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Vertical distribution of suspended sediment concentration - A case study in Cu Lao Dung Coastal Areas (Vietnam)

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Abstract. The vertical distribution of suspended sediments in the mangrove-mud coast is complicated due to the characterization of cohesive sediment properties, and the influence of hydrodynamic factors. In this study, the time-evolution of suspended sediment concentration (SSC) in water depth is simulated by a one-dimensional model. The model applies in-situ data measured in October 2014 at the outer station in Cu Lao Dung coastal areas, Soc Trang, Vietnam. In the model, parameters which have influence on 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 settling velocity is determined by the settling column experiment in the laboratory, which is a constant of 1.8 x 10^{-4} ms^{-1}. Two hydrodynamic conditions are simulated including a strong current condition and a strong wave condition. Both simulations show that the SSC near the bottom is much higher than ones at the surface due to higher turbulence at the bottom. At the bottom layer, the SSC is strongly influenced by the current.

Keywords: a one-dimensional model; Cu Lao Dung (Soc Trang, Vietnam); diffusion coefficient; settling velocity; suspended sediment concentration

1. Introduction

The dynamics of suspended sediments is complicated due to influences of hydrodynamic factors, cohesive sediment properties, or transport of sediments from other sources. Therefore, studies on suspended sediment dynamics in areas near mangroves or alluvial plains have been continued. Mathematical model is a method widely used to study suspended sediments. Previous studies have shown that tidal asymmetry is an important factor affecting sediment transport (Bunt and Wolanski 1980, Mazda *et al*. 1995, Furukawa *et al*. 1997). The relationship between flow velocity and sediment transport in mangroves is also considered in models such as: 3D Delft model (Temmerman *et al*. 2005), FVCOM and ESSed models (Li *et al*. 2014). Nevertheless, in highly turbid shallow water, short-term sediment re-suspension remains insufficiently documented in models, which

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generally do not consider forcings related to short events (at hourly time scale) and heterogeneous sediment grain-size. In the region of mudbanks off Alleppey on the southwest coast of India, a semi-empirical model was used to simulate the vertical distribution of SSC (Li and Parchure 1998), the results showed that the current-induced boundary layer influences wave-induced sediment resuspension. The simulation method emphasized the significance of local vertical transport mechanism in determining the structure and dynamics of suspended sediment profiles in the mud bank area. In addition, the vertical distribution of SSC was affected by the dispersion density of vegetation, hydrodynamic conditions, and the turbulent Schmidt number (Li *et al*. 2018). By solving the average-time diffusion equation for SSC and taking into account the effects of different bed forms, Zuo *et al*. (2019) showed that the effects of bed forms on SSC are complicated, especially in the transition zone from rippled bed to plane bed. In this zone, sediment suspension is not well understood, and more measured data and research are needed to improve our understanding of the turbulence process, sediment diffusivity, and roughness.

In Vietnam, studies on suspended sediment dynamics in alluvial and tidal wetlands have currently received more attention. However, the application of mathematical models to SSC studies has not been widely used and has certain difficulties. At Can Gio mangrove forest (Ho Chi Minh City), Nguyen and Nguyen (2007) used numerical models to simulate 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 for the river area and does not clearly show the values of the diffusion coefficient or velocity parameters as a function of the depth. Vo Luong *et al*. (2008) used a 1D model to calculate the vertical distribution of suspended sediment concentration (SSC) 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 in-situ data measured in mangroves.

SSC is one of the important topics in sediment study. Until recently, not many studies work on the parameterization of the SSC profile in mangrove-mud areas in Vietnam. In this study, the time-evolution of SSC with respect to water depth is simulated by a one-dimensional, vertical sediment transport model. The time-varying concentration profile is simulated for two different conditions: a strong wave condition and a strong current condition. In the model, parameters which have influences on 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.

2. Mathematical description of suspended sediment concentration profiles

The vertical distribution of sediment concentration profile can be described by (following Mehta and Li 2003):

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

where C is SSC [kgm^{-3}], W_s is the settling velocity [ms^{-1}], K_z is the vertical diffusion coefficient [m^{2}s^{-1}] and z is the vertical coordinate.

2.1 Boundary conditions

At the free water surface ($z = h$, h is the water depth)

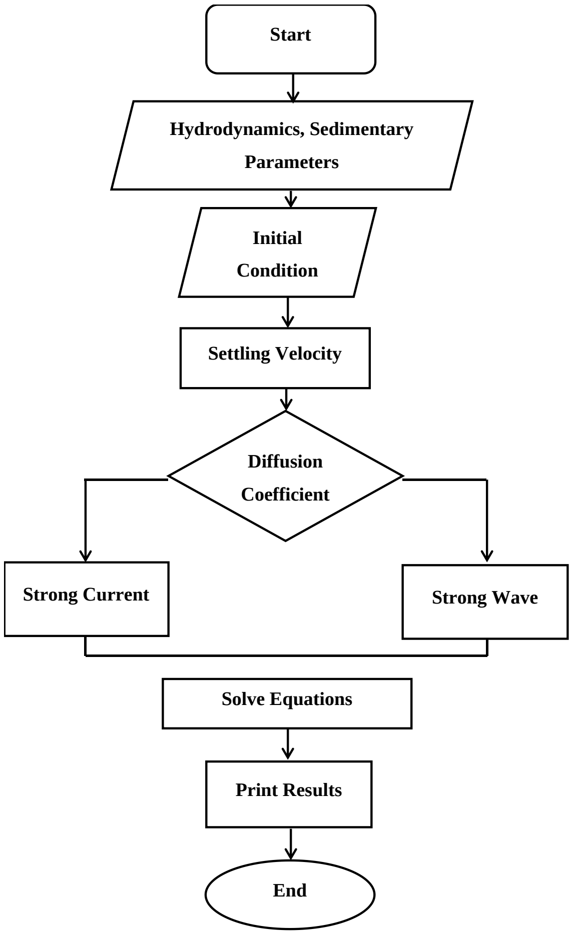

Fig. 1 The flow chart for the 1D model to calculate SSC profile

$$\left(\mathrm{K_z}\frac{\partial \mathrm{C}}{\partial \mathrm{z}} + \mathrm{W_s C}\right)\Big|_{\mathrm{z=h}} = 0 \tag{2}$$

and the boundary condition at the bottom of the water layer, $z = 0$:

$$\left(\mathrm{K_z}\frac{\partial \mathrm{C}}{\partial \mathrm{z}} + \mathrm{W_s C}\right)\Big|_{\mathrm{z=h}} = -F_n \tag{3}$$

In which, F_n is the net resuspension flux and F_n can be expressed by (following Li 1996).

$$F_n = \begin{cases} \rho_m u_b \beta\left(R_{ic}^2 R_{ig}^{-1} - R_{ig}\right) - & \left(R_{ig} < R_{ic}\right) \\ -w_s C|_{z=h} & \left(R_{ig} \geq R_{ic}\right) \end{cases} \tag{4}$$

where ρ_m is the density of fluid mud [kgm^{-3}], u_b is the amplitude of the horizontal velocity just outside the bottom boundary layer in water [ms^{-1}], β is a non-dimensional coefficient and R_{ic} is the critical value (for initiating entrainment) of the global Richardson number R_{ig} defined as

$$R_{ig} = \frac{\frac{\rho m - \rho}{\rho} g\delta}{\Delta u_0^2} \tag{5}$$

where δ is the thickness of the wave boundary layer in water and Δu_0 is the difference between the near-bottom velocity in water and the near-surface velocity in fluid mud, which must be obtained from a wave-mud interaction model.

Eqs. (1)-(3) can be approximated by using a finite difference method (Crank - Nicolson implicit difference). To solve the resulting equation, Thomas's method for a tridiagonal band type matrix is well suited (Lee 2011). Fig. 1 is the flow chart for modelling the time-evolution of the suspended concentration profile.

2.2 Diffusion coefficient

The vertical diffusion coefficient K_z can be calculated using the flow field and its modulation by density stratification (Li and Parchure 1998)

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

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

In which, 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 by using the formula proposed by Hwang and Wang (1982) (Li and Parchure 1998)

$$K_{0w} = \alpha_4 \frac{\omega \zeta_0^2}{8} \frac{sinh^2 k(h+z)}{sinh^2 kh} \tag{8}$$

In which, $\omega = 2\pi/T$ is the angular wave frequency, T is the wave period, ζ_0 is the wave amplitude, k is the wave number and α_4 is a diffusion scaling coefficient, with α_4 = 1.77/sinhkh (based on experimental data of Thimmakorn (1984), Li and Parchure 1998).

For diffusion coefficients due to the current-induced boundary layer, the Prandtl-von Karman expression for K_{oc} is selected (Li and Parchure 1998)

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

where κ is Karman constant, n is Manning's bed resistance coefficient, g is the acceleration due to gravity, U is the mean current velocity and h is the water depth.

2.3 Settling velocity

At the study site, sediment compositions are mainly mud and clay, they are cohesive sediments, hence the settling velocity of the fine sediment varies with the SSC. In the study, a semi empirical formula was used to describe the relationship between settling velocity and SSC (Hwang 1989):

$$W_s = \frac{aC^n}{(C^2+b^2)^m} \tag{10}$$

In which, W_s is the settling velocity; C is SSC; a, b, m, n are sediment dependent empirical coefficients.

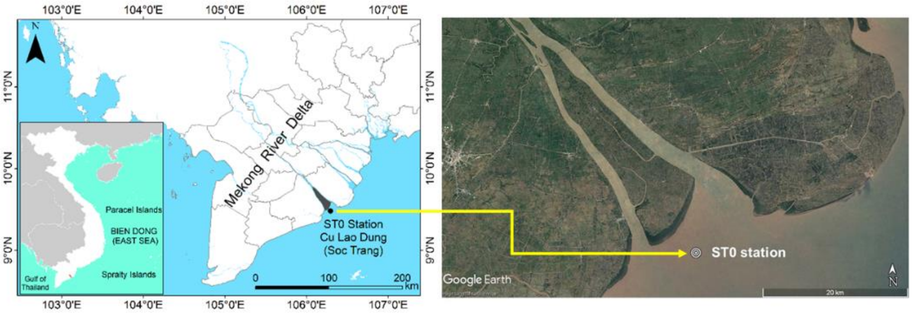

Fig. 2 The study site at Cu Lao Dung, Soc Trang, Vietnam

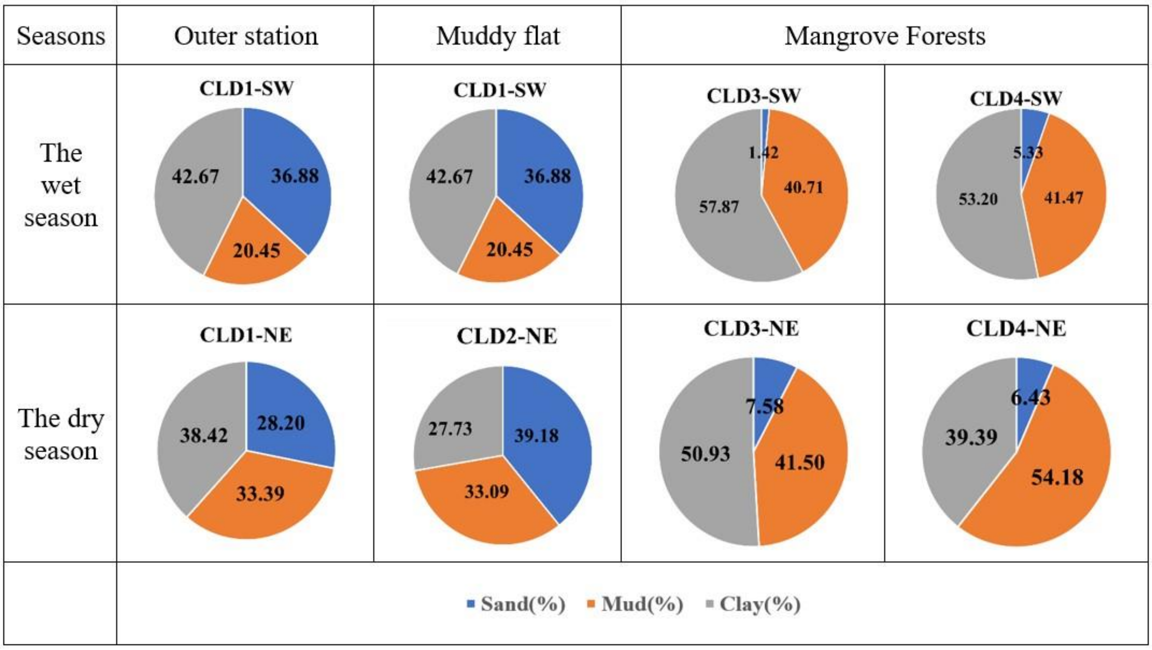

Fig. 3 Grain-size distribution at Cu Lao Dung, Soc Trang, Vietnam

3. Model application in Cu Lao Dung coastal areas

3.1 The study site and data collection

The study site is the mangrove-mud coast of the island of Cu Lao Dung, located at the mouth of the Hau River, one of the main distributaries of the Mekong Delta. The dataset from field measurement are extracted from the project "Hydrodynamics and sediments flux through the Cu Lao Dung mangrove forest" (Hong Phuoc Vo Luong, 2014-2016) in two seasons: the wet season

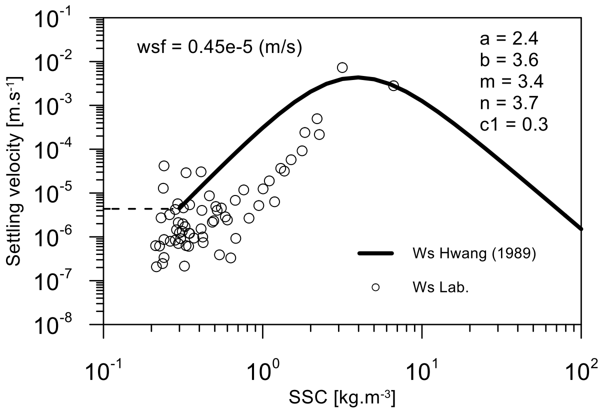

Fig. 4 The settling velocity of the cohesive sediments at Cu Lao Dung, Soc Trang, Vietnam

(21 September - 04 October, 2014) and the dry season (03 - 15 March, 2015). Collected data includes water depth, wave height, current velocity, and SSC (from turbidity measurements). The water samples were taken every 30 minutes for calibration SSC in laboratory. Sediment samples were also collected to determine particle size and settling velocity.

In the study, the model applies the in-situ data measured at the outer station ST0 (Fig. 2). Measured data was collected from 22 September - 04 October 2014. Coordinates of the outer station ST0 are: 9°28’47.9” N and 106°17’37.7” E. The instruments include Valeport MIDAS DWR (UK) and CTD ASTD102 (Japan) (ST0 station). 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 time interval is 30 minutes/1 record, and the sampling frequency was 4 Hz. For CTD ASTD102, the time interval is 60 minutes/1 sample and the depth interval is 0.1 m.

3.2 Determination and selection the settling velocity

❖ Determination settling velocity

Sediment samples for the experiment tests were collected from four different sites (one sample at the outer station, one sample at the muddy flat and two samples at the mangrove forest) at Cu Lao Dung mangrove area in two different seasons. The collected sediment samples will be analyzed in the laboratory to determine particle size and settling velocity. Samples to be analysed using the SediGraph method to determine of sediment particle size which is carried out in the laboratory at the University of Washington, United States. Figure 3 shows that mud and clay are the main sediment components, accounting for approximately 60-70% of the total. This proportion is particularly high in muddy flats and mangrove forests. The results show that the sediment in the study area is cohesive.

Due to the cohesive property of sediment in the study area, the multi-depth method was used to determine the settling velocity of fine sediment. This method uses multi-depth concentrations sampling and integration of the sediment settling equation (Hwang 1989). Settling test were carried out by using a specially designed 2 m tall settling column at laboratory in Department Oceanology, Meteorology and Hydrology, University of Science, Vietnam National University Ho Chi Minh City, Vietnam. Based on the empirical formulas of Hwang (1989) and the experimental data of Mehta and

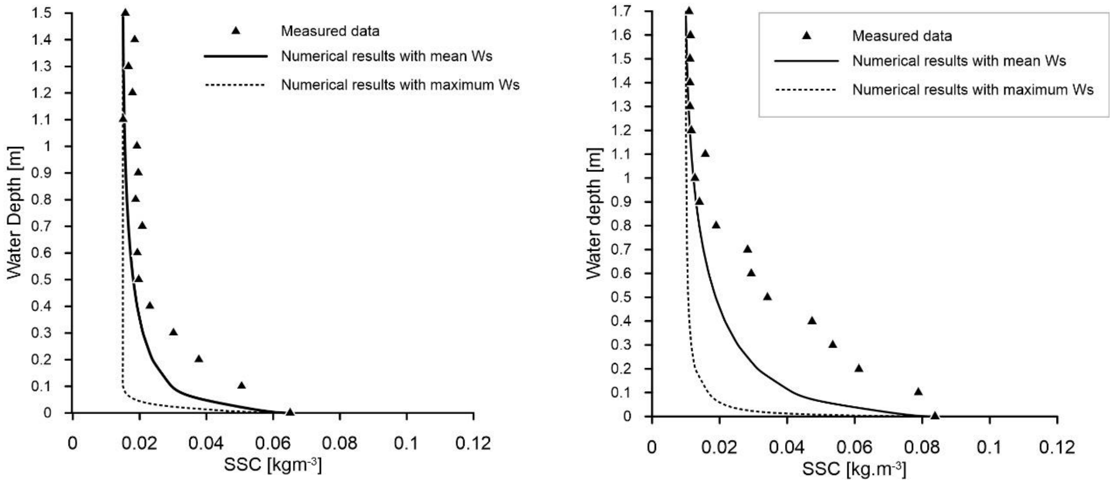

Fig. 5 Comparison of the calculated and measured SSC in two cases: mean settling velocity and maximum settling velocity

Table 1 The input wave - current parameters at ST0 station

Parameters	Case 1	Case 2	Case 3	Case 4
Depth [m]	2.2	1.0	1.7	1.6
Significant wave height Hs [m]	0.17	0.23	0.2	0.2
Mean current velocity [ms^{-1}]	0.1	0.16	0.31	0.23

Li (2003), the settling velocity by concentration is considered with variation of four parameters: *a, b*, *m*, and *n*, as defined in Eq. (10) in section 2.3. The parameterization of *a*, *b*, *m*, *n* is done by trial and error. The experimental data in Fig. 4 can be classified into two groups: flocculation region and hindered region. The settling velocity for cohesive sediments ranges from 2.08 x 10^{-7} ms^{-1} to 7.29 x 10^{-3} ms^{-1} with a maximum settling velocity of 7.29 x 10^{-3} ms^{-1} at a sediment concentration of 3.2 kgm^{-3} and the mean settling velocity of 1.8 x 10^{-4} ms^{-1} (Fig. 4).

❖ Selection of the settling velocity for modelling

The vertical SSC model is tested using two cases: mean settling velocity (W_s = 1.8 x 10^{-4} ms^{-1}) and maximum settling velocity (W_s = 7.29 x 10^{-3} ms^{-1}). The results (shown in Fig. 5) show that the mean settling velocity case agrees with the measured data, while the maximum settling velocity case results in a uniform SSC distribution with water depth, except for an increase in SSC at the bottom layer. Therefore, the mean settling velocity (W_s = 1.8 x 10^{-4} ms^{-1}) is selected for the time-evolution of the SSC model.

3.3 Verification

Some measured data were collected to compare with the numerical results. The input wave - current parameters were shown in Table 1. Fig. 6 shows the comparison of the calculated and measured SSC profiles at the ST0 station. It can be seen that, in case 1, under weak wave-current conditions, the calculated sediment concentration agrees well with the measured data. However,

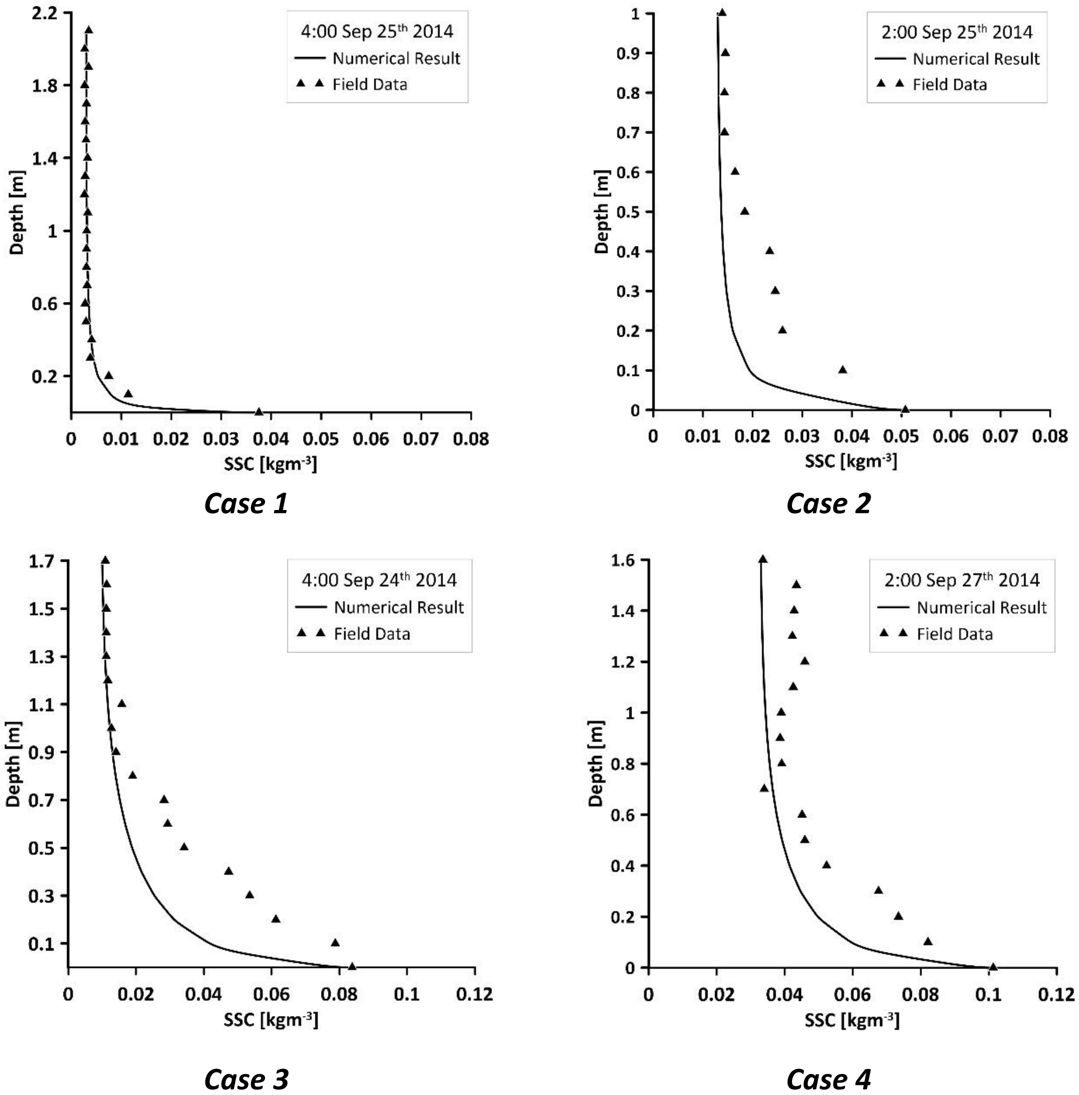

Fig. 6 Comparison of the calculated and measured SSC profile at ST0 station

under stronger wave-current conditions (cases 2, 3, and 4), the measured data is larger than the calculated sediment concentration, but the distribution trend of SSC is similar.

3.4 Input data for the time-evolution of suspended sediment concentration model

The model initially compares the role of wave-current dynamic factors affecting the SSC. Therefore, two hydrodynamic conditions are simulated including strong current condition and strong wave condition. Strong current condition means the current velocity reaches the highest value and strong wave condition means the wave height has the highest value during the survey period in the study area. Table 2 shows measured data for water depth, significant wave height, wave period and

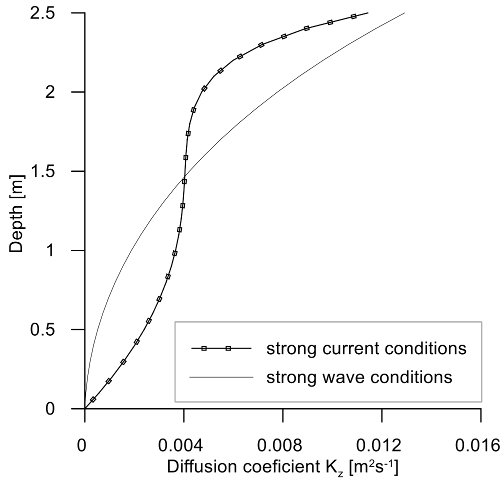

Fig. 7 Vertical profile of the diffusion coefficient

Table 2 Input data for two simulation cases

Cases	Water depth [m]	Significant wave height Hs [m]	Wave period [s]	Mean current velocity [ms^{-1}]
Strong wave condition	2.5	0.46	4	0.1
Strong current condition		0.1	0.8	0.56

mean current velocity for two hydrodynamic conditions. These are the parameters to calculate the diffusion coefficient K_z corresponding to different hydrodynamic conditions. Thus, two different dynamic conditions affecting SSC are shown by the difference of the diffusion coefficient K_z.

The results of the diffusion coefficient are shown in Fig. 7. In general, the diffusion coefficient reaches its maximum value at the surface, decreasing with water depth as the current velocity and wave energy decrease from the surface to the bottom. The diffusion coefficient under strong current conditions has a higher value at the bottom, whereas, the value of K_z under strong wave conditions is higher at the surface. At outer station at Cu Lao Dung area, the mean K_z value reaches 3.9 x 10^{-3} m^2s^{-1} in the strong current conditions and the mean K_z value reaches 4.2 x 10^{-3} m^2s^{-1} in the strong wave conditions. The calculation results of diffusion coefficient according to depth are also input data for SSC calculation corresponding to different dynamic conditions.

3.5 Results of vertical suspended sediment concentrations

The initial condition was selected as the SSC profile at 00:00 on 04 October 2014 at the outer station ST0 (the dashed lines in Figs. 8 and 9). Note that the SSC profile increases with the water depth. Both the results under the strong wave condition (Fig. 8) and the strong current condition (Fig. 9) agree with the theory of concentration distribution of suspended sediments. The SSC at the bottom is much higher than SSC at the surface. Sediment after deposition will be concentrated at the bottom. Over time, the concentration at the surface will decrease and this amount of sediment will settle, leading to an increase in sediment concentration at the bottom.

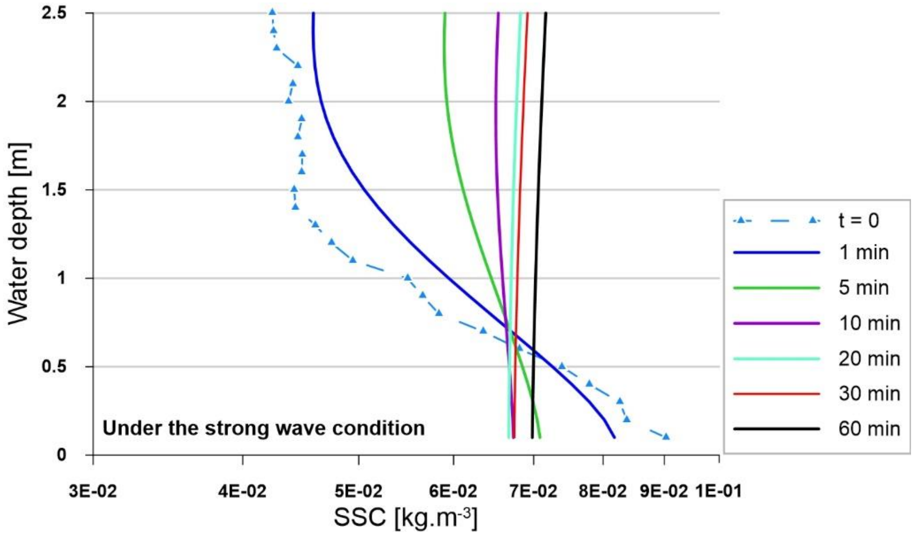

Fig. 8 SSC profile under the strong wave condition in 60 minutes. The first dashed curve on the left is the measured data

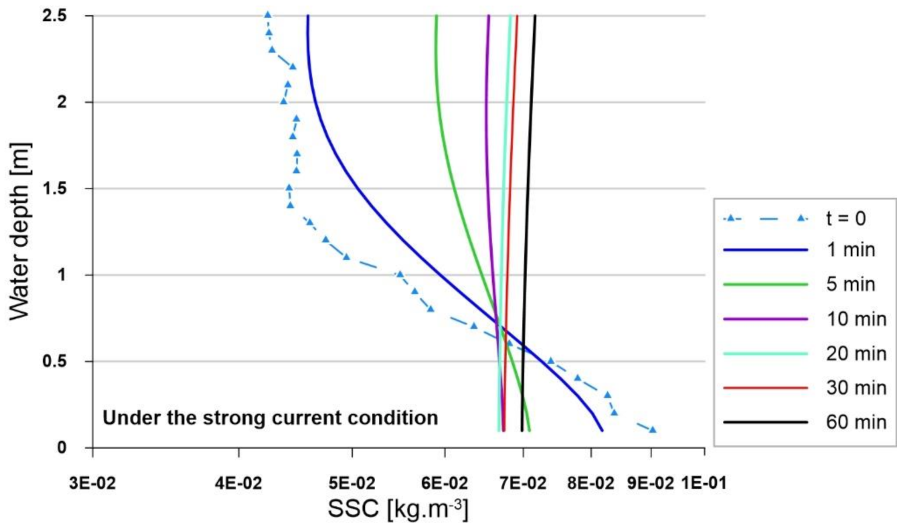

Fig. 9 SSC profile under the strong current condition in 60 minutes. The first dashed curve on the left is the measured data

Generally, in both dynamic conditions, the sediment diffusion process at the surface takes place faster than at the bottom because the diffusion coefficient in the upper layers is larger. At the surface, the sediment diffusion process is relatively similar in the two cases. However, at the bottom, sediment diffusion under strong current conditions is more obvious than under strong wave conditions, because currents will be more dominant than waves (at the bottom, the diffusion coefficient under strong current conditions is higher than ones under strong wave conditions).

Under strong wave conditions, diffusion takes place faster than under strong current conditions. Specifically, the concentration of SSC at the surface reached 0.04 kgm^{-3} (t = 0) and increased to a value of 0.07 kgm^{-3} in 10 minutes under a strong wave condition and in 30 minutes under a strong current condition. This is because the average value of K_z under strong wave conditions (4.2 x 10^{-3} m^2s^{-1}) is higher than that of strong current conditions (3.9 x 10^{-3} m^2s^{-1}).

Under strong current conditions, the SSC deposited faster, and the sediment concentration reached a uniform distribution with depth after about 10 minutes (Fig. 9). Meanwhile, under strong wave conditions, the concentration distribution is uniform after about 20 minutes (Fig. 8).

4. Conclusions

The study calculated the changes of the SSC profile by water depth in Cu Lao Dung coastal areas, Soc Trang, Vietnam under two different hydrodynamic conditions: the strong wave condition and the strong current condition. The parameters of suspended sediment such as settling velocity, and diffusion coefficient are calculated to estimate the general characteristics of the study site and apply in the 1D model of vertical suspended sediment profile. In addition, the re-suspension mechanism is considered. The results show that the distribution of SSC tends to increase with water depth. Over time, SSC stabilizes throughout the water column. The distribution of SSC under strong current conditions is more affected than strong wave conditions, especially at the bottom. In general, based on the field survey, the suspended sediment numerical model is an efficient tool for research on sediment transport. A 1D suspended sediment numerical model can be used to describe the vertical SSC distribution for some cases experiment that cannot be easily carried out. However, the model needs to be adjusted with more experimental data for various cases to achieve better simulation results.

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