CHAPTER 75

Pore pressure induced by wind waves in sand bed

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Abstract

The two projects (LUBIATOWO 79 and LUBIATOWO 86) were aimed at study pore pressure behaviour in natural sand bed in the coastal zone of the Baltic sea under the action of storm waves. During both projects, the wave induced pore pressures at the various levels in the sea bed were measured. The collected data were used to verify the applicability of the various theoretical approaches. In the conclusion, the range of the application of the particular analytical method is given.

1. Introduction

The problem of wave induced pressures and stresses in natural sea beds is important with regard to the design of foundations for various ocean and nearshore structures, such as gravity type breakwaters, offshore oil storage tanks and drilling rigs. The subject is also important when one considers the floatation of buried pipelines and the burial of rubble mounds by waves.

The wave-induced flow in a porous bed experiences a flow resistance and transmits forces, seepage forces, to the soil skelton. From a hydrodynamic point of view the flow induced by waves in a porous bed is of interest since energy dissipation, i.e., wave attenuation, is associated with this flow. Early papers (Putnam, 1949; Reid and Kajiura, 1957; Liu, 1973; Moshagen and Tørum, 1975) have focused on a permeable sea bed with a fixed rigid grain skeleton. Moshagen and Tørum (1975) considered the wave-induced flow in a porous medium under the assumption of a compressible pore fluid but an incompressible soil. They found that the inclusion of pore fluid compressibility in the analysis of wave-induced pore pressures in a porous soil significantly altered the vertical seepage forces acting on the soil. Yamamoto et al. (1978) have developed a quasi-static model of a poro-elastic sea bed using the equations developed by Biot (1941). They obtained solutions which, when best fit to laboratory data of pore pressure, showed reasonable

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for both magnitude and phase. Mei and Foda (1980) have shown that the boundary layer approximation well known in fluid dynamics, greatly facilitates the solution of Biot's equations for a variety of boundary conditions.

However, besides the numerous theoretical solutions, the lublished laboratory and field data are very scarce. Dunlap et al. (1978), Bennett and Faris (1979), and Cross et al. (1979) have presented the results of the experiments on the pore pressure generation in the sediments of Mississippi and coastal zone of Pacific. However, they are mainly related to the long-term changes. The relation of the observed pressure to the surface oscillations was not considered. The major objective of the present study is to describe the field measurement projects, i.e. LUBIATOWO 79 and LUBIATOWO 86 which were aimed at studying pore pressure hebaviour in natural sand bed in the coastal zone of the Baltic Sea. The pore pressure measuring system is described and experimental results are compared with results of various analytical approaches.

2. Field experiments

2.1. Scope of the work

The field experiments were carried out at the Coastal Research Staion in Lubiatowo (Poland) in the Southern Baltic (water depth $h \approx 6 \div 7$ m).

A set of over one hundred records were taken for various wave conditions at one profile. Simultaneous measurements of the sea surface oscillations, water pressures at two points in the water layer and pore pressures at four points in the soil layer were carried out (Fig. 2.1).

2.2. Porous layer characteristics

According to the geological information in the vicinity of the point of measurements, the thickness of the rather uniform sand is equal to ~ 6.5 m. The soil is of fine-grained type ($D_{10} = 0.135 \cdot 10^{-3}$ m, $D_{20} = 0.135 \cdot 10^{-3}$ m, $D_{60} = 0.150 \cdot 10^{-3}$ m, $D_{90} = 0.180 \cdot 10^{-3}$ m). Because the uniformity coefficient is less than 6 and the contents of the fraction $\leq 0.074 \cdot 10^{-3}$ m is less than 5%, the fine-grained sand can be classified as a poorly graded and fairly clean.

The density of soil or the porosity was not measured "in situ". Thus, only some estimation can be made. For very dense packing the porosity is about 26%, while for very loose it is about 47%. The large forces which were needed to push the pore pressure gauge indicated a rather dense packing of the sand at the measuring profile. Therefore, the porosity of sand is likely to be in the range $30 \div 40\%$.

Moreover, the experimental data on the permeability of the bed material were lacking. Thus, we adopted an empirical formulae to estimate the permeability from the grain-size distribution characteristics. The conclusion from these estimates is that the permeability coefficient is in the range of $10^{-5} \div 10^{-4}$ m/s.

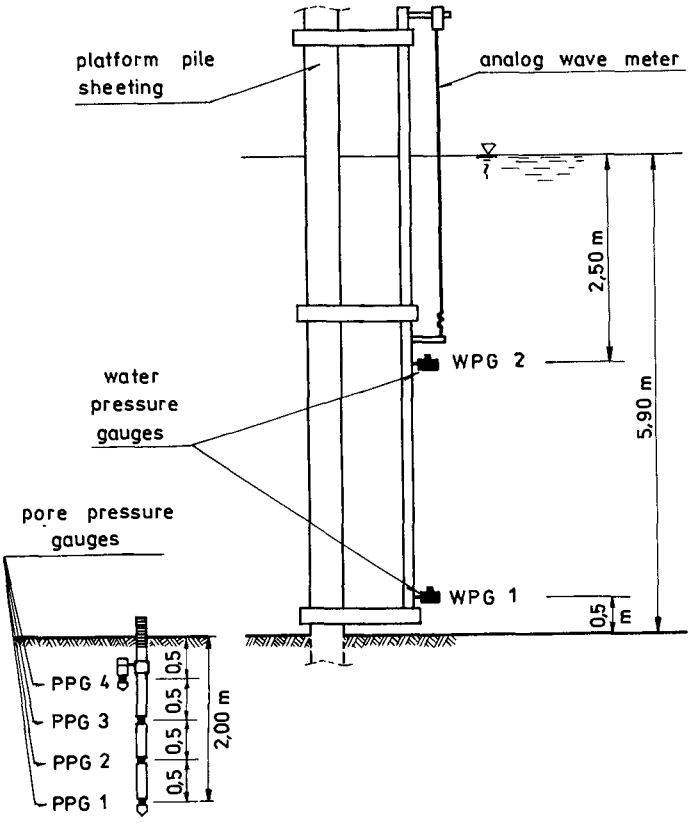

Fig. 2.1. Measurement gauges lay-out

2.3 Instrumentation and measurements

All sensors were arranged in one profile and the measurement signals were transferred by cables to the Station building on shore. Due to access convenience, the gauges were attached to a framework fixed to the sheet-pile section of the platform.

The data were recorded in the real time in digital form. The system of transmission and acquisition of data consists of the modules of PCM transmitter and receiver, Camac system, microcomputer BIZON 580, PC computer and analog and digital recorder. The technical description of the instrumentation and transmission modules can be found elsewhere (Massel and Moshagen, 1980, Kaczmarek, 1987) and it will not be repeated here.

3. Statistical and spectral analysis of data

The surface waves observed in the coastal zone are the waves caused by the wind and then propagating under the restoring force of gravity. Under the assumption of the narrow-band spectrum and uniform distribution of the random phase, the surface ordinates a Gaussian distribution (Phillips, 1977). Such assumptions is expected to be realistic for small amplitude waves, specially in the deep water. However, the statistical analysis of the collected records indicates that the wave motion can be treated as nearly Gaussian process. Therefore:

$$p(\zeta) = p_n(\zeta)\left\{1 + \frac{\gamma_1}{3!} H_3\left(\frac{\zeta}{\sigma_\zeta}\right) + \frac{\gamma_2}{4!} H_4\left(\frac{\zeta}{\sigma_\zeta}\right) + \cdots\right\} \qquad (3.1)$$

where $p_n(\zeta)$ - Gaussian distribution, γ_1 - skewness, γ_2 - kurtosis, and $H(\ )$ - Hermitte polynomial. In fact γ_1 and γ_2 are both small values for the surface waves and the pore pressure. This is clearly demonstrated in Fig. 3.1. in

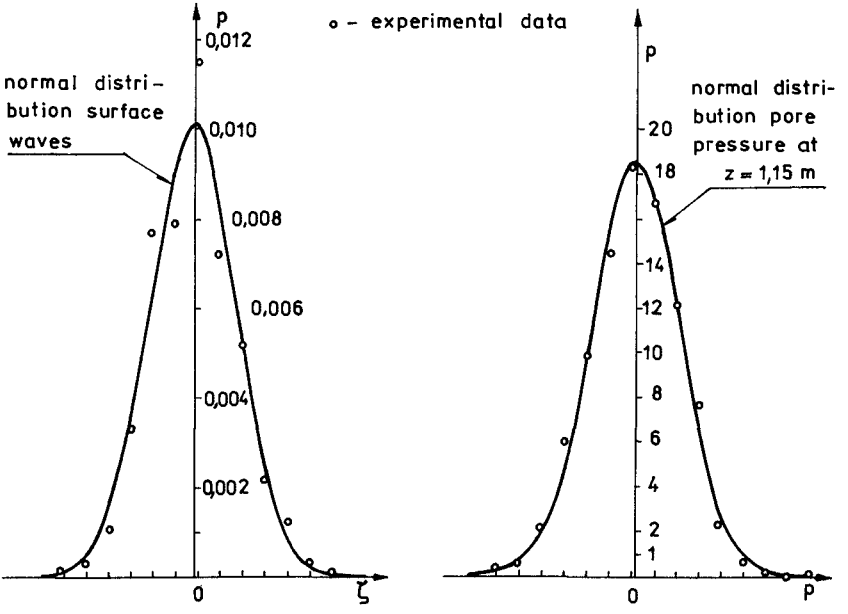

Fig. 3.1. Probability density distribution for surface waves and pore pressure.

which the corresponding probability density distributions are compared.

For the farther analysis we assume additionally that the system: surface waves - pore pressure is the linear system. Hence:

$$S_p(\omega) = |H(\omega)|^2 \cdot S_\zeta(\omega) \qquad (3.2)$$

in which:

$S_\zeta(\omega)$ - spectral density for the surface elevation,

$S_p(\omega)$ - spectral density for the pore pressure, and

$H(\omega)$ - transfer function.

As the empirical spectral density functions are known, the transfer function can be easy obtained. In the Figs. 3.2 and 3.3, the function $H_{p\zeta}(\omega)$ for the pore-pressure gauges at two points: z = -1.0 m (one meter below the bottom surface) and z = -1.5 m (one and half meter below the bottom surface). As should be expected, the function $H_{p\zeta}(\omega)$ is the decreasing function of the frequency. It should be noted, that during the measurements, the spectral peak frequency for the surface waves was in the interval of $0.80 \leqslant \omega_p \leqslant 1.50$ [rd/s], while the mean wave heights ($\bar{H}$) were of order (0.50 ÷ 1.5 m).

The calculations of the coherence function $\gamma^2_{p\zeta}$ (not shown here) indicate that the high values of the $\gamma^2_{p\zeta}$ function are related to the frequency band:

$$(0.6 \div 0.7) \leqslant \frac{\omega}{\omega_p} \leqslant (1.8 \div 2.) \qquad (3.3)$$

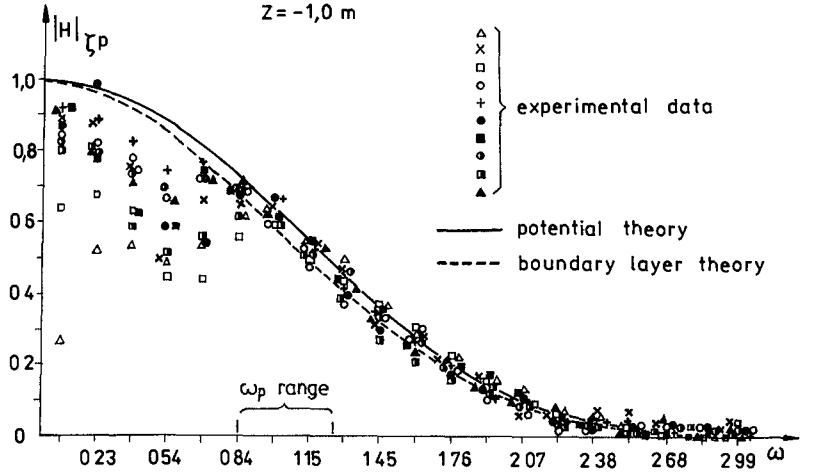

Fig. 3.2. Transfer function $H_{p\zeta}(\omega)$ for pressure gauge at z = -1.0 m

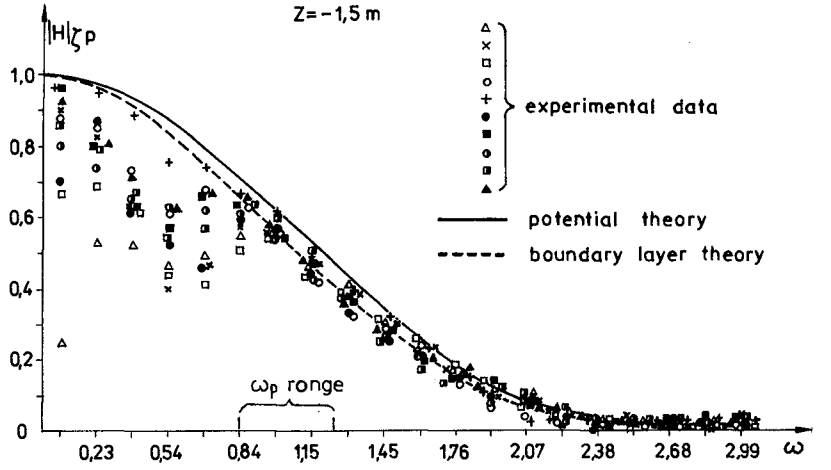

Fig. 3.3. Transfer function $H_{p\zeta}(\omega)$ for pressure gauge at z = - 1.5 m

Outside that band the value of the coherence function is very small. Thus, the usefulness of the theoretical linear model for the pore-pressure decaying is restricted to the frequency band given above.

4. Validity of the potential theory approach

In order to simplify the analysis we assume that the regular long-crested wave with a frequency ω is propagating on the constant water depth. A homogeneous isotropic sediment is considered which has a constant thickness (h_n - h) on a rigid and impermeable bed rock h - water depth, h_n- depth of nonpermeable bed.

The x axis is taken on the sea surface and the positive direction of the z axis is vertically upward.

We assume, that the soil skeleton obeys Hooke's law, i.e. the soil has linear, reversible isotropic, nonretarded mechanical properties. The exact solution for the pore-water pressure, the displacements, and the effective stresses in such elastic bed induced by water waves is based on the consolidation theory developed by Biot (1941). Since a complete description of the solution is given in the original paper, as well as in many text books (e.g. Verruijt, 1969), it will not be repeated here.

The general solution simplyfies considerably in the special case, when $G/E'_w \to 0$, in which G - shear modulus of soil, i.e.

$$G = \frac{E_s}{2(1+\nu)} \qquad (4.1)$$

where E_s - Young's modulus and ν - Poisson ratio.

The apparent bulk modulus of pore-water containing a some amount of air (E'_w) is related to the true bulk modulus of elasticity of water ($E_w = 2.3 \cdot 10^9$ N/m) by the relation:

$$\frac{1}{E'_w} = \frac{1}{E_w} - \frac{1-S_r}{P_o} \qquad (4.2)$$

where S_r - the degree of saturation and P_o is the absolute pore-water pressure.

The condition $G/E'_w \to 0$ corresponds to the soil completely saturated with pore-water which does not contain gas. Since the value of G for the fine sand as in LUBIATOWO experiments is about $10^7 \div 10^8$ N/m^2, the stiffness ratio, G/E'_w becomes :

$$G/E'_w \approx 10^{-2} \div 10^{-1} \qquad (4.3)$$

The general solution of the boundary value problem under the condition $G/E'_w \to 0$ yields (Yamamoto et al., 1978; Massel, 1981):

$$\nabla^2 p = 0 \qquad (4.4)$$

and

$$p \approx \cosh k(z+h_n) , \qquad (4.5)$$

in which k - wave number related to the frequency ω by the classical dispersion relation.

The result (4.4) is the same as that obtained by Massel (1976) (see also Putnam, 1949, Reid and Kajiura, 1957) who assumed that the soil is rigid and water is incompressible (the potential solution). The pressure attenuation for this case is small and independent of the permeability of the soil. From the theory given in Massel' (1976) paper, the following transfer function can be deduced:

$$H_{p\zeta}(\omega) = \frac{\cosh k(z+h_n)}{\cosh k(h_n-h) \cdot \cosh kh} \qquad (4.6)$$

when the pore-pressure is expressed in the water column. The solution (4.6) is shown in the Figs. 3.3 and 3.4 by the solid lines. They confirm the general agreement between theory and experiment; especially in the frequency band, in which the coherence function $\gamma^2 \geqslant 0.75$. Out of this range, for the low frequencies, the experimental transfer function is smaller than the theoretical one. Reason for such behaviour is not quite clear.

5. Others theoretical solutions

The solution of Biot's equations for the various boundary conditions is greatly facilitated by the boundary layer approximation introduced by Mei and Foda (1980).

In this approximation, two regions with different physical mechanisms are distinguished. In the interior of the soil the water and solid skeleton velocities are assumed to be of the same order. On the other hand, near the bottom surface, the drainage is much easier and relative fluid velocity is higher. The solution of the problem consists of the solution of the typical elasto-static problem and the boundary layer correction being appreciable only within this layer.

The results of the calculation, according Mei and Foda (1980) approximation, are shown in Figs. 3.3. and 3.4. by the dotted lines. The agreement with the experimental data is quite good.

It should be noted that the calculations using the full Yamamoto et al. (1978) solution for true G/E'_w value were carried out. The results of calculations are in complete agreement with those of the boundary layer approximation; therefore they are not shown in Figs. 3.3 and 3.4.

6. Conclusions

In recent years the understanding of the interaction of the wave motion and the porous sea and the ability to predict the poro-pressure has increased considerably. A lot of the theoretical solutions were obtained. They include the effects of the stiffness of porous medium and the bulk modulus of water elasticity on the pore pressure attenuation, displacements and stresses in the porous media. However, the field data are not numerous. In the paper, the two field experiments were reported. The pore pressure attenuation was measured at a few levels in the porous media under the wind waves action. The collected data were processed and the statistical and spectral characteristics were found. The comparison of the experimental data with the various theoretical solutions demonstrates that the boundary layer approximation and the full Yamamoto et al. (1978) solutions properly reflects the observed physical mechanisms. The potential theory only slightly overpredicts the experimental values. However, it should be noted that this conclusion is true for the soil conditions similar to that in LUBIATOWO experiments (fine-grained sand).

7. References

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