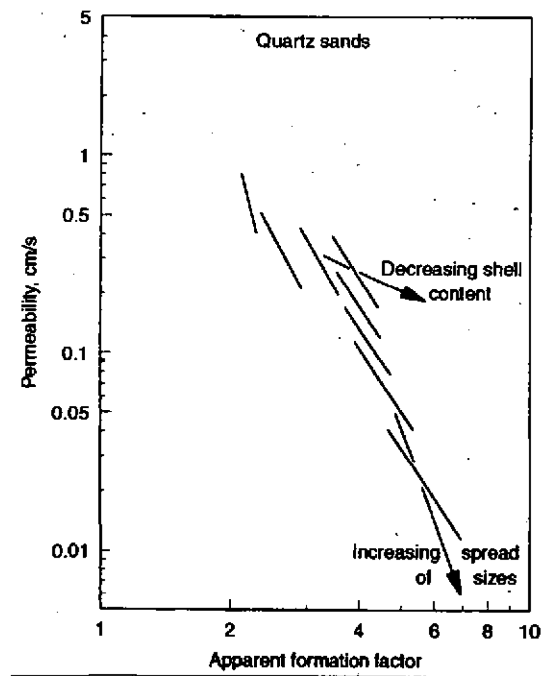

Fig. 10 : Lovell & Ogden [14]

3.2.1 The Biot model. What seems to be the most suitable model, to study both the consolidation history and elastic wave propagation through a marine sediment, is that established by Biot in a series of classical papers from 1941 onwards (e.g.[10]). The model is considered as a two component medium composed of a compressible skeletal frame which has shear stiffness and interconnected pore spaces, these being filled with a compressible fluid. In propagating seismic energy through such a medium there will be energy losses which are

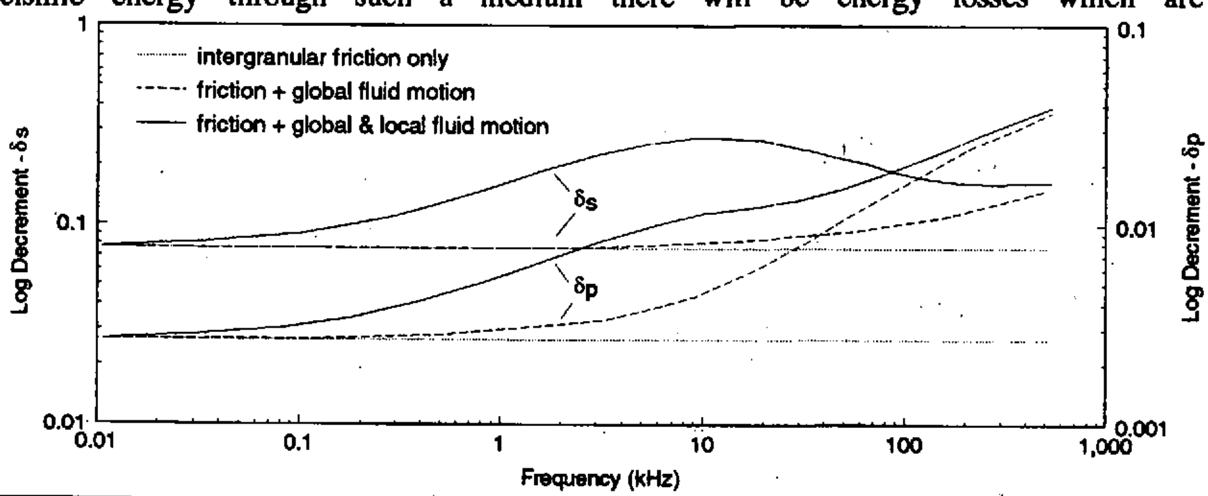

Fig. 11 : Stoll [11]

related to intergranular friction, to relative motion between fluid and frame, and to "local" fluid motion associated with the changes in the pore spaces during straining (Stoll [11]). The frequency range over which the

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second, viscous losses are important size and the fabric of the medium.

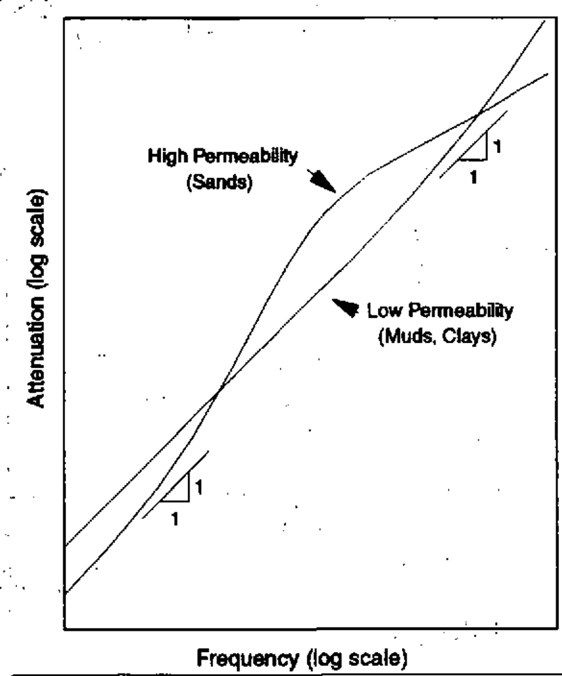

Fig. 12 : Stoll [12]

depend upon the permeability, grain In coarse granular material such as sands viscous damping can dominate the overall energy loss at very low frequencies, whereas very high frequencies are needed before this is the main cause of attenuation in fine sediments such as clays. The overall situation is probably best seen in two diagrams (Figs.11 and 12) from publications of Stoll ([11] and [12] respectively). Clearly the impediment to "local" flow in sands, caused by an increase in clay content, can have a profound effect on attenuation [13].

With these considerations in mind Biot produced two pairs of coupled partial differential equations, one pair describing the response of dilatational (compressional) waves and the other shear waves. Unfortunately the Biot model requires knowledge of 13 or more parameters to effect solutions. While some of these parameters can be obtained from standard tables, many require measurements of the seismic velocities and attenuations over a wide range of frequencies; equipment for so doing has only recently become available. Lovell & Ogden [14], using a modified Biot model (after Geertsma & Smit [15]) and an acoustically/electrically-instrumented oedometer, examined a range of marine clays from various sites and compared permeabilities derived from the consolidation experiment with those obtained from the geophysical model (Fig.13). Hurley [16] has applied a range of permeability measuring procedures (grain size, direct flow, consolidation, tidally-induced model and the Biot model) on various deep-sea sediments; the results of those for a North Atlantic turbidite are shown in Fig.14. Using data from Davis [9] it is possible to compare the geophysical model to other London Clay data for the same site (Fig.9). Without exception the geophysical (Biot) model produces permeability values for fine sediments which can be several orders of magnitude higher than those measured conventionally. However, for sandy sediments where the viscous attenuation peak is relatively low, Turgut & Yamamoto [17] obtain predicted permeability values which are almost identical to those obtained by direct flow. Clearly, for a sensible geophysical prediction of *in situ* permeability it is essential that observations are taken over a wide range of frequencies which for clays must require very precise measurements of velocity and attenuation well into the MHz range. Unfortunately, in the real world, much of the structure of

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sea-floor sediments is disturbed by the burrowing activities of benthic organisms: Richardson *et al* [18], Meadows & Tait [19], Jones & Jago [20] all indicate that changes in permeability occur, although in some instances burrowing increased permeability while in others a reduction occurred.

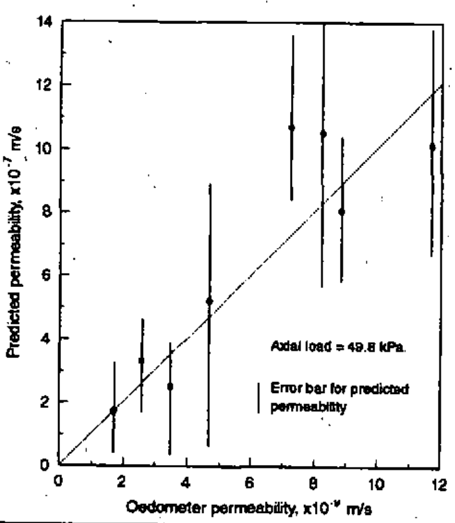

Fig. 13 : Lovell & Ogden [14]

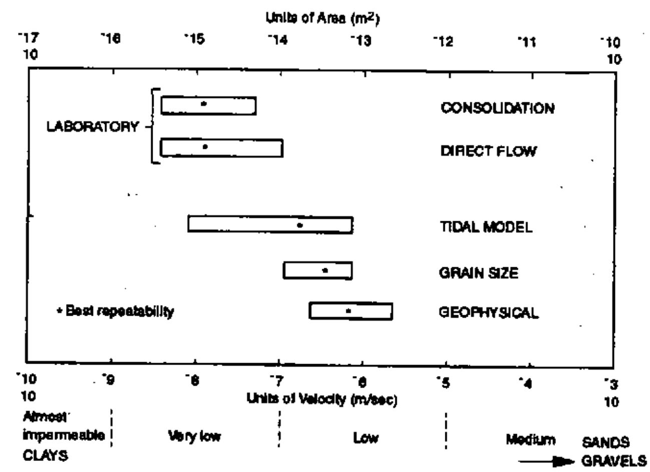

Fig. 14 : Hurley [16]

Quite obviously these effects, and their recognition, must be taken into account in any classification procedures for the seabed.

4. SHEAR WAVES

Seismic shear waves provide essential input data for the Biot model in the prediction of permeability. But the shear wave is more than that: it is a predictive property in its own right. The shear wave velocity, unlike the compressional wave which is a function of the properties of the phases in the porous medium and particularly susceptible to a replacement of pore liquid by gas, is determined largely by the stiffness of the solid skeleton (Fig.15) and the effective stress (Fig.8). The shear wave's polarisation phenomenon (into a horizontally-vibrating wave SH and into one, SV, whose vibrations are in the vertical plane) has considerable advantages in assessing any anisotropy in the foundation material (Fig.9b). The intimate relationships

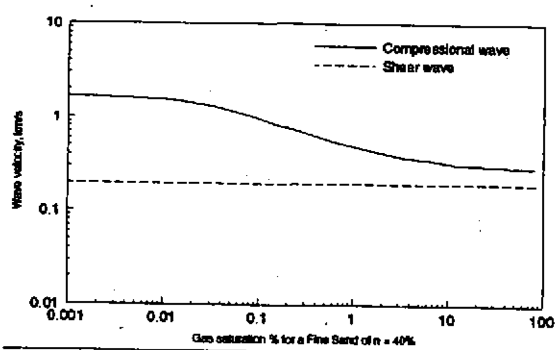

Fig. 15

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which exist between the shear wave velocity and the frame bonding of a sediment structure has already been referred to in the study of liquefaction conditions created by cyclic loading, a build up of pore pressure and a consequent reduction in effective stress until the sediment loses its resistance to shear and the seismic wave disappears (Fig.8).

Manifestly, the shear wave velocity is an extremely important sediment property: it is a function of the sediment texture and the biological controls of that texture; it can provide a value for the rigidity modulus from the product of density and the square of velocity; it has considerable directional sensitivity, indicating anisotropic conditions; and it disappears on the onset of liquefaction, of considerable value in sea floor strength monitoring and in earthquake areas. Its use as a standard survey tool also should not be underestimated, particularly in problem overburden areas (Davis & Bennell [21]). While such measurements are relatively easily carried out on land, and have been used in most of the British nuclear power station site investigations, their application to the sea floor is difficult. However various techniques are in the research and development stage (Hovem *et al* [5]); some will be referred to elsewhere in this volume.

The use of seismically-derived elastic parameters in foundation design still has certain difficulties to overcome in the engineering prediction game; most of these relate to strain level and strain rate, although relatively recently designers of large structures are moving towards lower foundation strain levels in their calculations. However the seismic strain amplitude is at least 2 orders of magnitude lower than those normally encountered in

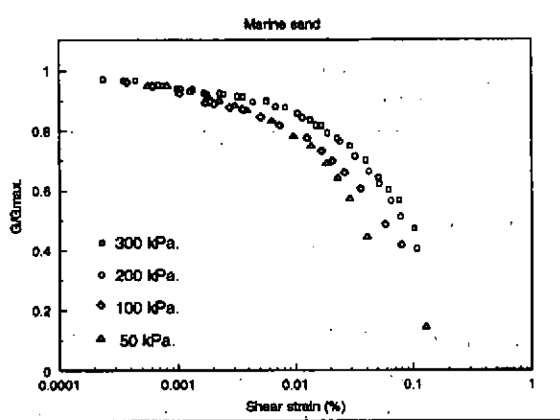

Fig. 16

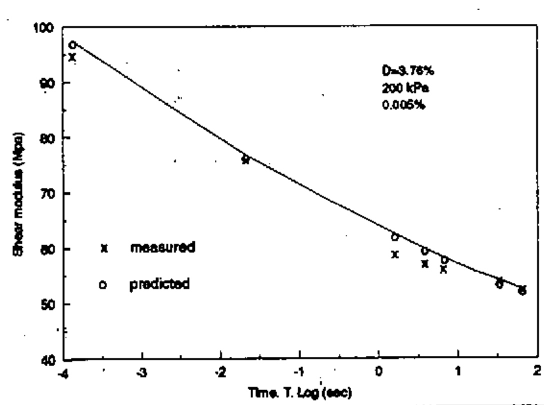

Fig. 17

traditional engineering tests and, of course, the rate of straining is very much higher. Corrections can be applied to the *in situ* data through the use of the resonant column provided that a representative sample of the seabed sediment is obtained.

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4.1 The resonant column

In the resonant column test a vertical cylindrical sample of the foundation material is contained within a rubber membrane to which a confining pressure is applied. The cylinder is either excited longitudinally or torsionally in one of its normal modes, and the wave velocity determined from the frequency at resonance and from the dimensions of the specimen. The resonant column is essentially a viscously-damped, single-degree-of-freedom, forced vibration system. The damping ratio D, which can be related to the quality factor Q or the attenuation, can be determined from the steady state magnification factor at resonance, or the width of the resonant response curve, or the logarithic decay of frec vibrations. After various corrections, which need not be gone into here (see Bennell & Taylor Smith [22]), the output of the apparatus consists of sediment Young's modulus E and rigidity modulus at various strain amplitudes (e.g. Fig.16). With a

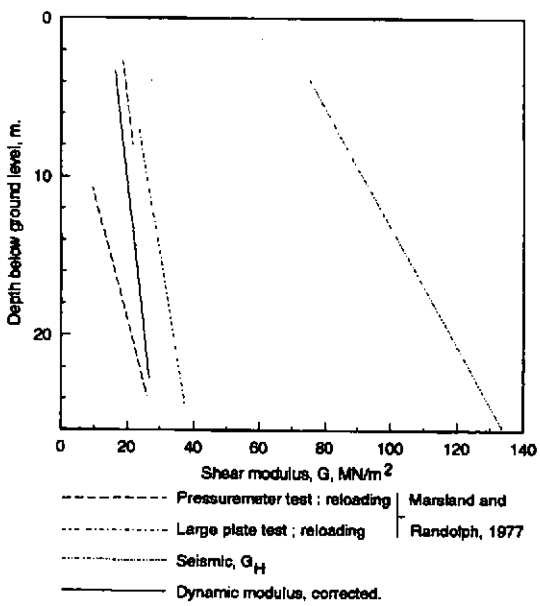

Fig. 18

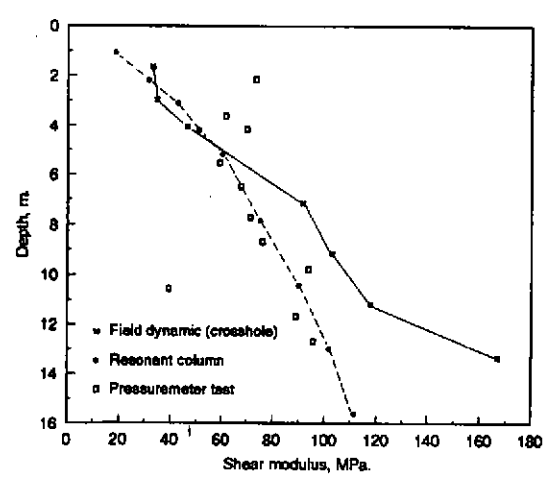

Fig. 19

knowledge of the damping ratio D, the modulus derived from a seismic observation G_1, with a time period T_1 of about 0.02 seconds, can be corrected to a static modulus G_2, with a time T_2 of (say) about 20 minutes, through the visco-elastic relationship

$$G_2 = G_1[T_1/T_2]^{4D/\pi}$$

The variation of the modulus in question with time of application can equally be obtained by making observations at various frequencies (seismic > resonance > static); an example of such a variation is shown in Fig.17 for an effective stress of 200kPa and a shear strain amplitude of 0.005% with a curve predicted for a damping ratio of almost 4%. The correction for the same London Clay site indicated in Fig.9 is shown in Fig.18: the seismically-derived horizontal shear modulus (GH), and its value corrected through the use of the above formula, is compared to London Clay moduli obtained by conventional means (Davis [9]). A prediction of the variation in shear modulus with depth for a sandy beach site, using a surface sample only, is compared to actual pressuremeter testing and data from shear wave crosshole observations in Fig.19 (Bennell *et al* [24]).

5. CONCLUSIONS

Clearly it is now possible, by the collection of good seismo-acoustic and electrical resistivity data, to predict many of the properties of the sea floor at the strain levels and rates required by the design engineer. Such predictions should be used, along with all the other predicting procedures, in any comprehensive assessment of the sea floor as a stable foundation. The geophysical information also has the additional advantage that it can map variations from place to place at the investigated site, such as the change in properties caused by burrowing organisms, or the deterioration in properties which could lead to failure such as liquefaction. However, the most important property, permeability, still eludes a comprehensive definitive determination; all efforts to draw up procedures for classification of the sea floor must give the prediction of this property a very high priority.

6. REFERENCES

[1] D A Ardus (ed), *Offshore Site Investigation*, Graham & Trotman (1980)

[2] O C Zienkiewicz, 'Predictions in civil engineering', *University of Wales Review (Science & Technology)* (1987).

[3] R D Barker & P F Worthington,'Some hydrogeophysical properties of the Bunter sandstone of NW England', *Geoexploration*, 11 p157-170 (1973).

[4] D Windle & C P Wroth,'In-situ measurement of the properties of stiff clays with self-boring instrument', *Proc 9th Int Conf Soil Mech and Found Engg*, Tokyo (1977).

[5] J M Hovem, M D Richardson & R D Stoll (eds), *Shear Waves in Marine Sediments*, Kluwer Academic (1990).

[6] T W Lambe & R V Whitman, *Soil Mechanics*, Wiley (1969).

[7] M T Hurley & P J Schultheiss, 'Sea-bed shear moduli from measurements of tidally-induced pore pressures', in [7] p411-418 (1990).

[8] R J Chandler, S Leroueil & N A Trenter, 'Measurements of the permeability of London Clay using a self-boring permeameter', *Geotechnique,* 40 p113-124 (1990).

[9] A M Davis, 'Dynamic-static properties if sedimentary material', PhD thesis, University of Wales (1982).

PREDICTIONS

[10] M A Biot, 'Theory of propagation of elastic waves in a fluid-saturated solid', *Jour.acoust.Soc.Am.*, 28 p168-191 (1956).
[11] R D Stoll, *Sediment Acoustics*, Springer-Verlag (1989).
[12] R D Stoll, 'Shear waves in marine sediments-bridging the gap from theory to field applications', in [7] p3-12 (1990).
[13] T Klimentos & C McCann, 'Relationships among compressional wave attenuation, porosity, clay content, and permeability in sandstones', *Geophysics*, 55 p998-1014 (1990).
[14] M A Lovell & P Ogden, *Remote assessment of permeability/thermal diffusivity of consolidated clay sediments,* European Atomic Energy Community: EUR-series, Report No.EN 9206 (1983).
[15] T Geertsma & D C Smit,'Some aspects of elastic wave propagation in fluid saturated porous solids', *Geophysics*, 26 p169-181 (1961).
[16] M T Hurley, 'Application of Biot's theory to sea-bed sediments', PhD thesis, University of Wales (1989).
[17] A Turgut & T Yamamoto, 'Measurements of compressional wave and shear wave speeds, attenuation, permeability and porosity in marine sediments', in [7] p403-410 (1990).
[18] M D Richardson, D K Young & K B Briggs, 'Effects of hydrodynamic and biological processes on sediment geoacoustic properties in Long Island Sound, USA', *Mar.Geol.*, 52 p210-226 (1983).
[19] P S Meadows & T Tait, 'Modification of sediment permeability and shear strength by two burrowing invertebrates', *Mar.Biol.*, 101 p75-82 (1989).
[20] S E Jones & C F Jago,'In situ assessment of modification of sediment properties by burrowing invertebrates', *Mar.Biol.*, 112 (1992).
[21] A M Davis & J D Bennell, 'Resolving overburden characteristics via shear wave propagation', *Bull.Aus.Soc.Expl.Geophys.*, 19 p41-44 (1988).
[22] J D Bennell & D Taylor Smith, 'A review of laboratory shear wave techniques and attenuation measurements with particular reference to the resonant column', in [7] p83-94 (1990).
[23] A Marsland & M F Randolph, 'Comparison of results from pressuremeter tests and large in situ plate tests in London Clay', *Geotechnique*, 27 p217-243 (1977).
[24] J D Bennell, D Taylor Smith & A M Davis, 'Resonant column testing of sediments', *Proc.Oceanology Internl.* OI 1.9/1-24p (1984).