STUDIES ON MORPHODYNAMICS IN SHALLOW RIVERS WITH EFFECTS OF VEGETATION AND LARGE WOOD USING COMPUTATIONAL MODELS

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Introduction

Vegetation is essential factor in river morphodynamics, and it continually affects the natural river system. In particular, some researchers have presented the argument that vegetation frequently affects channels through it reinforces a channel bank and reduces the number of active channels by inducing changes in sediment transport. On the contrary, another researchers presented that the vegetation area alters channel beds to increase bed erosion. This bed erosion may cause scour erosion and the generation of a number of threads channels and thalweg. It also leads to changes in the pattern of bar formation and bank erosion.

Most researchers have considered immobile vegetation types to study on bed morphology and water flow with vegetation effect. Immobile vegetation mainly indicates static motion, which means that change in the vegetation area is mainly due to the colonization process. In viewing the flood scale in the short-term (one flood event), some researchers have considered vegetation without growth (e.g., Kim et al., 2015; Iwasaki et al., 2016). In cases of long-term channel migration (more than one flood events), researchers have taken note of vegetation effects from time changes in the growing stage and the colonization process with decay (e.g., Crosato and Saleh, 2011; Kang et al., 2018). In particular, the vegetation growth and colonization play many diverse roles in river environments beyond simply disturbing the flood flow path, and growing vegetation affects different interactions between water flow and bed morphology (Kang et al., 2018).

In the past, torrential flow due to flood events has frequently occurred in the world due to climate change. This torrential flow, an unsteady flow, makes us face the limitation of our knowledge to predict flood events; torrential flow has been shown to cause enormous damage to humans. Thus, the importance in consideration of this unsteady flow has steadily increased. The vegetation effect by unsteady flow is different from steady flow. Accordingly, some researchers have pointed out that we should consider separately the rising stage and recession stage of unsteady flow because the bed morphology with each stage shows different bed changes; especially, the recession stage is important for mitigation of disasters such as bank erosion. Moreover, unsteady flow shows more complicated flow characteristics due to secondary flow of the first kind in a curved channel (Figure 1(a)). In this case, it is important to consider the sediment transport in the lateral direction because this secondary flow of the first kind is dominant due to the unbalanced pressure in the lateral direction induced by centrifugal force. In such conditions, if we consider the growing vegetation effect together with the curved channel, it should be one of the challenging tasks for researchers (for part 1).

Recently, along with immobile vegetation studies, studies related to mobile vegetation types also actively have increased. The study of large wood dynamics is familiar as well as immobile vegetation, and its importance increasingly has been noted in the field related to disaster mitigation due to debris flow and torrential flow with large wood.

Large wood (l/d > 10; l: length of wood, d: diameter of wood) is one mobile vegetation type. Rivers transport the large wood, and their deposition affects the river morphology by causing local scouring and the deposition of bed materials (Figure 1(b)). Such large wood enhances habitat diversity in the river environment and may initiate the formation of islands as a mid-channel bar in the bed morphology. The deposition patterns of large wood can change in response to input processes, channel morphology, and hydrological parameters, including flood events. Past research has shown that the relative influence of these factors changes along the river system, resulting in distinct downstream trends in the manner of large wood accumulation. The ratio of the log length to channel width is a key parameter in determining large wood deposition patterns; these patterns are also influenced by parameters

![Figure 1 Vegetation and Large wood.](a) vegetation area in the curved shallow channel, Korea (Kang, 2016)
(b) stored large wood due to shallow flow in the braiding channel, Italy (Google earth, 2018)
such as the drag force, water level, bed friction, and presence of obstacles.

Such large wood deposition is obviously associated with wood motion. The motion of large wood has been investigated by many researchers. Representatively, Braudrick and Grant (2000) and Braudrick et al. (2001) laid out the basic framework for describing large wood mobility and entrainment in rivers. Their work has allowed several researchers to undertake studies related to large wood transport dynamics. These studies have successfully predicted the relationship between wood characteristics (wood size, flow discharge, area of river basin) and the hydrodynamic and resistance forces, and have also extended the scope of transport systems.

The increase in experimental and observational research, as well as the enhanced importance of predicting and managing the stability of wood pieces and jams, has led to the active development of numerical models of large wood transport. For instance, hydrodynamic models of rivers have been combined with large wood transport models, such as the Iber-wood two-dimensional (2-D) hydrodynamic model (Ruiz-Villanueva et al., 2014) and the NaysCUBE (Kimura, 2012) three-dimensional (3-D) Reynolds-averaged Navier–Stokes (RANS) model (Kitazono et al., 2016; Kimura and Kitazono, 2017). Both of these models address wood transport using a Lagrangian method, whereby the water flow is coupled with the wood transport at every time step. The Iber-wood model considers the wood shape to be a simple cylinder. In contrast, the NaysCUBE large wood model applies a particle-based method to consider the impinging motion of large wood using a discrete element method (DEM). These studies have clarified the mechanism of large wood motion in deep water flows (where the water depth is greater than the wood diameter) and have reproduced the large wood motion well. However, these models overlook the bed morphology and large wood deposition factors such as the root-wad effect and anisotropic bed friction, although the effect of the wood on bed morphology is most relevant when being transported in shallow flows. Thus, clarifying such phenomena by coupling floating and deposition motions with bed morphology is crucial in enhancing our understanding of large wood behavior in rivers as well as the role of large wood floating advection on the permanent bed (for part 2).

To deal with two challenges in bed morphology with both types of vegetation (growing vegetation and large wood; immobile and mobile vegetation, respectively), these challenges should be independently approached in two parts. For the first challenge (immobile vegetation effect), bed morphology with vegetation effect should be studied based on a 2-D hydrodynamics model and observation data. In particular, it is necessary to review the previous studies associated with vegetation effect and to improve the previous model to consider both of vegetation growth and colonization in a curved channel with unsteady flow. For the second challenge (mobile vegetation effect), a model should be developed to study large wood dynamics. Thus, a laboratory experiment should be conducted to test the reproducibility of the developed model, and then this model should be applied to practical experiments on the basis of observation data.

Contents of dissertation

Chapter 2: In this chapter, we conducted simulations using a two-dimensional, depth-averaged river flow and river morphology model to investigate the effect of vegetation growth and degree of flow discharge on a shallow meandering channel (Figure 2). To consider the effects of these factors, it was assumed that vegetation growth stage is changed by water flow and bed erosion. The non-uniformity of the vegetation colonization by growth was induced by the non-uniform and unsteady

<table>
<thead>
<tr>
<th>No.</th>
<th>Peak Discharge (m³/s)</th>
<th>Total Flood Duration (h)</th>
<th>Growing Vegetation</th>
<th>Permanent Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-1</td>
<td>690</td>
<td>450</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Run-2</td>
<td>1381</td>
<td>450</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Run-3</td>
<td>2762</td>
<td>450</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Run-4</td>
<td>690</td>
<td>450</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Run-5</td>
<td>1381</td>
<td>450</td>
<td>Yes</td>
<td>Yes</td>
</tr>
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<td>Run-6</td>
<td>2762</td>
<td>450</td>
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<td>Yes</td>
</tr>
</tbody>
</table>

Figure 2 Simulation results (final channel patterns).
profile of the water depth due to the irregular shape of the bed elevation and the unsteady flow model reliant on hydrographs to evaluate three types of peak discharges: moderate flow, annual average maximum flow, and extreme flow (Table 1). To compare the effects of non-uniform growing vegetation, the change in channel patterns was quantified using the Active Braiding Index (ABI), which indicates the average number of channels with flowing water at a cross section and the Bed Relief Index (BRI), which quantifies the degree of irregularity of the cross-sectional shape. Two types of erosion were identified: local erosion (due to increased flow velocity near a vegetation area) and global erosion (due to the discharge approaching peak and the large depth of the channel) as shown in Figure 2 and 3. This chapter demonstrated that the growth of vegetation increases both the ABI and BRI when the peak discharge is lower than the annual average discharge, whereas the vegetation reduces the BRI when the peak discharge is extreme. However, under extreme discharge, the ABI decreases because global erosion is dominant. The conclusions from this chapter help to deepen the understanding of the interactions between curved river channels and vegetation.

Chapter 3: This chapter developed a computational model for large wood deposition patterns in shallow flows considering the effect of root wad based on laboratory experiments (Figure 4). For the computations, we used the depth-averaged two-dimensional model, Nays2DH, on iRIC to simulate shallow flows.

A newly developed large wood simulation model was combined with the shallow flow model. The laboratory tests were performed by changing several hydraulic

![Figure 3: Temporal change of ABI and BRI (MF: 690 m³/s, AMF 1381 m³/s, EF: 2762 m³/s, veg: growing vegetation, no veg: no growing vegetation).](image)

![Figure 4: Flume, wood piece and calculation method.](image)
parameters: discharge, channel slope, and anisotropic bed friction (Table 2).

In shallow water with a depth similar to the large wood diameter, the root effect draft for wood motion (the depth at which the large wood contacts the river bed) by lifting up the head of large wood. The experimental results showed two different patterns of motions: the large wood tends to move toward the side walls and deposit on the bed after passing an obstacle. In the experiment, the root wad of the large wood significantly affected the large wood motion. The computational results reasonably showed that the proposed coupling model reproduced the fundamental and physical aspects of the phenomena (Figure 5).

Chapter 4: This chapter develops a numerical model for simulating the hydrodynamics involved in the transport of large pieces of wood in a braided river considering the root wad effect and anisotropic bed friction. The newly developed numerical model can precisely simulate the behavior of large pieces of wood using a 2-D depth-averaged Eulerian flow model that calculates the water flow and bed morphology in generalized coordinates. A Lagrange-type wood transport model is developed and combined with the flow model, and the applicability of the combined model is determined through a comparison with experimental results (Figure 6 and Table 3). From the simulation results, we quantitatively calculate the Active Braiding Index, Bed Relief Index, and mean values of wood deposition position, and deposition angle. We then analyze the relationship between the bed morphology responses and the wood deposition patterns in terms of the root wad effect and input supply. The proposed model reproduces the prominent features of the flume experiment, indicating that the present numerical approach can clarify and predict the behavior of large pieces of wood in accordance with the bed morphology (Figure 7).
Conclusion

Growing vegetation (immobile vegetation) changes river environment by colonization. This study showed that vegetation colonies affect the water flow and the sediment. Vegetation effect increases the drag force, which decreases flow velocity and increases water depth. Thus, if growing vegetation makes a large vegetated colony, bed morphology patterns will be changed.

Large wood (mobile vegetation) also affects the water flow and sediment through its motion by dynamic force, which is interaction between the water flow and large wood. Large wood locally affects the bed morphology through accumulating stored wood at a point that is highly spatially and temporally variable, whereas the growing vegetation effect steadily activates through expansion of its area.

Based on the computational results obtained and analyses done in the preceding chapters, some conclusions can be drawn as follows.

Part 1: Immobile Vegetation Effect (Bed Morphology with Growing Vegetation)

Under a small peak discharge (690 m$^3$/s), vegetation works to accelerate local erosion because the flow velocity increases near the vegetation area, which increases the change in the ABI and BRI over time. If the peak discharge is high (1381 m$^3$/s), the strength of the secondary flow of the first kind becomes significant, thereby activating global erosion. The vegetation effect also activates local erosion, such that the change in the BRI over time is larger than for the no-growing case for the same discharge. On the contrary, if the peak flow discharge is extreme (2762 m$^3$/s), global erosion is dominant. The thalweg readily shifts toward the outer bank and the area of point bar with vegetation expansion. Under this scenario, the larger area of vegetation limits the scale of the secondary flow by reducing the flow velocity, which activates global erosion within the unvegetated areas such as the thalweg. As a result, the change in the BRI over time decreases compared to the no-growing vegetation case. This phenomenon should be further explored with more detailed field observation and experimental data.

Part 2-1: Mobile Vegetation Effect (Bed Morphology with Large Wood Dynamics): Large wood dynamic on the fixed flat bed

The wood piece tends to move toward the side walls after touching down on a lower water depth zone because of the small roll friction. Such motion becomes more dominant when the flow discharge decreases. The drag force and the water depth also increase when the flow discharge increases. Moreover, the wood piece easily flows away in the streamwise direction. However, the responses of the wood motion by change of the channel slope showed an unclear pattern because the employed values of channel slope were insufficient to affect the wood piece motion.

In the experiments, the wood piece can become deposited more easily if it has a root section because the presence of the root wad decreases the draft for the wood motion in the wood piece, lifting the head of the wood piece by the root wad.

Figure 7 Final water depth in simulation results. (a) C1; (b) C2; (c) C3; (d) no wood case
(red wood piece has no root wad and blue wood piece has root wad)
although weight and volume in part of root wad are larger than the stem of the wood piece. The simulation results also clearly reproduced the root effect well. However, in cases of wood without the root wad, the experiment results only showed deposited wood pieces near the wall. Through these results, we also discovered a relationship between the deposition angle of the large wood and flow discharge. The stemwise angle of the deposited wood piece becomes smaller when the flow discharge is larger. Consequently, it means that the deposited wood angle is associated with the projection area between the flow discharge and the wood piece. Thus, further study should consider additional parameters, such as the projection area of the wood piece considering the angle between stemwise and streamwise directions.

Part 2-2: Mobile Vegetation Effect (Bed Morphology with Large Wood Dynamics): Bed morphology with large wood dynamics

We neglected wood particle collision to reduce the computation time. However, the simulation results showed reasonable agreement with the experimental results (Bertoldi et al., 2014) in terms of deposition patterns and bed morphology. If we considered wood collision, we could expect to achieve better agreement.

The root wad effect is a remarkable factor in this study. We employed a root wad particle diameter some 3.3 times larger than that of the stem particle, and we considered changes in the settled height of each particle under the root wad effect. The simulation results showed that the presence of root wad decreases the wood mobility and enhances wood deposition. The same phenomenon was observed by Bertoldi et al. (2014). However, we considered simple spherical particles for the root wad, and these are insufficient for reflecting the complex behavior related to root wad, such as the hook effect and trapping of other wood pieces. This limitation can be overcome by expressing the root wad as a number of smaller particles.

In the simulation results, wood deposition and jam formation led to an increase in ABI and a decrease in BRI in comparison with the no wood case. This suggests that wood deposition can affect the bed morphology. However, when a large thalweg is generated, the influence of wood jams on bed morphology weakens. The number of stored wood pieces increases slightly when a large thalweg is created.

Through this study, we have identified some novel aspects to the relations between wood deposition and bed morphology. Thus, we believe that this approach is worth advancing to the relations between wood deposition and bed morphology. Such knowledge can be applied to disaster prevention research and the improvement of river environments.

Future work

In this study, we assume that growing vegetation and large wood consist of rigid bodies, which are able to neglect elastic bending moment. However, all vegetation has elastic stems. This should affect the motion of wood in being captured by obstacles, such as bridge piers and trees. Therefore, if we consider vegetation and large wood in the same computational domain, bending moment should be considered.

In this study, we did not consider the gravity effect on either vegetation or large wood, because a flat bed, which has mild slope, was employed. Thus, we could not consider the bank collapse by gravity effect due to using two types of vegetation. In addition, we did not consider the large wood going down to lower parts of the bed by rolling motion.

For the further study, we would conduct the simulation considering vegetation growth and large wood. This case is to attempt the combination of mobile and immobile types of vegetation for hydrodynamic computation. In this simulation we should consider equivalent quantities between vegetation and large wood. For instance, we can use equations related to vegetation density at drag force term, to consider the large wood as a vegetation (immobile state). Here, the stem diameter of large wood is regarded as the stem of vegetation. In this case, we should consider the density of large wood. Then, when this immobile vegetation (fixed large wood on the bed) is pulled by certain conditions (bed erosion and large flow velocity), it can be converted into large wood (mobile state).

The seeding process can also be applied in this model. In the computational domain, if a seed is feuded from upstream, this seed flows downstream. Then, the seed may deposit on a lower water depth area, which is appropriate for germination. When seed deposits occur over enough time for germination, the growing vegetation model is able to be applied at this grid area.

Reference