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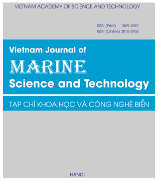

Modeling of suspended sediment concentration - case study in Can Gio, Ho Chi Minh city

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ABSTRACT

The dynamics of suspended sediments are complicated due to the influence of hydrodynamic factors and the characterization of cohesive sediment properties. A one-dimensional model is built to calculate the vertical distribution of suspended sediment concentration (SSC). In the model, parameters that influence the vertical distribution of SSC include the settling velocity (w_s) and the diffusion coefficient (K_z). The settling velocity depends on the cohesive sediment properties, and the diffusion coefficient depends on the wave-current dynamics. The model applies measured data in June 2014 on the mud flats in Can Gio, Ho Chi Minh city, Vietnam. In this study, the settling velocity w_s is a constant of 0.64 × 10^{-6} m/s. The diffusion coefficient depends on water depth, wave action, and tidal currents. Under strong wave - medium current conditions, the average K_z is 2.88 × 10^{-3} m^2/s. Under medium wave - strong current conditions, the average K_z is 6.11 × 10^{-3} m^2/s, while under strong wave - strong current conditions, the average K_z can reach 6.59 × 10^{-3} m^2/s. The resulting simulations demonstrate that the SSC increases rapidly near the bottom layers. Here, the clay sediments are easily disturbed by dynamic conditions. At the bottom layer, the SSC is strongly influenced by the current factor, while the role of the wave factor has not been clearly shown.

Keywords: Suspended sediment concentration, diffusion coefficient, settling velocity, one-dimension model, the mudflat, Can Gio.

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INTRODUCTION

The dynamics of suspended sediments is complicated due to the influence of hydrodynamic factors and the characterization of cohesive sediment properties. The mathematical model is a popular method widely used to study suspended sediments worldwide and in Vietnam. In mathematical models, the properties of sediments and hydrodynamic processes are reflected in settling velocity and diffusion coefficient parameters. Li Y. and Parchure T. M. (1998) used a semi-empirical model to simulate the vertical distribution of SSC in the region of mudbanks off Alleppey on the southwest coast of India [1]. Simulation results were compared with the measured data. The settling velocity and diffusion coefficient are constant and determined from experiment. The results showed that the current-induced boundary layer measurably influences wave-induced sediment resuspension. The simulation method emphasized the significance of the local vertical transport mechanism in determining the structure and dynamics of suspended sediment profiles in the mud bank area. Van Leeuwen et al., (2010) used the Delft3D model to study how clam shells at the bottom affect fine sediment dynamics in the Wadden coastal alluvium (Denmark) [2]. Results showed that the presence of mussel shells increases the roughness of the alluvium, leading to a decrease in the current velocity. This increased the deposition of the sediment. In addition, the clam layer is located on top of the sedimentary materials, causing a large amount of fine sediment to be retained in the mudflat. However, the author has not analyzed in detail the values of the parameters of settling velocity and diffusion coefficient. Li et al., (2018) proposed a two-layer theoretical model based on diffusion theory to predict the vertical distribution of SSC in a flow with submerged vegetation [3]. The vertical sediment diffusion coefficient was calculated through the momentum diffusion coefficient (described by the velocity gradient and the shear stress) affected SSC distribution. The predicted profile of SSC moderately agrees with the experimental data. SSC's vertical distribution was affected by vegetation’s dispersion density, the hydrodynamic conditions, and the turbulent Schmidt number. The dense vegetation makes the vertical distribution of SSC uneven, and the sediment is retained in the vegetation. However, this is a theoretical study and has not been applied in practice.

Studies on suspended sediment dynamics in alluvial and tidal wetlands have received more attention in Vietnam. However, the primary research method is measurement and field survey. Mathematical models’ application to SSC studies is not widely used and has difficulties. At the study site, Can Gio mangrove forest (Ho Chi Minh city), Nguyen Thi Bay and Nguyen Ky Phung (2007) used numerical models to simulate the current regime and sediment transport affected by tides and winds. The results showed that tides play an important role in sediment transport. However, the model mainly applies the calculation of the area in the river and does not clearly show the diffusion coefficient values or velocity parameters according to the depth [4]. Vo Luong Hong Phuoc et al., (2008) used the 1D model to calculate the vertical distribution of suspended sediment concentration under the influence of settling velocity and diffusion coefficient. However, the settling velocity and diffusion coefficient are both constant. These values were calculated from the measured data in mangroves [5]. Le Nguyen Hoa Tien and Vo Luong Hong Phuoc (2020) used the settling column experiment to determine the settling velocity for cohesive sediment collected in the mudflat and the mangrove area at Can Gio mangrove forest. The results showed that the settling velocity for cohesive sediments in the study area ranges from 0.64×10^{-6} m/s to 0.99×10^{-3} m/s [6].

In this paper, we have developed a numerical model that considers the two parameters of settling velocity W_s and diffusion coefficient K_z. The settling velocity is determined from the settling column experiment for sediment samples collected in the mud-flat - mangrove area, and the diffusion coefficient varies with depth under different hydrodynamic conditions. The model applies the measured data in the Can Gio mangrove area in June 2014 to calculate the vertical distribution of SSC.

THE VERTICAL SUSPENDED SEDIMENT CONCENTRATION MODEL

The study aims to develop a 1D model of the vertical distribution of SSC, which follows the approach of Vo Luong Hong Phuoc et al., (2008) [5]. However, there are differences in our model as followings:

The settling velocity w_s: based on experimental tests, which were carried out using a specially designed settling column [6].

The diffusion coefficient K_z: depends on water depth, wave action, and tidal currents.

Using measured data of hydrodynamic factors and SSC in June 2014 at Nang Hai area, Can Gio mangrove forest, Ho Chi Minh City, Vietnam.

The governing equation

The vertical settling-diffusion equation can be expressed:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(w_s C + K_z \frac{\partial C}{\partial z} \right) \tag{1}$$

in which: $C(z, t)$: suspended sediment concentration (SSC) (kg/m^3); w_s: settling velocity (m/s); K_z: vertical diffusion coefficient (m^2/s); t: time (s); z: vertical coordinate.

In Eq. (1), the unknown concentration C is a function of the independent variable z and time t. Based on the method of separation of variables, function $C(z, t)$ is represented as a product of function $C_z(z)$ and $T(t)$, each depending on variable x and t, respectively. Since wave period T is periodic, then $T(t) = e^{-i\omega t}$ where $\omega = 2\pi/T$, we have:

$$C(z,t) = C_z(z)T(t) = C_z(z)e^{-i\omega t} \tag{2}$$

Substituting Eq. (2) in Eq. (1), we can get an expression for vertical concentration $C(z)$ in the form:

$$K_z \frac{\partial^2 C_z}{\partial z^2} + \left(w_s + \frac{\partial K_z}{\partial z} \right)\frac{\partial C_z}{\partial z} + \left(i\omega + \frac{\partial w_s}{\partial z} \right)C_z = 0 \tag{3}$$

The equation can be solved for the surface and bottom boundary conditions:

At the water surface: $C = C_s$ (4a)

At the bottom: $C = C_b$ (4b)

C_s and C_b are SSC at the water surface and bottom, respectively; the value of C_s và C_b are determined from the field experiment.

The differential equation (3) can be approximated by a finite difference equation and becomes a system of matrix equations. To solve this equation, Thomas's method for a tridiagonal band type matrix is well suited [7].

Settling velocity

In the mud flat, sediment compositions are mainly mud and clay; hence it has a cohesive form (flocculation). In the field experiment, the settling velocity of the fine sediment varies with the shape, size, and density of flocs [8]. In laboratory experiments, the settling velocity is a function of the SSC [9]:

$$W_s = \frac{aC^n}{\left(C^2 + b^2 \right)^m} \tag{5}$$

where: W_s: the settling velocity; C: the suspended sediment concentration; a, b, m, n are sediment dependent empirical coefficients.

Vertical diffusion coefficient

The vertical diffusion coefficient K_z can be calculated using the flow field and its modulation by density stratification [1].

$$K_z = K_0 \phi \tag{6}$$

$$K_0 = \alpha_2 K_{0w} + \alpha_3 K_{0c} \tag{7}$$

where: K_{0w} and K_{0c} are the wave and current diffusion coefficients, respectively, and α_2

and α_3 are the corresponding weighting coefficients.

The wave diffusion coefficient is calculated using Hwang and Wang’s formula (1982) [1]:

$$K_{0w} = \alpha_4 \frac{\omega \zeta_0^2}{8} \frac{\sin h^2 k\left(h+z\right)}{\sin h^2 kh} \quad (8)$$

where: $\omega = 2\pi/T$: the angular wave frequency; T: the wave period; ζ_0: the wave amplitude; k: the wave number; α_4: a diffusion scaling coefficient, with $\alpha_4 = 1.77/\sinh kh$ (based on experimental data of Thimmakorn (1984)).

For diffusion coefficients due to the current-induced boundary layer, the Prandtl-von Karman expression for K_{0c} is selected [1]:

$$K_{0c} = \frac{\kappa n g^{1/2}}{h^{1/6}} U\left(h-z\right)\left(1-\frac{h-z}{h}\right) \quad (9)$$

where: κ: Karman constant; n: Manning’s bed resistance coefficient; g: the acceleration due to gravity; U: the mean current velocity; h: the water depth.

STUDY SITE

The study site is a mud-flat in the Dong Tranh river (Fig. 1). The Dong Tranh river is located in the South of Can Gio district, Ho Chi Minh city, with a length of about 67.5 km, between two communes, Ly Nhon and Long Hoa. Dong Tranh estuary is crucial because it is the junction of mangroves with the sea, where dynamic interactions occur between mangroves and the sea. The study site is located between the Capes Ly Nhon and Long Hoa side of the estuary; therefore, it is less affected by wind-induced strong waves [10].

Measured data were collected in June 2014 [11]. The measurement period was from 19th to 27th June 2014. The coordinates of the mud-flat station are 10°23’27.18”N; 106°52’48.12”E. Collected data include water depth, wave height, current velocity, and SSC. The instruments include Valeport MIDAS DWR (UK) and AEM-213D (Japan). The Valeport MIDAS DWR is integrated with sensors to measure the water depth, turbidity, current velocity, and wave height. For water depth and turbidity, the interval time was 30 minutes/1 sample. For current velocity and wave height, the interval times were 30 minutes/per record, and the sampling frequency was 4 Hz. The AEM-213D was installed with a frequency of 60 minutes/per sample. The water samples were taken every 30 minutes to calibrate SSC in the laboratory. Sediment samples were also collected [11].

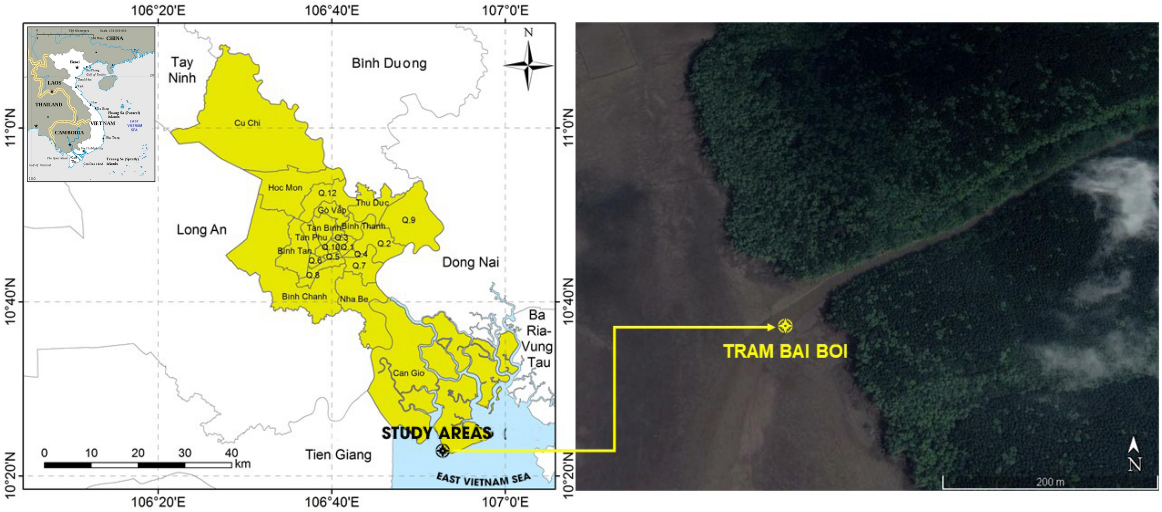

Figure 1. The study site in the mud-flat at Can Gio mangrove, HCMC

CALCULATION THE VERTICAL SSC DISTRIBUTION AT THE STUDY SITE

Input data

Based on the field data, three cases were calculated to analyze the influence of the hydrodynamic factors on SSC; they are:

Case 1: Medium wave - strong current condition;

Case 2: Strong wave - strong current condition;

Case 3: Strong wave - medium current condition.

Table 1 shows measured data for water depth, significant wave height, wave period, and average current velocity. These are the parameters to calculate the diffusion coefficient K_z corresponding to different hydrodynamic conditions.

Table 1. Input data for the case of calculation of diffusion coefficient K_z

Cases	Water depth (m)	Significant wave height H_s (m)	Wave period (s)	Mean current velocity (m/s)
Medium wave - strong current condition	1.68	0.08	0.7	0.05
Strong wave - strong current condition	1.6	0.15	0.9	0.06
Strong wave - medium current condition	1.43	0.11	0.8	0.04

Boundary conditions of the mathematical model, including the concentration of suspended sediment at the surface (Equation (4a)) and the concentration of suspended sediment at the bottom (Equation (4b)), are shown in Table 2.

Table 2. Boundary conditions for calculating the distribution of SSC

Cases	Layer	SSC (kg/m^3)
Medium wave - strong current condition	Surface	0.03
	Bottom	0.085
Strong wave - strong current condition	Surface	0.05
	Bottom	0.135
Strong wave - medium current condition	Surface	0.035
	Bottom	0.08

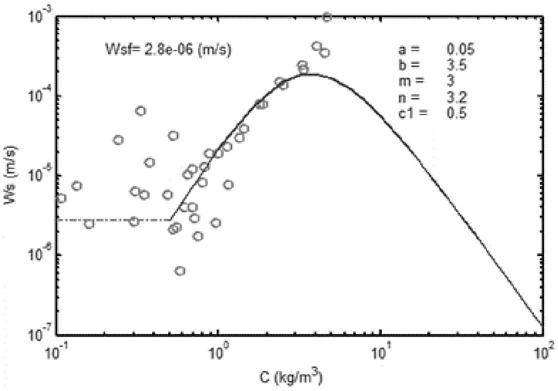

Figure 2. The settling velocity of the cohesive sediments at Can Gio, HCMC [6]

To determine the settling velocity, the model uses the calculating results of the settling velocity of the cohesive sediments from the column test of Le Nguyen Hoa Tien and Vo Luong Hong Phuoc (2020) [6]. The settling velocity for cohesive sediments ranges from 0.64 × 10^{-6} m/s to 0.99 × 10^{-3} m/s, with the maximum velocity w_{s2} = 0.99 × 10^{-3} m/s corresponding to the sediment concentration C_2 = 4.7 kg/m^3 (Fig. 2). In this model, the settling velocity will be considered as constant and equal to 0.64 × 10^{-6} m/s.

The dependence of vertical diffusion coefficient K_z on water depth

The results of diffusion coefficients varying with water depth are shown in Figure 3a, corresponding to different hydrodynamic conditions: strong wave - medium current, medium wave - strong current and strong wave

- strong current. The diffusion coefficient reaches its maximum value at the surface and decreases with water depth as the flow velocity and wave energy decrease from the surface to the bottom (Figure 3a). In this condition, at the surface layer, the effect of the wave factor on the K_z coefficient is stronger than that of the current factor. On the contrary, at the bottom layer, the influence of the current factor is stronger than the wave factor (Figure 3b).

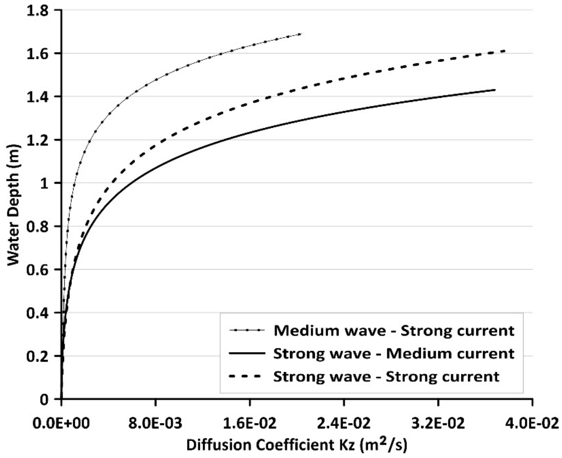

Figure 3a. The distribution of diffusion coefficient K_z depends on water depth

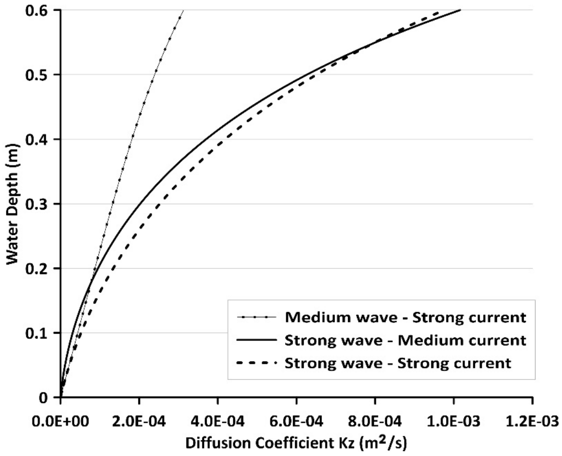

Figure 3b. The distribution of diffusion coefficient K_z depends at the bottom layer (from 0 to 0.6 m)

The results show that the stronger the hydrodynamic condition, the larger K_z will be. In strong wave - medium current case, the average value of diffusion coefficient reaches 2.88×10^{-3} m^2/s; in medium wave - strong current condition, the average value of K_z reaches 6.11×10^{-3} m^2/s; especially in strong wave - strong current conditions, the average value of K_z can reach 6.59×10^{-3} m^2/s. The K_z value varying with water depth in each case will be applied to calculate the concentration distribution of suspended sediments.

The dependence of SSC on water depth

Figure 4 shows the results of the vertical distribution of SSC under the influence of the diffusion coefficient in the different hydrodynamic conditions are shown in dimensionless form.

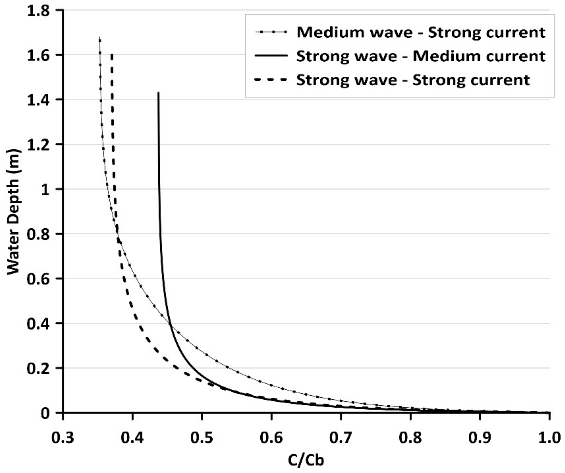

Figure 4. The results of the vertical SSC distribution from model

In general, the result of the vertical distribution of SSC shows that the SSC near the bottom is higher than the concentration at the surface; and the closer to the bottom, the faster the SSC increases because the clay sediment at the bottom is easily mixed without the impact of the hydrodynamic conditions. For each condition, SSC tends to be uniformly distributed from the surface to a certain depth; then, it will increase when reaching the bottom depth. SSC is vertically homogeneous in the strong wave - medium current condition, a 0.2 m layer depth. In the strong wave-strong current condition, the SSC is homogeneous from the surface to the depth of 0.4 m. In the medium wave-strong current condition, the SSC is homogeneous from the surface to the depth of 1 m. Thus, the diffusion process causes the sediment at the bottom to diffuse to the upper layers. In the medium wave-strong current condition, the amount of SSC carried up is stronger than in the other two cases.

Besides, in the strong wave - strong current and the strong wave - medium current condition, although the hydrodynamic condition is “strong waves”, the impact of the wave dynamics is negligible compared to the current dynamics at the bottom, consistent with the distribution of the diffusion coefficient K_z at the bottom; the effect of the current is stronger than that of the wave. The calculation results have shown the effect of diffusion coefficient K_z on SSC by depth. Therefore, the different hydrodynamic conditions will affect the distribution of SSC in the mudflats. The modeling results agree with the analyzed results of the measured data in the field experiment, which means that at the mud-flat, tidal current is the main factor affecting the values of SSC [12].

Compared with the study of Vo Luong Hong Phuoc et al., (2008), this study considers K_z as a constant; we find that:

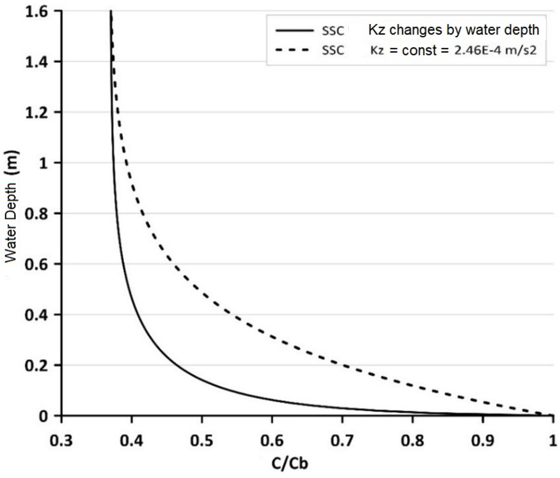

Figure 5. The compared results under the strong wave-strong current conditions

In three cases (Figures 5–7), the diffusion of SSC at the bottom happens more slowly in the case of K_z changing by depth than in the case of K_z being constant.

In strong waves (Figure 7), when K_z is a constant, the change of SSC by depth is almost linear. When K_z changes by depth, the SSC changes in an exponential form.

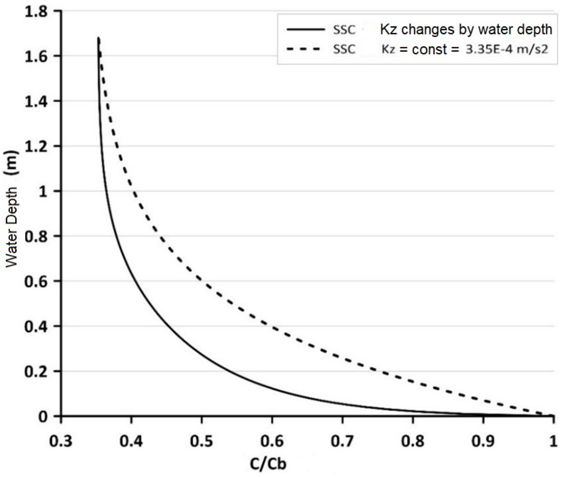

Figure 6. The compared results under the medium wave-strong current conditions (K_z for strong current)

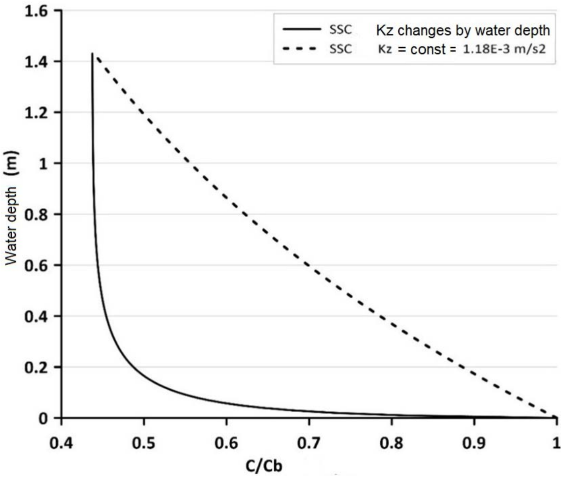

Figure 7. The compared results under the strong wave - medium current conditions (K_z for strong wave)

CONCLUSIONS

The study calculated the changes of the diffusion coefficient K_z by water depth in Can

Gio mangrove forest, Ho Chi Minh City, under three different hydrodynamic conditions. The results show that the stronger the hydrodynamics, the larger the K_z value. The average value of K_z at the study site in the case of strong wave-medium current, strong wave-strong current and medium wave-strong current has the following values: 2.88×10^{-3} m^2/s; 6.59×10^{-3} m^2/s and 6.11×10^{-3} m^2/s. A 1D model to calculate the vertical distribution of SSC has been developed and improved. The diffusion coefficients K_z and the settling velocity W_s values were calculated from experimental data at the study site and to be applied in the 1D model of vertical suspended sediment profile. The model results proves that the SSC depend on the diffusion coefficient K_z, especially at the bottom, where the current's factor role is more dominant than the wave factor. Thus, the calculation results from the model contribute to the findings that the distribution of SSC depends on the water depth under the influence of hydrodynamic factors.

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