

## A study on sediment transport inside and outside a permeable submerged breakwater with the Macroscopic turbulence model

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### ABSTRACT

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Sediment transport inside and outside a permeable submerged breakwater was examined in a laboratory experiment and a numerical calculation. The Macroscopic turbulence model, which has been applied for the thermal conduction in porous media, was used for the theoretical approach. A two- equation model for inside regions and 0- equation model was used for the outside region. Suspended sediment could be transported toward the onshore side due to two effects; vortex over sand ripples and the slope of a permeable breakwater. The amount of sediment deposited in the breakwater decreased gradually from the offshore to the onshore side during the experiment, while on the other hand decreasing rapidly in the numerical calculation. The surface profile over the submerged breakwaters could be reproduced excellently.

**ADDITIONAL INDEX WORDS:** *k- $\epsilon$ model, PTV, wave motion, numerical simulation*

### INTRODUCTION

Water quality improvements have been made globally by using porous media like a stone masonry-type breakwaters. For example, (ODA *et al.* 1992) have tried to improve water quality using tidal flows through a permeable breakwater, also having used biotic filtration by attaching organics to permeable layers. It is very important to investigate hydraulic characteristic in porous media. Therefore, the effects of a porous medium on the flow above it and the flow characteristic near the interface with the free flow have been studied previously (JAMES and DAVIS 2000, PRINOS *et al.* 2003). One study, (SHIGEMATSU *et al.* 2004), measured velocity vectors and turbulent kinematic energy in porous media with the particle tracking velocimetry (PTV) technique, and showed that both production and dissipation for turbulent kinematic energy do not depend on the Reynolds number.

The importance of renourishment by permeable breakwaters and dredged materials has been pointed out. Securing the land region for treatment of dredged material has become more difficult and beach erosion could also be promoted due to a decrease of sea sand by dredging. However, wave control could be reduced due to a decrease in permeability of the permeable breakwater by the renourishment, or shoaling of harbours might occur by suspended sediment through permeable breakwaters. Therefore, countermeasures against these processes have been attempted according to SAKAKIYAMA *et al.* (2004) and KUMAGAYA *et al.* (2004).

With these backgrounds in mind, the object of this study is to experimentally and numerically examine hydraulic characteristics inside and outside a permeable submerged breakwater (hereafter

referred to as PSB). Wave profiles over PSB consisting of gravels were measured, as well as suspended sediment concentration near it by image pictures and the rate of sediment transport inside it. Additionally, as a theoretical approach, a “macroscopic” model for the permeable layer in PSB was applied.

### PREVIOUS WORK

For a permeable breakwater, estimating the hydraulic resistance in permeable layers have been important issues. Therefore, a number of serial and exponential approaches have been developed for the stationary flow (HANNOURA and BARENDIS 1981) and the wave motion can be approximated by the Forchheimer equation with an additional inertia term (POLUBARINOVA-KOCHINA 1962). Many investigators have studied waves filed behind and scour around a PSB applying the results of these studies (e.g. YAMASHIRO *et al.* 1999).

On the other hand, for the sediment transport near a PSW (SAKAKIYAMA *et al.* 2004) used the diffusion equation with porous body model, calculating suspended sediment concentrations at the onshore and offshore side of a PSB. KUMAGAYA *et al.* 2004 have examined the bottom profile changes near PSB by using CADMAS-SURF. However, these examples are extremely rare.

### MACROSCOPIC MODEL

In order to investigate the turbulent flow around a submerged breakwater with a permeable layer, either the “microscopic” or “macroscopic” approach can be used. (TSUJIMOTO *et al.* 2000) applied the former for a horizontal plate with perforations. Considering the distribution patterns of porous regions into

calculated grids for the current problem is extremely difficult. The latter uses macroscopic characteristics to describe the variation flow characteristics within the permeable layer. Using this approach (GETACHEW *et al.* 2000), the turbulent flow inside a PSB is described by the RANS equations including the extended the Darcy term, the Forchheimer term and the Brinkman term. In these equations, continuity and momentum defined as follows:

$$\frac{\partial u_i}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_j u_i + \overline{u_j u_i})}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - \phi \frac{\nu}{K} u_i - \phi^2 \frac{c_F}{\sqrt{K}} \left[ (u_j + u_j') (u_j + u_j') \right]^{1/2} (u_i + u_i') + \nu J \frac{\partial^2 u_i}{\partial x_j \partial x_j} \quad (2)$$

where  $u_i$  is the time averaged fluid velocity in the  $x_i$  direction,  $u_i u_j'$  Reynolds stress,  $p$  pressure,  $\rho$  fluid density,  $\nu$  fluid kinematic porosity,  $K$  permeability,  $c_F$  Forchheimer coefficient and  $J$  the viscosity ratio.

Assuming  $u_i u_j \gg u_i u_j'$  and neglecting the higher order terms  $u_j u_j' \gg u_j u_j'$ , the third term in Eq. (2) yields

$$\left[ (u_j + u_j') (u_j + u_j') \right]^{1/2} (u_i + u_i') \approx (u_j u_j')^{1/2} u_i + \frac{u_j}{(u_j u_j')^{1/2}} \overline{u_j u_i'} \quad (3)$$

Substituting Eq. (3) into Eq. (2), the averaged momentum equation becomes

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \nu J \frac{\partial^2 u_i}{\partial x_j \partial x_j} - \overline{u_j u_i'} \right] - \phi \frac{\nu}{K} u_i - \phi^2 \frac{c_F}{\sqrt{K}} \left[ (u_j u_j')^{1/2} u_i + \frac{u_i}{(u_j u_j')^{1/2}} \overline{u_j u_i'} \right] \quad (4)$$

where the second term stands for Brinkman term, the third for Darcy term and the fourth for Forchheimer. (MATSUOKA *et al.* 1996 and ABTOHE *et al.* 1997) did not consider the second term in their calculations.

## EXPERIMENTS

### Experimental apparatus

Experiments were conducted in an 18m long, 0.6m wide and 0.8m deep wave tank. A permeable breakwater of 0.1m height, with a 1.7m crown width and 1:2 slope was formed by two kinds of gravel. Figure 1 shows the grain size accumulation curves. Gravel can be regarded as homogeneous if the ratio of  $d_{85}/d_{15}$  is smaller than 1.5, where  $d_{85}$  and  $d_{15}$  are gravel size of the percentage level of accumulation curves. Therefore, the present gravels are not regarded as homogeneous. The bed material was

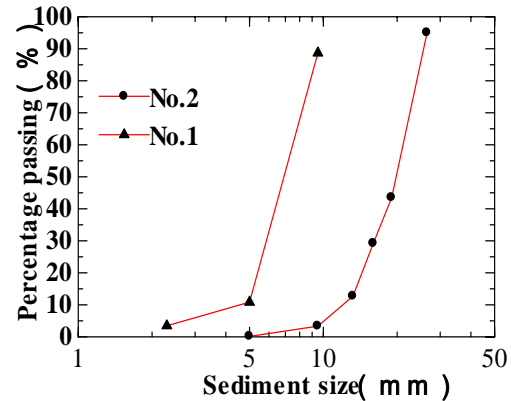


Fig. 1. Grain size accumulation curve.

placed in a uniform thickness of 2cm or 5cm at the offshore side of a PSB, about 1.5m long.

### Experimental procedure

Wave profiles over the PSB were measured by a digital video camera and the suspended sediment concentration close to the PSB by a PTV technique (TSUJIMOTO *et al.* 2000). The PTV system consists of double-pulse Nd:Yag lasers and a high resolution digital CCD camera. The CCD video camera, whose resolution is 1008(H) x 1018(V), was synchronised with the laser light sheet with the aid of a computer. The measurements of sediment transport rate into PSB are as follows. PSB was placed in the original site after removing all sand particles in the PSB and after waves had been generated for about one hour, the slope of the offshore side was sliced at intervals of 3cm and the sand which had deposited internally was taken out. Sand ripples, wavelengths from 6 to 7cm and wave heights from 2 to 2.5cm, were formed at the movable bed.

The values of  $c_F$  and  $K$  were decided in a permeability test. The above-mentioned gravels were put in a tube (7.5cm in diameter and 0.7m in length), a constant water flow was passed and the head loss between two points was measured. When the porosity value is large, the nonlinear Darcy's law proposed by Forchheimer (Eq. (5)) can be applied.

$$-\frac{1}{\rho} \frac{dp}{dx} = u(\nu/K + c_F / \sqrt{K} |u|) \quad (5)$$

where  $u = \phi u^*$  is section averaged velocity,  $u^*$  is the vector of infiltration flow. From a regression line with the head loss and the averaged velocity, values of  $c_F$  and  $K$  could be estimated. The estimated results are shown in Table 1.

### CALCULATION METHOD

Table 1: Gravel characterizations

	Size	porosity	$c_F$	$K$
	cm			cm <sup>2</sup>
No.1	0.34	0.384	0.875	0.000978
No.2	1.65	0.401	0.1425	0.000602

### Eddy viscosity

Closing Eqs. (1)-(4), the Reynolds stresses were estimated with the aid of a turbulence model. Turbulence models for submerge

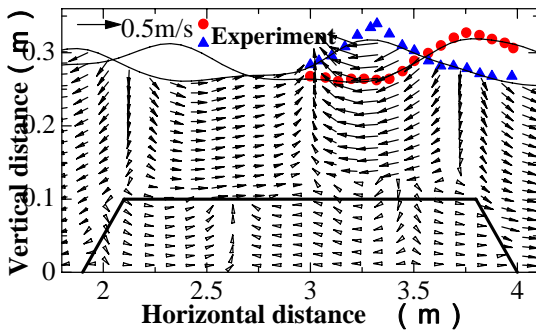


Fig. 2. Wave profile and velocity vectors.

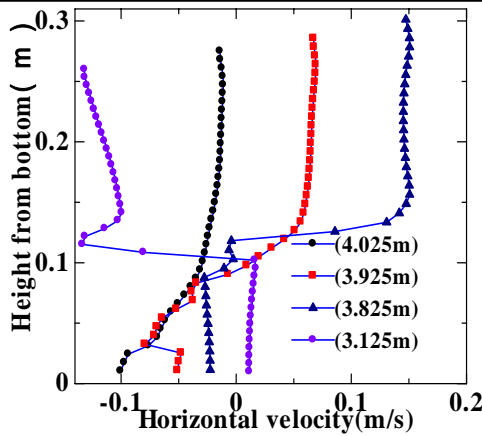


Fig. 3. Vertical distribution of horizontal velocity

breakwaters have been applied in numerous studies (TSUJIMOTO *et*

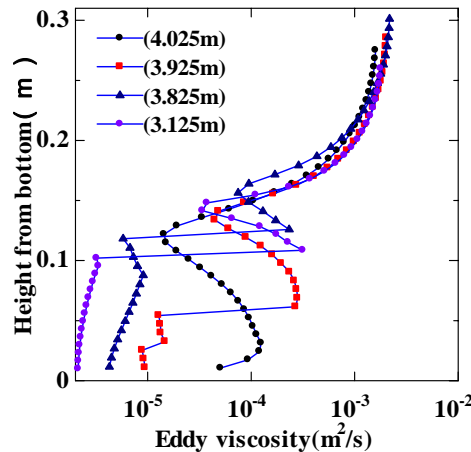


Fig. 4. Vertical distribution of eddy viscosity.

*al.* 2000). However, two types of vortices, namely the void and pseudo vortices are formed in the porosity, playing an important role in the transport mechanism of the turbulent flow. The former is the vortex in the order of the particle diameter and the latter the interstitial vortex between solid particles. Some two-equation turbulence models including these vortices were proposed by

(ABTHOHE *et al.* 1997 and GETACHEW *et al.* 2000). But calculated examples under wave actions are rather scarce. A 0-equation model proposed by (MATSUOKA *et al.* 1996), therefore, was used to estimate eddy viscosity inside the PSB as shown in Eq. (6).

$$v_t = C_\mu \cdot k^2 / \varepsilon \quad (\text{outside})$$

$$v_t = F / \sigma \cdot \sqrt{u^2} \sqrt{K} \quad (\text{inside}) \quad (6)$$

where  $C_\mu = 0.09$  is an empirical coefficient,  $k$  the turbulent kinetic energy,  $\varepsilon$ : its dissipation rate,  $F = 1.75 / \sqrt{150\phi^3}$ , and  $\sigma = 1$  the correction factor.

**Rate of sediment transport**

The diffusion equation was applied to estimate the rate of sediment transport as follows:

$$\frac{\partial c}{\partial t} + \frac{\partial(u_j c)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( v + \frac{v_t}{\sigma_t} \right) \frac{\partial c}{\partial x_j} - w_o c \cdot \delta_{2,j} \right] \quad (7)$$

where  $C$  is the suspended sediment concentration,  $w_o$  fall velocity of sand particle,  $\sigma_t$  Schmidt number and  $\delta_{2,j}$  the delta function.

Eqs. (1), (4), (7) and the  $k - \varepsilon$  turbulence model are converted to coordinates using the boundary fitted coordinate system and the boundary conditions are the same as in (TSUJIMOTO *et al.* 2000); the formulation of the solution algorithm is given in the same study.

**RESULTS**

**Surface profiles**

Figure 2 shows wave profiles over a PSB under the following conditions: wave height 6.7cm, water depth 28cm and wave period 1.21sec. In comparison with the calculated results, they are qualitatively satisfactory. They are about 10-30% of values outside the PSB though the scale of velocity vectors inside the PSB is different depending on wave phases or calculated grids. Additionally, no-slip but only horizontal velocities are seen on the PSB.

**Vertical distribution of horizontal velocity**

Figure 3 shows the calculated horizontal velocity at the wave phase when a wave crest passed over the offshore slope of the PSB, where numbers stand for horizontal distance. The velocity inside the PSB was uniform in the vertical direction and its values gradually decreased toward the onshore side. Moreover, the calculation grids locations where the flow direction inside the PSB was different from that outside the PSB are shown.

**Eddy viscosity**

Figure 4 shows the distribution of eddy viscosity corresponding to wave phase of Figure 3. The values close to the crown of the PSB have changed rapidly due to different approaches inside and outside the PSB. The values inside the offshore slope are about ten times that of the kinematic viscosity, decreasing gradually toward the inside. Therefore it is necessary to examine its validity thorough experiments.

**Suspended sediment concentration**

Since the suspended sediment that moves from the offshore to the onshore side over the crest of a PSB is hard to assess due to the small quantities, measurements of suspended sediment

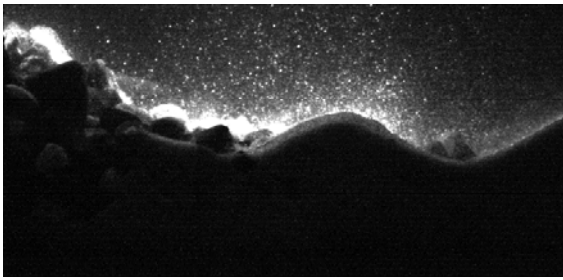


Fig. 5. Example of image picture.

concentrations by image analysis have been carried out closely to the slope of the offshore side.

Figure 5 shows an example corresponding to Figure 2. Sand ripples are formed at the slope on the offshore side and local scouring occurs at the toe of the slope. Generally suspended sediment clouds formed over sand ripples will be transported

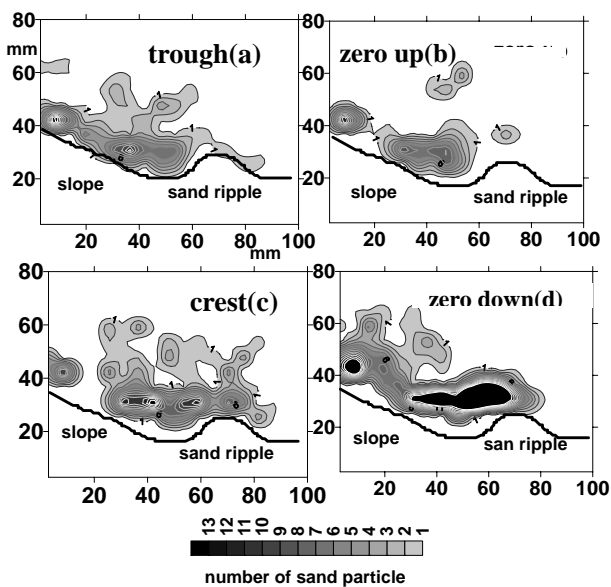


Fig. 6. Suspended sediment distribution.

toward the offshore side and the net sediment transport rate is in the offshore direction. An amount of sand, however, deposits inside the PSB as described later and movement of a suspended sediment cloud toward the onshore side is confirmed.

The space distribution of the number of sand particles is shown in Figure 6(a-d) at four wave phases. The amount of suspended sediment is small when the suspended sediment cloud is moving down along the slope at the wave phase of a wave trough as shown in Figure 6 (a). The number of sand particles would be decreasing more at the wave phase when the flow direction changes from offshore to onshore as shown in Figure 6 (b). The separated vortex will always be formed over the sand ripple at the wave phase of the wave crest but it is not formed under this bottom condition, therefore a part of the suspended sediment cloud could not be entrained into the vortex and moved up along the slope in Figure 6 (c). As shown in Figure 6 (d), the number of sand particles would be increasing when the flow direction changes from onshore to offshore, and a part of them are moving along the slope toward the onshore side.

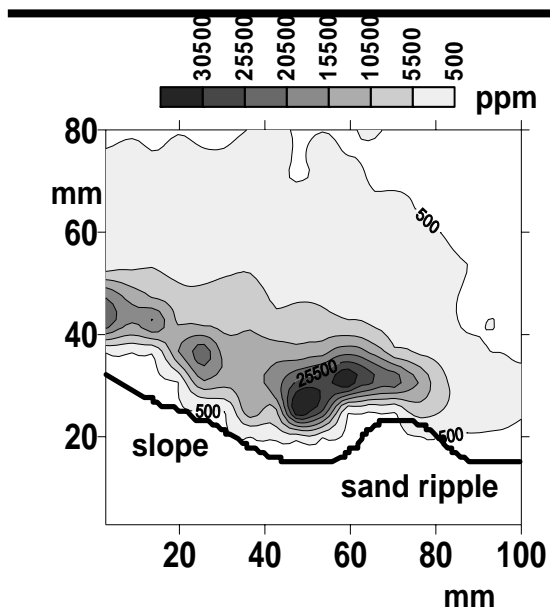


Fig. 7. Measured mean concentrations.

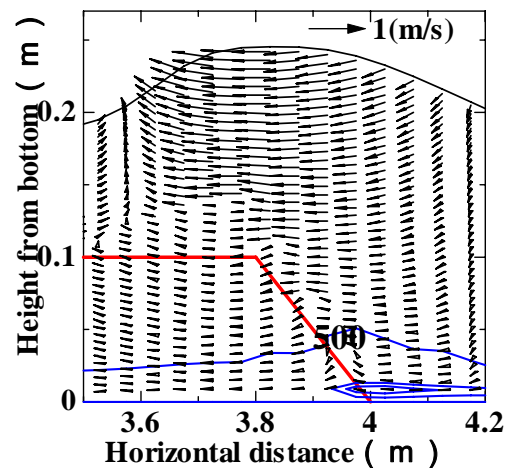


Fig. 8. Calculated flow velocities and concentrations.

Figure 7 shows the suspended sediment concentration averaged over a wave period. The concentration could be calculated by the number of sand particles. A couple of high concentration areas are seen over the slope.

Figure 8 shows the calculated concentration corresponding to Figure 7. The calculated maximum value is about 2000 ppm and is 50% of the experimental data. One of the reasons for the discrepancy between these is not to consider bottom profiles as sand ripples.

### Rate of sediment transport in PSB

The experimental data and the calculated results on the rate of sediment transported into a PSB are shown in Figure 9. The experimental curves were interpolated by the spiral function. The calculated results are estimated by velocity and suspended sediment concentration. The rate of sediment transport in the PSB decreases toward the inside in both the experiment and the calculation. However, the differences between both have

expanded toward the inside. As mentioned in Figure 8, the calculated concentration is smaller than the actual measurement. Therefore the flux of suspended sediment will be small.

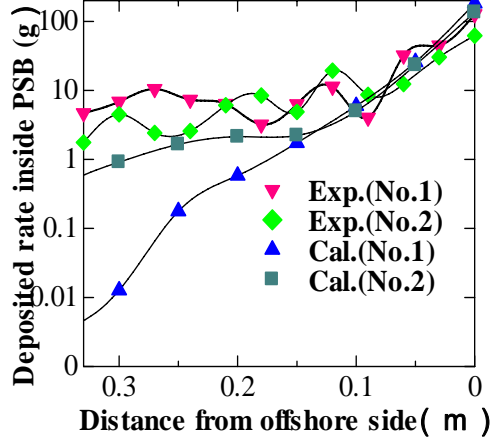


Fig. 9. Comparison between calculated deposited rate and experimental data inside PSB.

## CONCLUSIONS

Focussing on sediment transported through PSB, the mechanism of sediment transport and the rate of sediment transported in PSB were investigated by experimental approach and numerical simulation. The following conclusions have been reached:

(1) The macroscopic turbulence model is useful to study the hydraulic characteristics in a permeable submerged breakwater under wave motions. However, the bottom profiles like sand ripples must be taken into account in estimating the suspended sediment concentration.

(2) When applying Eq. (5) to the field data, the empirical coefficients and characteristic particle diameter for rubble stones and concrete blocks are described in some studies (e.g. MUTTRAY *et al.* 2005).

(3) Sand particles through the offshore slope of the PSB could be deposited and the rate of deposition decreased gradually toward the inside. The differences between the experimental data and model predictions in Fig.9, however, are seen. One of the reasons is that sediment transport mechanisms between the inside and outside of a PSB can be different. The graves inside the PSB could influence the pick up rate from the bottom. However, the boundary condition for suspended sediment concentration there is the same as on the outside. The other boundary conditions should be considered.

(4) A two-equation model for estimating the eddy viscosity in the permeable layer may be necessary.

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