CHAPTER 322

PRESSURE GRADIENTS WITHIN SEDIMENT BEDS.

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ABSTRACT

A new technique for measuring dynamic pressures and pressure gradients within sediments is developed. The pressure is measured with a series of small diameter steel probes connected to pressure transducers via semi-rigid tubing. The dynamic response of the system was evaluated and found to be satisfactory for typical laboratory wave frequencies. Comparisons with measurements of the pressure gradients obtained from conventional transducers show good agreement. The present technique is demonstrated with pressure measurements at the toe of breakwaters and across the surf zone of model beaches.

1) INTRODUCTION

Pressure gradients induced within sediment beds by surface gravity waves may have a significant influence on the transport of sediment and the stability of coastal structures. The pressure gradients may either be steady or transient. For example, the wave induced set-up of the water level at the shoreline will produce a steady flow within a beach (Longuet-Higgins, 1983). This may be increased by the percolation of swash through the upper part of the beach. Alternatively, transient pressure gradients may locally reduce the effective strength of the sediment, possibly temporarily fluidising the bed material (e.g Madsen, 1974; Yamamoto, 1978). This may lead to higher rates of sediment transport and reduce the stability of structures within the surf zone.

However, considerable uncertainty remains as to the effects of pressure gradients on sediment transport rates and previous work has provided conflicting

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results (Martin, 1970, Oldenziel and Brink, 1974). Loveless (1994) suggested that vertical wave induced pressure gradients were particularly important during toe scour and Conley and Inman (1992) suggested that bed ventilation could be an important aspect in scale modelling. Seepage within the beach may also be an important feature in both long term beach morphology (Turner, 1995) and short term (storm duration) beach evolution. This effect is highlighted by the performance of coastal drainage systems (e.g Vesterby, 1996; Sato et al, 1994). Nevertheless, the mechanism by which the watertable influences the beach dynamics is not immediately apparent. Sato et al (1994) suggest that the drain reduces offshore flows such as the undertow, in addition to increasing percolation into the upper beach, while Vesterby (1996) suggests that an increase in the beach stability and a reduction in wave induced liquefaction are the dominant factors. However, numerical calculations by Oh and Dean (1994) indicated that the pressure gradients induced by changes in the watertable within a beach were generally far to small to influence sediment stability.

Therefore, although the pressures within sediments have been measured by a number of authors (e.g. Sleath, 1970; Yamamoto et al, 1978), measurements of the pressure gradients will enhance the understanding of both sediment transport mechanisms and beach dynamics. The present study addresses this point and outlines the development of a flexible non-intrusive measurement technique. The method allows the pressure gradients at any position within the fluid or sediment bed to be determined quickly and easily, with minimum disturbance of the local flow field. The technique may also be used close to or under structures such as breakwaters, where it may be difficult to obtain results from conventional pressure transducers.

2) MEASUREMENT TECHNIQUE

Conventional pressure transducers have a number of disadvantages when attempting to measure pressure gradients. Firstly, they are relatively large and therefore when mounted close together may significantly disturb the local flow field. Secondly, a large number of transducers are needed to measure the pressure gradients at a number of points without repeatedly disturbing a sediment bed. Finally, the measurement position must be chosen *a priori* and cannot be changed readily. This is a significant drawback when measuring the pressure gradients within model beaches which evolve over time. For example, in order to measure the pressure gradients over either a bar, or at the toe of a beach, it would first be necessary to run a model test to predetermine the measurement positions.

The aim of the present study is to overcome these limitations and develop a measurement method that is as flexible as possible. The technique has been developed from a method used previously to investigate static pressures within model sand embankments. However, the method has not previously been used to measure either dynamic pressures or pressure gradients. The underlying principle is similar to that proposed by Nielsen et al (1994) and has also been used in medicine to measure blood and lumbar pressures (Kumar et al, 1993).

The pressures within the fluid or sediment are measured by means of a series of 2mm ID steel probes. Each probe is connected to a 0.1 Bar pressure transducer via a three way ball valve and short length of 3mm ID semi-rigid nylon tubing (figure 1). Air may be flushed from the tubing and probe by opening the valve to a small header reservoir mounted above the transducer/valve system. The pressure variation is transmitted into each probe through 12 0.4mm diameter holes drilled into the tip. In order to measure the pressure gradients, five probes are arranged in an array such that both the vertical and horizontal pressure gradients are obtained at a single point. The probes may be moved vertically within the bed by means of a traverse mechanism, with minimal disturbance of the sediment. The probe holder, pressure transducers and header tank are mounted on a carriage running on rails above the flume, which allows the probes to be positioned at any position within the sediment bed.

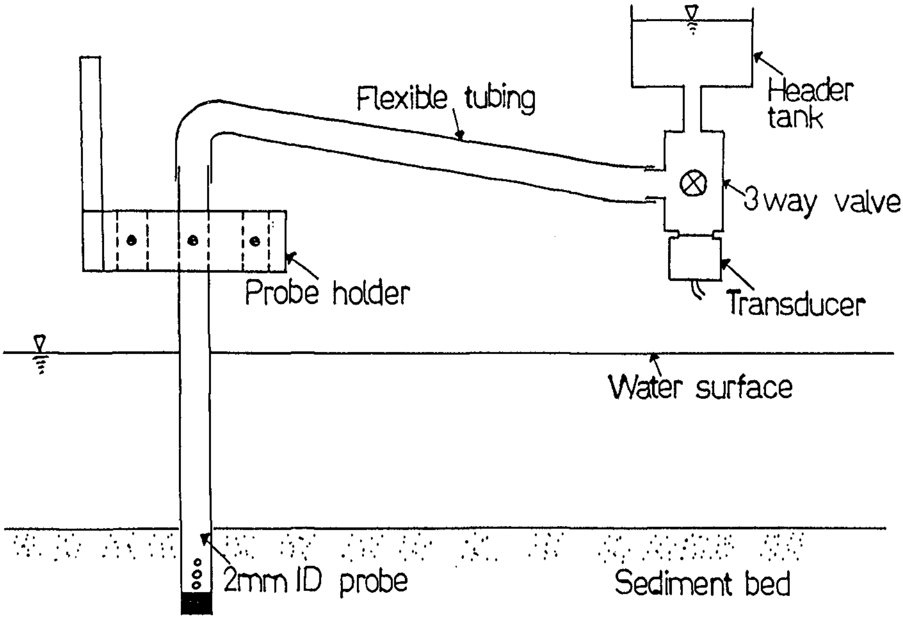

Figure 1. Pressure measurement system.

The static pressure recorded by the probes is the elevation head between the pressure transducers and the mean or still water level. This is generally negative and a variable offset was therefore added to the pressure transducer amplifiers. The "mean pressure" may therefore be set to zero, allowing amplification to be used when sampling the dynamic pressure. This increases the accuracy of the measurements, since the amplitude of the dynamic pressure may be considerably smaller than the static pressure in many practical circumstances. Note that moving the probes vertically does not change the recorded static pressure and that the probes do not measure a velocity head.

3) EVALUATION / CALIBRATION

For the purpose of measuring mean or steady pressure gradients the probe technique requires no calibration. However, for the purpose of measuring dynamic pressure gradients the dynamic response of the measurement system requires evaluation. The dynamic response depends on the length of the probe and tubing, the geometry of the valve/transducer connection and the speed of the pressure pulse. In order to achieve a satisfactory dynamic response the natural frequency of the system must be as high as possible. If it is assumed that the system behaves as a quarter length resonator (Nielsen et al, 1993) then the natural frequency, f_o, is given by

$$f_o = c / 4L \qquad \textbf{(1)}$$

where c is the speed of the pressure pulse and L the length of the probe and tubing. L is consequently kept as small as possible ($\langle$1m), while the speed of the pulse should be maximised. The pressure pulse is a one-dimensional wave, whose speed is dependent on the fluid density, ρ, the compressibility of the fluid, C, and the distensibility of the tubing, D (Lighthill, 1978).

$$c = \frac{1}{\sqrt{(\rho(C+D))}} \qquad \textbf{(2)}$$

The distensibility of the tubing is given by

$$D = 2a / tE \qquad \textbf{(3)}$$

where a is the tube radius, t is the wall thickness and E is the Young's modulus of the tube material (O~10^9 N/m^2). In the present instance D is of order 10^{-9}m^2/N and the compressibility of pure water is approximately 5.10^{-10}m^2/N, giving $c\approx$800m/s. However, the presence of small air bubbles within the tube will increase the compressibility of the water significantly. For example, an air content of 0.4% will give a compressibility of 5.10^{-8}m^2/N. Hence, from (2), a few small air bubbles (O~1mm) are sufficient to reduce c to about 150m/s. This results in a natural frequency of about 35Hz, far higher than the wave frequencies used in typical laboratory studies (0.5-2Hz). In order to confirm the estimates above, the speed of a pressure pulse along a 10m length of tubing was calculated by correlation of this signal with that obtained from a conventional transducer. In this instance the lag along the tube was found to be of order 0.06s, giving a value for c of 150m/s (figure 2). The lag along a 1m length of probe and tubing is therefore less than 0.01s. The difference in lag between probes is inconsequential for the purposes of calculating the pressure gradients (figure 3), although in this figure the ±0.02s lag on two of the probes indicates the wave speed.

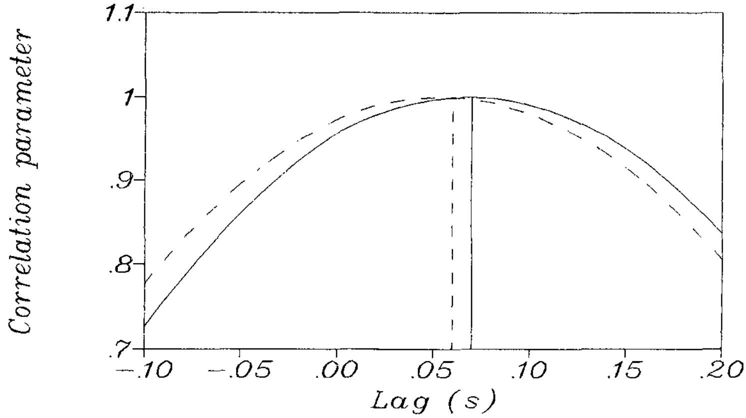

Figure 2. Correlation of the pressure signal from two probes with that from a conventional transducer. L=10m.

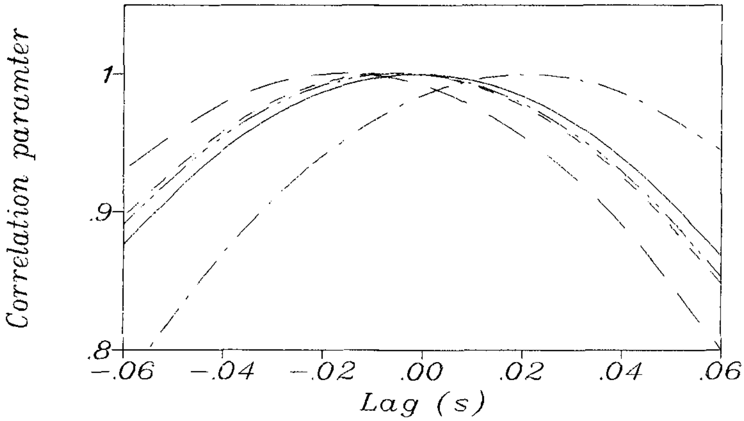

Figure 3. Correlation between the five probes arranged in the measuring array and a conventionally mounted pressure transducer. L=1m.

Regular waves

With a natural frequency of 35Hz, probe/transducer system was expected to have a linear frequency response function and a gain close to 1 over the required range of wave frequencies. However, some damping is to be expected due to energy losses. In regular wave tests the gain function was evaluated by comparing the amplitude of the signal recorded through the probe/transducer system with that obtained from a conventional transducer. Figure 4 shows the measured response functions for a range of frequencies. In each case the response function is very similar, although some difference is observed in the absolute gain values. This is probably due to slight variations in the concentration of air bubbles in each probe. Therefore, when regular waves are used, each probe is individually calibrated at the beginning of the test session. After calibration, the pressure signal recorded by each probe is very close to that recorded by a conventional pressure transducer (figure 5).

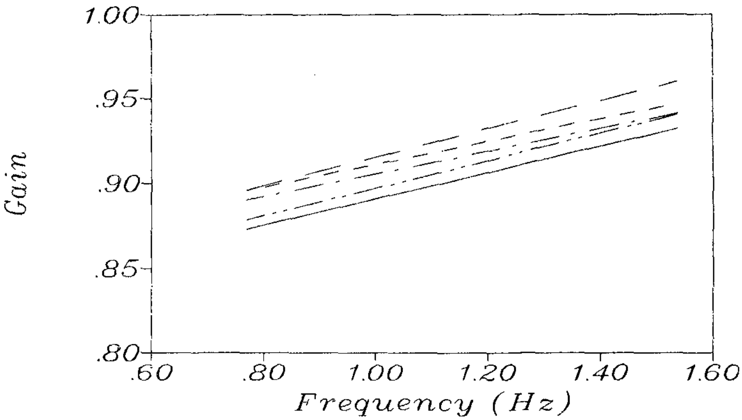

Figure 4. Gain functions measured for each probe/transducer system. L=1m.

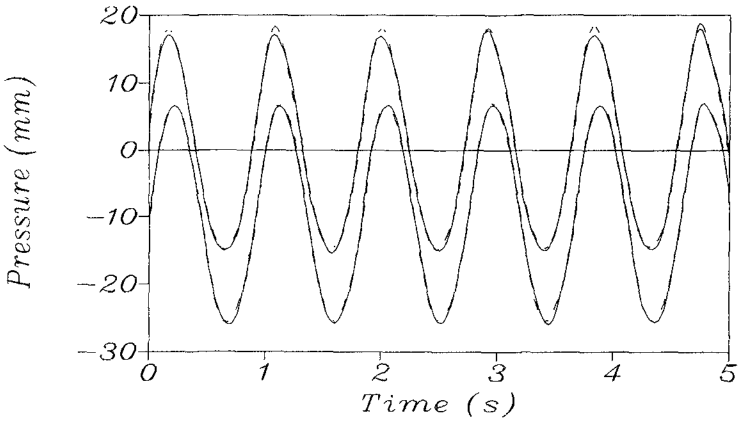

Figure 5. Comparison of the dynamic pressure recorded by two probes with that recorded by conventionally mounted pressure transducers. —— Transducers, – – – probes.

In order to obtain the pressure gradients, the pressure signals from each probe were first low pass filtered at 5Hz and then the gradients calculated with a simple finite difference scheme. The best results were obtained with a probe spacing of 0.06m in the horizontal direction and 0.02m in the vertical direction. The reduced vertical spacing was necessary to obtain the pressure gradients close to the surface of the sediment bed. A comparison of the dynamic horizontal pressure gradient calculated from probe measurements with that from equally spaced conventional transducers clearly shows good agreement (figure 6). Finally, it was necessary to check the performance of the system with all five probes operating and, in particular, to ensure that the phase relationship between the pressure and pressure gradient was accurately reproduced. Figure 7 shows that this was indeed the case.

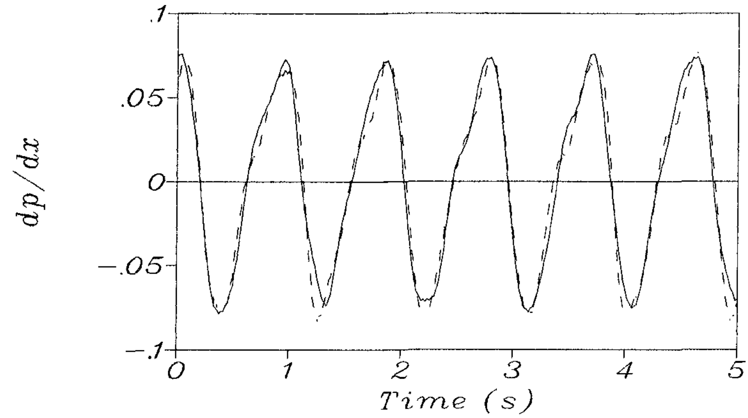

Figure 6. Comparison of the dynamic horizontal pressure gradient.
—— Transducers, – – – Probes.

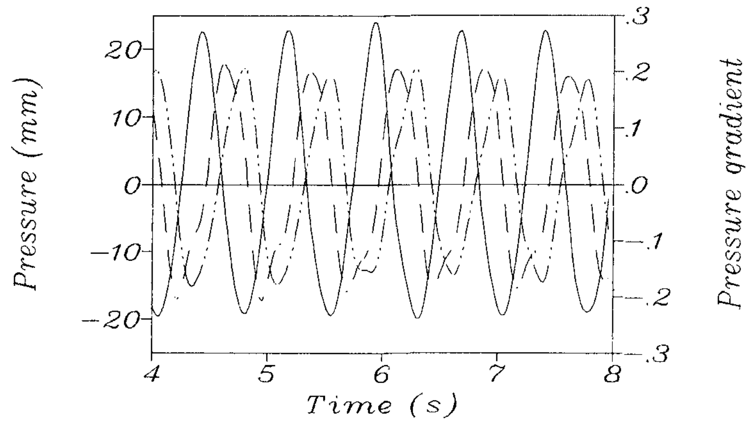

Figure 7. Pressure and pressure gradients within a sand bed.
—— Pressure, – – – Horizontal, —·· — Vertical.

Random waves

Two approaches are possible when using the present method to measure the pressure variation induced by random waves. The first is simply to calibrate each probe over the appropriate frequency range using regular waves. However, best results are obtained by calibrating the probes at the outset of a model test by using a random wave series and a spectral method. In this instance the pressure signal recorded by each probe is Fourier transformed and compared to the Fourier transform of a pressure signal recorded by a conventional transducer. An impulse response function may then be calculated for each probe and applied to all subsequent measurements. This approach gives gain functions very similar to those for regular waves shown above. Applying the appropriate impulse response function during subsequent tests then results in close agreement between the dynamic pressure obtained from the probe system and that obtained from a conventional transducer.

4) RESULTS / APPLICATIONS

The flexibility of the present technique has considerable advantages for a wide range of pressure measurements. For example, the minimal flow resistance of the probes makes it possible to measure the pressure and pressure gradients at any point within a fluid flow. This is not possible with conventional transducers, which must generally be mounted flush with a surface in order to minimise turbulence effects. A second advantage of the present method is that data may be obtained at a large number of positions within a sediment bed with a minimum number of pressure transducers. This is because the small diameter of each probe allows the probes to be moved vertically within the sediment with virtually no disturbance of the bed material. The variation in the dynamic pressure over the vertical is therefore easily obtained. For example, figure 8 shows measurements of the maximum dynamic pressure within a sand bed and an anthracite bed under regular waves. Data could be collected at a large number of points with only one pressure transducer and gave good agreement with the solution of Sleath (1970).

Pressure gradients

Figures 9 and 10 show the horizontal and vertical pressure gradients at the face of a vertical breakwater and at the toe of a sloping breakwater respectively. The face of the vertical breakwater is an antinode, and therefore the horizontal pressure gradient is small, while the vertical pressure gradient increases rapidly close to the surface of the sediment bed. The sharp discontinuity in the vertical pressure gradient expected at the fluid/sediment interface is also clearly visible, although the finite spacing of the probe tips is apparent. Nevertheless, data of this sort would be difficult to obtain with conventional transducers. The toe of the sloping breakwater lies between a node and antinode and therefore, in this instance, the horizontal and vertical pressure gradients are of similar magnitude at the sediment surface. However, the present measurement technique is sufficiently accurate to detect the change in the rate of decay of the horizontal pressure gradient at the fluid/sediment interface. This change occurs because the variation in the horizontal pressure gradient within the fluid approaches zero at the interface, while the rate of decay within the bed is proportional to the thickness of the sediment bed (e.g. Sleath, 1970).

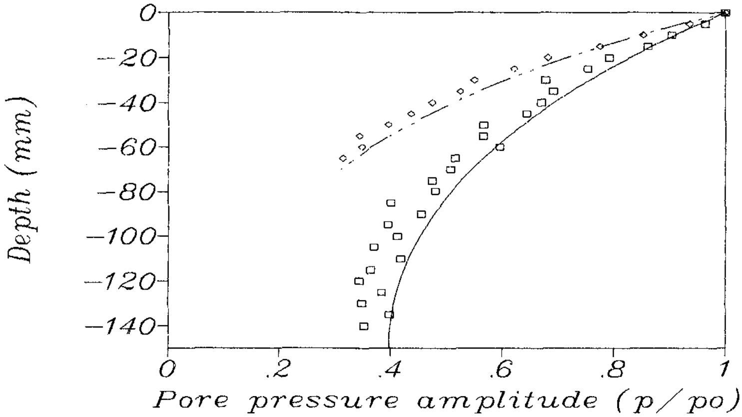

Figure 8. Dynamic pressure within a sand bed and an anthracite bed. □□□□ Sand, T=0.7s, ——— Sleath (1970), ◇◇◇◇ Anthracite, T=0.5s, —··— Sleath (1970).

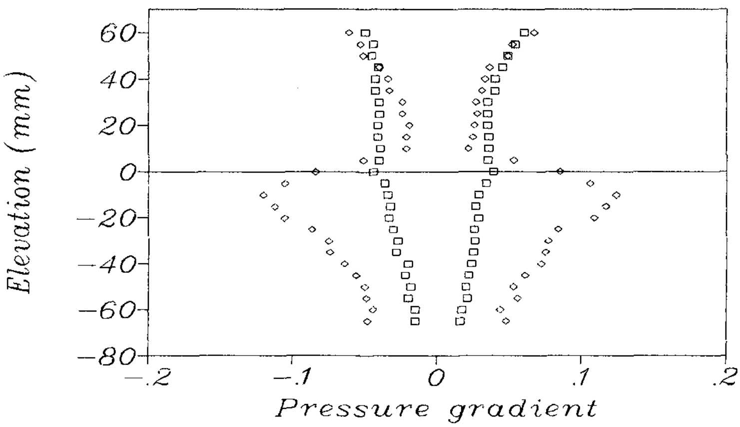

Figure 9. Horizontal and vertical pressure gradients at the face of a vertical porous breakwater. □□□□ Horizontal, ◇◇◇◇ Vertical.

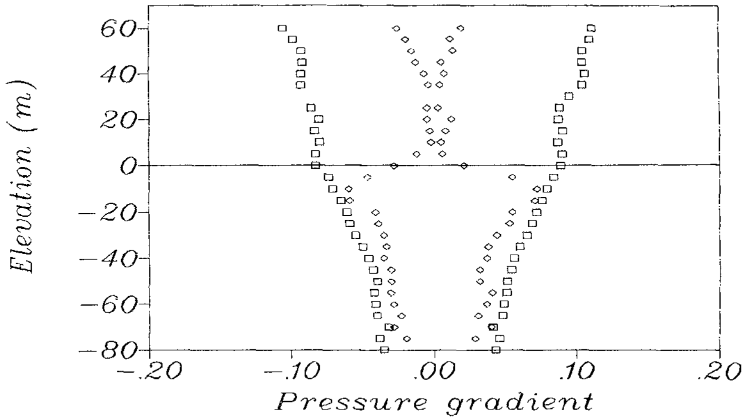

Figure 10. Horizontal and vertical pressure gradients at the toe of a sloping porous breakwater. □□□□ Horizontal, ◊◊◊◊ Vertical.

The pressure gradients within laboratory scale sediment beaches were also investigated with the present measurement technique. The first case considered a coarse sediment beach with a median grain size of 1.5mm and a thickness of 0.1m. Regular waves with a height of 0.1m and wave period of 1.5s were used. Waves were run until the initially plane beach reached a stable shape and the pressure gradients just below the bed surface were then measured at a number of locations across the surf zone. Measurements of this kind would be very difficult to obtain using conventional transducers, which would have to be positioned before the beach attained an equilibrium profile.

Figure 11 shows the mean horizontal pressure gradient increasing across the surf zone due to wave induced set-up and swash zone percolation, reaching a maximum of about 0.1 at the still water level. The vertical pressure gradient has a similar magnitude at this point and is again positive. The flow within the beach is therefore downward and seaward. The vertical pressure gradient reaches a minimum in the middle of the surf zone and, consequently, the flow is out of the beach. However, the mean pressure gradients appear too small to significantly influence the stability of the beach sediment, in general agreement with the numerical calculations of Oh and Dean (1994).

In a second experiment the maximum dynamic pressure gradients were measured across a barred laboratory scale beach. In this instance the beach consisted of sediment with a median grain diameter of 0.5mm and was again 0.1m thick. Regular waves were again run until a stable beach formed and the pressure gradients were measured 20mm below the bed surface in the region of the bar. The data show that both the horizontal and vertical pressure gradients reach a maximum just seaward of the bar and then decrease rapidly after wave breaking (figure 12).

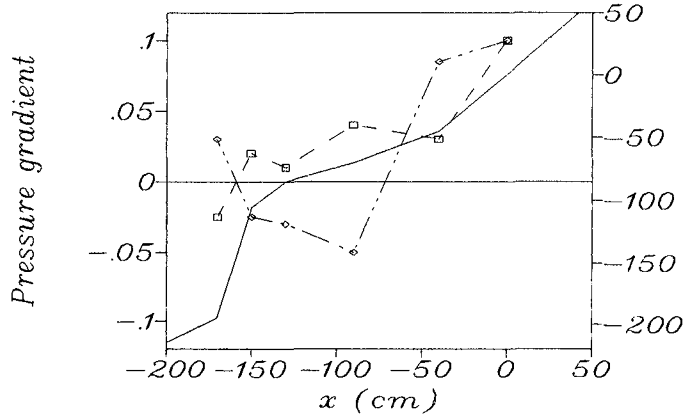

Figure 11. Mean horizontal and vertical pressure gradients within a laboratory scale sand beach. —— Water depth, —□—, horizontal, — ··◊·· — vertical.

The maximum horizontal gradient does not reach the value required for liquefaction of a sand bed (Madsen, 1974), but is nearly twice that required to initiate the failure of an anthracite bed. The negative horizontal pressure gradient is much larger than the positive gradient, indicating steep wave fronts, while the reverse is the case for the vertical pressure gradients, indicating steep crests and flatter wave troughs (figure 13).

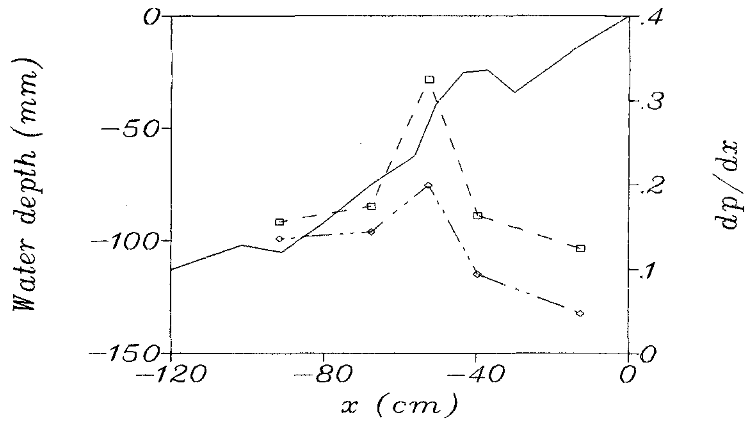

Figure 12. Maximum horizontal dynamic pressure gradient across a laboratory scale sand beach. —— Water depth, —□—, negative, — ··◊·· — positive.

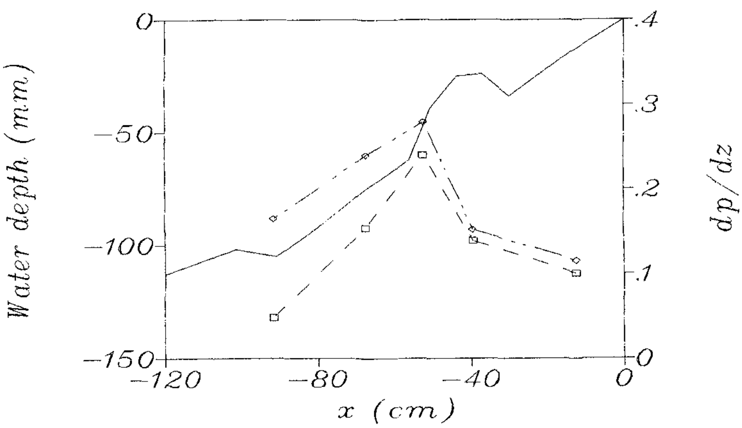

Figure 13. Maximum vertical dynamic pressure gradient across a laboratory scale sand beach.
—— Water depth, --□--, negative, — ··◊·· — positive.

CONCLUSIONS

The development of a new technique for measuring the pressure gradients within sediments is presented. The pressure gradients are measured using a series of small diameter steel probes connected to pressure transducers with semi-rigid flexible tubing. This allows the pressure gradients to be determined quickly and easily with minimal disturbance of the sediment. For the purpose of measuring mean pressure gradients the method requires no calibration. The dynamic response of the system was evaluated using both regular and irregular waves and was found to be satisfactory for typical laboratory wave frequencies. A comparison of the pressure gradients obtained by the present technique with those measured using conventional pressure transducers showed good agreement. Measurements of the mean and dynamic pressure gradients within laboratory scale sand beaches have demonstrated the advantages of the system. The measurement technique has already proved useful for investigating the role of pressure gradients in sediment transport mechanics (Baldock and Holmes, 1996) and will aid investigations into the flow pattern within laboratory scale beaches.

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