Numerical Simulation of Flow Characteristics In Compound Channels With Emergent Vegetation

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Numerical simulation of flow characteristics in compound channels with emergent vegetation

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Abstract

As part of the coastal wetland ecosystems, mangroves thrive at the interface between land and water. The slope connecting the main river channel and floodplain has been found with different angle. The vegetation density also influence the penetration of the flow. This research studied the hydrodynamics in a partially vegetated compound channel by using the 2DH RANS model in Delft3D. The numerical model is calibrated with the results of flume experiments. The drag coefficient with a value of 0.8 and the background horizontal eddy viscosity with a value of 10^{-4} m²/s are suggested according to calibration of the model. The influence of different slope angle and vegetation density on flow characteristics is studied. It is concluded from the model results that a denser vegetation patch leads to stronger momentum exchange at the edge of vegetation patch. It is also found that a slope angle around 1/10, which is the most typical slope angle in Mekong estuarine system, leads to the strongest eddy structure and the largest amount of momentum transport into the vegetation patch. It implies that a slope angle around 1/10 might be the equilibrium state of topography in mangrove coast.

Key words: hydrodynamics; compound channel; momentum transport; vegetation density; slope angle; numerical simulation.

1. Introduction

Mangroves thrive worldwide in tropics and sub-tropics because of their frost intolerance (Tomlinson et al., 1986), mainly between 30° N latitude and 40° S latitude with largest densities between 5° N and 5° S latitude (Giri et al., 2011). Six tropical regions of mangroves globally can be distinguished based on the continental borders : Western America, Eastern America, Western Africa, Eastern Africa, Indo-Malaysia and Australia (Duke et al., 1992). Approximately 75% of mangroves globally are concentrated in only 15 countries and the largest portion is found in Asia (42%) (Giri et al., 2011).

As part of the coastal wetland ecosystems, thriving at the interface between land and water, mangroves can benefit us in lots of ways: providing food and timber, purifying water and sequestering carbon, protecting coastal area through wave attenuation and coastal stabilization. Regarding the protection of coastal area, mangroves damp the waves and flow in short term and mitigate coastal erosion in long term. It is reported that mangroves weakened the impact of the 2004 Indian Ocean tsunami by reducing damage and saving lives in coastal area (Danielsen et al., 2005).

However, the total area of mangrove forests worldwide is experiencing a rapid decline of 1 to 2% per year (Duke et al., 2007). This is caused by combined effects of sea-level rise and human activities. Doody (2004) introduced a term "squeeze" to describe this phenomenon. The effect of sea-level rise tends to make mangrove forests retreat landward while the human activities such as urbanization, agriculture, and aquaculture prevents the mangroves from retreating. Consequently, the mangrove forests are pushed into a narrower fringe. The effect of human activities usually happens in a shorter period with a larger impact than the effect of sea-level rise.

The inundation of mangrove forests is caused by combined effects of overbank (sheet) flow and creek flow. Creek flow is usually ebb dominated and the ebbing mainly happens through creek flow (Aucan and Ridd, 2000). Horstman (2014) concluded that for the highly elevated mangroves, creek flow dominate when water levels remain below the high-density vegetation layer and overbank flow prevails when this threshold is exceeded. Kobashi and Mazda (2005) observed that in a smoothly sloping mangrove fringe without creeks, flow is parallel to the river at the interface of river and vegetation and it gradually turns perpendicular to the river further inside the forest.

Liu et al. (2013) applied the analytical solution to model the depth-averaged velocity in vegetated compound channels and gives good predictions. Fu et al. (2021) utilized a modified analytical model to successfully simulate the lateral profile of the depth-averaged velocity in a compound channel with floating vegetation islands. Jing et al. (2020) applied the lattice Boltzmann model to simulate the flow structure in a vegetated compound channel and the model results show high accuracy comparing to the laboratory experiments. Wang et al. (2014) researched flow characteristics in a vegetated multi-stage compound channel by combining the results from ADV and computational method. It is concluded that the vegetation can effectively reduce the bed shear stress, thereby achieving the effects of siltation and reducing erosion. Also, the maximum values of the Reynolds stress appears in the first stage of terraces in the vegetation patch. Zhang et al. (2021) researched the influence of vegetation coverage on hydrodynamic characteristics by conducting flume experiments, and concluded that under the condition of the non-flat slope, stem coverage degrees dominates the manning coefficient and slope angle dominates velocity and Froude number.

Heidi M. Nepf (2012) studied hydrodynamics at the interface of vegetation patch and main channel in perspective of blade scale, canopy scale and reach scale. It is found that the flow forms a mixing layer for dense canopies. The presence of mangroves alters the stream flow and create a mean velocity difference between flow in mangrove and main river channel. This leads to the formation of a shear

mixing layer where transportation of mass and momentum occurs. The penetration length of the shear layer is important to the sustainability of mangrove forests since space is needed to absorb the flow energy. If the width of the forest is larger than the penetration length, flow is dampened and the environment is favorable for sedimentation and propagules. It is believed that there exist a minimum width of mangrove forests for the survival of the ecosystem and for the case in Mekong estuarine system (MES) the minimum width is around 80 m (Truong Hong, 2018).

This study focuses on the hydrodynamics in and around fringing estuarine mangroves, which is mainly influenced by tidal action and river flow. According to the previous literature review, the existing problem is that the research on the influence of slope angle and vegetation density on the flow field is relatively rare. This study aims to research the influence of different slope angle and vegetation density on flow characteristics by calibrating the 2DH (two-dimensional horizontal) RANS numerical model and analyzing the model output in different scenarios.

2. Model development

2.1 Flume experiments

The flume experiments were conducted by Truong Hong (2018). The main purpose of the flume experiments is to capture the physics of momentum exchange between main river channel and mangroves through mixing shear layer. Because the experimental results are used in this study to calibrate the numerical model, a brief introduction of the flume experiments is given in this section.

The prototype of the experiments is Tue estuary in Vietnam. Due to the difficulties in implementation of undistorted experiments, only un-scaled experiments were conducted. However, several requirements are met in order to ensure the most important physical processes remain unchanged and can be captured in the experiments. Firstly, a 1/10 slope is adopted, which is the same slope as in the prototype. Secondly, the water depth in the floodplain is 0.12 m. Thirdly, the Reynolds number should be as large as possible.

Figure 1: Cross sectional profile of the flume

Figure 1 shows a cross section of the flume. The dimension of the flume is 20 meters long and 3 meters wide, but water only flows in the area with a width of 2 meters. The flume is zero-sloped in the stream-wise direction. The cylinders on the flood plain represent the mangroves. The height of the cylinders is 0.1 m and different densities are applied in the experiments. Discharge can be adjusted on the upstream side and water level can be controlled on the downstream side. More than 20 measurement points are employed along the cross-shore section. The velocity is measured at the middle

of the water depth so that the measured velocity is close to depth-averaged velocity. The cylinders are arranged in a staggered way . There are two different densities with sparse vegetation (139 cylinders/ m^2) and dense vegetation (550 cylinders/ m^2). Table 1 summarizes the experiment scenarios related to this study.

Table 1: Summary of all the experiment scenarios

ϕ	Density 1
Cylinder/ m^2	139, 550
Q input [m^3/s]	0.045
H control [cm]	0.12 m
Floodplain width [m]	0.5 m

2.2 Numerical model

2.2.1 Model introduction

The hydrodynamic module Delft3D-FLOW is able to simulate two-dimensional or three-dimensional unsteady flow and sediment transport resulting from tidal or meteorological forcing in shallow water environments (e.g. Temmerman et al., 2005). The flow model is applicable in shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. It is designed to model the flow field where the horizontal length and time scales are noticeably larger than the vertical scales (Deltares, 2018). Delft3D-FLOW solves the unsteady shallow water equations in two or in three dimensions. The system of equations includes the horizontal equations of motion, the continuity equation, and the transport equations for conservative constituents. The equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates. In curvilinear co-ordinates, the free surface level is related to a flat plane of reference. The continuity equation in ξ and η direction is given by:

$$\frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial [(d + \zeta)u \sqrt{G_{\xi\xi}}]}{\partial \xi} + \frac{1}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial [(d + \zeta)v \sqrt{G_{\eta\eta}}]}{\partial \eta} = Q \quad (1)$$

The momentum equations are given by:

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial u}{\partial \sigma} - \frac{v^2}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \\ + \frac{uv}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} - fv = -\frac{1}{\rho_0 \sqrt{G_{\xi\xi}}} P_\xi + F_\xi + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} (v_v \frac{\partial u}{\partial \sigma}) + M_\xi \end{aligned} \quad (2)$$

and

$$\begin{aligned}
& \frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial v}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial v}{\partial \sigma} + \frac{uv}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \\
& - \frac{u^2}{\sqrt{G_{\xi\xi}} \sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} + fu = - \frac{1}{\rho_0 \sqrt{G_{\eta\eta}}} P_{\eta} + F_{\eta} + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left(\nu_v \frac{\partial v}{\partial \sigma} \right) + M_{\eta} \quad (3)
\end{aligned}$$

ζ represents the free surface elevation above the reference plane and d is the depth below the reference plane. $\sqrt{G_{\xi\xi}}$ and $\sqrt{G_{\eta\eta}}$ are the transformation factors of coordinates in ξ and η direction

respectively. The average flow velocity in ξ and η direction is represented by u and v . Q represents the

water volume difference. σ co-ordinate system is defined as: $\sigma = \frac{z - \zeta}{H}$, z is the vertical co-ordinate

in physical space and H is the total water depth. The vertical eddy viscosity coefficient ν_v is defined by

$\nu_v = \nu_{mol} + \nu_v^{back}$, with ν_{mol} the kinematic viscosity of water, ν_v^{back} the background or "ambient"

vertical mixing coefficient. P_{ξ} and P_{η} represent the pressure gradients in the baroclinic pressure terms.

The forces F_{ξ} and F_{η} in the momentum equations represent the unbalance of horizontal Reynold's

stresses. M_{ξ} and M_{η} represent the contributions due to external sources or sinks of momentum

(external forces by hydraulic structures, discharge or withdrawal of water, wave stresses, etc.)(Deltares, 2018).

The numerical grid is the grid defining a computational control volume. The depth is defined at the corners of the computational control volume, the numerical grid is drawn through the depth points. Calculations are executed on every numerical grid cell.

For the purpose of studying the effects of vegetation on flow behavior and turbulence, Uittenbogaard (2000) developed a theory to include the effects of vegetation on momentum and turbulence equations and applied this in the "(Rigid) 3D Vegetation model". This model can also be used in 2DH environment. The application of this model has been calibrated and validated successfully for tidal systems (Temmerman et al., 2005). A brief introduction to the theoretical background of this model is given in this section because the vegetation model is used in this study.

This vegetation model extends the momentum equation with a vertical distribution of

vegetation-induced friction force F [N / m^3]:

$$F = \frac{1}{2} \rho_w C_D n D |u| u \quad (4)$$

Wherein ρ_w is the water density [kg / m^3]; C_D is dimensionless and represents the cylindrical drag

coefficient [-]; n indicates the vertical distribution of number of cylinders per unit area [m^{-2}] with the vertical distribution of stem diameter D [m]; u is the depth-dependent horizontal velocity [m/s]. Once taking into account the effects of vegetation, momentum exchange is influenced by the porosity of the vegetation $(1 - A_p)$ where A_p is the horizontal cross sectional vegetation area :

$$A_p = \frac{1}{4} \pi D^2 n \quad (5)$$

The vegetation effects are included in the momentum equation through the eddy viscosity ν [m^2/s], which is solved by $k - \varepsilon$ turbulence model. This model is modified to calculate (i) the turbulence and dissipation generated by vegetation and (ii) the turbulence diffusion with decreased horizontal cross sectional area $(1 - A_p)$ (Uittenbogaard, 2003).

The vegetation effects influence the vertical fluctuations through an extra source term T in the kinetic energy equation (Deltares, 2018):

$$\frac{\partial k}{\partial t} = T + P_k - B_k - \varepsilon \quad (6)$$

With k [$N * m$] the kinetic energy; P_k is the production term and ε is the dissipation term; B_k is the buoyancy flux term in transport equation for turbulent kinetic energy. T is the work done by the fluid per unit time [$N * m/s$]:

$$T = F \times u \quad (7)$$

Also another extra source term $T\tau^{-1}$ is added in the epsilon equation (Deltares, 2018):

$$\frac{\partial \varepsilon}{\partial t} = T\tau^{-1} + P_\varepsilon - B_\varepsilon - \varepsilon_\varepsilon \quad (8)$$

With τ the minimum time scale:

$$\tau = \min(\tau_{free}, \tau_{veg}) \quad (9)$$

With the dissipation time scale of free turbulence τ_{free} and eddies within vegetation τ_{veg} :

$$\tau_{free} = \frac{1}{c_{2\varepsilon}} \frac{k}{\varepsilon}, \tau_{veg} = \frac{1}{c_{2\varepsilon} \sqrt{c_\mu}} \sqrt[3]{\frac{L^2}{T}} \quad (10)$$

With $c_{2\varepsilon} = 1.92$ the calibration constants; L is the representative length restricted by the smallest distance between vegetation:

$$L = C_l \sqrt{\frac{1 - A_p}{n}} \quad (11)$$

C_l is a length scale coefficient for reducing the geometrical length scale to turbulence length scale.

Uittenbogaard (2000) suggests a C_l value of 0.8 for vegetation.

The parameters in the vegetation model mainly include height and diameter of stems, number of stems, value of C_d , vegetation type and distribution of vegetation patch.

2.2.2 Model set up

Figure 2 illustrates the schematized model domain used in this study. The model domain includes a main channel, a 1/10 slope and a flood plain. It should be noticed that the model domain is 20 meters long and 3 meters wide, and the area within 7 meters further upstream is a flat plain which is not included in the figure. The mangrove area is 8 meters long and 0.5 m wide. The grid size varies from 0.02 m x 0.1 m to 0.02 m x 0.02 m in the focus measurement area, which is 4-5 meters from the beginning of the vegetation patch. The water depth in the main channel and flood plain is 0.12 m and 0.04 m respectively. The "walls" at left and right sides of the model domain are 0.2 m high so that overflow will not happen and they are impermeable. The model is 2DH so that there is only one vertical layer. This can be justified by the fact that all the vegetation in this study is emergent and there is no variation of vegetation density over the depth. Therefore a 2DH model is sufficient to include the vegetation effects in this study.

Figure 2: 3D schematized model domain

The time step is 0.006 seconds. With a maximum flow velocity around 0.35 m/s the Courant number is around 0.1. This time step is chosen so that the model is stable enough to generate accurate results. The simulation time is 20 minutes. The bed roughness and background eddy viscosity are calibrated with the experimental results of lateral velocity profile.

On the upstream side a discharge boundary is chosen with a constant discharge of $0.045 \text{ m}^3/\text{s}$. A

water level boundary is prescribed on the downstream side with a constant water level of 0.12 m. On the water level boundary a reflection parameter alpha is set to 2. The reflection parameter alpha is used to make the open boundary less reflective for short wave disturbances so that the model becomes more stable. However, an excessively large alpha makes the model insensitive to changes of other parameters. The value of alpha can be estimated with (Deltares, 2018):

$$\alpha = T_d \sqrt{\frac{H}{g}} \quad (12)$$

In which T_d is the time needed for a free surface wave to travel through the model. With the depth of 0.12 m the travel speed is around 1.1 m/s. The length of the model domain is 20 meters so $T_d \approx 18.4s$, which leads to a value of $\alpha \approx 2$.

2.2.3 Calibration of the numerical model

The calibration of the model in this study bases on the experimental results from Truong Hong (2018). The experimental results give the depth-averaged velocity profile in cross-shore direction. The measurements are taken from around 4.8 meters downstream of the beginning of the vegetation patch and there are more than 20 measurement points in cross-shore direction. The calibration of the model focuses on fitting the model results with the experimental measurements.

In order to quantify the accuracy of the model results with respect to the experimental results, Nash-Sutcliffe model accuracy MA (Nash and Sutcliffe, 1970) is introduced and applied in this study:

$$MA = 1 - \frac{\sum (SIM - REF)^2}{\sum (REF - \overline{REF})^2} \quad (13)$$

In which SIM indicates the model results; REF represents the experimental results and $\overline{REF}$ is the mean value of the experimental results. This formula represents the ratio of squared difference between model and experimental results over the variance of the experimental results. The value of $MA = 1$ represents the perfect match between model and experimental results. If $MA \leq 0$, the model has no predictive skill in addition to the average of the reference data. This model accuracy parameter is frequently used for model simulations of discharge and water quality constituents so that it is also applicable in this study.

The calibration of the model with vegetation mainly focuses on the drag coefficient, eddy viscosity and bed roughness. A constant water level of 0.12 m is applied on the downstream side and the flume is zero-sloped in the stream-wise direction so that only the calibration of flow velocity is necessary. Figure 3 shows the lateral velocity profile of calibrated reference model with dense vegetation

($550/m^2$). For the reference model with dense vegetation ($550/m^2$), a drag coefficient $Cd = 0.8$

is used. The stem diameter is 0.1 m and the cylinder height is 0.1 m so that all the vegetation is emergent. The vegetation patch starts at 5 meters from the beginning of the model and ends at 13 meters. The patch width is 0.5 meter, which is the same width as the floodplain. The overall match is good so that the calibrated model is sufficiently accurate to simulate the flow characteristics in partially vegetated channels.

Figure 3: Calibration of the model with dense vegetation. The lateral velocity profile is taken at 9.8 m from the beginning of the model

(1) Drag coefficient

When a vegetation patch is considered, the flow decelerates as it approaches the vegetation. This leads to a pressure difference between the upstream and downstream of the vegetation and increases the drag force on it. The drag coefficient C_D is equal to 1 when a smooth cylindrical pile is considered (Deltares, 2018). Therefore, the value of drag coefficient should not deviate too much from "1". In this study, three values of drag coefficient are tested in order to find the optimum value to match the measurements : 0.8, 1 and 1.5.

Figure 4: Calibration of drag coefficient in the case with dense vegetation. X-coordinate " 0" corresponds to the vegetation edge

When the drag coefficient increases, the vegetation-induced friction also increases. A decrease of flow velocity within the vegetation patch is expected. As can be seen in Figure 4, a drag coefficient of 1.5 leads to a much lower flow velocity at floodplain and a higher flow velocity in the main channel since the total discharge is the same in all cases. When the drag coefficient increases, more water flow is deflected into the main channel, which leads to a higher flow velocity in the main channel.

However, it seems that the accuracy of the model with a drag coefficient of 0.8 and 1.0 is hard to compare. Nash-Sutcliffe model accuracy index "MA" described in Equation (10) is used to estimate the accuracy of these three models. Table 2 summarizes the accuracy of models with three different drag coefficient. Apparently, a drag coefficient of 0.8 leads to a best match with experimental measurements and it is used in the reference model.

Table 2 : Accuracy of models with different drag coefficient

Models	Cd=0.8 (B1)(reference)	Cd=1.0 (B10)	Cd=1.5 (B2)
MA	0.9799	0.9731	0.8705

(2) Background horizontal eddy viscosity

Figure 5: Model results by inputting different uniform values of background horizontal eddy viscosity

Background horizontal eddy viscosity is the background input value of the horizontal eddy viscosity, it is steady and constant in the model. It should be noticed that $\nu_H^{back} = 0 \text{ m}^2/\text{s}$ does not mean total viscosity is zero since in a 2D model the Elder formulation is already built in. In that case $\nu_{SGS} = \kappa u_* h / 6$ is applied by the model to represent the dispersive effect, which leads to a logarithmic horizontal velocity profile over depth. Figure 5 shows model results by inputting uniform values of background horizontal eddy viscosity with different orders of magnitude. When eddy viscosity is zero or in an order of $O(10^{-4}) [\text{m}^2/\text{s}]$, the model results converge and match the

measurements quite well. When eddy viscosity is in an order of $O(10^{-2}) [m^2/s]$, the lateral velocity profile generated by the model deviates too much from the measurements. Therefore, an uniform value of background horizontal eddy viscosity with an order of $O(10^{-4}) [m^2/s]$ or even smaller should be used in this study. The selection of uniform value of eddy viscosity should be further verified by looking into the calculated horizontal viscosity and eddies generated by these models.

Figure 6: Calculated horizontal viscosity distribution from calibrated model

Figure 6 illustrates the horizontal viscosity distribution calculated by the calibrated model. The maximum value of horizontal viscosity reaches $0.0002 \text{ m}^2/s$ around the edge of the vegetation patch, which means $\nu_H^{back} \leq 0.0002 \text{ m}^2/s$ should be applied. Otherwise, the calculated horizontal viscosity will be overrode by the background horizontal viscosity. Figure 7 shows comparison of flow patterns from experiments and numerical simulations with different background horizontal eddy viscosity. The numerical model reproduces the coherent structures best when the value of background eddy viscosity is $0.0001 \text{ m}^2/s$. Coherent structures become weaker as background eddy viscosity increases. When eddy viscosity is as large as $0.0008 \text{ m}^2/s$, eddy is damped out and the flow pattern tends to be regular. After analyzing the lateral velocity profile, distribution of horizontal viscosity and flow patterns generated by simulations with different values of ν_H^{back} , it is found that $\nu_H^{back} \leq 0.0002 \text{ m}^2/s$ should be applied. Actually, $\nu_H^{back} = 0 \text{ m}^2/s$ with only Elder formulation used for the turbulence model is sufficient in this study. However, a very low value of eddy viscosity may leads to instability of the model. In order to make sure the model will not crash in any cases,

296 $\nu_H^{back} = 0.0001 \text{ m}^2 / \text{s}$ is used for the reference model in this study.

297 Figure 7: Comparison of flow patterns from experiments and numerical simulations with different
 298 background horizontal eddy viscosity. The first picture from left is the results of flume experiment.
 299 $\nu_H^{back} = 0.0001, 0.0004 \text{ and } 0.0008 \text{ m}^2 / \text{s}$ from the second from left to right respectively

300 3 Response of flow characteristics to slope angle and vegetation density

301 In mangrove forests, the capability of mangroves to capture sediments leads to accumulation of
 302 sediments within the mangrove forests. Hence, the elevation of the floodplain, where the mangroves
 303 grow, is usually higher than the main river bed. In Mekong estuarine systems, the slope which connects
 304 main river channel and floodplain is around 1/10 (Truong Hong, 2018). The topography of the
 305 mangrove area is influenced by both sediment dynamics and hydrodynamics. The physical processes
 306 behind this is still not fully understood. In this study, only the hydrodynamics in a partially vegetated
 307 channel is studied due to a lack of data to calibrate the model with sediments.
 308 This research mainly focuses on the influence of slope angle and vegetation density on the penetration
 309 of flow into the forests. Special attention is paid into the horizontal Reynolds stress around vegetation
 310 area, which is related to the momentum transport.

311 3.1 Influence of vegetation on penetration of flow

312 Firstly, the vegetation effects on penetration of flow is studied. Cases of no vegetation, sparse
 313 vegetation and dense vegetation are simulated with the calibrated model. The slope angle is 1/10.
 314 Actually, these cases were already conducted in the flume experiments (Truong Hong, 2018) and the
 315 numerical model only works as a tool to analyze the momentum transport around the vegetation edge.

Figure 8: A summary of model results and measurements with different vegetation density.

As can be seen in Figure 8, after calibration the model is able to estimate the lateral velocity profile quite well when vegetation density changes. This part mainly focuses on the penetration of flow by looking into the horizontal Reynolds stress calculated from model results. The horizontal Reynolds stress, which is interpreted as momentum transport in this case, is calculated with

$$T_{xy} \approx \rho_w \langle \overline{u'v'} \rangle = \rho_w \nu_c \frac{\partial U}{\partial y}. \text{ So the horizontal Reynolds stress mainly depends on the velocity}$$

gradient. Figure 9 shows the influence of vegetation density on horizontal Reynolds stress.

Figure 9: Influence of vegetation density on horizontal Reynolds stress with sparse vegetation ($139/m^2$) and dense vegetation ($550/m^2$).

As can be seen in Figure 9, the presence of vegetation leads to a sharp increase of horizontal Reynolds stress around the vegetation edge. This implies that the vegetation patch strengthens the momentum exchange in the shear mixing layer. It should be noticed that the dense vegetation leads to stronger momentum exchange at the edge of vegetation patch comparing to that of the sparse vegetation. It can even be expected that when sediment is considered, a denser vegetation patch can cause a larger influx of sediment into the mangrove area.

3.2 Influence of slope angle on penetration of flow

As described previously, the typical slope angle in Mekong estuarine system is 1/10 though gentler slope was measured in Thailand. This section focuses on the influence of slope angle on penetration of flow. This subject has not been studied in the flume experiments. Partially vegetated channel with dense vegetation ($550/m^2$) is simulated with different slope angle with other parameters remaining the same as the reference model.

Figure 10: influence of slope angle on lateral profile of streamwise velocity (velocity is represented by ratio of velocity to average velocity over the cross section).

Figure 10 summarizes the lateral profile of streamwise velocity in cases with different slope angle. The streamwise velocity magnitude is mainly influenced by the wet area since the upstream discharge is constant. It can be seen that a slope angle of 1/1 leads to the highest flow velocity on the slope, and the lowest flow velocity in the floodplain. The flow velocity on the slope reaches the lowest value when the slope angle is 1/12.5. In order to study the effects of slope angle on penetration of flow, a further

look into the lateral momentum exchange is needed. Again, the horizontal Reynolds stress is calculated, which is interpreted as momentum transport in this case.

Figure 11: Influence of slope angle on horizontal Reynolds stress.

Figure 11 shows the distribution of momentum exchange calculated from model with different slope angle. The horizontal Reynolds stress, which is interpreted as lateral momentum exchange here, is mainly dependent on the lateral velocity gradient. The combined effects of slope angle and vegetation-induced friction dominate the momentum exchange in the shear mixing layer, which makes the situation rather complex. In Figure 11, attention should be paid into the area between distance=0 m and distance=0.2 m. It can be seen that with a slope angle of 1/10, the momentum transport into the vegetation patch is larger than that of other slope angles. It implies that a slope angle around 1/10, which is the most typical slope angle in Mekong estuarine system, might be the equilibrium state of topography. Because with a 1/10 slope, the vegetation patch receives most "attack" from the river flow.

Also, the inner penetration of momentum transport is also reflected in the patterns of coherent structures generated in the shear mixing layer. Figure 12 shows the flow patterns of simulations with different slope angle. It can be seen that with a slope angle of 1/10, the strongest eddy structure is observed. This also proves that a slope angle around 1/10 can lead to largest amount of momentum transport into the vegetation patch.

Figure 12: flow patterns of simulations with different slope angle. The slope angle of models from left to right are 0, 1/12.5, 1/10 (reference) and 1/1 respectively.

4. Conclusion

This research studied the hydrodynamics in a partially vegetated compound channel by using the 2DH RANS model in Delft3D, and the influence of slope angle and vegetation density on flow characteristics is highlighted.

The numerical model is calibrated according to the results of flume experiments so that the model is able to capture the flow characteristics. The calibrated parameters include drag coefficient, background horizontal eddy viscosity. Drag coefficient is a physical parameter and it should be within a reasonable range of value. The drag coefficient is 1 for single cylinders and in this study a value of 0.8 is recommended after calibration of the model. An uniform background horizontal eddy viscosity value of $10^{-4} \text{ m}^2/\text{s}$ is suggested according to calibration of the model. It is recommended to keep this value as small as possible.

The research focuses on the influence of response of flow characteristics to slope angle and vegetation density. Regarding the vegetation density, the presence of vegetation leads to a sharp increase of horizontal Reynolds stress around the vegetation edge. This implies that the vegetation patch strengthen the momentum exchange in the shear mixing layer. Also, a denser vegetation patch leads to stronger momentum exchange at the edge of vegetation patch.

The slope angle is also influential under circumstances with dense vegetation on the floodplain. A slope angle around 1/10, which is the most typical slope angle in Mekong estuarine system, leads to the largest amount of momentum transport into the vegetation patch. Also, with a slope angle of 1/10 the strongest eddy structure is observed. It implies that a slope angle around 1/10 might be the equilibrium state of topography in mangrove coast.

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