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TIME-VARIATION OF BOTTOM SHEAR STRESS UNDER IRREGULAR WAVES OVER ROUGH BED

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SYNOPSIS

Many researchers have carried out experiments on bottom friction under waves, in connection with sediment transport due to wave motion. However, most of the previous studies were conducted under sinusoidal waves. Some researchers have performed experiments under irregular waves, though, they are mostly limited to a smooth bed condition (e.g., Tanaka et al. (1)), which is different from an actual situation on a sea bottom. In this present study, an experiment is carried out by means of an oscillating tunnel, in which the bottom surface is covered with roughness elements. Furthermore, a simple estimation method of instantaneous bottom friction under irregular waves is proposed, and is verified by making a comparison with experimental results in an oscillating wind tunnel.

INTRODUCTION

Beach evolution models have been developed in view of irregularity of wave motion in recent years (e.g., Kabiling and Sato (2)). In general, a model consists of wave motion and sediment transport compartments, and an evaluation of the bottom shear stress is needed to correlate these two compartments. Up to now, much research on the bottom boundary layer has been done (e.g., Hino et al. (3), Jensen et al. (4)). However, most of them have been limited to sinusoidal waves and few have focused on irregular waves.

Samad and Tanaka (5) studied a bottom boundary layer under irregular wave motion by means of numerical model, and they proposed a simple calculation method to compute instantaneous turbulent bottom shear stress from the variation in free stream velocity for a smooth bed condition. In addition, the boundary layer characteristic is examined by an experiment under irregular waves (Samad et al. (6)). However, it should be noted that these studies have dealt with smooth beds only, and more extensive studies of rough bed conditions are required for practical applications of sediment movement.

This paper examines experimental results of bottom shear stress characteristics under irregular waves over the rough bed. Moreover, a simple method for estimating bottom shear stress is proposed.

EXPERIMENTAL SET-UP AND EXPERIMENTAL METHOD

An experiment was conducted by using a wind tunnel system depicted in Fig.1. It consists of two major components, namely, a wind tunnel in which velocity measurements were carried out, and a servo-motor system by which irregular motion was generated in accordance with an input signal. Aluminum balls with a diameter of 1.0 cm were pasted over the bottom surface of the wind tunnel. The Bretschneider-Mitsuyasu spectrum was used to generate an input signal in this experiment.

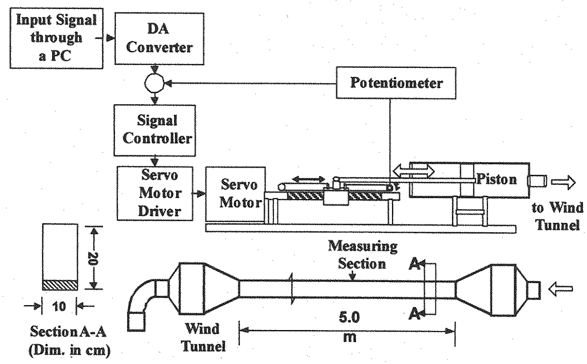

Fig.1 Schematic diagram of experimental system

In the wind tunnel, Laser Doppler Velocimeter (LDV) was installed for the flow measurements. Velocities were measured at 20 points in the vertical direction at the center of the tunnel. The flow velocity was recorded by means of a digital-analog (DA) converter with 1/100 s intervals, and the mean velocity and turbulence intensity were obtained by ensemble averaging over 50 wave cycles.

The present experiment was carried out for the case with $Re_{1/3}=5.0\times10^5$ to reach a fully turbulent regime, where the Reynolds number is defined by Eq.(1).

$$\mathrm{Re}_{1/3}=\frac{U_{1/3}^2}{\nu\omega_{1/3}},\quad \omega_{1/3}=\frac{2\pi}{T_{1/3}} \tag{1}$$

where $U_{1/3}$: the amplitude of flow velocity based on parameter of significant wave, $T_{1/3}$: the significant wave period, and ν : the kinematics viscosity. Moreover, an experiment with R_e=5.0x10^5 was carried out under sinusoidal wave motion, to investigate the effects of irregularity, where R_e is defined by the following form:

$$R_e=\frac{\hat{U}_w a_m}{\nu} \tag{2}$$

where $\hat{U}_w$: the maximum of wave-induced velocity just outside the boundary layer, and a_m: the excursion length of a water particle under wave motion.

RESULTS AND DISCUSSIONS

Flow Regime

The condition of the actual experiment is plotted in the flow regime diagram (Fig.2) proposed by Tanaka and Thu (7), where k_s: Nikuradse's equivalent roughness, which is assumed to be equal to the diameter of the roughness element. The diagram is extended to irregular wave motion using the Reynolds number and angular frequency defined by Eq.(1) as representative quantities. It can be concluded that the condition of the present experiment lies in the rough turbulent regime according to the Reynolds number defined in terms of significant wave.

However, because of the irregularity of the input signal, there are waves with smaller Reynolds numbers. Then, the crest phase or the trough phase of the free stream velocity is regarded as a half cycle of wave motion, and the Reynolds number Re_p is defined by Eq.(3) for individual waves.

$$\mathrm{Re}_p = \frac{U_p^2}{\nu\omega_p}, \quad \omega_p = \frac{\pi}{T_p} \tag{3}$$

where U_p: the maximum velocity during crest or trough phases, and T_p : the period of crest or trough phases.

Thus the Reynolds number thus defined for each wave cycle is plotted in Fig.2. It is observed that all waves are located in the rough turbulent regime, though, it can be concluded that some of the waves are not fully turbulent. This phenomenon will be explained in a later section of this paper.

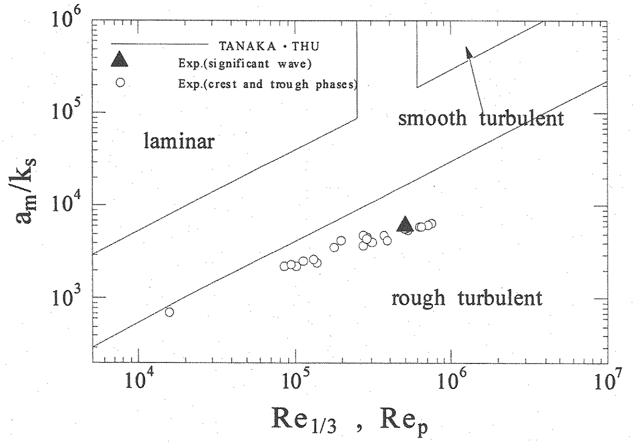

Fig.2 Flow regime diagram

Time Variation of Mean Velocity and Turbulence Intensity

The time-variation of mean velocity at several measuring elevations are shown in Fig.3, where U is the free stream velocity and u is the horizontal velocity inside the boundary layer. It should be that the time-variation inside the boundary layer is remarkably different from that outside the boundary layer, as denoted by the arrows in Fig.3. This phenomenon is not seen under the sinusoidal wave motion. Moreover, turbulence intensity measured at z=2.0cm is also shown at the bottom of the figure. It is seen that turbulence shows fluctuation in accordance with the change in free stream velocity. For example, turbulent intensity is very low at t=4-6s and t=26-30s.

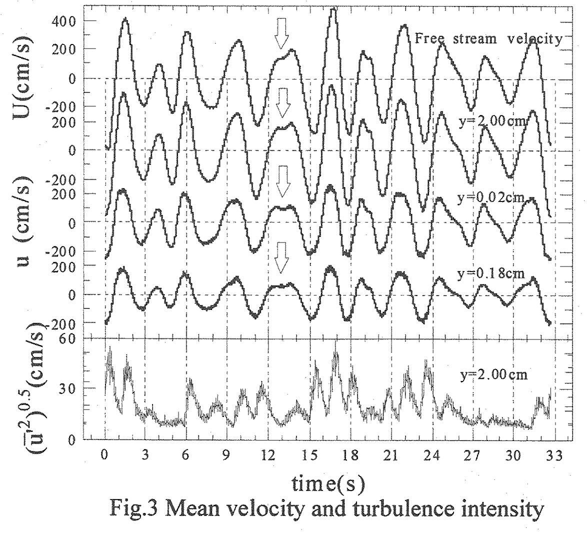

Fig.3 Mean velocity and turbulence intensity

History Effect

The influence of history effect is further examined by the temporally and vertically averaged turbulent intensity defined by Eq.(4).

$$\sqrt{\overline{u'^2}}_{avg} = \frac{1}{T_p}\int_0^{T_p}\sqrt{\overline{u'^2}}\,dt \tag{4}$$

The result is shown in Fig.4 along with the Reynolds number for individual waves, Re_p. It can be inferred that the temporal variations of Re_p and $\sqrt{\overline{u'^2}}_{avg}$ are almost similar, but it is not always the case as indicated by the arrows in Fig.4. This is caused by the history effect, as already reported by Samad et al. (8) for smooth bottom experiment.

The contours of turbulence intensity and mean velocity profile are shown in Figs.5 and 6 respectively, for the period when the history effect is predominant. Although the maximum velocity is almost similar to the two waves with the arrow in Fig.5, it is clearly observed that the intensity of turbulence is remarkably different between these two. Furthermore, the velocity profile is clearly affected by the turbulence. For example, under the wave motion (A), the velocity is more uniform as compared with (B). This is due to momentum transfer caused by turbulent mixing.

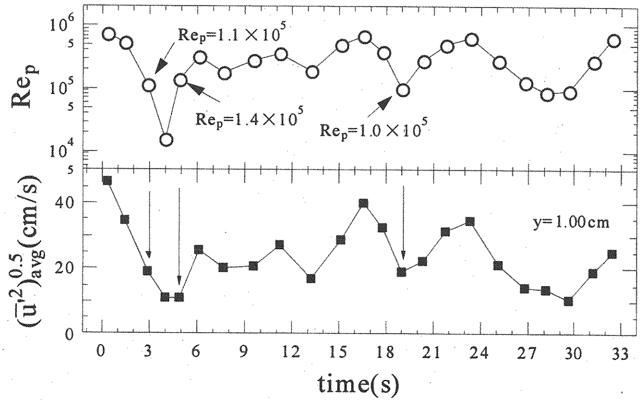

Fig.4 Re_p and mean turbulence intensity

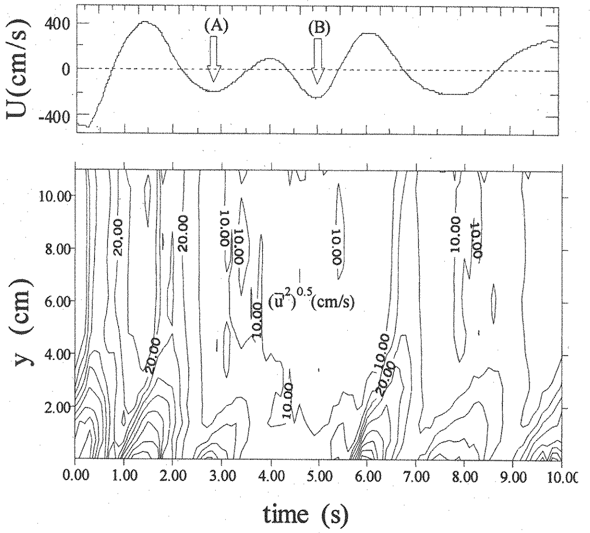

Fig.5 Contour plot of turbulence intensity

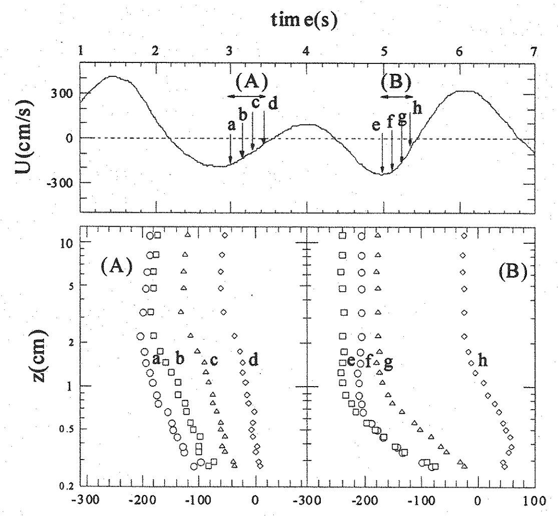

Fig.6 Vertical distributions of velocity

Estimation of Bottom Shear Stress

Bottom shear stress is obtained by fitting the logarithmic velocity distribution, Eq.(5), to the measured velocity

$$u(z) = \frac{U_\tau}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{5}$$

$$U_\tau = \sqrt{\tau_o / \rho}\,, \quad z = y + \Delta z \tag{6}$$

where U_τ: the friction velocity, ρ: the fluid density, τ_0: the bottom shear stress, κ: von Karman's constant (κ =0.4), y: the height from the top of roughness, and Δz: the height of virtual bottom. The values of Δz and z_o are determined in a preliminary experiment under sinusoidal wave conditions.

An example of the vertical distribution of the velocity is shown in Fig.7. The logarithmic law can be applied to the wide range in the near-bottom region.

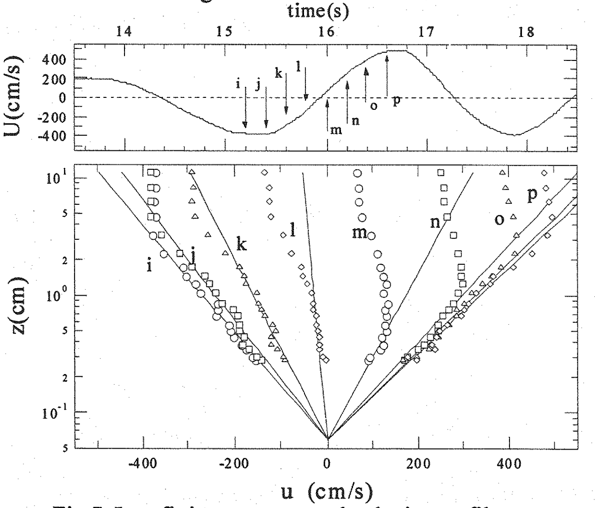

Fig.7 Log-fitting to measured velocity profile

Calculation Method of Bottom Friction

A simple method will be proposed herein for estimating instantaneous bottom shear stress from the time-variation of the free stream velocity under irregular waves. By considering an expression for the friction coefficient under a sinusoidal wave motion, it is reasonable to assume that the time-variation of bottom friction can be expressed by Eq.(7) for an arbitrary variation of $U(t)$, as proposed by Kabiling and Sato (2).

$$\tau_o(t)=\frac{\rho}{2}f_w U(t)|U(t)| \tag{7}$$

here f_w is the wave friction coefficient. The friction coefficient formula proposed by one of the authors (Tanaka and Thu (7))

$$f_w=\exp\left\{-7.53+8.07\left(\frac{a_m}{z_o}\right)^{-0.100}\right\} \tag{8}$$

can be used for evaluating f_w in Eq.(7).

Depending on the selection of the fluid particle orbit amplitude, a_m in Eq.(8), the following two methods are proposed. First, a fluid particle orbit amplitude corresponding to the significant wave, $a_{m1/3}$ given by Eq.(9) is utilized as a representative one to obtain the friction coefficient from Eq.(8).

$$a_{m1/3}=\frac{U_{1/3}T_{1/3}}{2\pi} \tag{9}$$

This method will be hereafter called Method 1. An alternative method is to use maximum velocity and period in individual waves, as defined by Eq.(10).

$$a_{mp}=\frac{U_pT_p}{\pi} \tag{10}$$

This method will be referred to as Method 2.

The correlation between the measured bottom shear stress and the free stream velocity is shown in Fig.8. The relationship indicated by the loop denotes that the phase difference between these two should be considered to make a precise evaluation of the bottom shear stress from the free stream velocity. Therefore, the following estimation method will be more effective as compared with Eq.(7).

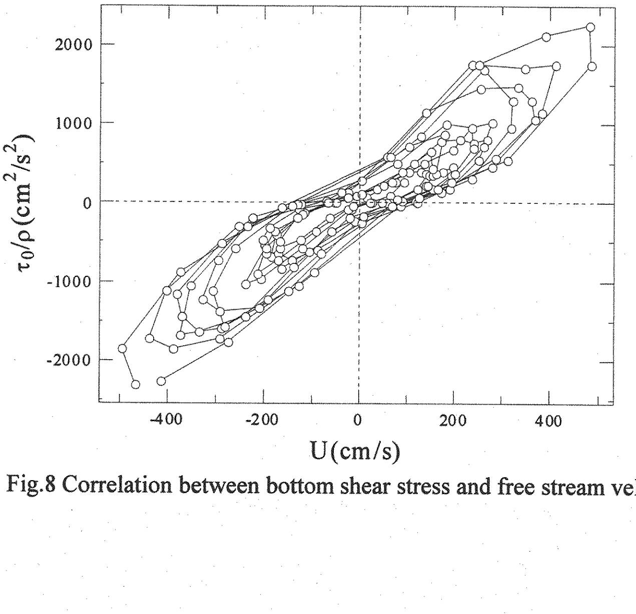

Fig.8 Correlation between bottom shear stress and free stream velocity

$$\tau_o(t-\theta/\omega)=\frac{\rho}{2}f_w U(t)|U(t)| \tag{11}$$

where θ is the phase difference between the bottom shear stress and the free stream velocity. The following equation proposed by Tanaka and Thu (7) will be used to consider the phase difference.

$$\theta = 42.4C^{0.153}\frac{1+0.00279C^{-0.357}}{1+0.127C^{0.563}} \tag{12}$$

$$C=\frac{1}{\kappa\sqrt{\frac{f_w}{2}\frac{a_m}{z_0}}} \tag{13}$$

Two alternative methods can be proposed here again; (i) using Eq.(12) for significant waves, and (ii) using the same equation for individual waves.

The phase difference is obtained from measured data under irregular waves, as well as from a sinusoidal wave experiment. The results are shown in Fig.9, in which the triangles indicate the estimation by Eq.(12) for individual waves. Although the measurements are slightly lower than Eq.(12), this difference is negligible. The estimation changes between 20.0deg. and 25.7deg., with the mean value of 21.3deg., whereas the use of the quantities for significant waves yields 20.4deg. from Eq.(12), which is very close to the averaged value shown earlier. Thus, it is advisable to use constant phase difference, which can be obtained from significant wave quantities, instead of calculating for individual waves.

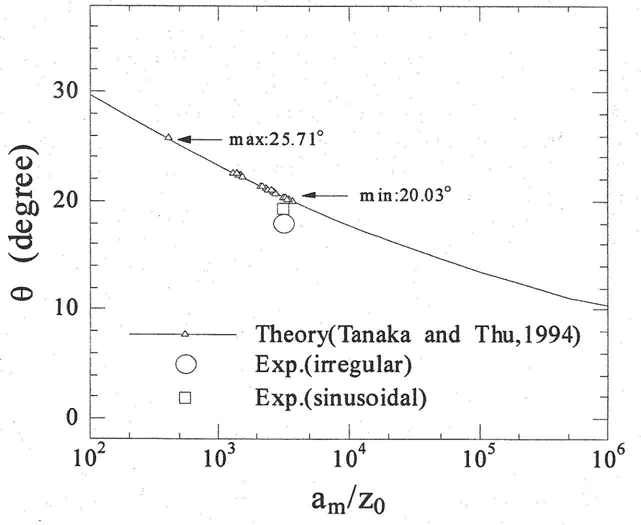

Fig.9 Phase difference

Similarly, the angular frequency in the left-hand side of Eq.(11) can also be defined using two methods. We add the method without considering the phase difference. Then, three methods can be proposed as follows:

- Method A: Without considering the phase difference in Eq.(11).
- Method B: Using the angular frequency of significant wave.
- Method C: Using the angular frequency of an individual wave.

Thus, by combining two methods for friction factor estimation and three methods for angular frequency, six methods can be proposed as a whole as shown in Table 1.

Table 1 Calculation methods of instantaneous bottom shear stress

Method	Calculation method	
1-A	$\tau_0(t)$	$= \frac{\rho}{2} f_w\left(\frac{a_{m1/3}}{z_0}\right) U(t)\lvert U(t)\rvert$
1-B	$\tau_0\left(t - \frac{\theta}{\omega_{1/3}}\right)$	
1-C	$\tau_0\left(t - \frac{\theta}{\omega_p}\right)$	
2-A	$\tau_0(t)$	$= \frac{\rho}{2} f_w\left(\frac{a_{mp}}{z_0}\right) U(t)\lvert U(t)\rvert$
2-B	$\tau_0\left(t - \frac{\theta}{\omega_{1/3}}\right)$	
2-C	$\tau_0\left(t - \frac{\theta}{\omega_p}\right)$	

A comparison between the experiment and the estimation from three methods out of six is shown in Fig.10. Among these, Method 1-A gives underestimated values during the period with smaller magnitude of free stream velocity. Moreover, the phase difference behind the measurement can be seen in the estimation from Method 1-A, whereas Method 2-B and Method 2-C give almost the same values. The correlation between the measurement and the estimation is plotted in Fig.11 for three methods. It can be observed that the difference between Method 2-B and Method 2-C is very small. Considering the fact that use of Method 2-C is more laborious, and that it gives discontinuity in time series of bottom shear stress, it can be concluded that Method 2-B can be used for practical applications.

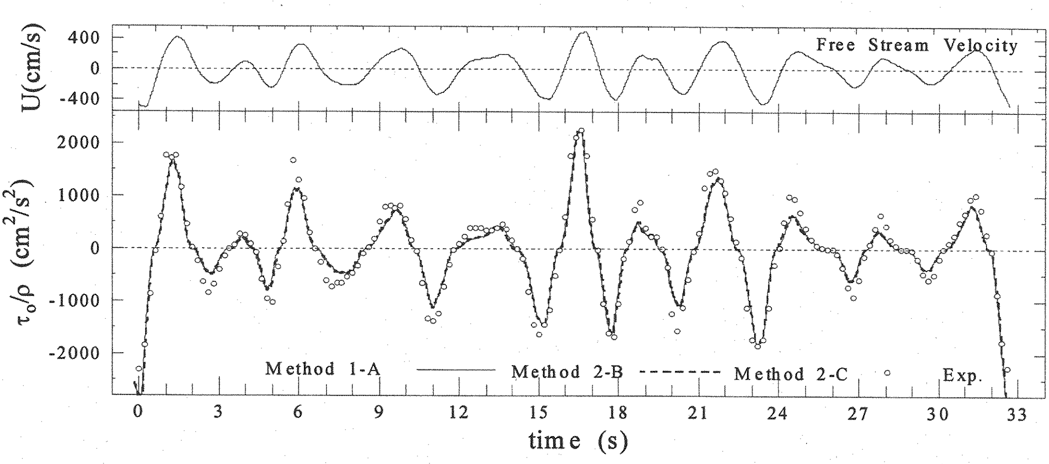

Fig.10 Comparison of bottom shear stress

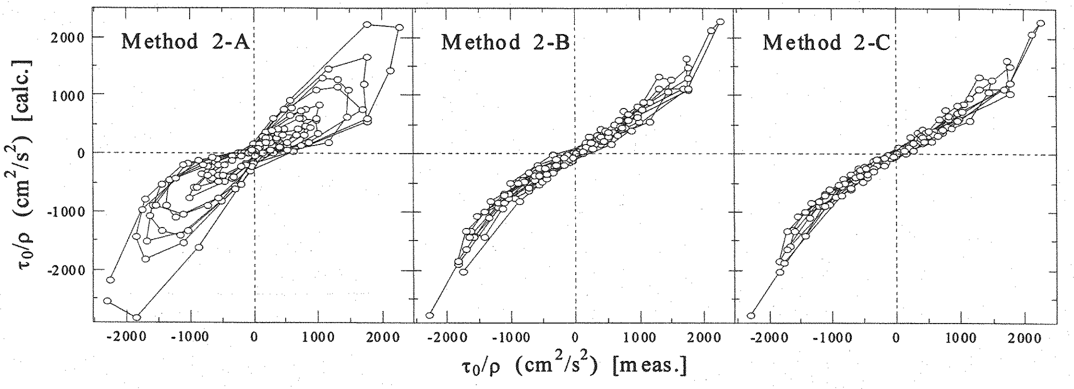

Fig.11 Comparison between measurement and estimation for Method 2-A, 2-B and 2-C

CONCLUSIONS

In this study, bottom shear stress under the irregular wave motion is examined based on an oscillating wind tunnel experiment. The main findings of this study are as follows:

(1) The history effect on turbulence structure has been examined in the experiments. This effect causes a distinct difference of mean velocity profile, depending on the intensity of turbulence.
(2) A simple calculation method of instantaneous bottom shear stress is proposed. The friction coefficient calculated for each crest and trough phase yields a good estimation. Furthermore, the phase difference defined based on significant wave is sufficient for this purpose. It can be concluded that the estimation method of instantaneous bottom shear stress proposed in this study has a sufficient accuracy. Therefore, it can effectively be utilized in a beach evolution model by combining it with the irregular wave transformation model, such as one based on the Boussinesq equation.

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