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Determination of Settling Velocity for Cohesive Sediments Using a Settling Column Experiment—Case Study: Ca Mau, Vietnam

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ABSTRACT

The settling velocity (Ws) is a fundamental parameter in sediment dynamics, particularly in the coastal zones as estuarine and mangrove ecosystems, where various physical processes interact to influence sediment transport and deposition. Determining settling velocity is essential for understanding and predicting sediment transport, erosion–deposition processes in coastal environments. This study aims to determine the settling velocity and examines how sediment concentration affects settling velocity, using empirical models. The study applies these methods to compute the settling velocity of fine sediments in Ca Mau, Vietnam, which were collected in the Song Doc area (Western) in August 2014 and Rach Goc area (Eastern) in August 2015. The particle size analysis results indicate that the sediment samples from Western Ca Mau are coarser than those from Eastern Ca Mau, with sand ratios of 42.78% and 7.08% at the outer station, and 19.09% and 4.39% at the mangroves, respectively. The results also show that the average settling velocity of the sediment samples from Western Ca Mau is higher than that of the samples from Eastern Ca Mau. Specifically, the settling velocity in Western Ca Mau is 2.80×10^{-4} m s^{-1} at the outer station and 1.68×10^{-4} m s^{-1} at the mangroves. Meanwhile, in Eastern Ca Mau, the settling velocity of the sediment samples is 1.99×10^{-4} m s^{-1} at the outer station and 1.42×10^{-4} m s^{-1} at the mudflat-mangrove. Hence, it can be seen that the settling velocity of cohesive sediments corresponds well with the

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sediment's particle size.

Keywords: Settling Velocity; Cohesive Sediment; Particle Grain Size; Ca Mau

1. Introduction

Due to climate change, rising sea levels, and human development, coastal communities are increasingly threatened by flooding, land loss, and water quality degradation. Most of these urgent issues are directly or indirectly related to sediment transport, which carries organic carbon, nutrients, and pollutants [1]. In coastal and estuarine environments, sediment particles with varying compositions and structures can coexist in suspension, either as individual particles or flocs [2]. Suspended sediment concentrations (SSC) in estuaries often fluctuate seasonally, influenced by river flow and tides [3]. The deposition of these sediments can significantly influence erosion and accretion processes, thereby impacting geographic morphology and the surrounding environment. The sediment deposition process is governed by the balance of gravitational, buoyant, and drag forces, which are determined by the properties of the fluid (density, viscosity) and the particles (density, size, shape, permeability) [4]. Factors such as temperature, salinity, size, shape, and sediment concentration will have varying degrees of influence on the sediment deposition process in nature. Typically, deposition velocity increases as sediment concentration increases, but when a certain threshold is reached, further increases in SSC will lead to a reduction in velocity due to particle interactions, especially for cohesive sediments. Regarding particle size, for particles with the same composition and density within a certain size range, larger particles tend to settle faster. Spherical sediment particles tend to settle faster than flat or disc-shaped ones due to encountering less water resistance. Temperature and salinity also impact the increase in settling velocity as temperature and salinity rise, and according to many research findings, there seems to be a threshold value for this correlation as well [5]. Conversely, the presence of organic matter, along with changes in the characteristics of the water mass, significantly affects the sedimentation process, and the removal of organic matter will accelerate particle settling [6].

Research on sediment deposition velocity can employ theoretical methods, laboratory experiments, and fieldwork. Theoretical methods derive equations for the settling velocities of sediment particles in water, often based on Stokes' law. These theories can be applied in experiments to test the effects of external factors such as temperature, salinity, organic matter, and pH on deposition velocities. Field surveys are essential to obtain a comprehensive understanding of deposition velocities and the interaction of sediments with external factors [5]. Each method has advantages and disadvantages, and measurements from different instruments can yield varying results.

The distance a suspended particle can travel before settling is indicated by its settling velocity, which plays an important role in spatial models of sediment deposition. Significant efforts have been made to develop the best methods for measuring settling velocity. Zhu et al. [7] used a probability-based method derived from the Tsallis entropy theory to model the relationship between settling velocity and concentration. The results compared favorably with other models and experimental data, showing great potential for predicting the hindered settling velocity of a particle falling in a particle-liquid mixture. Asensi and Alemany [8] proposed a model to calculate settling velocity after the coagulation process as a function of fractal dimension and floc characteristics. This model is effective for floc sedimentation with fragmentation and aggregation mechanisms of mud. Researchers as McDonell et al. [9] calculated settling velocities using methods such as eddy covariance and Rouse profile inversion, identifying the influence of turbulence on sediment settling velocity in estuarine regions. Lotfiman, Bhattacharya and Parthasarathy [10] employed a novel approach to determine settling velocity using Electrical Resistance Tomography (ERT) to locate particles via electrical conductivity, while also measuring sediment layer accumulation rates in mud. Another method is remote sensing, as demonstrated by Nasiha, Shanmugam and Sundaravadivelu [11] who used Landsat 8 OLI and HICO images data to estimate sedimentation velocity in estuarine and coastal waters, as a function of drag coefficient, Reynolds number, particle shape, specific gravity, and size, based on their inherent optical properties. These methods and approaches have all produced settling velocity results in various cases. Still, a very effective traditional method for determining sediment settling velocity in water columns is the use of settling columns. This method has been applied in numerous studies over time. Wendling et al.[12] used a series of optical sensors installed along a settling column to transmit light through a suspension during static settling, thereby determining settling velocity and floc suspension trends. The method can also be applied in cases of non-cohesive sediments. Smith and Friedrichs[13] combined a settling column with video image analysis techniques, significantly reducing uncertainty in measuring settling velocity and floc particle density. Ali, Kirichek and Chassagne[14] also combined a settling column with a high-resolution digital camera to study settling velocity and its relationship to the amount of transferred flocs and clay concentration. Yang et al.[15] used a settling column to determine settling velocity under the influence of various factors, including still water case, and developed an empirical equation to estimate the average settling velocity of cohesive fine sediments, incorporating the effects of both salinity and sediment concentration. Jing et al.[16] used a settling column along with fiber optic sensors and Particle Track Velocimetry (PTV) to measure settling velocity at various sediment concentrations, obtaining a size-graded curve and settling velocity of non-cohesive sediments with SSC. The research results by Wan et al.[17] determined sediment settling velocity in the Yangtze River estuary (China), Gratiot et al.[18] quantified the influence of sediment concentration, turbulence, and deposition of various particles on sediment flocculation in the Mekong River estuary (Vietnam), Lee, Hyeong and Cho[19] estimated the size distribution and flocculation process of waste through apparent settling velocity for samples collected in the Clarion-Clipperton Fracture Zone (CCFZ) in the Pacific Ocean, Defontaine et al.[20] surveyed temporal and spatial changes in suspended sediment settling velocity in the Garonne Tidal River (France), Andros et al.[21] measured particle dispersion and size distribution using an automatic optical settling column for soil samples collected across the U.S, have demonstrated the effectiveness of this method not only in determining settling velocity and variations in settling velocity with depth but also in assessing the particle size distribution, the impact of factors such as suspended sediment concentration, particle shape, temperature, salinity, and organic matter on sediment settling velocity.

2. Methodology

2.1. The Study Site and Data Collection

The study area was selected as the Ca Mau mangrove forest area, Vietnam, in the Mekong River Delta. The hydrodynamic regime of the study area is influenced by tides, river discharge, and monsoon conditions. The tides along the East Sea are mixed, mainly semi-diurnal[22]. The coastline of the Gulf of Thailand shows a mixed tidal regime, mainly diurnal. The total discharge of the Mekong River is $\sim$500 km^3 per year, of which 85% flows during the flood season (September to November) and 15% during the low flow season (December to August)[23, 24]. The coastal current along Mekong Delta varies with the monsoon force; it is directed Southwestward during the Northeast monsoon (dry season) and Northeastward during the Southwest monsoon (wet season)[25].

Bottom sediment samples were collected at Ca Mau mangroves area, Vietnam including Rach Goc—Eastern Ca Mau and Song Doc—Western Ca Mau (**Figure 1**) to determine particle size and settling velocity.

The sampling stations include the outer station, the muddy flat station, and the mangrove forests station. For the outer stations, the sampling equipment is Ponar 'grab' sampler; for muddy flat and mangrove stations, sediment samples are collected by a tube sampler. A total of six bottom sediment samples were collected from both Eastern Ca Mau and Western Ca Mau. The sediment sample collection area was also the area surveyed and studied for hydrodynamic regimes (waves, currents, tides) and erosion−deposition processes by Department of Oceanology, Meteorology, and Hydrology, University of Science, VNU-HCM. The bottom sediment sampling locations were selected based on the positions where hydrodynamic factors were measured or cross-sections where changes in topography or shoreline were surveyed. After collection in the field, the bottom sediment samples were preserved and transferred to the laboratory for settling column experiments.

At Rach Goc, Eastern Ca Mau, four samples included an outer sample at offshore area (sample ECM-1: 8°39′40.50″ N; 105°9′47.28″ E) and three samples at muddy flat-mangrove area (sample ECM-2: 8°39′34.61″ N; 105°7′36.40″ E; sample ECM-3: 8°39′34.83″ N; 105°7′35.98″ E and sample ECM-4: 8°39′34.17″ N;

105°7′36.08″ E). Sediment samples were collected in August 2015. In settling column experiments, three samples at muddy flat-mangrove area were mixed.

At Song Doc, Western Ca Mau, there were two sediment samples including one sample in the outer station (sample WCM-1: 9°5′8.67″ N; 104°46′17.57″ E) and one sample in the mangrove forest (sample WCM-2: 9°3′35.59″ N; 104°48′23.53″ E), which were collected in August 2014.

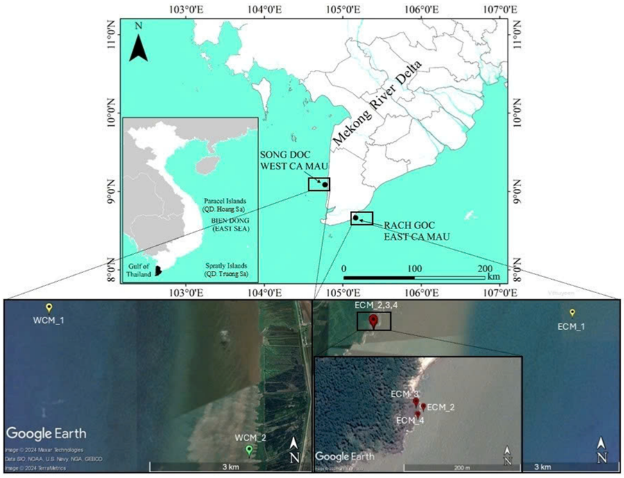


Figure 1. The study site at Ca Mau, Vietnam.

2.2. The Settling Column Test

2.2.1. Determination of Particle Size

To determine the cohesive properties of the sediments, the study on sediment particle size was conducted. The determination of sediment particle size using a Sedigraph device was conducted in the laboratory at the University of Washington (USA) as part of the Vietnam-US collaborative project "Hydrodynamics and Sediment Flux through the Cu Lao Dung Mangrove Forest".

2.2.2. The Settling Column Test

Some methods for determining settling velocity include using the settling column, observation with a camera system, and modern equipment such as LISST. However, the use of cameras and LISST is quite expensive, so the settling column remains a popular method. Its simple setup ensures that experiments can be easily repeated with consistent results, making it useful for comparing different sediment samples or varying environmental conditions like water temperature and salinity. Moreover, camera systems and laser diffraction equipment may not provide optimal results in highly turbid environments, where high concentrations of mud-clay can reduce light penetration into the sediment samples. Nevertheless, we must also acknowledge certain limitations of the settling column, such as the assumption of laminar flow, wall effects, or the inability to fully replicate real-world conditions like currents and waves that can influence the sediment settling process.

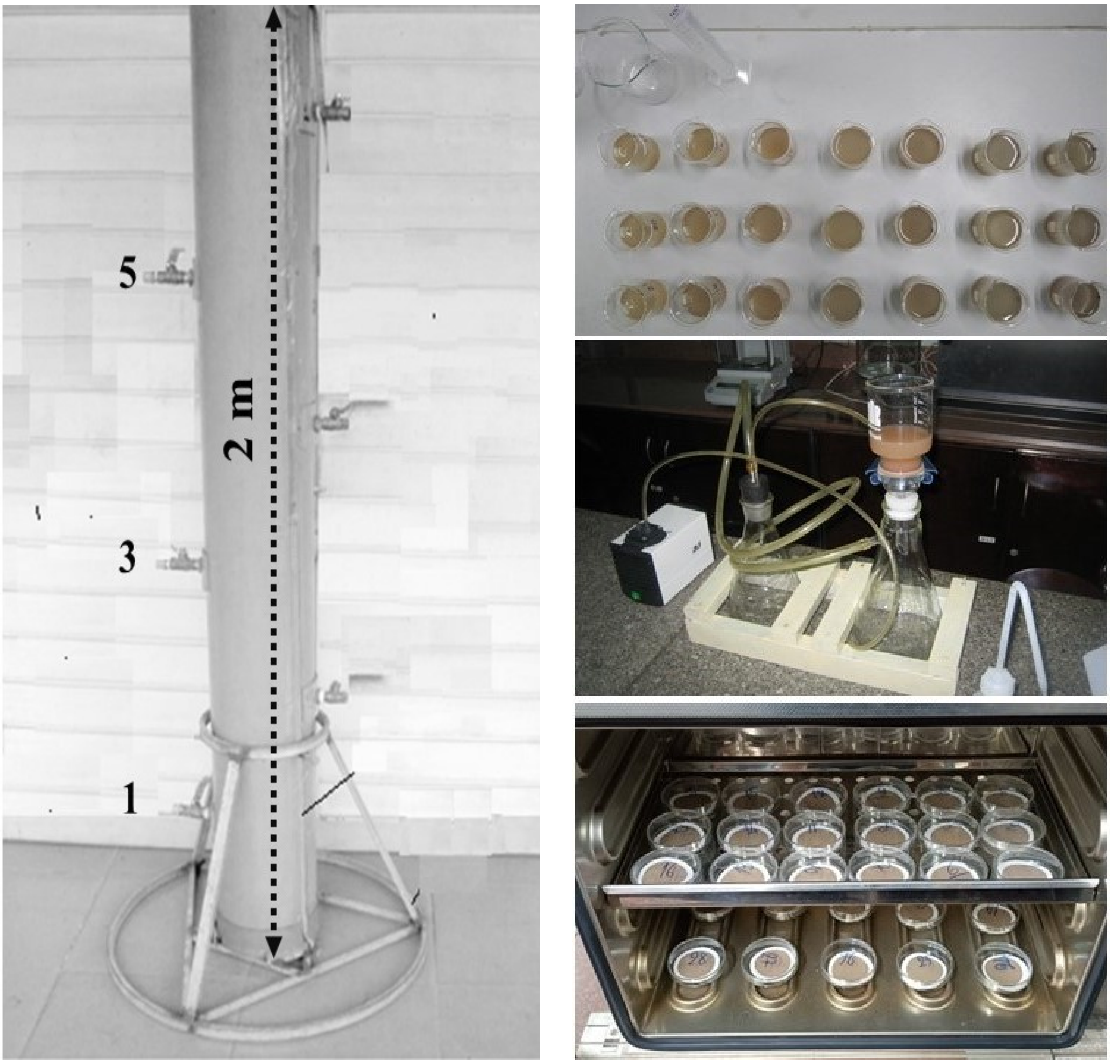
In this study, the grain size results showed that the sediments in the study site had a high proportion of clay-mud (discussed in the results section), hence, to determine the settling velocity of cohesive sediment, the study utilizes a settling column experiment in the laboratory. The settling column was designed and constructed based on the design of the settling column from the Environmental Laboratory of the U.S. Army Corps of Engineers. This method uses multi-depth concentration sampling and numerical integration of the sediment settling equation (mass conservation) [26]. The sediment settling column is a multi-valve sampling column, 2 m in height, with an inner diameter of 0.22 m and an outer diameter of 0.23 m (**Figure 2a**). The settling column is equipped with six sampling valves made of brass, spaced 0.3 m apart. The sediment settling column is in the laboratory of the Department of Oceanology, Meteorology, and Hydrology at the University of Science, VNU-HCM [27]. Samples were taken at three levels: 0.3 m, 0.9 m, and 1.5 m, corresponding to valves 1, 3, and 5, respectively. The samples were filtered and dried to determine the sediment concentration in the laboratory (**Figure 2b**), from which the settling velocity was calculated based on the sediment concentration.

2.3. Determination of Settling Velocity

At the study site, sediment compositions are mainly mud and clay, they are cohesive sediments; hence the settling velocity of the fine sediments varies with the SSC. In this study, a semi empirical formula was used to describe the relationship between settling velocity and SSC [26]:

$$W_s = \begin{cases} W_{s\,free} & C < C_1 \\ \frac{aC^n}{(C^2+b^2)^m} & C_1 < C < C_2 \end{cases} \tag{1}$$

Where: W_s is the settling velocity; C is the suspended sediment concentration; a: velocity scale coefficient; n: flocculation settling exponent; b: hindered settling coefficient; m: hindered settling exponent; C_1, C_2: zone concentration limits between free regime and flocculation regime, and hindered regime and consolidation regime, respectively.



(**a**) (**b**)

Figure 2. (**a**) The settling column. (**b**) Sample analyzed in the laboratory.

Furthermore, a simple differentiation of Equation (1) with respect to C gives the peak value of the settling velocity, W_{s2}. The maximum value, W_{s2}, and the corresponding C_2 are defined by Hwang[26]:

$$C_2 = \frac{b}{\left(\frac{2m}{n} - 1\right)^{1/2}} \tag{2}$$

$$W_{s2} = ab^{n-2m} \frac{\left(\frac{2m}{n} - 1\right)^{m-n/2}}{\left(\frac{2m}{n}\right)^{m}} \tag{3}$$

The settling velocity can be programmed in Fortran based on the flowchart shown in **Figure 3**.

Input:

- C_{in} (kg m^{-3}): the concentration of suspended sediments in the settling column test corresponding to water levels and times.
- Initial simulation parameters: The values of parameters m and n; sediment concentration C_2 (kg m^{-3}) corresponding to the maximum settling velocity W_{s2} (m s^{-1}); the threshold sediment concentration for the free settling zone C_1; values of b and a are calculated according to Equations (2) and (3), respectively.

Output:

- W_{out} (m s^{-1}): The settling velocity of sediments calculated based on experimental concentration measurements.
- W_s (m s^{-1}): The simulated settling velocity of sediments based on sediment concentration.
- Coefficients a, b, m, n for the formula calculating experimental sediment settling velocity.

Thus, the parameterization of a, n, b, m and C1 is carried out by trial and error. Each time the four parameters are entered, the sedimentation velocity calculated based on Equation (1) is displayed graphically along with the experimental data. By comparing the calculated results with the experimental data, we can accept the parameters or adjust them and repeat the calculation if necessary. This is shown by the arrows related to Ws(C) in **Figure 3**.

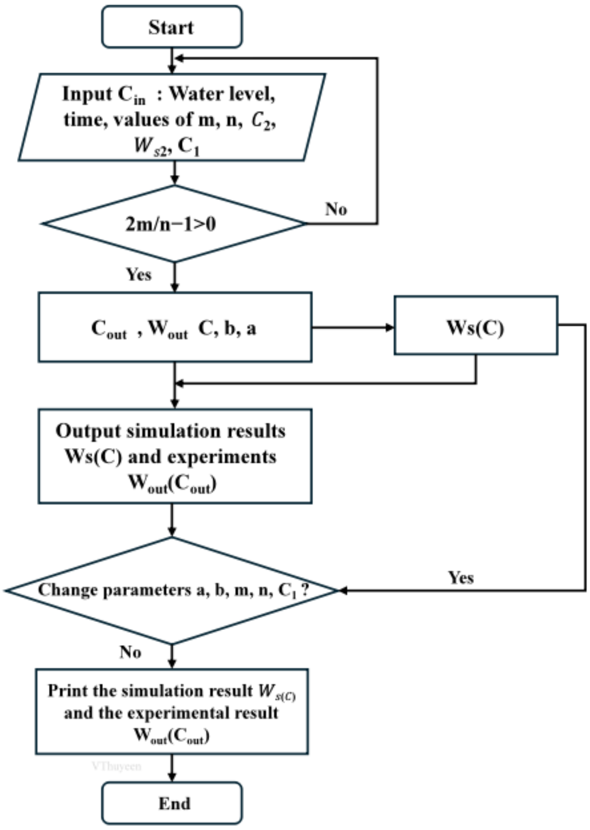


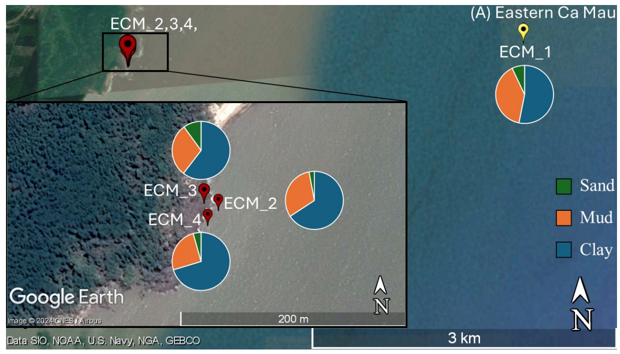
Figure 3. Flowchart to calculate the settling velocity.

3. Results

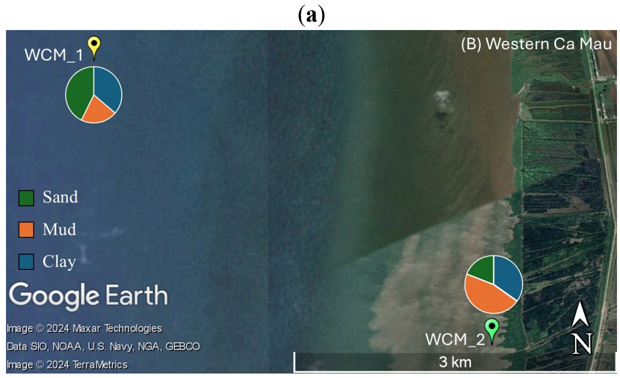
3.1. Particle Size

Figure 4 shows the grain-size distribution of the sediment samples. The results showed that mud and clay accounted for a large proportion. This result shows that the sediments in the study area are cohesive sediments.

The sediment samples collected in Eastern Ca Mau (**Figure 4a**) during the Southwest monsoon (August 2015) show that at the outer station (sample ECM-1), the proportions of sand:mud:clay is about 7.08%:39.77%:53.15%. Moving into the muddy flat area (sample ECM-2), the results show an increase in the sand-mud ratio and a decrease in the clay proportion, although the differences are minor. Notably, sample ECM-3, collected near the edge of the mangrove forest, had the highest sand content among all samples (∼10.02%). This is due to sample ECM-3 being associated with sand ridges running parallel to the coastline (**Figure 1**). For sample ECM-4, the results show the highest clay content of all samples (70.37%). The results indicate a similarity in the mud-clay ratio between samples ECM-2 and ECM-4, as both were collected from the muddy flat area near the mangrove forest.



(**a**)



(**b**)

Figure 4. Grain-size distribution of the sampled fine sediments: (**a**) Eastern Ca Mau and (**b**) Western Ca Mau.

The particle composition analysis of sediment samples from Western Ca Mau (**Figure 4b**) in August 2014 shows a difference between the outer station (sample WCM-1) and the mangroves station (sample WCM-2). In the outer station (sample WCM-1), sand had the highest proportion (nearly 43%), followed by clay (∼36%), with mud having the lowest proportion (21%). In contrast, the mangrove forest (sample WCM-2) had the lowest sand proportions (approximately 2%, 6%, and 19%, respectively), followed by mud and clay. There is a trend from the outer station to the forest: an increase in sand and mud proportions and a decrease in clay proportions, in the mangrove forest, mud becomes dominant (at ∼46%). This result shows that the sediments in mangrove forests were uniform, primarily consisting of mud and clay. This is due to the low hydrodynamic energy, which indicates stable conditions for the deposition process in the mangroves.

Compared to the sediment samples from Eastern Ca Mau, it can be observed that the grains in the outer station and mangrove forest here are coarser, with higher proportions of sand and mud.

3.2. Vertical Distribution of Sediments Concentration

The total duration of the experiment for each sediment sample was largely determined by the initial sediment concentration (C_0). The time intervals between consecutive sample collections were also influenced by the observed rate of change in sediment concentration over time. Specifically, at the onset of the experiment, when the sediment concentration was at its highest, the intervals between sample collections were relatively short to capture rapid changes in concentration. As the experiment progressed and the concentration decreased, these intervals became longer. For instance, in the settling column experiments for the sediment samples ECM-1, ECM-2, ECM-3, ECM-4, WCM-1, and WCM-2, the durations were 100 hours, 100 hours, 196 hours, and 226 hours, respectively.

Given the considerable amount of data collected over such long experimental periods, presenting all the results over time would be challenging and difficult to interpret. Therefore, in this study, we focus on analyzing the variation in sediment concentration during the first 480 minutes (8 hours) of the experiment, which provides valuable insights into the initial settling behavior of the sediments. The depth distribution of sediment concentration over time, as observed from the settling column experiments, is illustrated in **Figure 5**. In particular, **Figure 5a** and **Figure 5b** present the results for sediment samples collected from the Western Ca Mau region, while **Figure 5c** and **Figure 5d** correspond to samples from the Eastern Ca Mau region. The variation in sediment concentration at different depths is most pronounced during the first 5 minutes, when the settling process is most active.

During the initial period, between 0.5 and 5 minutes after pouring the sediment samples into the settling column, the sediment concentration was highest near the surface at 1.5-meter water depth. This was because the fine particles remained suspended longer, while the larger particles began to settle more rapidly. As a result, at 0.9-meter and 0.3-meter water depths, the sediment concentration was lower compared to the 1.5-meter water depth, since only the coarser particles had settled at these levels during the early phase of the experiment.

As the experiment progressed, the sediments began to settle further, leading to changes in the concentration profile across different depths. At later time intervals, the sediment concentration at the 1.5-meter water depth became lower than at the 0.9-meter and 0.3-meter water depths. This trend was particularly noticeable in the sediment samples collected from Eastern Ca Mau, as shown in **Figure 5c** and **Figure 5d**. However, for the samples from Western Ca Mau, the sediment concentration at the 1.5-meter water depth remained higher than at the lower depths of 0.9-meter water depth and 0.3-meter water depth for the first 30 minutes of the experiment.

Moreover, the difference in sediment concentration across depths was strongly influenced by the initial sediment concentration (C_0). This was especially evident in the period from 0 to 30 minutes, where a higher initial concentration led to a more pronounced difference in concentration between the water depths. For the Western Ca Mau samples, the initial sediment concentrations for samples WCM-1 (**Figure 5a**) and WCM-2 (**Figure 5b**) were 1.57 kg m^{-3} and 3.68 kg m^{-3}, respectively. By the 30-minute mark, the concentration difference between the 1.5-meter and 0.3-meter water depths for sample WCM-1 was approximately 0.12 kg m^{-3}, whereas for sample WCM-2, this difference was significantly larger, around 1.14 kg m^{-3}.

In conclusion, these experimental results demonstrate that the variation in sediment concentration over time and at different water depths is significantly influenced by the initial sediment concentration. This observation is critical for understanding the settling dynamics of different sediment types under various initial conditions.

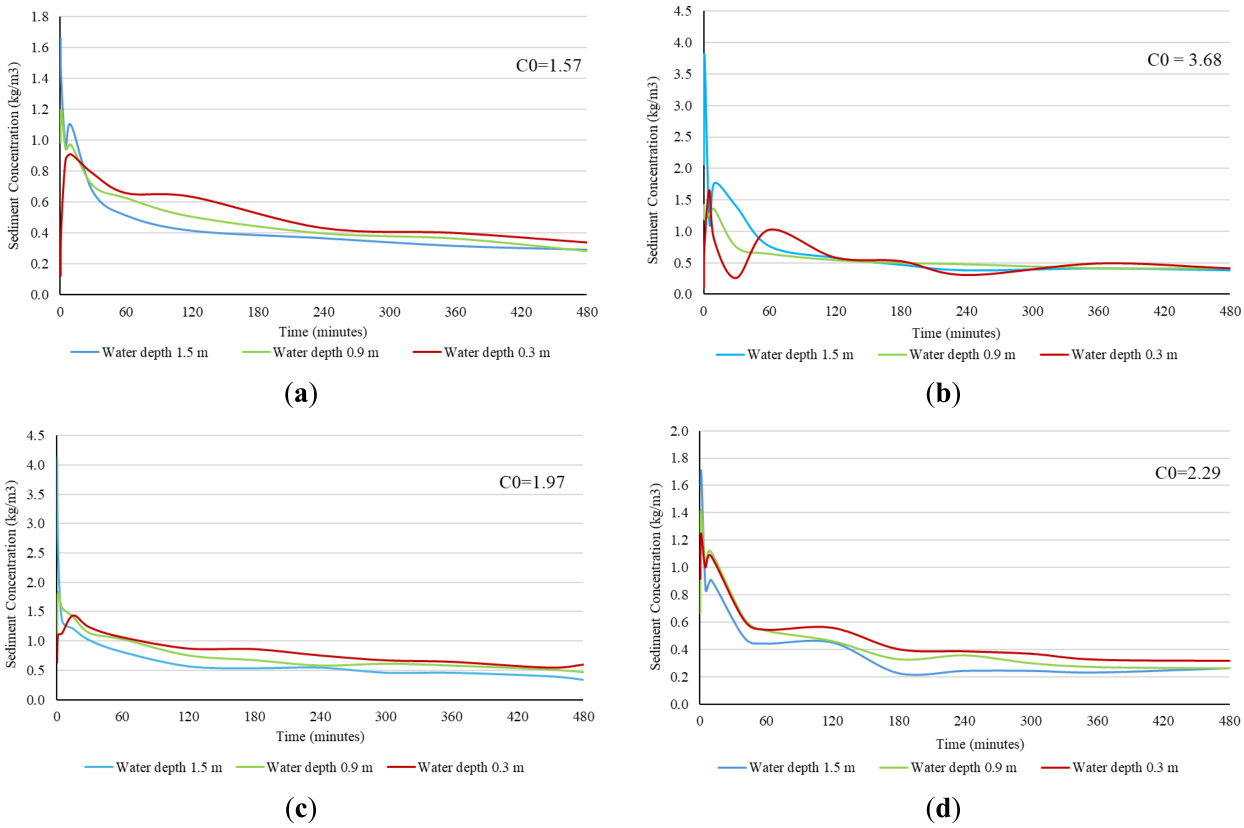


Figure 5. Vertical distribution of sediment concentrations from the settling column test: (**a**), (**b**)—Western Ca Mau; (**c**), (**d**)—Eastern Ca Mau; (**a**), (**c**)—Outer station; (**b**), (**d**)—Muddy flat-mangrove station.

3.3. Settling Velocity

Figure 6 illustrates the experimental settling velocity as a function of sediment concentration and the results of adjusting the parameters a, b, m, and n. **Figure 6** shows that the measured data primarily concentrate in the flocculation settling region and is not clearly represented in the hindered settling region. Except for the outer station in Western Ca Mau (**Figure 6a**), the remaining stations (**Figure 6b**, **Figure 6c** and **Figure 6d**), there are the measured data in the hindered settling region. Based on the experimental results of settling velocity with respect to sediment concentration, the semi-empirical curve is determined.

Table 1 summarizes the maximum and average values of settling velocity.

For sediment samples at Western Ca Mau, the average settling velocity at the outer station is 2.80×10^{-4} m s^{-1} and at the mangroves is 1.68×10^{-4} m s^{-1}. The maximum settling velocity (4.06×10^{-3} m s^{-1}) corresponding to maximum concentration (1.31 kg m^{-3}). Meanwhile, at the mangroves station, the sediment concentration reaches its maximum value (1.85 kg m^{-3}) and then sediment concentration decreases (1.22 kg m^{-3}), at this sediment concentration, the settling velocity reaches its maximum value (4.86×10^{-3} m s^{-1}). This result helps illustrate the impact of sediment concentration on the settling velocity of cohesive sediments. In the flocculation settling region, the settling velocity increases as the sediment concentration increases. However, when transitioning to the hindered settling region, as sediment concentration begins to decrease, the settling velocity increases again.

For sediment samples collected in Eastern Ca Mau, the average settling velocity at the outer station is 1.99×10^{-4} m s^{-1}, while at the muddy flat-mangrove station it is 1.42×10^{-4} m s^{-1}. In general, the concentration reaches its maximum value, then the concentration begins to decrease, at which point the settling velocity reaches its maximum value. At the outer station, the highest settling velocity recorded is 2.71×10^{-3} m s^{-1}, which corresponds to a maximum concentration of 1.17 kg m^{-3} (**Figure 6c**). At the mangrove station, sediment concentration peaks at 1.85 kg m^{-3} and then decreases to 1.4 kg m^{-3}, where the settling velocity reaches its maximum of 1.77×10^{-3} m s^{-1} (**Figure 6d**).

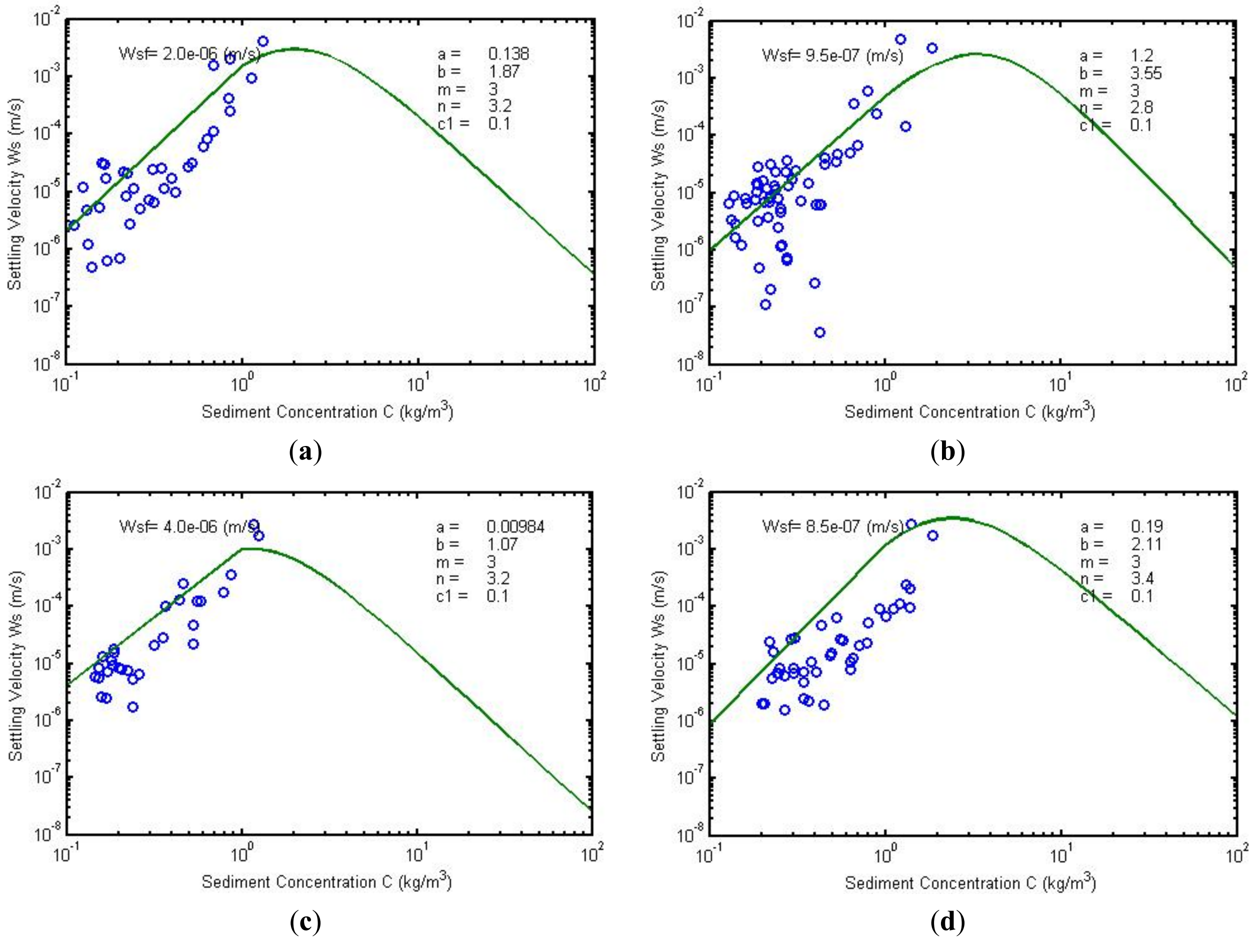


Figure 6. The settling velocity of the cohesive sediments at Ca Mau, Vietnam: (**a**), (**b**)—Western Ca Mau; (**c**), (**d**)—Eastern Ca Mau; (**a**), (**c**)—Outer station; (**b**), (**d**)—Muddy flat-mangrove station.

This study only determines the variation in settling velocity relative to sediment concentration. However, the results still help to demonstrate the influence of sediment particle size distribution on settling velocity. When considering the average settling velocity values (**Table 1**), the results show that coarser sediment particle distributions have higher settling velocities. This means that the settling velocity of sediment samples from the outer station is greater than that of sediment samples from the mudflat-mangrove station. This is clearly seen in the sediment samples from Western Ca Mau, where the settling velocity at the outer station and the mangrove station are 2.80×10^{-4} m s^{-1} and 1.68×10^{-4} m s^{-1}, respectively. When considering the maximum values of settling velocity, the results show inconsistent trends between sediment samples from Eastern and Western Ca Mau. **Figure 3** shows that sediment samples from Western Ca Mau have a clearer particle size distribution compared to those from Eastern Ca Mau, meaning that the particle size at the offshore station (WCM-1) is coarser than at the mangrove station (WCM-2). Meanwhile, the sand-mud-clay composition ratio of the four sediment samples in Eastern Ca Mau is quite similar. The results from Western Ca Mau indicate that finer sediment samples achieve higher maximum settling velocities, which may be due to the flocculation of finer sediments. For Eastern Ca Mau, this is not as clearly shown, possibly because the experimental sediment sample was a mixture (ECM-2, ECM-3, ECM-4), and the sand content of the ECM-3 sample is quite high.

Table 2 demonstrates the comparison of the calculated results with previous studies and some conclusions are as follows. In general, the free settling velocity and the maximum settling velocity are of the same order of magnitude as those in previous studies. However, the calculated settling velocity at Ca Mau is lower than that in previous research. The maximum sediment concentration C_2 obtained is lower. The maximum settling velocity results in Western Ca Mau are

Table 1. Summary of the settling velocity of the cohesive sediments at Ca Mau.

Area	W_s (m s^{-1})	Outer Station	Muddy Flat-Mangrove Station
Western	Maximum	4.06×10^{-3}	4.86×10^{-3}
Ca Mau	Average	2.80×10^{-4}	1.68×10^{-4}
Eastern	Maximum	2.71×10^{-3}	1.77×10^{-3}
Ca Mau	Average	1.99×10^{-4}	1.42×10^{-4}

more consistent compared to those in Eastern Ca Mau. This difference may be due to the characteristics of the sediments in each study area. In this comparison, we only consider the cohesive properties of the sediments through their particle size distribution. Comparing the average settling velocity of cohesive sediments in some areas of Vietnam (Can Gio, Ho Chi Minh City [28] and Dinh An estuary, Tra Vinh [18]), the settling velocity results in Eastern Ca Mau are more consistent than in Western Ca Mau.

In actual conditions in the study site, cohesive sediments flocculate, and the flocculation depends on the water salinity. Additionally, other factors influencing the settling velocity of fine sediments such as water temperature, flow velocity, or turbulence have not been considered. The objective of the study is to determine the settling velocity of sediment materials in the research area under static conditions. These are some of the limitations of the results.

Table 2. Comparison of settling velocity calculation results with other studies.

Studies	Study Site	Free Settling Velocity W_{sf} (m s^{-1})	Maximum Velocity W_{s2} (m s^{-1})	Maximum Concentration C_2 (kg m^{-3})
Hwang and Mehta (1989) [26]	Okeechobee lake (USA)	-	0.73×10^{-3}	3.18
You (2004) [29]	Moreton Bay (Queensland, Australia)	$W_s = W_{sf}\exp(0.9779C - 0.1080C2)$		4.30
Sverdrup, Duxbury, Duxbury (2005) [30]	-	1.05×10^{-5} – 2.40×10^{-3}	-	-
Nguyen and Vo Luong (2015) [28]	Can Gio, Ho Chi Minh City, Vietnam	-	0.63×10^{-3}	2.58
Gratiot et al. (2017) [18]	Dinh An estuary, Tra Vinh, Vietnam	1.50×10^{-5}	1.80×10^{-3}	2.70 ± 0.20
Results	Western Ca Mau	0.20×10^{-5} 0.09×10^{-5}	4.06×10^{-3} 4.86×10^{-3}	1.31 1.22
	Eastern Ca Mau	0.40×10^{-5} 0.09×10^{-5}	2.71×10^{-3} 1.77×10^{-3}	1.17 1.85

4. Conclusions

The study conducted a settling column experiment in the laboratory to study the effect of sediment concentration on the settling velocity for a specific study area (Ca Mau, Vietnam). In addition, the experimental results also contributed to showing the effect of particle size on the settling velocity.

The results showed that the coarser the sediments, the greater the average settling velocity. The settling velocity calculations demonstrate consistency, with the average settling velocity of sediment samples from Western Ca Mau being higher than those from Eastern Ca Mau. In particular, the settling velocity at the outer station in Western Ca Mau is 2.80×10^{-4} m s^{-1}, while at the mangrove forest station, it is 1.68×10^{-4} m s^{-1}. In contrast, in Eastern Ca Mau, the outer station's sediment settling velocity is 1.99×10^{-4} m s^{-1}, and the mixed sample from the mudflat-mangrove area has a settling velocity of 1.42×10^{-4} m s^{-1}. This indicates that the settling velocity of cohesive sediments aligns well with the particle size of the sediments.

Although some actual conditions were not considered, the experimental results can show some rules. The effect of sediment concentration on the average settling velocity is consistent with the rules of previous studies: settling velocity increases with sediment concentration in the flocculation settling region and settling velocity decreases as sediment concentration increases in the hindered settling region (although the experimental data for the hindered settling region is limited). Additionally, the complexity of cohesive sediment settling velocity is evident when considering the influence of particle size distribution. Coarser sediments do not necessarily achieve higher maximum settling velocities compared to finer sediments. Therefore, future studies under different conditions (salinity, water temperature, turbulence) are needed to determine the settling velocity of cohesive sediments. We should also explore whether there is a phase where settling velocity becomes independent of sediment concentration.

In general, the method of determining settling velocity by semi-empirical curve is simple but contributes to limiting the difficulties when measuring the settling velocity of cohesive sediments in the field. Calculations of settling velocity by semi-empirical curve method will be applied to mathematical models to calculate the distribution of sediment concentration in Ca Mau, Vietnam.

Author Contributions

T.X.D. and L.N.H.T. conceived and designed the manuscript; T.X.D. and V.L.H.P. conducted field experiments; T.X.D. and L.N.H.T. conducted the experiments in laboratory; T.X.D. processed and analysed the data; L.N.H.T. and V.L.H.P. interpreted and discussed the results; T.X.D. edited the manuscript; T.X.D. and L.N.H.T. revised the manuscript; T.X.D. and L.N.H.T. handled the submission steps. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this study have been generated but are not currently available in a public repository. The data can be made available by the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

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