

CHAPTER 184

FIELD OBSERVATION OF WAVE-INDUCED POREWATER PRESSURES

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ABSTRACT

Wave-induced transient porewater pressures were measured near a seabed surface at a coast facing the Japan Sea. The data are compared with the solution using a boundary layer approximation by Mei and Foda (1981). The effective bulk modulus of porewater, β , is estimated $1.0 \times 10^8 \text{ N/m}^2$ so that the solution matches the observation. A similar analysis is done for the field data obtained by Zen et al. (1989) at a coast facing the Pacific Ocean. The value of β scatters from $1.0 \times 10^7 \text{ N/m}^2$ to $1.0 \times 10^8 \text{ N/m}^2$.

INTRODUCTION

The wave-induced transient porewater pressure is an important quantity for a seabed stability (Sakai et al., 1992). The solution using a boundary layer approximation by Mei and Foda (1981) is simple and useful for the estimation of the wave-induced transient porewater pressures. The uncoupled analysis proposed by Finn et al. (1983) is applicable only to soft and coarse sand.

Mei and Foda (1981) modeled the seabed response to waves as a summation of an elastic response of one-phase medium and a

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seepage flow near the bed surface (Fig.1). The seepage flow is appreciable only in a thin layer near the bed surface. They called this layer "boundary layer".

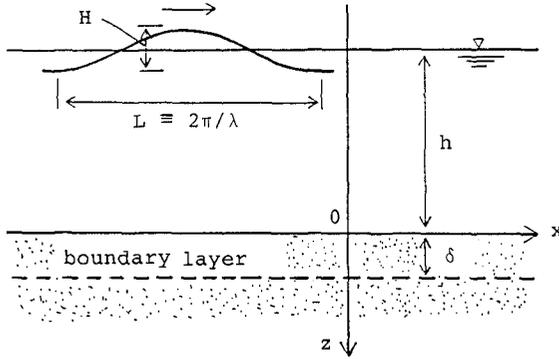


Fig.1 Boundary layer approximation of seabed response to waves (Mei and Foda, 1981)

In the solution using the boundary layer approximation, when the bottom wave pressure, p_b , is given by the small amplitude wave theory as

$$p_b = p_0 \cos(\lambda x - \omega t) = \frac{1}{2} \frac{\rho_w g H}{\cosh(\lambda h)} \cos(\lambda x - \omega t), \quad (1)$$

the porewater pressure variation, p' , is given by

$$p' = p_0 \frac{1}{1+m} \exp\left(-\frac{2\pi z}{L}\right) \cos(\lambda x - \omega t) + p_0 \frac{m}{1+m} \exp\left(\frac{-z}{\sqrt{2}\delta}\right) \cos\left(\lambda x - \omega t + \frac{z}{\sqrt{2}\delta}\right), \quad (2)$$

where p_0 is the amplitude of the bottom wave pressure, $\lambda (= 2\pi/L)$ is the wave number, L is the wave length, x is the horizontal distance in the wave propagation direction, $\omega (= 2\pi/T)$ is the wave angular frequency, T is the wave period, t is the time, ρ_w is the density of the water, g is the gravity, H is the wave height, h is the water depth, and z is the depth beneath the seabed surface.

The first term in the right hand side of Eq.(2) is the so-called outer solution as the one-phase elastic response. The second term is the boundary layer correction. In the boundary layer correction, a

phase delay $z/(\sqrt{\Sigma}\delta)$ exists. Eq.(2) includes two parameters m and δ . The m is a non-dimensional parameter described by Eq.(3), and proportional to a ratio of the shear modulus of the solid skeleton G and the effective bulk modulus of the porewater β ,

$$m = \frac{n}{(1 - 2\nu)} \frac{G}{\beta} . \quad (3)$$

The δ is the thickness of the boundary layer described by Eq.(4):

$$\delta = \left(\frac{KG}{\omega} \right)^{\frac{1}{2}} \left(n \frac{G}{\beta} + \frac{1 - 2\nu}{2(1 - \nu)} \right)^{-\frac{1}{2}} , \quad (4)$$

where n and ν are the porosity and Poisson's ratio of the solid skeleton, $K = k/\rho_w g$ and k is the permeability coefficient.

The effective bulk modulus of the porewater β is related to the degree of saturation of porewater, S , through an empirical equation (Mei and Foda, 1981),

$$\frac{1}{\beta} = \frac{1}{\bar{\beta}} + \frac{1 - S}{\bar{p}} , \quad (5)$$

where $\bar{\beta}$ is the effective bulk modulus of saturated water, and \bar{p} is the fluid pressure. β is 2×10^9 N/m² for saturated porewater, but it decreases rapidly to 10^6 N/m² due to gas content of 1%. The β is a dominant parameter for a momentary liquefaction (Sakai et al., 1992). In this paper, we try to estimate the value of β from field observation data of the wave-induced transient porewater pressure variation.

FIELD OBSERVATION

Field observations were carried out at the Ogata Wave Observatory of Kyoto University. It is facing the Japan Sea. The measurements of the wave-induced porewater pressures were done in a sandy bed under a head of the wave observation pier, shown in Fig.2, in March 1990. The length of the pier is 256 m with a wing of 107 m length at the head. The water depth at the measuring location was about 6 m. The median diameter of the bottom sediment was reported to be from 0.2 mm to 0.5 mm (Akamura, 1989 ; Kawata et al., 1990).

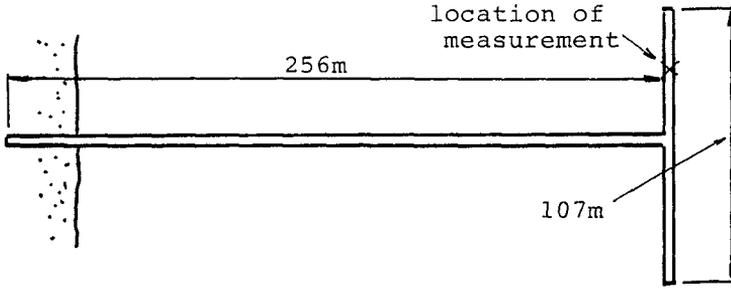


Fig.2 Pier of Ogata Wave Observatory of Kyoto Univ.

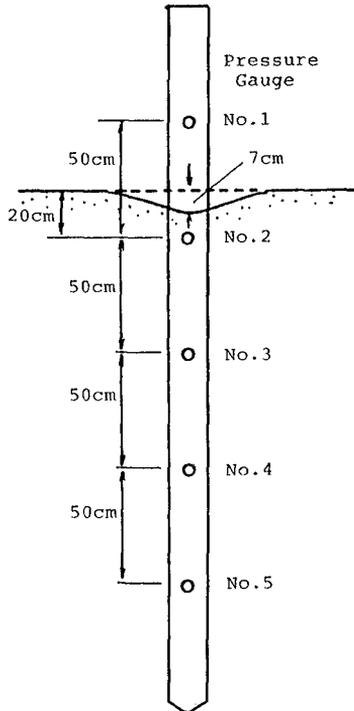


Fig.3 Measuring apparatus of porewater pressures

Five pressure gauges were attached to a side wall of an aluminum pipe of rectangular section as shown in Fig.3. The length of the pipe was 3.0 m. The length between two adjacent gauges was 50 cm. The capacity of the pressure gauges was 1.0 kgf/cm². A brass filter of 40 μ m was attached to the diaphragm of the gauge.

A part of the pipe of 2.2 m was inserted into the seabed. The highest gauge was located 30 cm above the seabed surface. The second gauge was located 20 cm below the bed surface. The bed surface around the pipe was about 7cm lower than the surrounding bed surface.

Unfortunately the waves were small during the first observation. Two months later after leaving the apparatus in the seabed, the second observation was tried again. But the output was very small compared with that of the first observation. The reason was found, after lifting out the apparatus from the seabed, that the brass filters of the upper three gauges were covered by small marine organic bodies.

Figure 4 is a part of the record on March 28th, 1990. The unit of the abscissa is second, and that of the ordinate is cm, where the porewater pressure is shown by water head. Several waves, Nos. 2 and 3 of which are shown in the figure, were selected for the following analysis. Figure 5 is a part of the record on March 30th.

Five waves were selected from the record of March 30th. Table 1 shows the wave periods and the total amplitudes of pressure head variation at five pressure gauges for five waves. The amplitude of gauge No.2 of wave No.1 is slightly larger than that of gauge No.1. The same trend was seen in two waves in the record of March 28th. At this moment it is impossible to find the reason. In the following analysis, the level of gauge No.2 is assumed to be the bed surface level.

VALUE OF EFFECTIVE BULK MODULUS OF POREWATER β

To estimate the value of effective bulk modulus of porewater β , the total amplitude of p' , given by Eq.(2), was calculated at the lower three levels and compared with the measured amplitude. The value of p_0 in Eq.(2) was taken to be equal to the amplitude of the measured porewater pressure at gauge No.2. The phase lag, $z/(\sqrt{2}\delta)$, was neglected.

The values of parameters are as follows: $n = \nu = 0.33$, $G = 1.0 \times 10^8$ N/m², and $k = 2.8 \times 10^{-4}$ m/sec. These values are typical

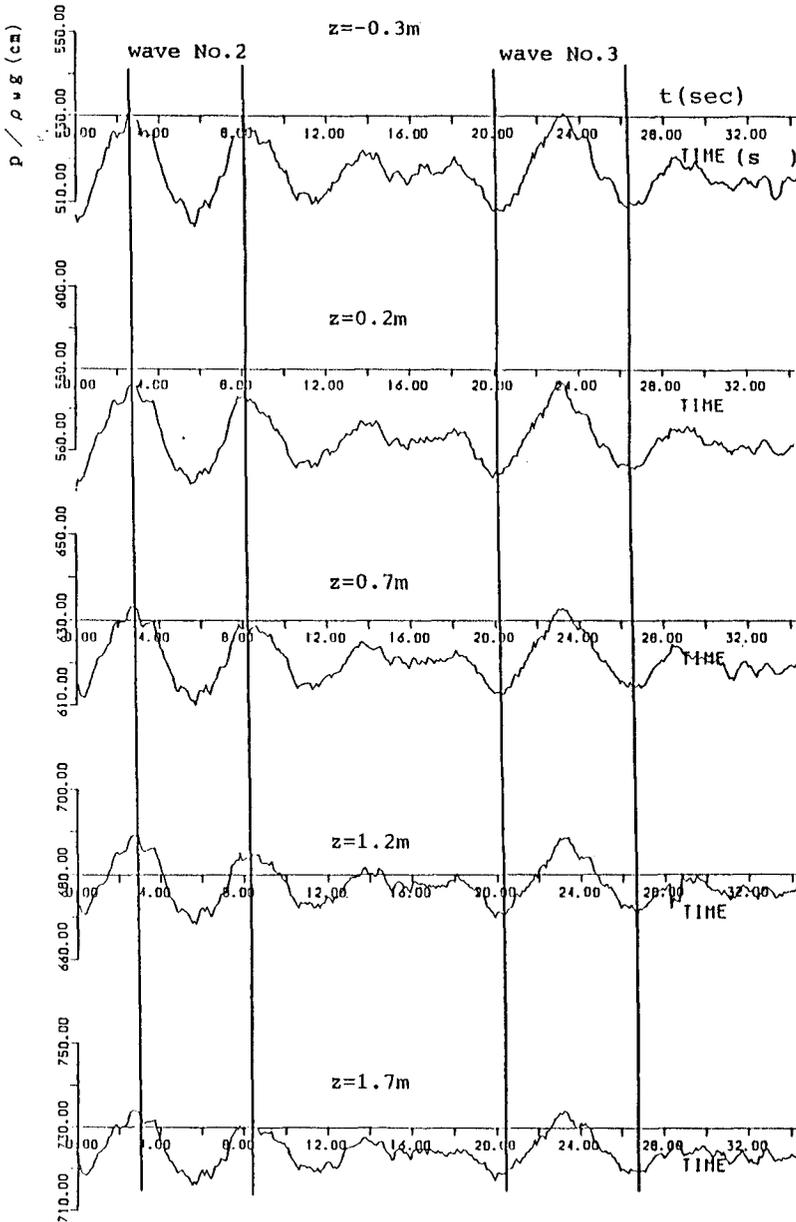


Fig.4 Example of record of measured porewater pressures (March 28th, 1990)

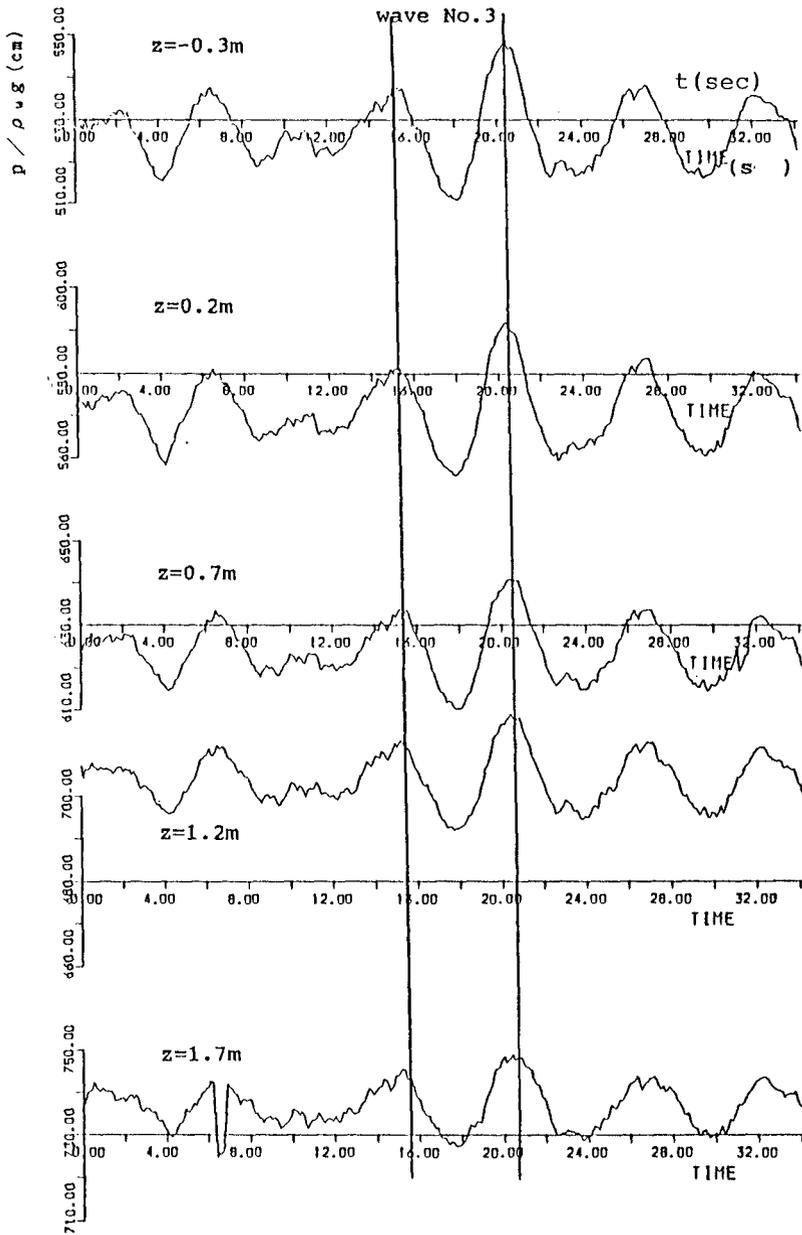


Fig.5 Example of record of measured porewater pressures (March 30th, 1990)

**Table 1 Total amplitude of porewater pressure head
(March 30th, 1990)**

wave No.	1	2	3	4	5
wave period(s)	6.0	5.6	5.2	6.4	5.6
pressure gauge	total amplitude (cm)				
No.1	32	25	38	26	27
No.2	33	24	36	25	26
No.3	29	21	31	23	22
No.4	27	19	27	20	20
No.5	23	17	24	18	17

values of sandy bed. As already mentioned, the value of β changes very rapidly due to small content of gas in the porewater. For saturated porewater, the order of β is 10^9 N/m². Due to 1% gas content, the order of β decreases to 10^6 N/m². Considering this fact, three kinds of value of β are taken, $\beta = 1.0 \times 10^7$ N/m², 2.0×10^7 N/m² and 1.0×10^8 N/m². $h = 5.6$ m - 5.7 m, and $T = 5.2$ sec - 6.4 sec.

From the comparison between the measured and calculated total amplitudes of pressures, it was found that the calculated result using $\beta = 1.0 \times 10^8$ N/m² agreed best with the measured results.

As seen from Eqs. (1) and (2), the phase of the porewater pressure variation is not in phase with that of the bottom wave pressure. Then the measured time profile of the porewater pressure variation is compared with the calculated profile. The bottom wave pressure was assumed sinusoidal. **Figure 6** shows one example of the comparison. The given sinusoidal bottom wave pressure does not coincide so well with the measure porewater pressure variation of gauge No.2; However, judging from the phase shift, it is found again that the calculated results using $\beta = 1.0 \times 10^8$ N/m² agrees best with the measured results.

ANALYSIS OF DATA OF ZEN ET AL.(1989)

Zen et al. (1989) measured the wave-induced porewater pressure in a surf zone at a coast facing the Pacific Ocean. The measurement was done at the head of an observation pier of the Port and Harbour Res. Inst. of Japanese Ministry of Transport. The

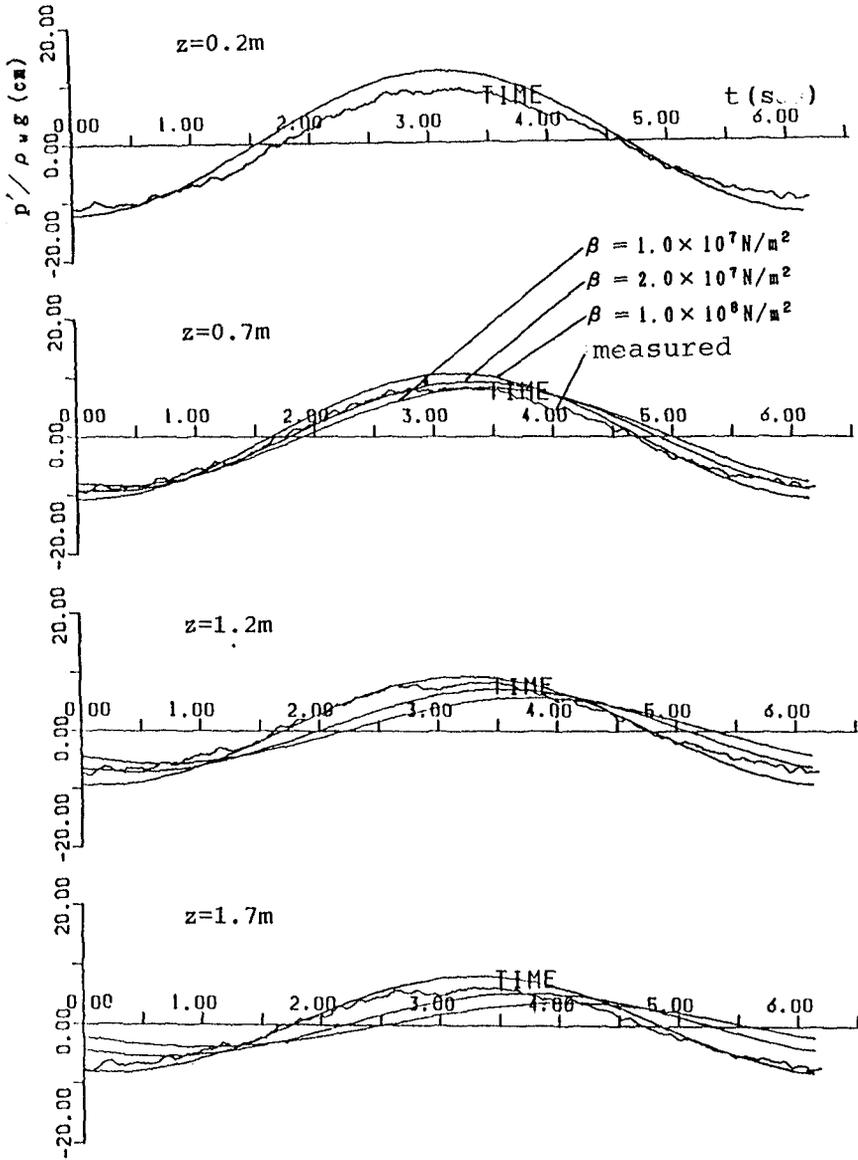


Fig.6 Comparison of measured and calculated time profiles of porewater pressure (March 30th, 1990)

water depth h was about 4 m (Hattori et al., 1992). The 50% sand grain size was 0.16 mm.

They showed a part of the records of three observation series. Fig.4 of Hattori et al. (1992) is that of series No.2. The waves had sharp crests as usually seen in surf zone. One wave was selected from each series, including wave No.7 in series No.2.

The time profile of the bottom wave pressure of the selected waves was decomposed into its Fourier series components. The porewater pressure variation p' was calculated for each component by using Eq.(2). The porewater pressure variation was obtained by summing up those of all components, since the boundary layer approximation solution Eq.(2) is linear. Typical values in sandy bed were used for the parameters: $n = \nu = 0.33$, $G = 1.0 \times 10^8$ N/m², and $k = 2.8 \times 10^{-4}$ m/sec. Three kinds of value for the bulk modulus of porewater β were taken, 1.0×10^7 N/m², 3.0×10^7 N/m² and 1.0×10^8 N/m².

Figure 7 shows the comparison between the calculated and measured results for wave No.7 of series No.1. Since the figures of the time profile of the pressure variation shown in Zen et al.s paper (1989) were small, the time profile could not be read in a small interval. This is the reason why the curves are not smooth.

At the highest level, that is, 40cm below the bed surface, the amplitude of the measured pressure variation is roughly explained by the calculated curve of $\beta = 1.0 \times 10^7$ N/m². But the phase of the measured profile is not so delayed as the calculated one. At the second level, 90 cm below the bed surface, the value of measured peak is almost the same as the calculated one using $\beta = 3.0 \times 10^7$ N/m² or 1.0×10^8 N/m². At the lowest level, 140cm below the bed surface, the tendency is the same as at the second level. The measured peak value is explained by the calculated value using $\beta = 3.0 \times 10^7$ N/m² or 1.0×10^8 N/m².

From the similar comparisons for other two waves in series Nos.2 and 3, it is found that the value of β which explains best the measured results varies from 1.0×10^7 N/m² to 1.0×10^8 N/m².

DISCUSSION

As seen in Eq.(2), the relative importance of the boundary layer correction depends on m or G/β . In surf zone, a non-dimensional parameter related to the boundary layer thickness δ given by Eq.(4) is $kG/\rho_w g^2 T h$ (Fig.2 in Hattori et al.(1992)). The vertical profile of the non-dimensional porewater pressure variation is determined by

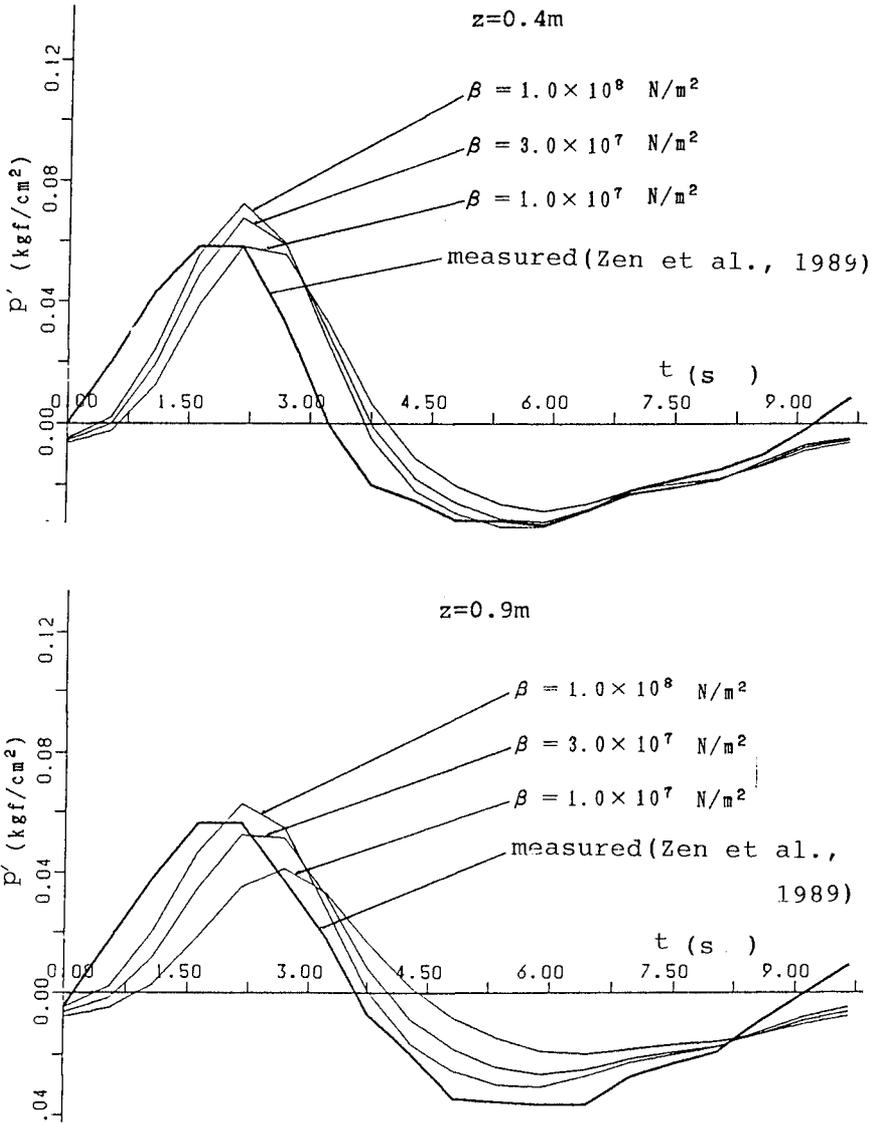


Fig.7 Comparison between measured and calculated time profiles of porewater pressure ($z = 40\text{cm}$ and 90cm , wave No.7, series No.1, Zen et al.(1989))

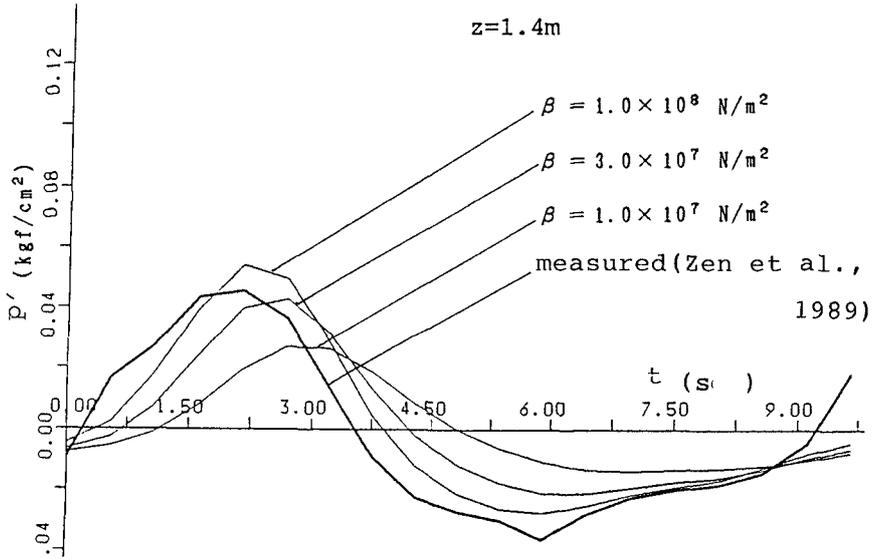


Fig.7 continued ($z = 140\text{cm}$)

two non-dimensional parameters G/β and $kG/\rho_w g^2 T h$.

When G/β becomes large, the correction becomes large (Fig.8). Then the scale of the vertical profile of porewater pressure variation is dominated by δ which is assumed to be smaller than the wave length L . Also when $kG/\rho_w g^2 T h$ becomes small, the boundary thickness δ becomes small. In both cases, the downward decrease becomes fast.

If the value of $kG/\rho_w g^2 T h$ is small, a smaller value of G/β explains the vertical profile of measured porewater pressure variation. If the value of $kG/\rho_w g^2 T h$ is large, a larger value of G/β is necessary to explain the vertical profile. For a given value of G , if the value of k is small, a larger value of β explains the vertical profile. If the value of k is large, a smaller value of β is necessary. The estimation of value of β depends on the assumed value of k . The result of this investigation should be understood keeping this fact in mind.

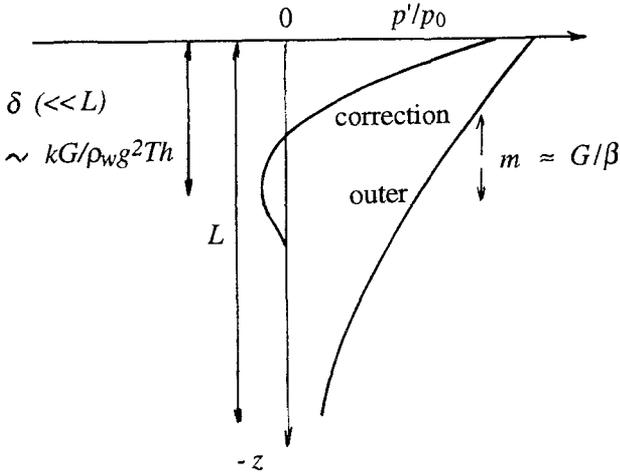


Fig.8 Two non-dimensional parameters G/β and $kG/\rho_w g^2 T h$ dominating vertical profile of non-dimensional wave-induced transient porewater pressure in surf zone

CONCLUSIONS

A measurement of the wave-induced transient porewater pressures was done near a seabed surface at a coast facing the Japan Sea. The value of the effective bulk modulus of the porewater β was estimated so that the solution using the boundary layer approximation by Mei and Foda(1981) agreed with the measured pressure variation.

- (1) The estimated value of β is 1.0×10^8 N/m² under the condition of shear modulus of the solid skeleton $G = 1.0 \times 10^8$ N/m² and the permeability coefficient $k = 2.8 \times 10^{-4}$ m/sec.
- (2) A similar estimation for Zen et al.s data(1989) measured at a coast facing the Pacific Ocean results in from $\beta = 1.0 \times 10^7$ N/m² to 1.0×10^8 N/m².
- (3) The estimation of the value of β should be understood keeping in mind that it depends on the assumed value of the permeability coefficient k .

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