Attenuation of Groundwater Flow Due to Irregular Waves in Permeable Sea Bottom

Anna Przyborska

Abstract The disappearance of wave energy in porous medium, expressed by the decreasing pore pressure, depends on the properties of the soil matrix and compressibility of water in the matrix pores. On the other hand, the compressibility of pore water depends to a large extent on the content of air/gas in water. Thus, it seems that the problem of water circulation resulting from surface waves is in fact a problem from the theory of multiphase media. Transmittance functions between surface waves and pore pressure at different depths as a result of the linear wave theory well reproduce the experimental data at frequencies close to the spectrum of peak energy.

Keywords Pore pressure • Permeable beach • Circulation of groundwater Filtering • Modeling • Irregular waves

1 Introduction

For tideless seas the groundwater flow is governed entirely by the surface wave dynamics and current on the beach, the crucial role is played by the surface wave dynamics. As waves propagate towards the shore, they become steeper owing to the decreasing water depth and at some depth the waves lose their stability and start to break. When waves break, wave energy is dissipated and the spatial changes of the radiation stress give rise to changes in the mean sea level. After the wave reaches the shore, it will run up and run down the beach face. This phenomena drives a complex groundwater circulation in a porous medium. Water infiltrates into the coastal aquifer on the upper part of the beach near the

A. Przyborska (✉)
Institute of Oceanology, Polish Academy of Sciences, Warsaw, Poland
e-mail: aniast@iopan.gda.pl

T. Zielinski et al. (eds.), *Insights on Environmental Changes*, GeoPlanet: Earth and Planetary Sciences, DOI: 10.1007/978-3-319-03683-0_8,

maximum run-up, and exfiltration occurs on the lower part of the beach face near the breaking point (Longuet-Higgins 1983).

The research on the propagation above a permeable bottom, but over constant depth, began about 35 years ago (Moshagen and Torum 1975; Massel 1976). It turned out that the loss of wave energy in a porous medium, expressed by the loss of pore pressure depends on the properties of the soil matrix and the compressibility of water moving within the pores of the matrix.

The compressibility of pore water depends to a large extent on air/gas content in water. The relation shows that circulation of water induced by surface waves is essentially a problem of the multiphase media dynamics (Biot 1956; Mei and Foda 1981). Water in a porous medium, which transports oxygen, plays an important role in maintaining the biological life in the beach sand (McLachlan 1989; Shum 1993; Weslawski et al. 2006). It was observed that natural sea-water filtration in bottom sand consists of two types of processes: physical and biological. Advective physical processes have a significant impact on sedimentary processes. Sandy sediments may thus be a unique environment that differs significantly from cohesive sediments (Huettel and Rush 2000; Huettel et al. 2003).

Some interesting results were obtained in a three-year international research program COSA. The COSA (Coastal sands as biocatalytic filters) demonstrated the important role of sand in the functioning of marine coastal ecosystems. One of the most striking features of beach sand is the fact that these deposits can effectively catch particles in the water column near the bottom, allowing thereby to provide effectively non-organic matter to the sediment (Huettel and Rush 2000).

Numerous references show that the potential solution well reproduces the movement of water in a porous bottom of high permeability, i.e. fine stones, coarse and medium sand. For very low permeability potential solution differs from experimental data (e.g. Massel et al. 2004), since such soil requires taking into account the consolidation of the bottom material and water compressibility. Previous studies showed that pore water is not a single phase medium. Initial work on the development of two phase liquid-matrix theory, was started by Terzaghi (1943). Biot (1956) improved and generalized his theory. The basic idea is the adoption of Biot's theory of elastic soil matrix and laminar flow of pore fluid, according to Darcy's law. Massel et al. (2004, 2005) formulated a solution based on the theory of multiphase media with an assumption of constant sea depth. This article is an extension of these studies and presents the results for irregular waves. The paper is organized as follows. At the beginning it discusses the governing equations for groundwater pressure and its circulation. In particular, it describes transmittance functions between surface waves and pore pressure at different depths as a result of the linear wave theory. The next part compares the theoretical results with the experimental data obtained during laboratory measurement on Grofier Wellenkanal (GWK) in Hannover (Germany) and the experimental data collected in natural conditions. Finally, the last section gives the summary and main conclusions.

2 Theoretical Basis

In natural conditions and sometimes in the laboratory—generated waves have random nature. Consider, therefore, the stochastic relationships between the sea surface and the pore pressures based on linear systems theory.

According to the theory of linear systems, the relationship between the output signal $y(t)$ and the input signal $x(t)$ is described using the convolution integral:

$$y(t) = h(t) \star x(t) = \int_0^\infty h(\tau)x(t-\tau)d\tau \tag{1}$$

where the symbol $\star$ is a convolution operation and $h(\tau)$ is the impulse response function.

For transmittance function $H(\omega)$ we have the (Otnes and Enochson 1972) relation:

$$H(\omega) = \int_0^\infty h(\tau)e^{-i\omega\tau}d\tau \tag{2}$$

Knowing $h(t)$ for the input $x(t)$, the $y(t)$ system response may be determined. Equation (1) is not always practical, the relationship between the respective input signal spectrum densities and the system responses is more useful:

$$Y(i\omega) = |H(i\omega)|^2 X(i\omega) \tag{3}$$

where

$$H(i\omega) = \mathcal{F}(h(t)) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} h(t)\exp(-i\omega t)dt \tag{4}$$

is the Fourier transform of the response $h(t)$, and:

$$X(i\omega) = \mathcal{F}(x(t)) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} x(t)\exp(-i\omega t)dt \tag{5}$$

and

$$Y(i\omega) = \mathcal{F}(y(t)) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} y(t)\exp(-i\omega t)dt \tag{6}$$

are respective Fourier transforms of signals $x(t)$ and $y(t)$.

If we assume that the spectral wave density $S_\zeta(\omega)$ is the system input function and the output function is pressure spectral density at a set depth, $S_p(\omega, z)$ in (3), we obtain:

$$S_p(\omega, z) = |H(\omega, z)|^2 S_\zeta(\omega) \tag{7}$$

and

$$S_{\zeta p}(\omega) = H(\omega) S_{\zeta(\omega)} \tag{8}$$

In practical applications the so-called coherence function between the signals at the input and output is often used. Thus, we have:

$$\gamma^2_{\zeta p}(\omega) = \frac{|S_{\zeta p}(\omega)|}{S_x(\omega) S_y(\omega)} \tag{9}$$

First let us consider planar motion in the plane $O(x, z)$ (Fig. 1).

Let the surface wave of height H, frequency ω and the wave number k move towards the positive sense of axis x. The water depth is constant and is h, and under the bottom there is a porous layer of thickness (h_n − h).

The proposed solution is based on the theoretical concepts of multiphase flows in porous media of the beach. The basic value determined experimentally or calculated in the model is pore pressure in the beach sand.

In the general case, the loss of pore pressure in the soils is complex and depends strongly on the mechanical and hydraulic properties of the medium and the surface wave properties forcing water movement. Theoretical model, based on Biot's theory, takes into account soil deformations, the content of the air/gas dissolved in pore water and the change of pore water volume and flow direction (Biot 1956), resulting in vertical gradients and vertical pore pressure gradient. It is assumed that the deformation of the soil matrix satisfied the linear elasticity law and the relationship between the pressure gradient and the pore water velocity is expressed by the Darcy's law. This means that we examine the case of low

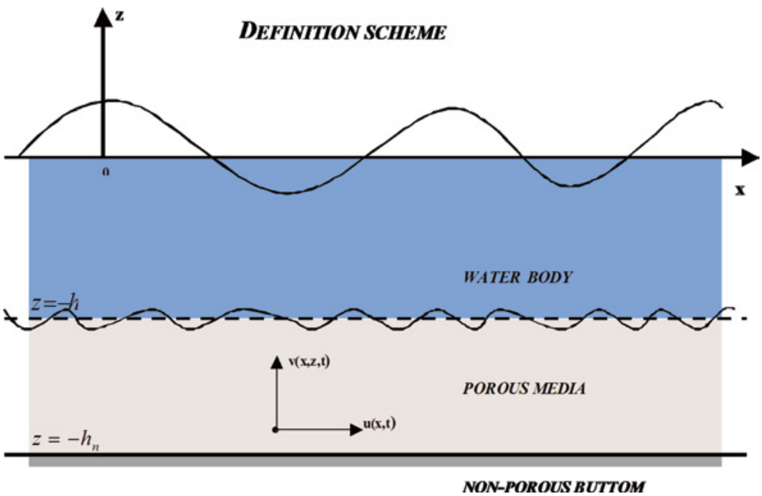

Fig. 1 Reference system

permeability. The case of high permeability. When the Darcy's law cannot be used, requires a different approach.

It is important for the studied issue that when waves break, they inject air and gases into the porous medium. In addition, gases are produced by organisms living in the sand. As a result, we deal with a three-phase medium which consists of a soil skeleton, pore water and gas/air. As a result, the elastic modulus of pore water E'_w depends on the degree of water saturation with air (Verruijt 1969):

$$\frac{1}{E'_w} = \frac{S}{E_w} + \frac{1-S}{p_0} 1 - S \ll 1, \tag{10}$$

where:

- E_w true bulk modulus of pore water without air $\left(E_w = 2.3 \cdot 10^9 \mathrm{N/m}^2\right)$,
- S the degree of saturation of the soil matrix pores with water,
- p_0 absolute pressure at a given point (the sum of pressure hydrostatic pressure and pressure induced by sea surface),
- E'_w apparent bulk modulus of water.

E'_w is different for different levels and decrease with depth of the pore layer, which suggests that E'_w ratio depends not only on the air content but also on the absolute pressure. Even at low air content, ca. 0.1 %, modulus E'_w is about 10 times lower than the modulus of E_w, (Verruijt 1969).

The value of E'_w is very difficult to estimate in experimental conditions due to the lack of a good device for measuring gas content in the porous seabed. de Rouck and Troch (2002) conducted field research on the basis of $(1-S)$ in pore water was estimated at about 3 %. The measurements were carried out in connection with the planned expansion of the Zeebrugge Port in Belgium. Pore pressures were measured at a depth of 18 m under the sea bed in areas where water depth ranged between 5 and 10 m. Under laboratory conditions (Tørum 2007), assessed the value of the parameter S at 3–10 %.

In the paper by Massel et al. (2005) they proved that an important parameter that determines the accuracy of the solution is the ratio of the soil matrix modulus G and the modulus of elasticity of pore water E'_w. The shear modulus of the soil G takes the following form:

$$G = \frac{E_s}{2(1+\nu)} \tag{11}$$

where:

- E_s Young's modulus of soil,
- ν Poisson's ratio.

The following general equation for disappearance of pressure in the porous layer, resulting from the Biot theory, was obtained:

$$\nabla^2 p - \frac{\gamma n}{K_f E'_w}\left[\frac{\partial p}{\partial t} + \frac{E'_w}{n}\left(\frac{\partial \nu_x}{\partial x} + \frac{\partial \nu_z}{\partial z}\right)\right] = 0 \tag{12}$$

where:

K_f	coefficient of permeability,
$\gamma = \rho g$	specific gravity of water,
k	wave number,
n	porosity of the porous medium,
ω	frequency wave,
L	wavelength,
E'_w	the bulk modulus of pore water,
G	modulus of the soil matrix,
$(nu_x\ nu_z)$	components of the velocity vector of the soil matrix deformation,
p	pore pressure.

Equation (12) expresses the effect of saturation of soil matrix with air/gas and the influence of the dynamic pressure on the do formation of the matrix. When soil is completely saturated with water and pore water does not contain air $\left(\frac{G}{E'_w} \to 0\right)$, the solution of Eq. (12) for the steady state is identical to that received by Putman (1949), who assumed that soil is stiff and water is incompressible.

Therefore, for fully saturated soil, e.g. rough gravel when K_f is high, the expression (12) reduces to Laplace's equation:

$$\nabla^2 p = 0 \tag{13}$$

and the solution of boundary value problem has the following form:

$$p(x,z,t) = \rho_w g \frac{H}{2} \frac{\cosh(kh)\cosh[k(z + h_n)]}{\cosh[k(h_n - h)]} \cos(kx - \omega t) \tag{14}$$

or:

$$p(x,z,t) = \rho_w g \frac{\cosh[k(z + h_n)]}{\cosh[k(h_n - h)]} \zeta(x,t), \tag{15}$$

where $\zeta(x,t)$ is the see surface elevation.

On the basis of the above, there is no phase delay between the ordinates of the sea surface elevation and pore ~ pressure, and the change of the sea surface elevation causes an immediate change in pore pressure. Massel et al. (2005), analyzed the results of laboratory experiments and showed that Eq. (13) cannot be used for fine sand. In another extreme case where fine sand is saturated with air or gas, soil stiffness becomes significantly greater than the stiffness of pore water. When $\left(\frac{G}{E'_w} \to \infty\right)$, part of the equation $\frac{E_{w'}}{nG}\left(\frac{\partial \nu_x}{\partial x} + \frac{\partial \nu_z}{\partial z}\right) \to 0$ and the equation for pore water pressure (12) can be written in a simpler form:

$$\nabla^2 p - \frac{\gamma n}{K_f E'_w}\frac{\partial p}{\partial t} = 0 \tag{16}$$

For example, when $S = 95\ \%$ (air content is therefore 5 %), the modulus of water elasticity is about three orders of magnitude lower than the modulus for water without air and is $E'_w = 2 \cdot 10^6 \text{N/m}^2$ (Tørum 2007). For example, for fine sand, where $G \approx 10^8 \text{N/m}^2, \frac{G}{E'_w} \approx 100$.

The solution of Eq. (16) is a function of:

$$p(x,z,t) = \Re\left\{\rho_w g \frac{H}{2} \frac{\cosh[\psi(z+h_n)]}{\cosh(kh)\cosh[\psi(h_n-h)]} \exp[i(kx - \omega t)]\right\} \quad (17)$$

where

$$\psi^2 = k^2\left(1 - i\frac{n\gamma\omega}{k^2 K_f E'_w}\right), \quad (18)$$

where n is a measure of porosity (volume ratio of free to total volume of pores), $\Re$ is the real part of complex value. Solution (17) can be rewritten in the following form:

$$p(x,z,t) = \Re\left\{\frac{\rho_w g}{\cosh(kh)}\left|\frac{\cosh[\psi(z+h_n)]}{\cosh[\psi(h_n-h)]}\right| \exp[i\varphi)]\right\}\zeta(x,t) \quad (19)$$

The solution (19) shows that air in the porous medium causes a phase delay φ between the deflection of the sea surface elevation and pore pressure. The experiment in Hannover showed that the ratio $\frac{G}{E_w} \in (50, 400)$.

For $\frac{G}{E_w} > 50$, vertical pressure distribution in soil pores was very close to the distribution from Eq. (16), identical to the solution obtained in the work of (Moshagen and Torum 1975), where the soil matrix is stiff and the fluid is compressible which indicates that the compressibility of soil matrix in the case of fine sand does not affect the distribution of pore water pressure.

The solutions of Eqs. (12) and (16) coincide well with the experimental data (Massel et al. 2004). Due to a simpler form of Eq. (16), it will be used in further analysis.

Spectral properties of the relation between surface waves and pressures in the soil layer are described based on the selected test data.

Let us assume the following labels:

ζ elevation of the free surface registered by the wave probe,
p_{ij} pore pressure measured by sensor j in system i.

Thus, we determine the transmittance functions resulting from the linear theory and compare them with the corresponding experimental values.

For linear system, the following spectral relation is true, (Bendat and Piersol 1976):

$$S_p(\omega, z) = |H(\omega, z)|^2 S_\zeta(\omega) \quad (20)$$

$$H(\omega, z) = \sqrt{\frac{S_p}{S_\zeta}} \quad (21)$$

As a result of the calculation, the theoretical transmittance function has the following form:

- surface—pressure in soil at a depth of zm

$$|H(\omega, z)| = \frac{\cosh(\psi(z + h_n))}{\cosh(kh)\cosh(\psi(hn - h)} \tag{22}$$

- pore pressure at a depth of z_1m—pore pressure at a depth of z_2m

$$|H(\omega)| = \frac{\frac{\cosh(\psi(z_2 + h_n))}{\cosh(kh)\cosh(\psi(hn - h))}}{\frac{\cosh(\psi(z_1 + h_n))}{\cosh(kh)\cosh(\psi(hn - h))}} \tag{23}$$

3 Experimental Data

To enhance the knowledge of marine hydrodynamics of coastal zone for permeable sandy bottom, experiments were performed in a laboratory and in natural conditions and data on the dynamics of pore pressure in the permeable seabed layer immediately adjacent to the aqueous layer were collected.

Given the many constraints and technical difficulties of such an examination in natural conditions, the main material is the data from the experiment in the Grosse Walencannal in Hannover. The methodology of this study was extensively described in Massel et al. (2004). On one hand, the huge wave channel allowed to create conditions of movement of water in almost natural scale 011 the other hand. It allowed to repeat the tests and provided strict control of input and output parameters.

During the study, natural sand was heaped to form an artificial beach with a uniform slope 1:20. The bottom material was well sorted out fine sand of which more than 95 % grains fell within the range of 0.125–0.5 mm.

Four sensor systems were installed to measure pore water pressure in the beach sand. This paper will present the results of the system located where still water level was 2 m. The place was chosen so that the system was located before the breaking zone and the sensors recorded only the *phase-resolving* component, the *phase-average* component was not observed in that location.

Each system consisted of four piezoelectric pressure sensors attached to the metal rod arranged in the form of a cross (Fig. 2). This approach made it possible to estimate not only the pore pressure but also the horizontal and vertical velocity of water in the beach sand.

The systems were buried so that the upper pressure sensor was 10 cm below the bottom. Additionally waring was measured using wave probes. In the experiment with irregular waves wave sequences corresponding to the JONSWAP spectrum ($\gamma = 3.3$) were generated. 13 tests were carried out for irregular waves (Table 1) which aimed at simulating wind waves in almost natural conditions.

Wave surface in the wave channel, just like the surface of the sea in the real world, had irregular and complex shape. Analysed data consisted of 20–25 min recordings of surface waves and pore pressures at various depths. The data were recorded with a frequency of 120 Hz.

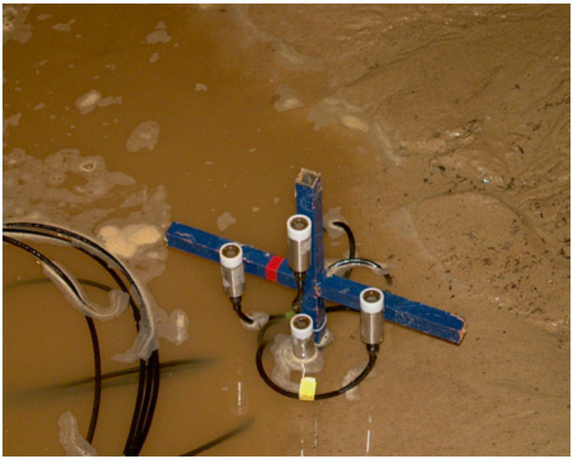

Fig. 2 System with pressure sensors

Table 1 Tests with irregular waves

Number test	File (number)	$H_s m$	T_p (s)	Water depth (m)	H_{max} (m)	$\{x_{br}\}_{min}$	x_{max}
43	28110303	0.2	6.0	4.10	0.330	221.0	235.0
44	01120301	0.1	6.0	4.10	0.660	214.0	–
45	02120301	0.6	6.0	4.10	0.781	212.0	244.0
46	02120302	0.8	6.0	4.10	1.016	206.0	248.0
47	02120303	0.2	7.0	4.10	0.261	224.0	236.0
48	02120301	0.1	7.0	4.10	0.523	216.0	240.0
49	02120305	0.6	7.0	4.10	0.781	214.0	242.0
50	02120306	0.8	7.0	4.10	1.016	204.0	248.0
51	02120307	1.0	7.0	4.10	1.731	196.0	251.0
52	03120301	1.0	6.0	4.10	1.731	192.0	250.0
53	03120302	0.2	8.0	4.10	0.261	223.0	238.0
54	03120303	0.1	8.0	4.08	0692	212.0	241.0
55	03120301	0.6	8.0	4.08	0784	212.0	244.0

The study provided valuable material for comparison of experimental data with theoretical solutions.

The method of distribution of energy supplied between individual frequencies of surface waves is illustrated by the features the spectral energy density $S(\omega)$. The energy distribution is approximated by the spectrum estimation based on the Wieiier-Kliinchine'a theory called the Blackmail-Tukey method. The basis of the Blackmail-Tukey method is determining the estimator of the power spectral density function as the Fourier transform of the product of the autocorrelation function and the smoothing function, such as e.g. Hanning function.

The Blackmail-Tukey method improves the resulting spectrum vector, emphasizing proper components, while suppressing the noise effect. Figures 3 and 4 show the autocorrelation function for the selected tests 44 and 45, and the corresponding spectral function waveforms $S(\omega)$.

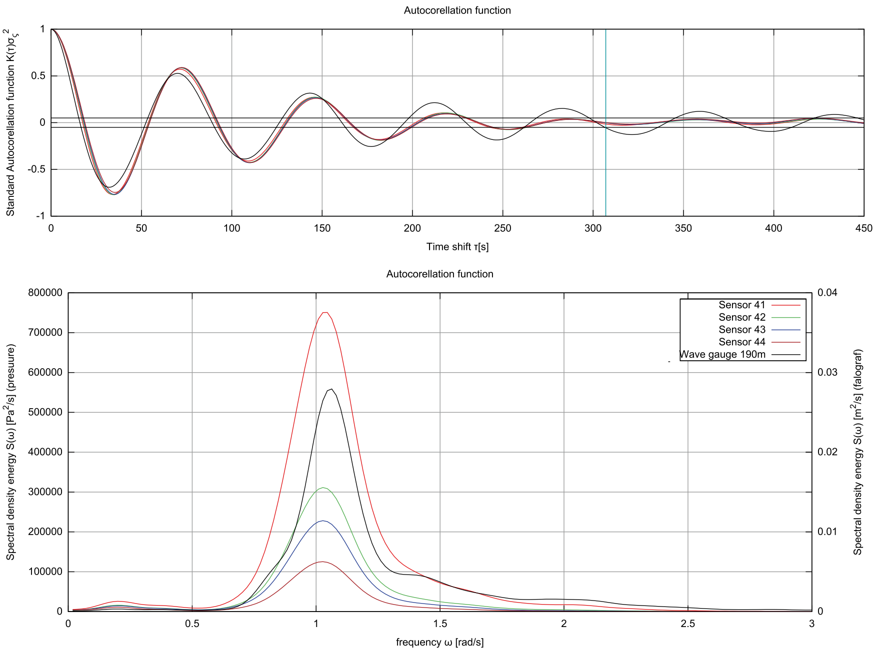

Fig. 3 Autocorrelation functions and frequency spectra of pore pressure—test 44

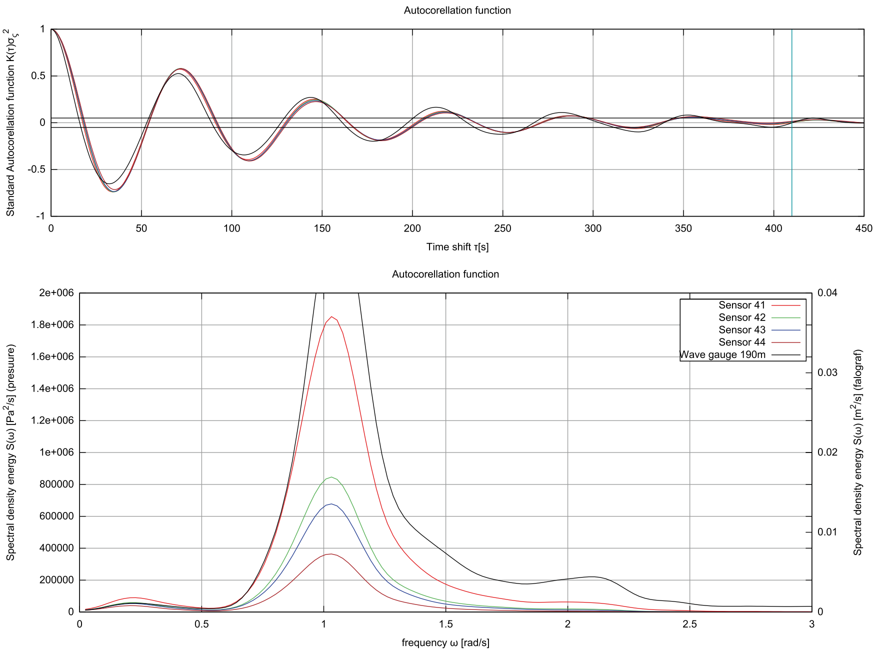

Fig. 4 Spectrum of the wave function and the spectrum of pore pressure—test 45

These figures shows that individual waves that make up the final shape of wave surface are supplied with energy in a non uniform way. Most energy is transferred to wave of frequency ω_p and adjacent frequencies. Vertical lines in figures indicate the maximum number of shifts m, which corresponds to the normalized autocorrelation function $K = 0.05$

Slight shift of the peaks of surface wave spectra and pore pressures indicates the presence of non-linear mechanisms. This is confirmed by the spectral wave function. Additional peaks, both in the band of high and low frequencies, in relation to the primary peak frequency, are visible for both the wave function spectra. These additional peaks disappear as the depth increases. This means that the movement of pore water becomes more linear as the depth of the porous bottom increases.

Figures 5 and 6 show comparison between experimental and theoretical transmittance function for test 45 and 46. $H_{pi\varsigma}$ are transmittance functions between surface waves ς and pore pressure register by gauges p_i (p_i was located at the depth $z = 0.1\ m$, $p_2z = 0.2\ m$, $p_4z = 0.3\ m$.) Function H_{p4p1} is a transmittance function between pore pressure at various depths, for gauge 1 (depth z = 0.1 m) and pore pressure registered by sensor 4 (depth 0.3 m).

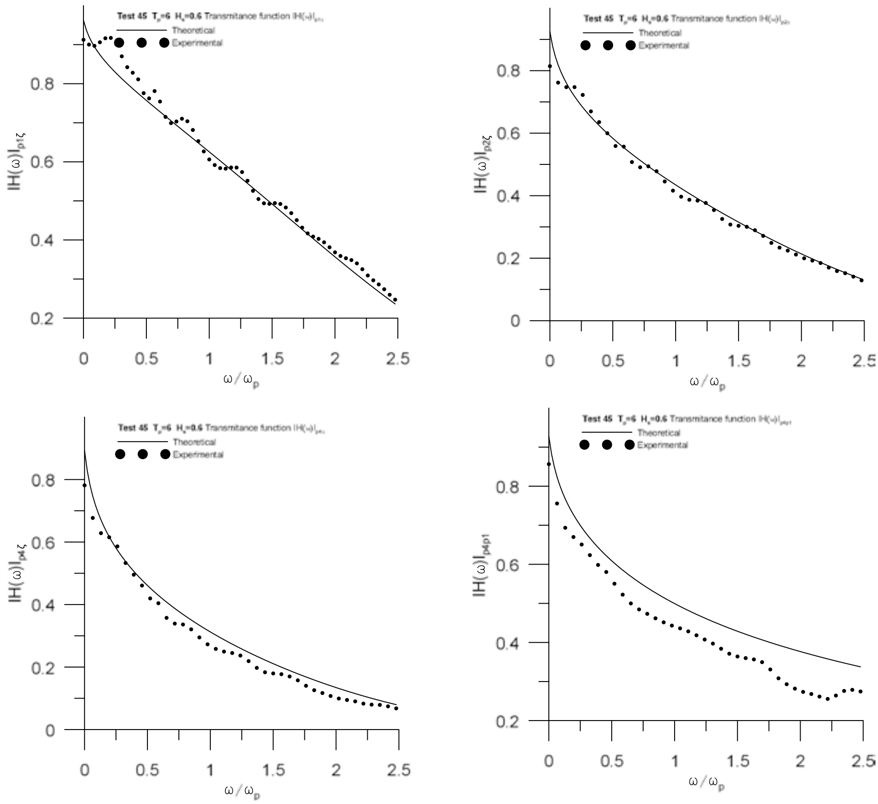

Fig. 5 Theoretical and experimental transmittance function for the test no. 45

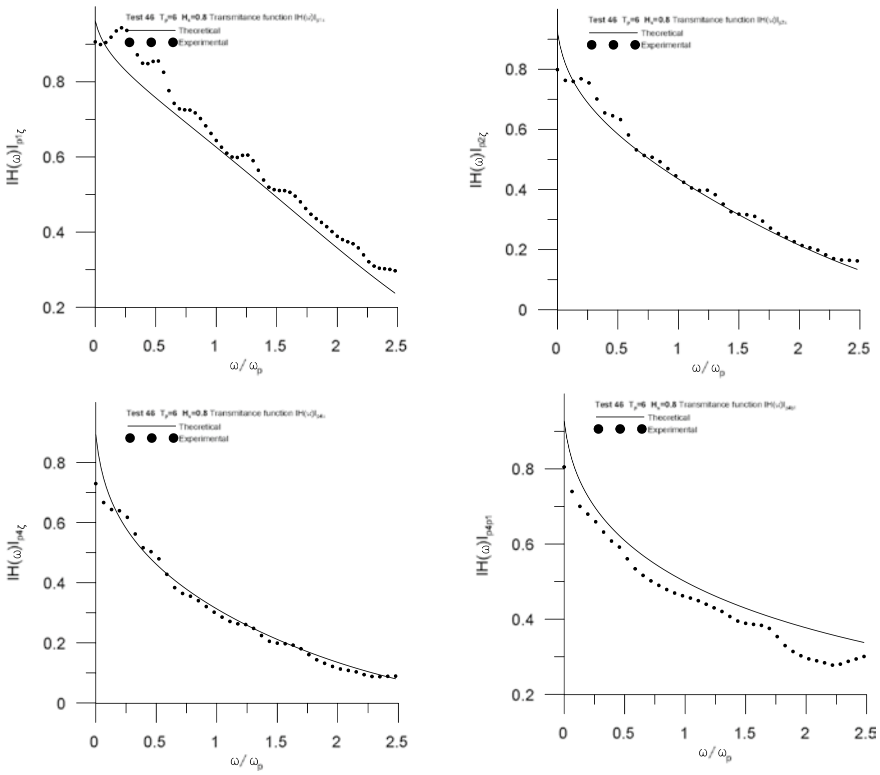

Fig. 6 Theoretical and experiential transmittance function for the test no. 46

Results show that in frequency range $0 < \frac{\omega}{\omega_p} < 2.5$ experimental transmittance function does not deviate too much from the theoretical functions.

This suggests that in laboratory conditions pore pressure in the soil surface layer disappears according to the presented theory. Less compliance for transfer function H_{p4p1} is probably due to a condition of errors in estimating both pressure p_1 and pressure p_4.

Similar results were obtained from the analysis of the data collected in natural conditions on the Jurata beach. The soil in the area of research was fine, homogeneous and relatively clean sand. The porosity of n size was not measured during the test; its value was estimated at 0.3–0.4 based on the reference data.

The measurement of pore pressure at various depths in the seabed permeable layer immediately adjacent to the aqueous layer was performed with a set of pressure sensors (Fig. 7) designed and built by the Institute of Oceanology.

This instrument consists of six membrane pore pressure sensors, sensitivity of 0.019 mbar, contained in a metal tube at 0.1 m intervals. During the study on the Jurata beach the pore pressure sensors took measurements for 20 min at the frequency of 5 Hz with 15 min breaks. The structure with the sensors was placed in the porous bottom in such a way that the sensors were at the following depths: 0.18,

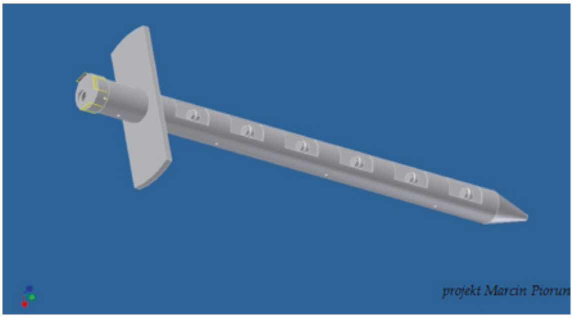

Fig. 7 Housing of pore pressure sensors

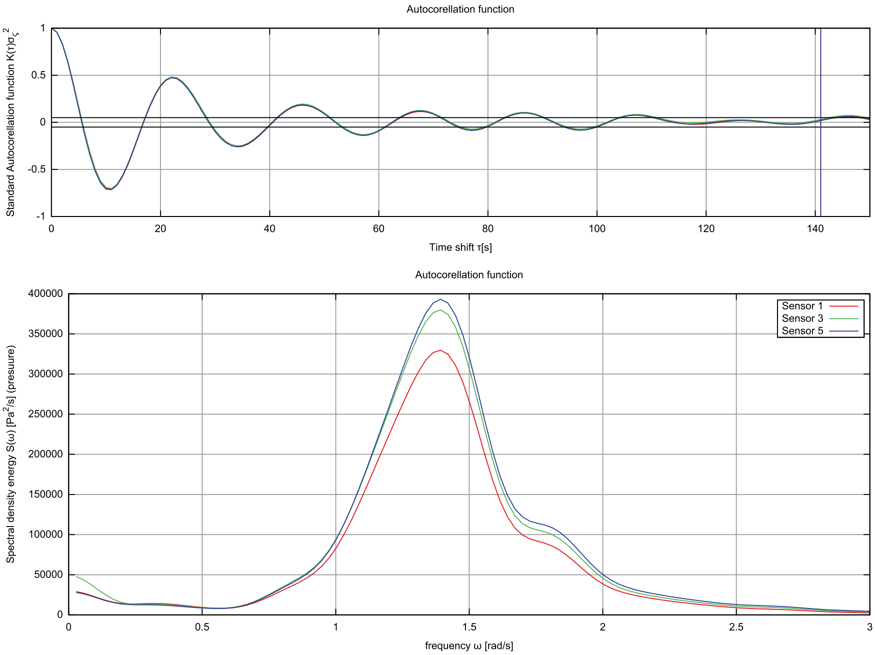

Fig. 8 Autocorrelation functions and spectra of pore pressure for the data from Jurata (record 2)

0.28, 0.38, 0.48, 0.58 and 0.68 m. The device with pressure sensors was placed in a location where water depth was ca. 0.6 m, which was ca. 30 m from the shore.

Next, a test was performed on the Data Logger in front of the breaking zone, ca. 70 m from the shore where water depth was ca. 1.4 m, and the pressure sensor on wave recorder was at the level of 0.6 m above the bottom. Although the experiment in Jurata was part of the tests of the newly built instrument, and its purpose was to check the quality of the data collected by the newly constructed Data Logger, and still requires testing in different conditions, the outcome confirms the results obtained in laboratory. Figures 8 and 9 show the autocorrelation functions and the corresponding spectral functions $S(\omega_k)$ for selected logs.

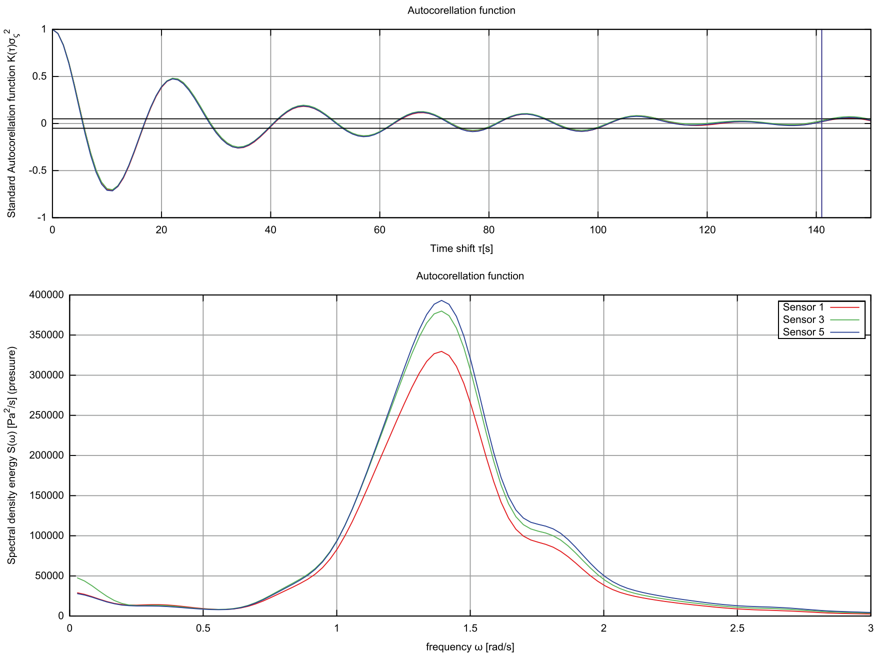

Fig. 9 Autocorrelation functions and spectra of pore pressure for the data from Jurata (record 4)

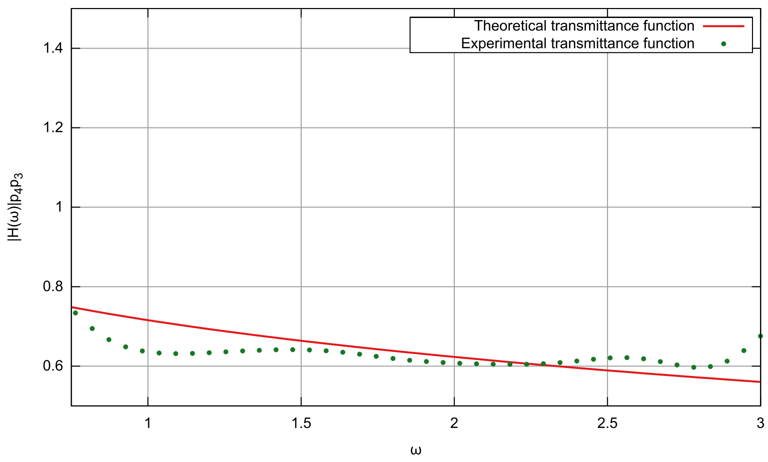

Fig. 10 The transmittance between the pore pressure at different depths

Equation (7) was used to determine theoretically the transmittance functions between the pore pressures at two different depths, 0.36 and 0.46 m, and to compare the data recorded by the sensor p_3 and sens or p_4. An example of transmittance functions for the data from Jurata is shown in Fig. 10. In the frequency range of ($0.8 < \omega < 2.5$) the transmittance function between the pore pressures at two different depths fairly well coincides with the transmittance function determined from the linear theory (23), except for the band of low frequencies. This is likely due to the fact that exact depth of pressure sensors is not known. The values are estimated only on the basis of what was recorded when the equipment was being installed. A similar result was obtained by Massel (1982) during the coastline experiment in Lubiatowo.

4 Summary

Natural seawater filtration mechanism in the sand is a very complex system, it includes knowledge from many fields. Research has shown that the sands are very active. High rate of the process is due to high level of water permeability. Water easily soaks into the sand and actually in the spaces between the grains, transporting dissolved oxygen which, combined with the activity of seabed organisms and porous sand sediments, from a high efficiency filtration system, which is necessary for transformation of organic matter into simple inorganic compounds, combined with the activity of the organisms present on the seabed sediments form a porous sand filtering system with high efficiency.

This paper proposes a theoretical model of determining pore water pressure for typical sandy beaches when the slope of the bottom of the area before the breaking zone is very small, which takes into account the deformation of the soil matrix and the content of air dissolved in the pore water, as well as the change matrix of pore water flow volume and direction with an assumption that soil matrix deformation satisfies the linear elasticity of law and the relationship between the pressure gradient and the pore water velocity is expressed by Darcy's law. Research is performed on a three-phases medium consisting of soil matrix, pore water and air.

The present model, as an approximation to a very slowly varying medium, provides useful information; we known that in natural condition, it is possible that in homogeneous environments characterised by more complex and steep variations can be more consistently treated by coupled-mode models, as the one presented in Belibassakis (2012).

Biot's theory of multi-phase media is a good basis for building models of the decay of pore water pressures induced by varying sea surface. The analysis shows that transmittance functions between surface waves and pore pressure and between the pore pressures at various depths for fine uniform well-graded sand correspond quite well with the experimental data and the in situ data. The transmittance functions between the surface waves and the pore pressure, and between pore pressures at various depths resulting from the linear wave theory, well reproduce the experimental data in the frequency band close to the peak wave energy. This method may be used in static calculations for structures erected on seabed and for evaluating the impact of waves on the movement of bed material.

As the estimation of infiltration into beach sand is very difficult to carry out under real sea conditions, a controlled large-scale laboratory experiment was

carried out in the Groser Wellenkanal (GWK) in Hannover (Germany) as part of the project “Run-up of waves on beaches and induced infiltration in the beach body” supported by the European Community (contract HPRI-CT-2001-00157).

The experimental data were collected in natural conditions under the supervisor’s research from the Ministry of Science and Higher Education- Circulation of groundwater induced by surface wave dynamic on the beach N N306 003536.

The theoretical results of the paper have been compared with the experimental data collected during the laboratory work and in natural conditions experiment and showed very good agreement.

References

Belibassakis K (2012) Water-wave induced groundwater pressure and flow in variable bathymetry regions and sandy beaches by an enhanced coupled-mode model. Ocean Eng 47:104–118

Bendat JS, Piersol AG (1976) Metody analizy i pomiaru sygnalow losowych. PWN, Warszawa

Biot MA (1956) Theory of propagation of elastic waves in a fluid-saturated porous solid. Part 1: low frequency range, Part 2: higher frequency range. J Acoust Soc Am 28:168–191

Huettel M, Roy H, Precht E, Ehrenhauss S (2003) Hydrodynamical impact on biogeochemical processes in aquatic sediments. Hydrobiologia 494:231–236

Huettel M, Rush A (2000) Transport and degradation of phytoplankton in permeable sediment. Limnol Oceanogr 45(3):534–549

Longuet-Higgins MS (1983) Wave set-up, percolation and undertow in the surf zone. Proc Roy Soc London A390:283–291

Massel SR, Przyborska A, Przyborski M (2005) Attenuation of wave-induced groundwater pressure in shallow water. Part 2. Theory. Oceanologia 47(3):291–323

Massel SR, Przyborska A, Przyborski M (2004) Attenuation of wave-induced groundwater pressure in shallow water. Part 1. Oceanologia 46(3):383–404

Massel SR (1982) Rozkład ciśnień porowych wywołanych falowaniem wia-trowym w piaszczystej warstwie dna morskiego. Rozprawy Hydrotech- niczne -Zeszyt 44

Massel SR (1976) Gravity waves propagated over a permeable bottom. J Waterway Div 102:111–121

McLachlan A (1989) Water filtration by dissipative beaches. Limnol Oceanogr 34:774–780

Mei CC, Foda MA (1981) Wave-induced responses in a fluid-filled poro-elastic solid with a free surface—a boundary layer theory. Geophys J Roy Astron Soc 66:597–631

Moshagen H, Torum A (1975) Wave-induced pressures in permeable sea-beds. J Waterway Div 101:49–57

Otnes EK, Enochson L (1972) Analiza numeryczna szeregów czasowych. Tytuł oryginalny: Time-series analysis—data processing. Wiley, New York, 467 stron

Putman JA (1949) Loss of wave energy due to percolation in a permeable sea bottom. Trans Am Geophys Union 30:349–356

de Rouck J, Troch P (2002) Pore water pressure response due to tides and waves based on prototype measurements. PIANC Bull 110:9–31

Shum KT (1993) The effects of wave-induced pore water circulation on the transport of reactive solutes below a rippled sediment bed. J Geoph Res 98:10289–10301

Terzaghi K (1943) Theoretical soil mechanics. Wiley, New York

Tørum A (2007) Wave induced pore pressure—air/gas kontent. J Waterway, Port, Coastal, Ocean Eng 133:83–86

Węsławski JM, Andrulewicz E, Kotwicki L, Kuzebski E, Lewandowski A, Linkowski T, Massel SR, Musielak S, Olenczuk-Neyman K, Pempkowiak J, Piekarek-Jankowska H, Radziejewska

T, Różynski G, Sagan I, Skóra KE, Szefler K, Urbanski J, Witek Z, Wołowicz M, Zachowicz J, Zarzycki T (2006) Basis for a valuation of the polish exclusive economic zone of the Baltic Sea: rationale and quest for tools. Oceanologia 48:145–167

Verruijt A (1969) Elastic storage of aquifers. In: Deweist RJM (ed) W zbiorze: flow through porous media. Academic Press, New York, pp 331–376