PORE PRESSURE MEASUREMENTS IN A SEA-BED CONTAINING GAS BUBBLES

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1. Introduction

An understanding of soil behaviour as a foundation and building material has developed both from experience and from experimental and theoretical studies. In the majority of applications, the soil is fully saturated, so that the pore fluid is water, which may be taken to be incompressible by comparison with the soil structure. However, there are situations where the soil contains undissolved gas bubbles which will have a fundamental effect on the soil response to load. The pore fluid is now a mixture of gas and water, and is therefore compressible, so that the undrained response to a load increment no longer occurs under conditions of no volume change. The initial distribution of total load between the soil structure and the pore fluid will be different from the fully saturated case, with particular importance in the case of dynamic loading. This physical situation is encountered comparatively frequently in the sea-bed where tiny gas bubbles, usually methane, are found in the surface sediments, either due to percolation upwards from gas pockets under pressure or to bacterial action. The engineering properties of the sea-bed are relevant to the construction of marine structures such as oil rigs, using traditional piles, tension piles or gravity foundations, and coastal developments, such as harbour walls, and land reclamation.

Indications of the presence of gas bubbles in the sea-bed can be obtained in a number of ways. In seismic profiling, an acoustic signal is reflected from acoustic interfaces within the bed, normally associated with density changes in the sediment. However, the presence of gas

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bubbles will also cause a change in the acoustic impedance, with the additional effect of a phase change in the reflected signal. Thus, analysis of seismic profiling records, using different frequencies to obtain different penetration, can identify the occurrence of gas. Other indications include the expansion of cores on recovery followed by the need to apply to a soil sample in the laboratory a confining pressure higher than the in-situ hydrostatic value in order to obtain an incompressible response to a load. Gas bubbles occur very often in soft sediments, but they may also be found in stiffer soils — as, for example, associated with the pockmarks in the North Sea. Major areas of soft sediment in which undissolved gas has been identified include the Gulf of Mexico, the Irish Sea and coastal regions such as the Bristol Channel.

Assessment of the in-situ volume of gas bubbles is difficult, and can normally only be achieved by indirect methods, such as analysis of cores in the laboratory. However, the stress release during the retrieval of a core causes bubble volumes to change, and gas to come out of solution, producing changes which are unlikely to be reversible. Interpretation of results from such cores is made more complicated by effects such as the dependence of methane solubility on the soil itself. Esrig and Kirby (1977), for example quote measurements by Whelan and Roberts (1976) of reduced solubility of methane in the Gulf of Mexico silty clays by comparison with water. An indirect measurement of the significance of gas can be related to the compressibility that it causes, and this can be studied in situ, provided that a suitable total stress increment is available. This paper describes the results of some measurements undertaken in two specific field situations to discover the possible magnitudes of the effect of gas bubbles in the sea-bed.
2. The Experiment

a) Conditions

A total stress change is required in conditions under which the fully saturated response can be predicted accurately. If the actual response in a soil containing gas bubbles is measured, then any difference from the fully saturated prediction may be attributable to the presence of gas. A suitable field condition, therefore, is a changing water depth due to tides. If the sea-bed contains no gas, then the pore pressure measured at some depth in the bed will always be equal to the hydrostatic pressure at that point. Thus the pore pressure and tidal changes are equal, and the effective stress remains unaltered. The situation approximates closely to a one-dimensional condition, since the lateral variation of total pressure is comparatively small, owing to the long wavelength of the tidal change. This is, of course, in contrast to the pressure changes caused by waves. The presence of gas bubbles will have the effect of making the pore fluid compressible, so that as the water depth (total pressure) changes, the pore pressure in the bed changes also, but the amplitude of the pore pressure cycle is reduced and some of the total pressure change is carried by the effective stress. Since the effective stresses now change during the tidal cycle, strains will occur in the soil and the surface of the bed will rise and fall as the bubble volumes change. Both the pore pressure and the effective stresses are influenced by the presence of gas bubbles.

b) Measurements.

Figure 1a shows an idealized, sinusoidal tidal cycle, represented by the solid line. The broken line indicates a possible pore pressure response in a sea-bed containing undissolved gas bubbles, with the
difference between these two measurements giving an indication of the
compressibility of the system. The actual response will be determined by
the compressibility of the soil as well as the volume of gas bubbles,
since the applied total stress of the tide must be shared between the
solid and water phases of the soil in such a way that the volume change
experienced by the gas bubbles equals the strains induced in the soil by
effective stress changes. The behaviour of the gas is governed by
Boyle's law, where \( pv = \) constant, \( p \) being the absolute pressure and \( v \) the
volume where, for simplicity of argument, the change in gas volume in
solution is neglected. The gas volumes at different points in the tidal
cycle are therefore related in proportion to the ratio of their absolute
pressures, not the pressure increments, so that the volume change between
mid-tide and high water is different from the volume change between
mid-tide and low water. This will in general correspond to an effective
stress change around high water that is different from the effective
stress change around low water.

There will also be a permeability effect in the pore pressure
response. Since the pore pressure response is reduced by the presence of
gas, a hydraulic gradient is set up through the sea-bed. This could then
cause a small lag \( \alpha \) in the pore pressure curve as water flow occurs
through the bed.

Maximum sensitivity of pore pressure measurement is obtained by a
direct differential measurement of the excess pore pressure above the
hydrostatic. This is shown in fig. 1b, which is the difference between
the two curves in fig. 1a. It also represents the variation in effective
stress. If no gas bubbles existed in the soil, both the differential
pore pressure, and the effective stress would be zero. The lag \( \alpha \) has
become a lag in the differential curve of \( (\pi-\beta) \) relative to the tidal
curve.

In order to measure directly the differential pore pressure, a suitable piezometer was designed and constructed, and is described later.

If the relationship between effective stress and strain or void ratio can be determined for the soil, this can be used, together with the piezometer output and the hydrostatic pressure, measured at the sea-bed surface, to estimate the in-situ gas volumes as follows. The total vertical in-situ effective stress is obtained using a nuclear densimeter, or by estimate. Since the differential pore pressure is a measure of the effective stress change occurring during a tidal cycle, the extreme values of the effective stress at the position of the piezometer transducer can be calculated. If a core is taken, and a stress-strain curve obtained from an oedometer test at the appropriate mean stress level, the volume change associated with this effective stress change can be calculated, and is equal to a change in gas volume between high and low water. The applications of Boyle’s law gives the second relationship between the gas volumes as high and low water, thus allowing their determination. This method of estimating gas content is not very precise, mainly due to the difficulties of determining accurately the stress-strain parameters, but is likely to be as reliable as a direct examination of a core, in which decompression losses will have occurred.

c) Choice of field site.

The main specifications for the field measurement are a sea-bed containing gas bubbles, and a sufficient tidal range. One-dimensional conditions could be difficult to achieve near a structure founded on the sea-bed, so that there is considerable advantage in the use of a ship to deploy the instruments. The penetration of the instruments to an
acceptable depth is more easily achieved in a soft sediment than a stiff soil, and these various considerations led to the choice of two sites: Bridgewater Bay in the Severn Estuary in September 1978 and Holyhead Harbour, Anglesey, in September 1979.

3. The differential piezometer

Figure 2 shows a schematic representation of the differential piezometer. The transducer consists of a strain gauged beryllium-copper diaphragm, with the sea-bed pore pressure acting directly on the front face, through a porous element, while the hydrostatic pressure acts on the back face, being transmitted from the sea-bed surface, via an oil/water interchange through an oil reservoir inside the body of the stainless steel piezometer. Two transducers are mounted in the single instrument, with one near the tip and the other a distance of 1.7m from it. The 65mm diameter tip had been designed and built at the Building Research Station, who also provided the two transducers. The instrument was constructed of stainless steel throughout.

Two different forms of the oil/water interface have been used. In the first there was continuous large bore connection between oil and water inside the instrument, so that the response on the back face of the diaphragm was very fast, but included short period wave effects. Later, an air space was introduced, so that a change in external pressure would cause flow through a porous stone into the interior of the instrument, as shown in fig. 2, thus damping the short transients in the reference hydrostatic pressure.
A certain amount of signal conditioning was located at the top of the piezometer, to amplify the output signals and reduce the number of conductors required. Thus six-core cable was sufficient to provide power and return the output from both transducers and a simple inclinometer (to provide a warning should the piezometer inclination exceed 12 degrees from the vertical).

The accuracy and stability of the transducers, supplied by CEL Transducers Ltd., were quite acceptable. The range, at $+150\text{kN/m}^2$, was higher than required by the differential measurements, but allowed a vacuum to be drawn during de-airing. The calibration remained stable both with time, and with temperature variation, giving an overall accuracy of pressure measurement better than $\pm 0.2\text{kN/m}^2$ ($\pm 20$ mm head of water), over the range 0-20kN/m$^2$. The level of output from the piezometer with 100m of cable was typically 14mV/kN/m$^2$.

A standard preparation technique was followed before the use of the piezometer. After assembly, with vacuum checks for tightness of the seals between sections, the instrument was filled with Diala B oil. The transducers were connected and switched on for a minimum of two hours, at the end of which a calibration was carried out, using pressure chambers designed to fit over the piezometer, isolating each transducer in turn. The calibration check was repeated after recovery of the instrument. The zero reading, corresponding to zero excess pore pressure, was obtained at both the beginning and end of the instrument deployment while the piezometer was held in the sea-water above the bed. The piezometer was de-aired before use with particular care, since air in the porous elements or the chamber in front of the diaphragm would produce a similar effect to that due to gas bubbles in the sea-bed. A latex membrane was placed over the porous element, with rubber bands or O-rings placed well
above and below the porous section to seal the membrane. The transducer chamber was evacuated through a pressure fitting in the membrane connected to a vacuum pump. Water was then drawn into the chamber as the vacuum was released. This process was repeated until no further air bubbles were drawn through the reservoir of water on evacuating the system. The membrane was adjusted sufficiently to allow the pressure fitting to be moved away from the porous element, and an additional sealing band was placed between the two. The pressure fitting was then removed, and the membrane remained in place until it was eventually pushed off the porous element by the penetration of the piezometer into the sea-bed.

The method of installation of the piezometer depends on the lifting facilities available on the ship and on the resistance of the sea-bed. At both sites, the sea-bed was soft, and full penetration was achieved under gravity, with the addition of extra lead weights. On the first occasion a vibrocorer rig was available for use. The rig folded for transport, and when erect, had the shape of an inverted tee, with the base spreading the load sufficiently to prevent the system sinking into the soft sediment. The differential piezometer was mounted on a weighted sliding frame on the upright section. A year later, with unsufficient room on the R.V. Prince Madog to deploy the rig, the piezometer was used freely suspended on a lifting wire with lead weights mounted on a chassis at the top of the instrument. These two deployment techniques are shown in figs. 3 and 4.
4. **Measurements in Bridgwater Bay**

a) Site

During a detailed study of the Bristol Channel in SW England by the Institute of Oceanographic Sciences, Taunton, seismic profiling records were taken which indicated the presence of undissolved gas in the sea-bed. The gas appears to be methane which is biogenic in origin. It is generated by bacterial action in anaerobic conditions, and normally occurs below the top couple of metres of sea-bed sediment. The tidal range in the Bristol Channel has a maximum at spring tides of about 14m, and a suitable location was found with a minimum depth of water of 7m. The approximate position is indicated in Fig. 5.

A core taken from this site showed a soft clayey silt with occasional silt and fine sand partings. The shear strength was of the order of 10kN/m².

b) Facilities

It was anticipated that piezometer readings would be required for a number of tidal cycles to allow driving pressures to dissipate, and during this time a ship would be required to hold a stable position near the instrument. The large tidal range in the Bristol Channel is associated with strong currents, so that a good fore and aft anchoring capability was essential. The Gardline Locater is 52m long, gross tonnage 698 tons and has four high holding power anchors in addition to the normal ship's anchor, and proved to be eminently suitable during a
joint charter with I.O.S. (Taunton). Fig. 6 shows a photograph in which all five of her anchors can be seen to be deployed.

The piezometer was mounted on a sliding rig as already described, with, in addition, two pressure transducers for depth measurement and an inclinometer to record the rig inclination. The depth sensors gave an accuracy of measurement of a few centimetres. These facilities were lent by I.O.S. (Taunton). Two total pressure piezometers were also deployed, one a Geonor vibrating wire instrument on loan from the Building Research Station and the other manufactured and lent by Soil Instruments Ltd. The three piezometers can be seen mounted on the rig in fig. 3, with the Oxford instrument in the centre and the others at the ends of the slider just outside the main legs of the rig. Measurement of depth was also made with the ship's echosounder, and two cores were taken with the I.O.S. gravity corer.

The instrument signals were recorded in three different ways. Each analogue signal was recorded on a chart recorder and on an f.m. tape recorder and readings were noted manually from a digital volt meter at intervals ranging from five to fifteen minutes. Exceptions were the echosounder reading and the Soil Instruments piezometer, both of which were only read manually.

The rig was lowered to the sea-bed and the piezometers penetrated without difficulty. The two depth sensors, one on the slider and one on the main body of the rig, indicated that full penetration had been achieved, and this was confirmed by clear mud marks at the top of the piezometers after recovery.
c) Results

The results are presented in fig. 7, 8 and 9, and will be further discussed in the next section.

Two consecutive sets of measurements were made at adjacent sites, with the rig lifted from the sea-bed but held beneath the water surface to prevent air entering the piezometers while the ship's position was adjusted on her anchors. Both depth sensors were damaged during this move, but none of the other instruments were affected. Fig. 7 shows the pressure variation acting on the sea-bed, for the second experiment, using the ship's echosounder. The reliability of measurement was probably of the order of 20 cm of water. The total pore pressure measurements obtained with the Geonor and Soil Instruments probes are also shown in this figure. The hydrostatic pressures at the levels of the transducers are obtained by adding to the sea bed pressure a head of water appropriate to the penetration i.e. about 32 kN/m². As expected, the total pore pressure measurements are not very informative. A slight amplitude reduction appears to have occurred but, taken alone, this would not be conclusive. The differential results are more useful, and are shown in figs. 8 (experiment 1) and 9 (experiment 2). Fig. 8 shows the behaviour that would be expected for a basically fully saturated soil, with both transducers behaving similarly, and showing very low differential pressures. The high values of differential pressure seen at about 1600 hours on 17th September, 1978, briefly on the lower transducer, and for about two hours on the upper transducer, are somewhat surprising. They may be due to too great a tension on the lifting wire to the piezometer rig: the tide was rising fast at the time and the operator's log notes both at 1600 hours and at 1800 hours that the lifting wire had become very taut, and required slackening. After this
occurrence, a check was made on the lifting wire and cable every twenty
minutes: on a rising tide, slack was paid out as necessary and taken in
on a falling tide. Too much slack cable in a fast current can cause
fouling problems. Isolated high values of differential pore pressure did
not occur again. Fig. 9 shows the readings for experiment 2, located
about 40m from the site of experiment 1. The lower transducer is at a
penetration of 3.2m into the sea-bed, with the upper one 1.5m below the
sea-bed surface. Both transducers show some initial driving pressures,
which appear to dissipate quickly. The upper one then approaches a
uniform zero output, indicative of little or no gas, while the lower
transducer exhibits the sinusoidal variation to be expected from a gassy
sea-bed. The amplitude of this variation is of the order of 9 kN/m², or
0.9m head of water, around 7% of the total stress change of about 120
kN/m², or 12m head of water.

d) Discussion of results

The seismic profile records obtained in Bridgwater Bay showed that a
highly reflective interface with a signal phase change indicative of gas
bubbles occurred at a depth of about 2m into the sea-bed. This therefore
confirms the differential piezometer interpretation that the sea-bed is
virtually fully saturated at the level of the upper transducer (1.5m),
and contains undissolved gas at the lower level of 3.2m. A calculation
of gas content by the method outlined earlier (again neglecting changes
in dissolved gas content) gives an estimate of 2-3% by volume of the pore
space at 3.2m penetration, so that, even at the deeper level, the gas
content is not very high.
One curious feature of these measurements is the relative position of the stationary values of the differential measurement, by comparison with those of the tide. Referring again to fig. 1, a lag $\alpha$ might be expected in the total pore pressure curve relative to the tide, and this would be translated into a lag $(\pi - \beta)$ in the differential curve. Assuming that $\alpha$ is comparatively small, this means in practice that a minimum on the excess pore pressure curve should occur just before the maximum on the tidal curve. However, the field measurements indicate that the differential pore pressure minimum occurs half an hour after the tide maximum.

The magnitude of the lag $\beta$ would be expected to be dependent upon the permeability and compressibility of the soil. However a theoretical analysis, undertaken by S. Nageswaran at Oxford suggests that the effect observed here could be at least partly due to the presence of gas bubbles in the porous stone of the piezometer. The stone is a rigid framework, containing a compressible fluid, and this combination can be shown to cause very large phase changes. Another possibility is that the observed phase change may be due in some way to rate effects. Thus, the idealized pore pressure response postulated in fig. 1 suggested that the only effect of flow in the sea-bed would be to produce a lag without modifying the shape of the curve. In fact, since the pore pressure gradient changes continuously through a cycle, the change in pore pressure at any instant due to the flow (as distinct from the change due to the tide) will vary even with a constant permeability. It is possible that the pore pressure value may depend both on the pore pressure gradient and on the rate of change of gradient. This would make it difficult to anticipate accurately the pore pressure response. The effect is magnified in the differential curve: if the hydrostatic head and the differential pore pressure are added to give the total pore pressure,
this appears to lead the tide by only a few minutes. The existence of the expected pore pressure lag cannot be confirmed or disproved by the total pore pressure piezometers as the accuracy of measurement is inadequate.

The lower transducer is showing a mean value slightly above zero, which is a feature that might be expected with a gassy soil, as indicated earlier.

5. Measurements in Holyhead Harbour

a) Site

The choice of Holyhead harbour, on Anglesey off the coast of N. Wales, was dictated by bad weather conditions. A core showed a uniform soft clayey silt with water depth ranging from about 11m at low water to 14.5m at high tide. The location is indicated in Fig. 10.

b) Facilities

Four berths on the R.V. Prince Madog, belonging to the University College of North Wales at Bangor, were made available by the Institute of Geological Sciences, London. The piezometer was deployed on its own, with the addition of a depth sensor, as already described. An underwater television camera was used to confirm that full penetration had been achieved. The transducer signals were recorded in the same way as on the previous exercise.

c) Results

The results are presented in figs. 11 and 12. Fig. 11 shows the water pressure at the sea-bed surface and fig. 12 shows the differential piezometer output. The penetrations of the two transducers are
respectively 1.8m and 3.5m, and both show a cyclic variation of
differential pore pressure following the initial dissipation of driving
pressures. The amplitude of this variation is of the order of 0.45m head
of water, (4.5 kN/m$^2$) to be compared with a tidal amplitude of 3.5m of
water. (35 kN/m$^2$).

Another feature of this cyclic curve is that the mean excess pore
pressure appears to be significantly greater than zero, even making
allowances for the fact that driving pressures may not yet be fully
dissipated, and that some elevation of the mean was anticipated.

d) Discussion of results

The cyclic variation at 1.8m and 3.5m suggest that both transducers
are responding to the presence of gas bubbles. The effect is somewhat
larger than in Bridgwater Bay, since the total pore pressure response is
now 87% of the total stress change. A calculation of gas content
suggests that, at low water, the degree of saturation at 3.5m penetration
is about 0.97.

The differential curve is much less sinusoidal in character than
that measured at Bridgwater Bay, showing, in particular, flattened maxima
and minima.

The flattened minima can be predicted from the discussion earlier,
in section 2b, about the expected shape of the differential pore pressure
(or effective stress) response. The flattened maxima may well be a
consequence of some stress-strain characteristic of the sediment.

The flattened maxima and minima make it difficult to draw any
definite conclusions about the existence of a phase lag. However, there
is no suggestion of the phase lead that apparently occurred previously
and the last two cycles do suggest the possibility of a small lag.

The existence of a comparatively large positive mean excess pore pressure could have a number of explanations. The Boyle's law effect already described suggests only that positive and negative parts of the excess pore pressure will not be equal, but cannot explain the absence of a negative part. It may be due in part to the continued presence of driving pressures, or to the soft sediment being under consolidated, or in some way a consequence of the presence of gas. In the latter case, this pore pressure elevation may be real or at least partly an instrument effect. Laboratory measurements made at Oxford University after these field measurements, and to be reported in detail by Sills and Nageswaran, show that the design of the transducer housing can be critical in the measurement of pore pressures in gassy soils. Despite high air entry pressure values of the porous stones, gas quickly moves through the stone. If a narrow bore connection exists between the stone and the transducer, this can be blocked by a gas bubble which breaks the continuous pore water connection between the soil and the transducer. The recorded pressure then includes the effect of surface tension forces existing between the gas, the water and the soil particles, and is higher than the pore water pressure as a result. In the laboratory experiments, when the narrow bore was widened from 3mm to 10mm, then, although gas still entered, it did not hinder the measurement of pore water pressure. It is possible that the design of the differential piezometer, with passages of minimum diameter 3mm, could have allowed the inclusion of surface tension pressures.

High excess pore pressures have also been recorded in the gassy seabed soils of the Mississippi Delta and the Gulf of Mexico (for example, Dunlap et al, (1978), Bennett (1977), Hirst & Richards (1977)). It may
be that these could also be due in part to the piezometer design.

7. **General Conclusions**

It appears that the presence of gas bubbles in the sea-bed can have a real effect on the soil behaviour. The proportions of gas encountered in these field experiments were not high. There is evidence of similar and higher in-situ gas volumes in soft estuarine and coastal deposits in many areas, of which the Gulf of Mexico, the Mississippi Delta, Hong Kong, Nigeria, and the Orinoco River are only a few.

There are two major implications of these results, the first relating to the instantaneously compressible nature of gassy sea-bed soils, and the second to the strains and movements associated with total stress changes. In the analysis of sea-bed foundation stability, an elastic analysis can be used to determine the response of the soil to dynamic forces due to storm loading of the structure, or of the sea-bed itself. The normal assumption that this response occurs under conditions of no volume change for an incompressible material with a Poisson's ratio of 0.5 is not now tenable.

It is not clear at this stage whether the compressibility will have a beneficial or detrimental effect. In particular, since the present study has considered only the quasi-static pore pressure response, it gives no indication of how the cyclic pore pressure response might be different. The present differential piezometer is not appropriate for measurement of dynamic forces such as wave effects, since the back face of the diaphragm will be affected by pressures acting through the water column and it is not possible to isolate the sea-bed pore pressure response. A second differential piezometer has therefore been designed and built specifically for wave pressure measurements. The reference
pressure on the back face of the diaphragm can be allowed to vary with
the hydrostatic pressure, or can be fixed at an appropriate level. In
the latter mode, the transducers respond only to pore pressure changes in
the sea-bed (due to pressure changes at the surface of the sea-bed).
This instrument has a diameter of 35mm, smaller than the original one, so
that driving pressures are lower, and a more sensitive transducer,
ensuring accuracies of measurement of better than \(+0.03\text{ kN/m}^2\) to be
achieved.

It is known that sea-bed surface movements can become quite large
during storms, particularly in areas of soft silty clays. Estimates of
the magnitude of movements that would be possible before reaching failure
should take into account the presence of gas bubbles. One application of
these results that is very close to the field experimental conditions is
in the definition of navigable depth. Hydrographic surveys to measure
available water depth above soft gassy sediment (a common occurrence) may
lead to substantially different conclusions if undertaken at different
states of the tide. Thus, as the tide changes, the actual position of
the sea-bed surface will move also.

Gas bubbles occur in many underwater soils and commonly, although
not exclusively, in soft sediments. The field measurements reported here
give some indication of the compressibility that is associated with such
soils. They are sufficiently wide-spread to pose a real engineering
problem, and, despite the difficulties involved in making measurements,
both in the laboratory and in the field, there is a clear need for
further studies, with analysis and comparison of stress/strain behaviour
and strength properties. Until then, traditional approaches should be
used with care.
References


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The Oxford differential piezometer
Time (hours)

Excess pore pressure kN/m²

- Upper transducer (1.5 m penetration)
- Lower transducer (3.2 m penetration)

Bridgeport Bay Experiment 2