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Effective Roughness Height in High-Concentrated Flows

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ABSTRACT

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The effective roughness height is an important parameter in coastal sediment transport models. It has been extensively investigated in the past but few research results are related to the high-concentrated flows which often occur in a silty coast. A series of experiments has been carried out in a wave-current flume with silt-sized sediment bed. The mean velocity profiles were measured under different combined wave-current conditions. The effective roughness heights were calculated based on the curve fitting of measured velocity profiles by following the velocity profile model of You (1994). The accuracy of three empirical models, namely, Grant and Madsen (1982), Li and Amos (1998) and You (1996) was examined with the 'measured' effective roughness heights. The results show that all the models are not much accurate for the high-concentrated flows, particularly in the case with a relatively small sediment size. Therefore, cautions should be taken when applying those models in the silty coast, particularly during the extreme events.

ADDITIONAL INDEX WORDS: *bed resistance, silty coast, sediment transport model.*

INTRODUCTION

Silty coast is a type of coast which distributes widely in the north and east of China (Cao *et al*., 2009). In this type of coast, silt-sized sediments could be easily stirred up and transported acutely during extreme weathers and quickly deposit when the weather comes back to normal. This phenomenon may cause a big trouble to the ports which are built in the silty coast since the sudden deposition inside the navigational channel can seriously affect the port operations.

Based on the study carried out by Zhao *et al.* (2002), a high-concentrated layer exists between the bed-load layer and the suspended layer when large waves are presented in the wave-current flume with a silt sediment bed. The existence of this layer may change the physical characteristics of the boundary layer, and then change the effective roughness height, which is an important parameter to quantify the resistance force to the flows from the sea bed in the coastal sediment transport models.

The common method to calculate the effective roughness height is based on the curve fitting of the measured velocity profile (You, 1996). Apart from that, the effective roughness height may also be derived from the energy dissipation (Camenen *et al*., 2009) or the empirical relationship with the sheet-flow layer thickness (Pugh and Wilson, 1999). Among these methods, the first one is the most prevailing method because it is easy to be carried out and is suitable for different kinds of flows.

There are many models for estimation of flow velocity profiles in combined wave-current flows, such as the models of Grant and Madsen (1979), Sleath (1991) and You (1994). Most of these models applied the eddy viscosity concept to build the connection between the shear stress and the velocity gradient, in order to close the fluid motion equations and then derive the theoretical solutions which can be used to predict the distribution of current velocity profiles. Among them, the model of You (1994) is the most efficient one because it does not need any iterations when calculating physical parameters, while its accuracy can be guaranteed at the same time.

There are several models intended to predict the effective roughness height with simple empirical formulas. Grant and Madsen (1982) divided the effective roughness height into three parts, namely, grain roughness height, form roughness height and bed-load roughness height. The grain roughness height is related to the skin friction drag of bed materials, and it can be determined by the grain size; the form roughness height is related to the horizontal pressure gradient which is generated by ripples; and the bed-load roughness height is related to the energy dissipation inside the bed-load layer. Their model was derived based on the experiments carried out under the wave only conditions. Li and Amos (1998) modified the model of Grant and Madsen (1982) and expanded it to a combined wave and current condition based on the field data measured in the Scotian Shelf. You (1996) also proposed a model to estimate the effective roughness height. Unlike aforementioned two models, this model did not consider the mechanism of roughness but derived directly from the model of wave-current velocity profiles (You, 1994). There is an important assumption in this

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model, which is that the flow should be regarded as "clean water". It should bear in mind that the above models were derived under the conditions of sandy beds. Up to now, few research studies have been conducted on the effective roughness height in silty coasts. When we face the sediment transport problems in this kind of coast, we usually refer the models derived from sandy coasts; however, whether those models are applicable to the silty coasts need to be further investigated.

In this study, a series of flume experiments over silty beds with the presence of high-concentrated flows has been carried out. The effective roughness heights derived from the experimental data and from the empirical models were compared to verify whether those models are suitable in the silty coast, particularly with high-concentrated flows.

Experimental setup

The experiments were carried out in a large wind-wave-current flume in Hohai University, China. The flume is 85 m long, 1.0 m wide and 1.5 m deep. A wave generator is set up at one end of the flume, and a gravel beach is placed to reduce the wave reflection. Two types of sediments, *i.e.*, d_{50}=47 μm and 88 μm, collected from Jiangsu silty coast were put into the flume as the sediment beds, respectively. The length of the sediment bed is 15 m and the height is 0.15 m. Two concrete ramps were placed at the beginning and the end of the sediment bed respectively to support the sediment bed. The horizontal section of ramps are both 50 cm and the slope of them are 1:40. The schematic design of the flume is shown in Figure 1.

Three wave height meters were fixed along the flume to monitor and record the water surface variations (see Figure 1). An Acoustic Doppler Velocimeter (ADV) was used to measure the current velocity. It was set up on a beam which could be moved up and down automatically by the remote control of a computer and the positioning accuracy is 1 mm. The measuring points of combined wave-current velocity were 0.6cm, 0.1h, 0.2h, 0.3h, 0.4h, 0.5h, 0.6h above the bed (h is the water depth). The sampling frequency of ADV was 25 Hz and the total sampling time was 60 s. The instantaneous sediment concentration was measured by an Optical Backscatter Sensors (OBS). A suction system was also used to measure the average sediment concentration.

The water depth was set as 0.3 m in all experimental cases. Regular waves were generated, with a constant wave height of 12 cm and wave period of 1.5 s. The depth-averaged current velocities varied in the range from 0.28 m/s to 0.38 m/s in two directions (*i.e.,* following and opposing waves). Detailed parameters of the experiments are listed in Table 1.

Table1. *Basic experimental parameters and effective roughness height*

NUMBER	Wave Height H(m)	Water Depth h(m)	Wave Period T(s)	$\overline{U}$(m/s)	k_s(m)
S1CWF1	0.12	0.3	1.5	0.34	0.01
S1CWF2	0.12	0.3	1.5	0.36	0.0001
S1CWF3	0.12	0.3	1.5	0.38	0.00001
S1CWO1	0.12	0.3	1.5	0.32	0.01
S1CWO2	0.12	0.3	1.5	0.34	0.05
S1CWO3	0.12	0.3	1.5	0.38	0.08
S2CWF1	0.12	0.3	1.5	0.28	0.40
S2CWF2	0.12	0.3	1.5	0.33	0.20
S2CWF3	0.12	0.3	1.5	0.37	0.10
S2CWO1	0.12	0.3	1.5	0.30	0.50
S2CWO2	0.12	0.3	1.5	0.35	0.25
S2CWO3	0.12	0.3	1.5	0.38	0.20

Note: S1 = the median size of sediment is 47 μm; S2 = the median size of sediment is 88 μm; CWF = currents following waves; CWO = currents opposing waves; $\overline{U}$ = mean current velocity; k_s =effective roughness height.

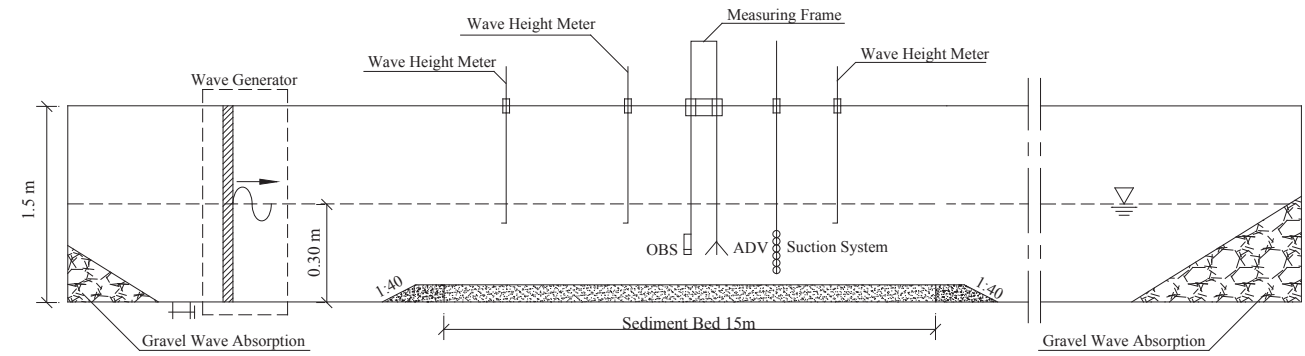

Figure 1.Schematic design of the wind-wave-current flume and the layout of measured instruments.

METHODS

Following the model of You (1994), the wave-current velocity profiles can be divided into three layers, namely wave-dominant layer, wave-current interaction layer and current-dominant layer. The velocity equations in each layer are as follows:

$$\bar{u} = \frac{\overline{u_*}}{\kappa}\left(\frac{\overline{u_*}}{u_w^*}\right)\ln\frac{z}{z_0} \quad z_0 \le z \le \delta_1 \tag{1}$$

$$\bar{u} = \frac{\overline{u_*}}{\kappa}\left(\frac{\overline{u_*}}{u_w^*}\right)\left\{\frac{z}{\delta_1} + \ln\frac{\delta_1}{z_0} - 1\right\} \quad \delta_1 \le z \le 2\delta_1 \tag{2}$$

$$\bar{u} = \frac{\overline{u_*}}{\kappa}\ln\frac{z}{z_1} \quad z \ge 2\delta_1 \tag{3}$$

κ is the von Karman constant, which is approximately equal to 0.4.

δ_1 is the thickness of the wave boundary layer which can be calculated by:

$$\delta_1 = \frac{0.5\kappa u_w^*}{\omega} \tag{4}$$

in which ω is the angular frequency of regular waves and $\omega=2\pi/T$; T is the wave period.

z_0 is the zero-intercept of logarithmic current profile. It can be estimated by:

$$z_0 = \frac{k_s}{30} \tag{5}$$

in which k_s is the effective roughness height.

z_1 is the apparent roughness due to the presence of waves. It can be estimated by:

$$z_1 = 2\delta_1\left\{\frac{e\delta_1}{z_0}\right\}^{-\bar{u}_*/u_w^*} \tag{6}$$

u_w^* is the maximum wave friction velocity associated with the wave motion, which can be calculated by the following equation:

$$u_w^* = \sqrt{0.5 f_w}A\omega \tag{7}$$

in which f_w is the wave friction factor. The explicit formula for this factor was suggested by You *et al.* (1991):

$$f_w = 0.108\left(\frac{A}{K_s}\right)^{-0.343} \tag{8}$$

where A is the semi-excursion just outside the wave boundary layer. It can be calculated by:

$$A = \frac{H}{2\sinh kh} \tag{9}$$

in which H is the wave height, k is the wave number and h is the water depth.

$\bar{u}_*$ is the current friction velocity which can be calculated by:

$$A_1 = \frac{\ln\left(\frac{e\delta_1}{z_0}\right)}{u_w^*} \quad B_1 = \ln\left(\frac{z_r}{2\delta_1}\right) \quad C_1 = -\kappa\bar{u}_r \tag{10}$$

$$\bar{u}_* = \frac{-B_1 + \sqrt{B_1^2 - 4A_1C_1}}{2A_1} \tag{11}$$

in which $\bar{u}_r$ is a reference current velocity at an arbitrary level z_r. The reference current velocity should be given in advance and the reference level is suggested to be a little higher than the wave-current interaction layer.

According to the above equations, we can calculate the effective roughness height k_s by the following procedures. First, an estimated value is assigned to effective roughness height k_s. Then the reference current velocity $\bar{u}_r$ at z_r is given by the measured data. In this study, we select the 0.2h as the level of the reference velocity. After that, all the parameters in Equations (1)-(3) can be calculated by Equations (4)-(11). Finally, the current velocity profile can be derived from Equations (1)-(3). By comparison with the measured data, the value of effective roughness height can be adjusted until the correlation coefficient between the calculated current velocities and measured data from 0.1h to 0.3h is more than 0.95.

RESULTS

The effective roughness heights derived from the curve fitting of the measured data for each case are listed in Table 1. The comparison between the best-fitted flow velocity profiles and the measured experimental data show that the model of You (1994) can be applied to fit the measured data, as shown in Figure 2. Although there are a few deviations near the bottom and the upper part (above 0.4h) in some cases, those deviations might be attributed to the measurement error and the nonlinear effect between the wave and current, which is expected to have less effect on the calculation of effective roughness height.

As we have got the values of effective roughness height for each case, we can use those data to examine the accuracy of the models of Grant and Madsen (1982), Li and Amos (1998) and You (1996) in the prediction of roughness height, under our experimental conditions. The results are shown in Figure 3(a), Figure 3(b) and Figure 3(c), respectively.

It can be seen from Figure 3(a) and Figure 3(b) that the models of Grant and Madsen (1982) and Li and Amos (1998) overestimate the effective roughness height significantly for the cases with the sediment median size of 47 μm. As for the cases with median size of 88 μm, these two models behave much better. In these cases, the predicted values are about 0.51-1.24 times of the measured ones. It is shown that there is only a little difference between these two models, despite that Li and Amos (1998) modified the model of Grant and Madsen (1982) with the consideration of the combined wave-current effect.

Figure 3(c) show that the model of You (1996) over-predicts the effective roughness height in all cases. However, unlike the former two models, the discrepancies between the predicted and measured results in this model are relatively small when the median size of sediment is 47 μm.

Figure 4 displays the overall performance of these three models. In general, all the three models predict the effective roughness height reasonably when the median size of sediments is 88 μm, but there are quite large discrepancies for the case that the median size is 47 μm, although the model of You (1996) behaves slightly better than the other two models.

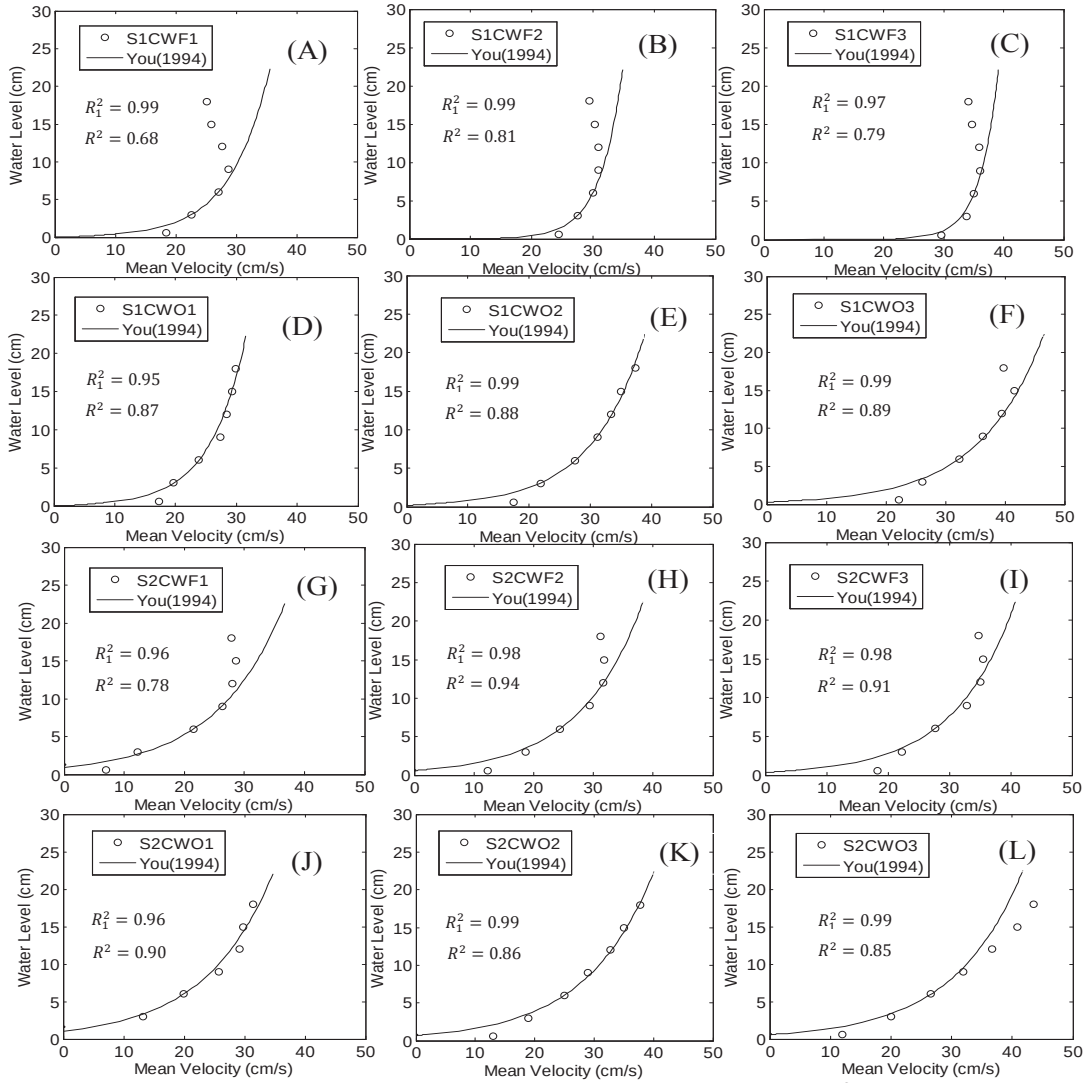

Figure 2.Comparison of wave-current velocity profiles of You's model (1994) and measured data. Note that $R_1^2$is the correlation coefficient between You's model (1994) and measured velocities in the range from 0.1h to 0.3h. R^2 is the correlation coefficient in the entire water depth.

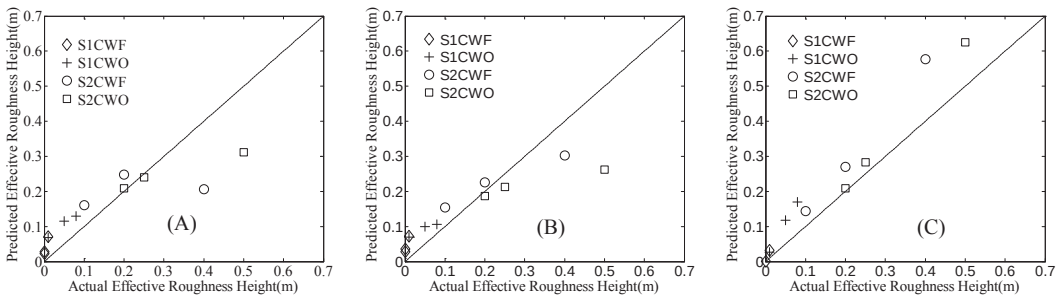

Figure 3.Comparison of 'measured' effective roughness heights with the ones predicted by the models of (A) Grant and Madsen (1982); (B) Li and Amos (1998) and(C) You (1996).

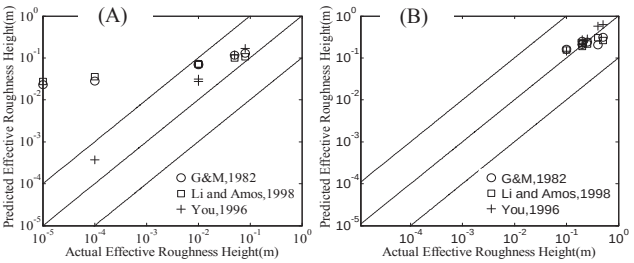

Figure 4.Comparison of 'measured' effective roughness heights with the ones predicted by aforementioned three models when (A) the median size is 47 μm and (B) the median size is 88 μm.

DISCUSSION

According to the above results, the models of Grant and Madsen (1982) and Li and Amos (1998) both over-predict the value of effective roughness height when the median size is 47 μm; and both deviate the 'measured' values slightly when the median size is 88 μm. The main reason leading to the deviations is that these two models are both derived from sandy beds. As the silty sediment is much easy to be initiated under combined wave-current conditions and the sediment concentration near the bottom is quite high based on the measured data (Yao *et al.,* 2015), we can surmise that sediments mainly move as suspended load. If there are many suspended sediments in the water, the viscosity of flow can be changed. It means that the energy dissipation would be decreased and the resistance caused by the bed would be reduced accordingly. Therefore, the formulae which were given by Grant and Madsen (1982) and Li and Amos (1998) shall be modified to account for this issue.

As for the model of You (1996), its predicted results are all larger than the 'measured' ones. Although his model could fit well with the measured data in his study, it is debatable whether it is suitable for the high-concentrated flows. The reason is that the high sediment concentration developed over a silty bed will reduce the rationality of the assumption of "clean water" as that over a sandy bed. But, this assumption is fairly important in his model. Therefore, it is not surprising to find that the predicted results of this model are not very good. If the "clear water" assumption was modified, the prediction accuracy might be improved for the silty coasts. It will be addressed in more detail in our future study..

CONCLUSIONS

Based on a series of experiments, the effective roughness height in high-concentrated flows was studied and the following conclusions can be found:

(1)The wave-current velocity model of You (1994) can generally fit the experimental data well. (2)The model of Grant and Madsen (1982) and Li and Amos (1998) both over-predict the effective roughness height when the median size is 47 μm. It is because these two models are derived from sandy beds and they may not be suitable for silty beds. (3)The model of You (1996) over-predict the effective roughness height in all cases. It is because flows could not be regarded as "clean water" when the sediment concentrations are fairly high. (4) In general, all the three models are demonstrated not suitable for the calculation of effectiveness height of high-concentrated flows at their present forms. Hence, we should be careful if we have to apply those formulae in the sediment transport model of silty coast, particularly during the extreme events.

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