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A METHOD FOR INVESTIGATION OF SEDIMENT RETENTION IN SANDY TIDAL FLATS

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ABSTRACT: Recently, coastal environmental engineers have made attempts to understand the role of sediment (particulate organic matter adsorbed on fine soil particles, diameter range 1–100 μm) in subsurface environment which is considered to be related to the biodiversity of estuaries. Since the retention amount of sediment is one of important factors in considering the biodiversity, understanding sediment retention is vital to good management of the estuarine environment. In this study, laboratory experiments were conducted to propose a model for investigating the sediment retention based on variations of water head in a sand bed. Field observations were also conducted to verify the validity of the proposed model. From laboratory experiments, variations of water head in the sand bed could be represented by our proposed model with a maximum relative error of 3%. As the proposed model takes the porosity and the hydraulic conductivity of the sand bed into account, sediment retention in the sand bed can be evaluated on the basis of variances in the porosity and the hydraulic conductivity when variations of water heads at the boundary and in the sand bed are known. A method was proposed to measure variations of river water head and water head in a tidal flat. Furthermore, sand material of the tidal flat was sampled in order to determine the porosity and the hydraulic conductivity of the tidal flat. Based on the observation results, the variation of water head in the tidal flat could be reproduced by the proposed model when the porosity and the hydraulic conductivity of the tidal flat were applied into the model. In other words, the porosity and the hydraulic conductivity of the tidal flat can be predicted by the proposed model when variations of river water head and water head in the tidal flat are measured, leading to the understanding of sediment retention in the tidal flat from temporal changes in the porosity and the hydraulic conductivity.

Keywords: Sediment retention, water head, seepage flow, Dupuit-Forchheimer approximation, sandy tidal flat.

INTRODUCTION

In riverbank filtration, organic compounds are important factors associated with both the quality of subsurface water and the biodiversity of the riverbank. During the process of riverbank filtration, river water passes through riverbeds and aquifers that serve as natural filters, and various contaminants such as trace organic pollutants, bacteria, viruses, and inorganic compounds are removed (Sontheimer 1980). Organic matter or mobile particles in groundwater aquifers and soils can facilitate the transport of contaminant as a mobile carrier, and can also be utilized as a food source for bacteria (Ryan and Elimelech 1996). Therefore, understanding biocolloids and particle transport is needed, and the amount of research has increased substantially over the last decade (Sinton et al. 2000; Volker et al. 2002; Kim and Corapcioglu 2002; Bekhit et al. 2009).

Sinton et al. (2000) applied the groundwater transport model AT123D, in conjunction with the PEST optimization routine, to the results of two tracer experiments to estimate transport velocity, longitudinal dispersivity, and removal rate of biocolloids in an alluvial gravel aquifer. In the works by Kim and Corapcioglu (2002) and Bekhit et al. (2009), conceptual, mathematical, and numerical models were developed to account for the different physiochemical and biological processes, reaction kinetics, and different transport mechanisms of the combined system (contaminant–colloids–bacteria–organic matter) in porous media. Bolster et al. (2007) investigated the influence of flow patterns on the transport of conservative contaminants in a coastal aquifer. They suggested that saltwater intrusion forces contaminant transport towards the upper seaward boundary. Zhang et al. (2001) and Volker et al. (2002) presented a comparison of numerical predictions for a simplified seaward boundary condition with experimental results for corresponding realistic conditions including a saltwater interface and tidal variations. These studies can help engineers to understand the transport behavior of contaminants, can be a predictive tool through field investigations, and can also be practically applied to biocolloid transport.

In recent years, coastal environmental engineers have made attempts to understand transport mechanisms of sediment (particulate organic matter adsorbed on fine

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soil particles, diameter range 1-100 μm). This is because the biodiversity of estuaries near densely-inhabited districts and enclosed coastal zones has been heavily damaged due to large deposited amounts of sediment that has been transported from coastal zones or the upstream of river. The large deposited amounts of sediment decreases the purification capacity of the estuaries, and causes the inhibition of benthos and water pollution. Therefore, many methods have been developed by engineers either in environmental or coastal engineering to immediately restore the biodiversity of the estuaries (Tomida et al. 2005; Fujiwara et al. 2007; Fukuma et al. 2009).

According to the works by Fujiwara et al. (2007), groundwater flow significantly encouraged the biodiversity, the environment of an aggravated tidal flat was restored after making currents of water in the ground. It is thought that sediment transport by the water currents into the ground is a significant factor associated with the resotoration of the tidal flat environment. Therefore, understaning sediment retention in the ground has yielded a large body of information used to consider the biodiversity of estuaries, such as the restoration of tidal flat environment and the design of an artificial tidal flat with biodiversity.

The overall objective of this study is to propose a model to predict the sediment retention in estuaries. A laboratory experiment were conducted to propose a model to predict variations of water head in a sand bed along with oscillating boundary water head. Since the porosity of the sand bed is taken into account in this model, sediment retention in the sand bed can be predicted from temporal variations of the porosity. Based on the model, a method is proposed for investigating sediment retention in a tidal flat. A field observation was conducted to show the validity of the proposed method.

METHODS AND MATERIALS

Laboratory Experiment

All experiments described here were run on an apparatus as schematically displayed in Fig.1. The flow tank was made of acrylic plates 500 mm in height, 250 mm in width, and a total length of 1000 mm. The test section, which formed a sand bed, is of 250 mm in width, 250 cm in height, and a total length of 600 mm. The stainless nets (plain square, 0.10 mm on a side) were used as permeable boards at both ends of the test section. The pressure head (piezo-metric head) along the bed was measured by the use of a vinyl tube with an internal of 2 mm. The tubes (manometers) were connected to the bed at intervals of 40 mm in the vertical and 100 mm in the horizontal directions. To measure water head

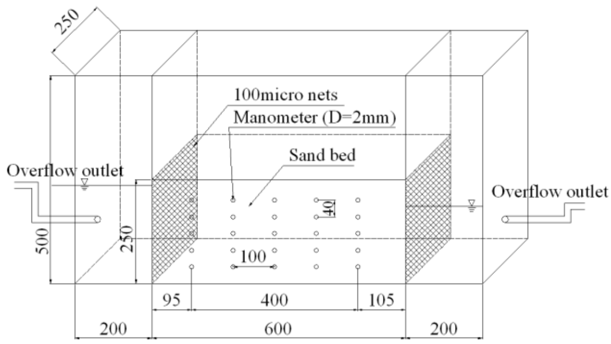

Fig. 1 Apparatus used in the experiment

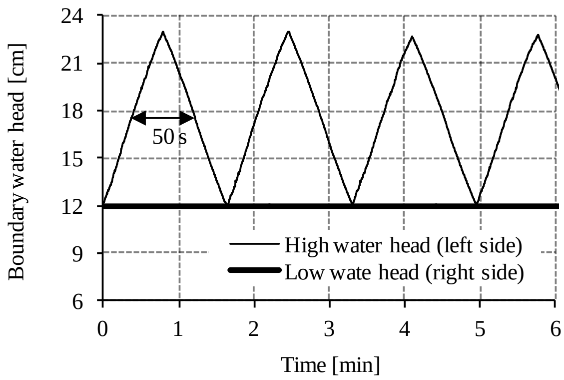

Fig. 2 Boundary water heads of seepage flow

continuously, pressure sensors (SSK, P310A-02) were installed at the inlet section (x= 0) and at x= 10, 20 cm in the sand bed (10 mm from the bottom of the sand bed).

The fluid was added to the inlet section using a pump, to allow the fluid to flow across the test section. Seepage flow was made with boundary water heads viewed in Fig. 2. The right boundary water head was kept at 12 cm (from the bottom of the sand bed) throughout the experiment using the constant head overflow method. On the other hand, the left boundary water head was varied from 12 ↔ 23 cm in 50 seconds. The experiment was conducted using supply water at an ambient temperature of approximately 20 to 25°C.

Sand material was packed in the test section to form a porous bed with a fixed porosity. Fig. 3 depicts the particle size distribution curve of the sand material, which was measured using the sieve analysis. The fines (smaller than 0.075 mm) existing in the sand material were removed by washing and sieving. The particle density of the sand material was 2.65 g/cm^3, and the saturated hydraulic conductivity of the sand material was in a range of 0.34–0.63 cm/s (porosity range 34–64%), based on one-dimensional Darcy experiments.

The test section was partly filled with water, and then washed and dried sand material was partly poured into the test section to form a sand bed. After pouring the sand material, the deposited sand material was stirred to remove air bubbles existing in the deposited sand material. The deposited sand material was stirred until there was no outflow of air bubbles. The porosity of the sand bed estimated from variations of the water volume in the apparatus was equaled to 36.15%.

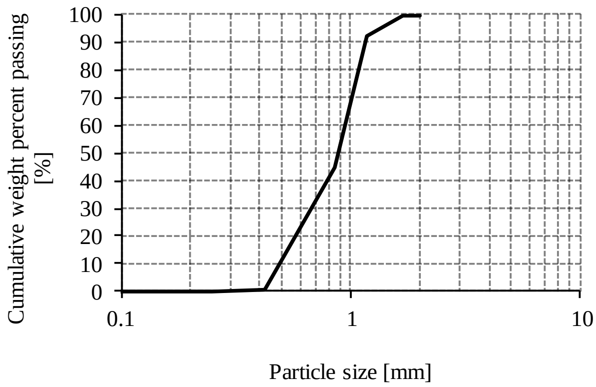

Fig. 3 Particle size distribution curve of the sand material measured using the sieve analysis

Field Observation

A filed observation was conducted in a tidal flat located at the midstream of the Ota River Floodway (Hiroshima, Japan) (Fig. 4). To understand soil conditions of the tidal flat in the observation area, soil sampling was performed vertically (5 cm-layer). The sand samples were analyzed in laboratory to obtain porosity and soil gradation. From the laboratory analysis, the porosity of the tidal flat varied from 34.04 to 42.37% due to different sampling places. This porosity was determined based on the volume and the mass of the sand samples. Fig. 5 presents particle size distribution curves of the sand samples, which were measured using the sieve analysis. It can be seen from Fig. 5 that there was no change in the soil gradation vertically, thus it is assumed that the sand layer (0-15 cm) is uniform vertically.

A method for measuring variations of water head in the tidal flat and the river is shown in Fig. 6. Pressure sensors (SSK, P310A-02) were installed at a depth of 25 cm from the ground surface. Two pressure sensors were used to measure the water head in the sand layer, and another was used to measure river water head. The pressure sensors were connected to a computer for transferring the recorded data. The measurement was conducted during the rising tide.

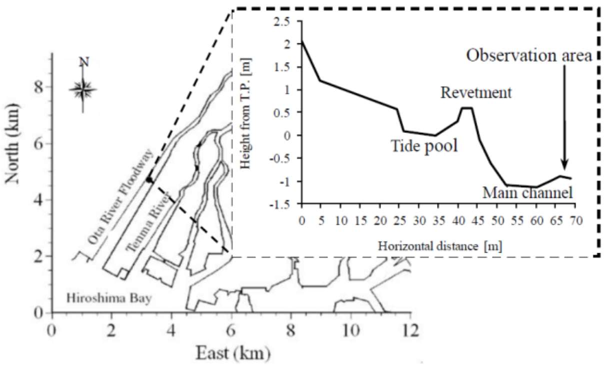

Fig. 4 Location of a field observation in the Ota River Floodway (Hiroshima, Japan)

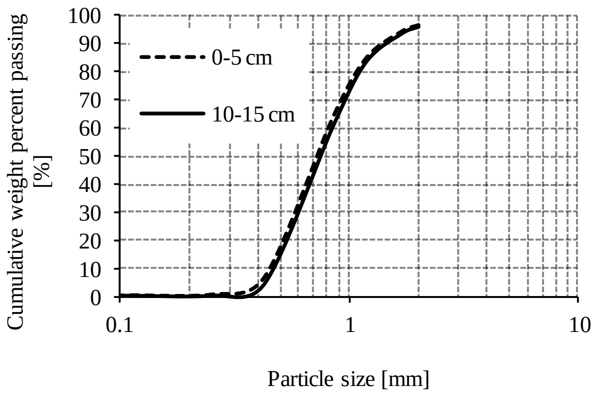

Fig. 5 Particle size distribution curves of the sand samples collected from the tidal flat

PREDICTION OF WATER HEAD VARIATIONS IN THE SAND BED

In a sand bed, the fluid flow through the sand bed causes pressure drop along the sand bed in direction of flow. In other words, the pressure drop in the sand bed must be known to predict the water head in the sand bed. In this section, first an explanation of how to determine the pressure drop is provided, and then a model is propose to predict variations of water head in the sand bed along with variations of the left boundary water head.

Fundamental Theories

Let consider the porous media is a bundle of straight parallel tubes; the particles formed the porous media are spheres; the flow of an incompressible fluid through the porous media; and the flow is driven by the pressure gradient. Thus, the pressure drop along porous media in a laminar flow condition can be described using the Kozeny-Carman model (Carman 1937):

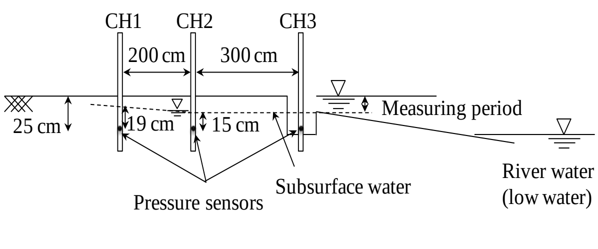

Fig. 6 Method for measuring variations of water head in the tidal flat and the river

$$\frac{\Delta P}{L}=\frac{h_k \mu v_s}{D_e^2}\frac{(1-n)^2}{n^3} \tag{1}$$

where ΔP is the pressure drop along porous media, L means the length along the macroscopic pressure gradient in porous media, v_s is the average velocity (defined by $v_s = Q/A$, where Q is the total flow rate through a cross-section of area A), μ implies the dynamic viscosity of the fluid, n means the porosity of porous media, h_k indicates the Kozeny constant, and D_e is the effective diameter (a typical characteristic length scale of the internal structure of the porous media) of the material used.

According to Touch et al. 2009, the pressure drop along a saturated sand column packed with the sand material used in this work could be significantly represented by Eq. (1) with conditions that h_k was equaled to 72, the volume average diameter of the sand material (Eq. (2)) was utilized as D_e, and the porosity calculated from mass and volume of the sand column (Eq. (3)) was used.

$$D_e=\frac{\sum\left(N_i D_i^3\right)}{\sum\left(N_i D_i^2\right)}\ ,\ \text{and}\ N_i=\frac{\left(W_{ri}/\rho_s\right)}{(4/3)\pi D_i^3} \tag{2}$$

where N_i is the number of particles in each sieve, D_i denotes the diameter of each sieve, ρ_s means the particle density of sand particles, and W_{ri} indicates the weight of particles in each sieve.

The porosity of a sand column can be determined using the following equation.

$$n=1-\frac{W_s}{\rho_s V} \tag{3}$$

where n is the porosity of the sand column, V indicates the total volume of the sand column, and W_s means the total weight of sand particles used to form the sand column.

Variations of Water Head in the Sand Bed along with Variations of the Left Boundary Water Head

Fig. 7 shows variations of water heads measured using the pressure sensors. From this figure, it can be seen that the variation speed (or gradient) of the left boundary water head (x = 0) was larger than that of the water heads in the sand bed (x = 10, 20 cm). As a result, the variable amplitude of the water head in the sand bed was smaller than that of the left boundary water head. This is because, pressure drop occurred in the sand bed by the seepage flow. Furthermore, as the pressure drop increases along with increases in seepage distance, the pressure drop at x = 10 cm was smaller than that at x = 20 cm. Hence, the variable amplitude of the water head at x = 10 cm was larger than that at x = 20 cm.

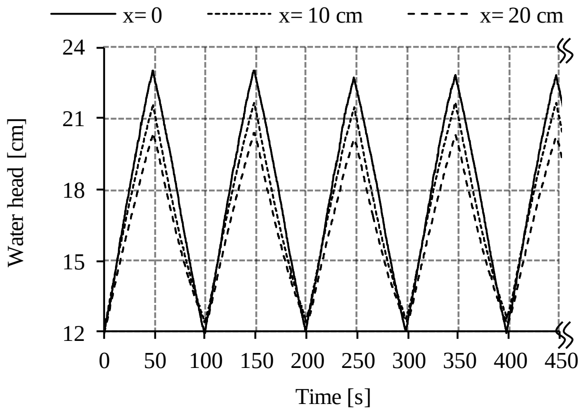

Fig. 7 Variations of water heads in the sand bed (x = 10, 20 cm) along with variations of the left boundary water head (x = 0)

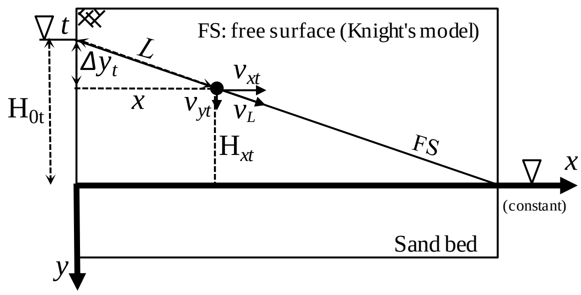

Fig. 8 Assumptions to predict variations of water heads in the sand bed

As can be seen from Eq. (1), since the pressure drop is a function of the porosity, the porosity can be predicted if the pressure drop is known.

Prediction of the Variations of Water Head in the Sand Bed

Model concepts

To predict variations of water heads in the sand bed (Fig. 7), the following assumptions were made (Fig. 8):

- The initial hydraulic conductivity of the sand bed was uniform, and was equaled to the hydraulic conductivity estimated in the steady-state flow condition (the left boundary water head = 23 cm and the right boundary water head = 12 cm). The hydraulic conductivity was determined based on the Depuit-Forchheimer approximation.
- The difference between the left boundary water head (x = 0) and the water head in the sand bed (x = 10 or 20 cm) presented in Fig. 7 was the pressure-head loss caused by the seepage flow.
- Based on Eq. (1), the water head in the sand bed was calculated by the following equation:

$$\frac{\Delta P}{L}=\frac{\rho g(H_{0t}-H_{xt})}{L}=\frac{72\mu(1-n)^2}{D_e^2 n^3}v_L \tag{4}$$

where H_{xt} is the water head in the sand bed at t, H_{0t} indicates the left boundary water head at t (Fig. 7), ρ is the density of fluid, g is the gravity acceleration, v_L means the flow velocity along streamline at x, and L implies the seepage distance (Fig. 8).

Table 1 lists values of important parameters used in the calculation. v_L is also needed in the calculation. In our present study, the velocity distribution of seepage is calculated on the basis of the model proposed by Knight (2005). Previously, it has been pointed out that this model is more precise than the Depuit-Forchheimer approximation, and much easier than solving the full two-dimensional problems. According to Knight (2005), for the sake of simplicity, we consider that the velocity can be expressed by the following equations:

$$\left(\frac{\Delta\eta}{\Delta x}\right)^2=\frac{\eta^2-h_{x=0}^2-\left(\frac{x}{L}\right)\left(h_{x=L}^2-h_{x=0}^2\right)}{h_{x=0}^2+\left(\frac{x}{L}\right)\left(h_{x=L}^2-h_{x=0}^2\right)-\eta^2/3} \tag{5}$$

$$W(x)=\frac{h_{x=0}^2}{2}+\left(\frac{x}{L}\right)\left(h_{x=L}^2-h_{x=0}^2\right)\Big/2 \tag{6}$$

$$\phi(x,y)=\frac{\eta}{4}\left[1+\frac{6W}{\eta^2}+\left(\frac{y^2}{\eta^2}\right)\left(3-\frac{6W}{\eta^2}\right)\right] \tag{7}$$

$$v_{Lx}=-k\frac{\partial\phi(x,y)}{\partial x}\quad\text{and}\quad v_{Ly}=-k\frac{\partial\phi(x,y)}{\partial y} \tag{8}$$

where η is the free surface, L indicates the length of the sand bed, $h_{x=0}$ implies the free water head at x = 0 (the left boundary water head), $h_{x=L}$ refers to the free water head at $x = L$ (the right boundary water head), W means the Younges potential, ϕ is the piezo-metric head, and k is the hydraulic conductivity of the sand bed (0.34 cm/s). In our calculation, Δx and Δy were equaled to 0.5 cm.

Fig. 9 presents the velocity distribution in the sand bed in the case that $h_{x=0}$ = 22 cm and $h_{x=L}$ = 12 cm. From this figure, variations of the flow velocity in the vertical and horizontal directions were computed (Fig. 10). As can be seen in Fig. 10, the velocity difference in the vertical and horizontal directions was small (1/1000 order of magnitude), thus the average velocities in the vertical and horizontal directions "v_{xt}(x), v_{yt}(x)" were used in the calculation.

$$v_L=\left([v_{xt}(x)]^2+[v_{yt}(x)]^2\right)^{1/2} \tag{9}$$

$$L=(x^2+\Delta y_t^2)^{1/2} \tag{10}$$

Fig. 11 shows a comparison of the water head in the sand bed calculated by Eq. (4) with that measured using

Table 1 Values of important parameters used in the calculation

Parameter	Value
ρ	997*10^{-3} [g/cm^3]
μ	9.495*10^{-3} [g/cm/s]
g	981 [cm/s^2]
n	36.15 [%]
D_e	0.0593 [cm]

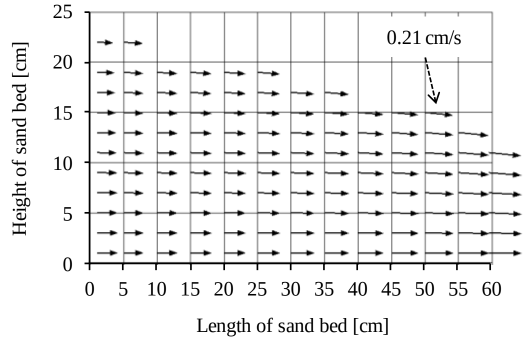

Fig. 9 An example of the velocity distribution predicted by Knight's model ($h_{x=0}$ = 22 cm and $h_{x=L}$ = 12 cm)

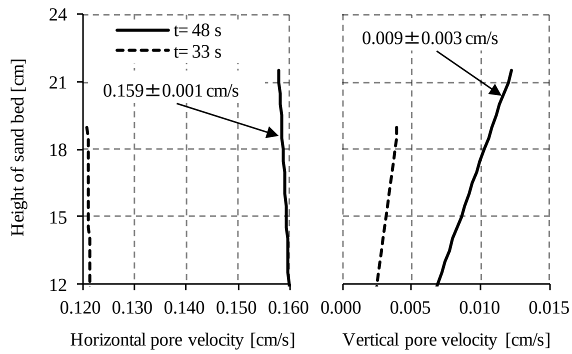

Fig. 10 Horizontal and vertical distributions of the pore velocity at x= 10 cm. ($h_{x=0}$ = 20 cm (t=33 s), 23 cm (t= 48 s); $h_{x=L}$ = 12 cm)

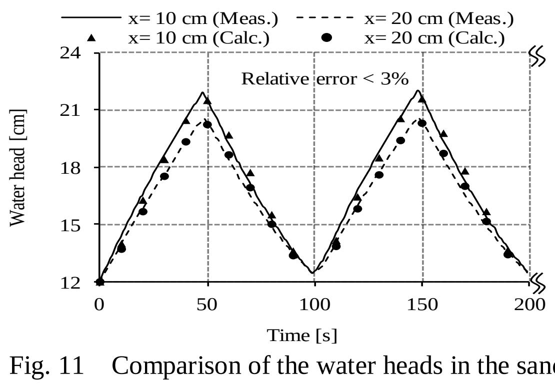

Fig. 11 Comparison of the water heads in the sand bed predicted by Eq. (4) with that measured using the pressure sensors

the pressure sensors. It can be seen that the measured water head could be accurately reproduced by Eq. (4) (the relative error was less than 3%). This ensures that the porosity of the sand bed can be predicted based on Eq. (4) if variations of water heads in the sand bed and at the boundary are measured.

PREDICTION OF THE POROSITY OF A TIDAL FLAT

Measurements of River Water Head and Water Head in a Tidal Flat

River water head and water head in the tidal flat were measured using the pressure sensors, as shown in Fig. 6. Fig. 12 depicts water heads calculated using the data obtained from the pressure sensors. It was found that the increasing speed (or gradient) of river water head "CH3" was larger than those of water heads in the tidal flat "CH1 and CH2". It is thought that the seepage flow of river water occurred in the tidal flat, which generates the pressure drop in the tidal flat. This suggestion is similar to that obtained from the laboratory experiment (Fig. 7). It is strongly evident that the porosity of the tidal flat can be determined from these results, leading to the prediction of sediment retention.

Relationship between the Variation of Water Head and the Porosity of the Tidal flat

If water head in the tidal flat can be predicted using the porosity of the tidal flat, sediment retention can be investigated based on temporal variations of the porosity. Here, we try to compute alterations of the water head in the tidal flat "CH2" using the measured data (Fig. 12). In the calculation, the following assumptions were made:

- Water heads of CH2 and CH3 were used as the boundary water heads.
- The water head in the tidal flat was predicted on the basis of Eq. (4). As seepage distance is relatively larger than the difference of the boundary water heads (free surface gradient was less 1/57), only the flow in the horizontal direction was taken into account.
- The flow velocity can be determined based on the Depuit-Forchheimer approximation. The water head of CH3 was considered as the inflow section of seepage.

To determine the flow velocity based on the Depuit-Forchheimer approximation, the hydraulic conductivity of the tidal flat is need. To calculate the water head based on Eq. (4), the porosity of the tidal flat is also need. Unfortunately, both the hydraulic conductivity and the porosity are unknown parameters that we try to determine.

To obtain the hydraulic conductivity and the porosity, Darcy experiments were carried out using the sand

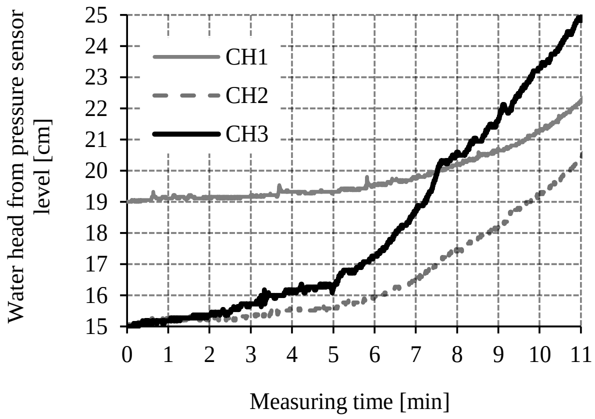

Fig. 12 Water heads calculated using the data obtained from the pressure sensors (field observation)

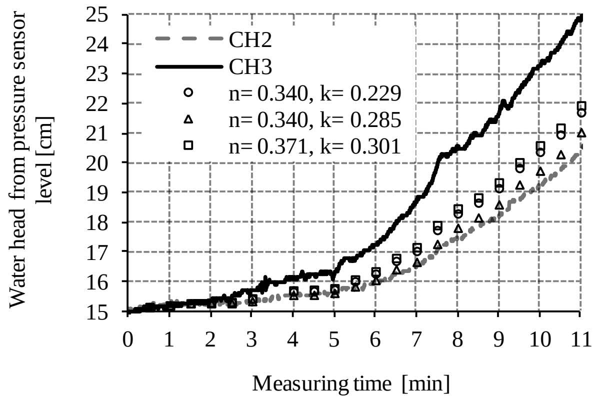

Fig. 13 Comparison of the predicted water head (plots) in the tidal flat with that measured using the pressure sensors (lines).

samples collected from the tidal flat. As a result, the hydraulic conductivity of the sand material collected from the tidal flat is in a rage of 0.229–0.301 cm/s for the porosity range of 0.340–0.371. In fact, these values are not correct values of the hydraulic conductivity and the porosity of the tidal flat. This is because soil conditions (e.g., sediment retention, pore structures) of the tidal flat may different from those of the laboratory columns. Here, we aim to know the accuracy of the prediction when the laboratory parameters are used.

Fig. 13 shows the predicted water head in the tidal flat (plots) compared with that measured using the pressure sensor (lines). It can be seen that the predicted water head was higher than the measured water head. The relative error of the difference was about 6% for the hydraulic conductivity range of 0.229–0.301 cm/s (Fig. 13, ○ and □). As explained earlier, the hydraulic conductivity and the porosity of the tidal flat may be smaller than the laboratory values due to sediment retention. Therefore, the accuracy of the prediction can be improved when the correct values are used in the calculation. For example, in a case that the hydraulic conductivity was decreased from 0.301 cm/s to 0.285 cm/s, it was found that the variation of water head in the tidal flat was reproduced accurately (Fig. 13, ∆). It is thought that the water head in the tidal flat can be predicted with a maximum relative error of 6%, and the error may partly due to the use of incorrect values of the hydraulic conductivity and the porosity of the tidal flat. In other words, the water head can accurately predicted if correct values of the hydraulic conductivity and the porosity of the tidal flat are used.

These results suggest that variations of the water head in the tidal flat along with variations of river water head can be predicted. As a results, the hydraulic conductivity and the porosity of the tidal flat can be determined from water heads measured based on our proposed method and model. Hence, the sediment retention in a tidal flat can be investigated by our proposed method and model.

CONCLUSIONS

In this study, laboratory experiments were conducted to propose a model and a method for investigating sediment retention in estuaries. Field observations were also conducted to verify the validity of the proposed method.

From laboratory experiment, the variation of water head in the sand bed along with oscillating boundary water head was sensitively represented by our proposed model with a maximum relative error of 3%. From this model, the porosity of the sand bed could be determined when variations of water heads at the boundary and in the sand bed were measured.

A method was proposed to measure the water head in the tidal flat and of river water, and was verified by a field observation. The results suggested that variations of the water head in the tidal flat could be predicted by our proposed model when the hydraulic conductivity and the porosity of the tidal flat were used. In other words, the hydraulic conductivity and the porosity could be determined if variations of river water head and the water head in the tidal flat are measured. Therefore, sediment retention in the tidal flat can be investigated from temporal changes in the porosity.

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