Responses of Bed Morphology to Hydrological Events with Effect of Vegetation

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In this study, we simulated river flows and morphological changes on a sharp meandering channel, which consists of sand topography, to evaluate the secondary flow effects, the development of point-bar and braided channel with the vegetation effect using a two-dimensional numerical model, iRIC software. In the simulation results, meandering channel with vegetation showed diverse river bed deformations, such as braided channel, sub-meadandering channel, mid-channel bars, and a point-bar. In particular, vegetation area is changed by flood events, and then vegetation changes the flow characteristics and river environment.

Key Words: Vegetation effect, Non-equilibrium secondary flow, Responses of bed morphology, Hydrological events, Meandering channel, Shallow flow mode

1. INTRODUCTION

There has been studied river flows and sediment transport under flood events to predict disasters and to mitigate them for many years. Many researches have been conducted by using numerical models, directly surveying and laboratory experiments for those purposes. Recently, to predict disaster in rivers, we can simulate with one-dimensional models to three-dimensional models focusing on the effects of meandering, vegetation, obstacle structure, and so on. Especially, the vegetation is one of the most important factors in river phenomena, so that it has been studied by many researchers¹. The vegetation may not only disturb the flood flow path, but also, has diverse roles, such as habitat, natural purification, landscape and so on. Vegetation is influenced by diverse factors, for instance, topography, groundwater, soil depth, soil moisture, flood duration, flood frequency, etc. After flood events, vegetation forms a unique habitat area and environment by the changes of stable vegetation area²³. In addition, high density of vegetation changes flow friction, and the formation and breaching of log-jams, and then increases the water depth and flow resistance and decreases the hydraulic radius of the channel⁴. Besides, vegetation area can be changed by the flood events and the sediment supplement, which are affected by several factors such as dam construction, and this change affects the river environment⁵. Some of researchers⁶⁷ argued that the development of braided channel patterns may be activated by high sediment supply due to local destruction of vegetation area.

We also should consider that most of natural channels are curved and meandered. In recent years, the transformation of river pattern has been given considerable attention; particularly, it is of great significance in the understandings of the dynamic process of river system⁸⁹. The patterns have been greatly diversified including straight, meandering, braiding and anabranching¹⁰¹¹¹², in which meandering is the most common and fundamental phenomenon. Many researchers have devoted their efforts into modeling meanderings in laboratory conditions, while it proved to be technically challenging. And also, it is essential to consider such plane topography to address channel designs or flood controls and so on. Especially, the morphological behavior in river channel change is
influenced by diverse factors such as channel width, discharge, water depth, slope, bed materials and vegetation. Vegetation, in particular, plays a significant role in the riverbed deformation and is still important in hydraulic and environmental engineering. However, the studies related to vegetation is not enough\(^2\).

In this paper, we study the vegetation effect on generations of the geomorphic deformation in a natural sharp shallow meandering channel. To study the geomorphic phenomena, we use a plane 2D (two-dimensional) numerical simulation, which is one of powerful tools to elucidate the influences of vegetation on rivers. The present study area is Hoeryongpo (回龍浦) basin in Naesung stream, Korea (Fig.1). Many researchers have been interested in this area because this area shows distinctive hydraulic geomorphic topography, such as a sharp bend, a point-bar, a braided channel, etc. Since these diverse topographies have unique scientific factor, many researchers urge that this area has to be protected from development and construction. Recently, this area has been faced with new environment due to the change of flood patterns, because Yeong-ju Dam is being constructed about 32km upstream this area from 2009. In addition, since 2009, discharge has been decreased due to significant drought (Fig.2), which has affected the conditions of vegetation on the area.

The main change of environment due to the decrease of flood discharge is that vegetation area has increased and the area of sandy plains has decreased. An armoring phenomena is also occurring and sediment deposition is decreasing. Those phenomena may cause significant bed change with influences of vegetation. Besides, to control the flood and sedimentation after the construction of the dam, the adjustment of discharge will become necessary. For these hydraulic issues, the importance of the prediction of the bed change and sediment discharge on the study area depending on vegetation is being magnified. Especially, this area has a significantly developed point-bar, which length is around 1km because most of the stream consists of sand including a sand plain, a sand point-bar and sand alternate bars. The topography is one of the most unique geomorphic characteristics in the world.

Therefore, this site has a lot of important scientific factors, and then it is necessary to be preserved in the future. For the preservation of such diverse topographies, firstly, we should understand the two main topics; one is how the point-bar and the braided channel were generated, and if vegetation increases due to the decrease of flood events, what will happen with river environment such as change of point-bar shape, increasing and decreasing braided channel, change of erosion and deposition ratio and so on.

2. STUDY AREA AND COMPUTATIONAL CONDITIONS

This study area has been suffered from diverse flood event. Over the time, vegetation area also repeatedly changed depending on the flood events and the season. The total length of the computational domain is set 2,376m and the average channel width of the domain is 252m. The averaged bed slope is 0.00159. The Manning
Roughness coefficient is estimated as 0.02 from the averaged sediment diameter, 1.49mm with the Manning Strickler equation. And in this computation domain, grid size is around 8m×5m, total grid number is 16,269 (319 × 51). Computational time step is temporally changeable due to using Courant–Friedrich–Lewy (CFL) condition for reducing CPU time.

In this study area, for more than 10 years, vegetation area has been existed as shown Fig.3. This figure shows the historical change of vegetation and river bed. This area has a sand topography in the overall domain so that vegetation can grow only near the water such as near the river, excluding no water area in the central area of the point-bar. In this figure, vegetation area shows gradual increase, especially, in 2015, vegetation area covers the overall study area despite of after flood events. Besides, thread channel is also gradually developed due to increase of vegetation area depending on decrease of flood events within the straight part. Moreover, recently, as shown in Fig.2, this study area has been suffered from big drought and even the maximum flood discharge is less than half of annual averaged maximum discharge (=690m³/s). The wider vegetation area and the generation of thread channel in it may be induced by the drought.

Several researchers describe that vegetation affects the sediment transport, which can cause the deformation of riverbed (e.g. Hickin, 1984; Murray and Paola, 2003; Jang and Shimizu, 2007; Smith, 1976; Ikeda and Izumi, 1990; Millar and Quick, 1993; Huang and Nanson, 1997; Millar, 2000). Therefore, it is necessary to understand the influence of vegetation on the study area from geomorphic and scientific points of view.
3. UNIT HYDROGRAPH

To consider the diverse flood event, we should use the unit hydrograph which expresses the typical shape of hydrographs at this location. The unit hydrograph is made from measurement data. In the reality, the flood event is not only occurred at one time but also continued with other flood events. At this time, each flood event is partially overlapped between each other. Therefore, it is difficult to select the typical hydrograph in the measurement data.

There are several methods for getting the hydrograph, such as, using rain fall data, discharge data and water level data. In this study, we use the discharge data because we should focus on the sediment transport and river bed deformation. The process of generating the unit hydrograph is as follows:

First, annual maximum flood events are selected from measurement data for 15 years excluding 2015 year’s flood event, which is less than half of averaged annual maximum discharge (690m³/s), and all of such hydrographs are rearranged to adjust the location of the peak discharge. And then, flood events are cut off by considering inflection point at the recession stage. The discharge of 37m³/s, which is total averaged discharge for 16 years, is considered as the normal discharge. Second, each flood event is divided by the peak discharge of the flood event for normalization. Then the tail of the flood event is cut off if it has a different slope section. Finally, all flood events are averaged. To get a typical hydrograph with a certain discharge, we can generate it as unit hydrograph \times peak discharge.

To check the reproducibility of this method, the several cases of observed hydrographs are compared with the results of the present method in Fig. 4. We can see that the estimated hydrographs with the present method are in good agreement with the real hydrographs.

Fig. 5 also shows diverse hydrographs using unit hydrograph with the peak discharges of 690m³/s (half of averaged annual maximum discharge), 1,381m³/s (averaged annual maximum discharge), and 2,762m³/s (twice of averaged annual maximum discharge). In this study, we use those different scales of flood events to investigate the characteristics of the study area.

4. NUMERICAL SIMULATION

In this paper, we adopted Nays2DH\textsuperscript{(19,20)} solver of iRIC. Nays2DH solver employs Cubic Interpolated Pseudo-Particle (CIP)\textsuperscript{(21)} scheme on the advection term, central scheme on the Reynolds stress term and zero-equation type turbulence model based on the shallow flow equations. The effect of vegetation is evaluated as drag forces on the momentum equations. The Ashida and Michiue’s model\textsuperscript{(22)} is used to estimate the bedload flux and a bed collapse model considered the angle of repose is incorporated. Since this study area has particularly complicated topography, the CIP scheme is used on most of computational domain though the upwind scheme is used near the downstream outlet to stabilize the calculation.

In addition, at boundary condition for upstream, the inlet velocity at each grid cells are locally calculated with the uniform flow equation considering the bed profile in the lateral direction. The detailed descriptions of the present model are as follows:

(1) Momentum equations and continuity equations

This model uses the depth-averaged momentum and continuity equations to calculate plane two-dimensional flows with the following equations.
Continuity equation:
\[
\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0
\]  
(1)

Momentum equation:
\[
\frac{\partial}{\partial t} \left( \frac{hu}{\rho} \right) + \frac{\partial}{\partial x} \left( \frac{hu^2}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{huv}{\rho} \right) = -h \frac{\partial H}{\partial x} - \tau_x + D_x + F_x
\]
\[
\frac{\partial}{\partial t} \left( \frac{hv}{\rho} \right) + \frac{\partial}{\partial x} \left( \frac{hu}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{hv^2}{\rho} \right) = -h \frac{\partial H}{\partial y} - \tau_y + D_y + F_y
\]
\[
\frac{\partial D_x}{\partial x} \left[ v_t \frac{\partial (uh)}{\partial x} + \frac{\partial}{\partial y} \left( v_t \frac{\partial (uh)}{\partial y} \right) \right]
\]
\[
\frac{\partial D_y}{\partial y} \left[ v_t \frac{\partial (hv)}{\partial y} + \frac{\partial}{\partial x} \left( v_t \frac{\partial (hv)}{\partial x} \right) \right]
\]
\[\]  
(2a)- (2h)

where, \( h \): water depth, \( t \): time, \( u \): velocity in the \( x \) direction, \( v \): velocity in the \( y \) direction, \( g \): gravitational acceleration, \( H \): water surface elevation, \( \tau_x \): riverbed shearing force in the \( x \) direction, \( \tau_y \): riverbed shearing force in the \( y \) direction, \( D_x \): turbulence term in the \( x \) direction, \( D_y \): turbulence term in the \( y \) direction, \( F_x \): resistance by vegetation in the \( x \) direction, \( F_y \): resistance by vegetation in the \( y \) direction, \( C_f \): riverbed shear coefficient, \( \nu_t \): kinematic turbulent viscosity coefficient, \( C_D \): drag coefficient of vegetation, \( \alpha_s \): area of interception by vegetation per unit volume, \( G_r(t) \): vegetation growing function depending on time.

(2) Zero equation model for eddy viscosity
To consider the turbulence, we used zero equation model for wide and shallow water channel as given Eq.3.
\[
\nu_t = \frac{\kappa}{6} Au, h + B
\]  
(3)

where, \( \nu_t \): eddy viscosity coefficient, \( \kappa \): von Karman constant (0.4), \( u_* \): friction velocity, \( A \) and \( B \): user defined parameters for the eddy viscosity coefficient (default values of \( A \) and \( B \) are 1 and 0, respectively).

(3) Typhoon occurrence in Korea
We considered the frequency of typhoon for estimating the number of flood events per year. According to Typhoon White Book in Korea[22], typhoon has usually come to Korea three times (July, Aug., Sep.) every year. Hence, three times of flood events in one year is assumed for the present calculations.

(4) Vegetation model
In this study, we assumed the dominant vegetation species as the Reed (see Fig.6) which is perennial plant. The growing period is around six months (April~Sep.). After the growing, it keeps the height (Fig.7)[24]. The average length is 3m, common root length is 80cm[23][24]. The average germination time is 6 days. We focus on the vegetation influence (decrease and increase by flood event) and development of point-bar or other topography. Therefore, we assumed that the rate of the Reed growth is constant and keeps growing during flood event (until the end of August).
We also assumed that if vegetation area is submerged, this vegetation will be disappeared due to sand and gravel grinding during flood event because sediment transport is active during flood. In addition, the plane shape of the study area is not changed even though the occurrence of flood event. Therefore, it is difficult to consider the vegetation removal by erosion and deposition. Another vegetation removal method is considering submerge condition as shown Fig.8. In this figure, $G_i(t)$: vegetation growth rate, $t_1$: germination time (6 days), $t_2$: vegetation growing time (6 month), $t_3$: critical vegetation removal time (2 days).

In this study, we assume that the submerge time to eliminate the vegetation is 173,800s (2 days). Woo et al. (2011)\textsuperscript{25}) surveyed the vegetation area in this study site. They confirmed that all vegetation area has disappeared after the flood event with the peak discharge of (703m$^3$/s). Therefore, we consider the half the duration time of the hydrograph with the peak discharge of 690m$^3$/s flood (=2 days) as a critical removal time. That means if the submerged time exceeds 2 days, all the vegetation under the water is removed.

Besides, we consider the effect of vegetation density to the drag force so that the vegetation density is defined as the area of interception by vegetation per unit volume $a_s$, which is set in each computational cell as given by Eq.\textsuperscript{4}\textsuperscript{26}).

\begin{equation}
    a_s = \frac{n_s D_s}{S_s^2}
\end{equation}

where, $n_s$: the number of vegetation in the grid cell, $D_s$: the average diameter of trunks and $S_s$: the sampling grid width. According to KICT (2015)\textsuperscript{27}), averaged density of overall vegetation on this study area in July is 95.34m$^2$. Moreover, all vegetation is not type of trees so that we assume that $D_s$ is 1cm. And also, we estimated the average number of vegetation stems in unit area is approximately 10 from the photographs of vegetation in this site. Therefore, the value of $a_s$ in this area is estimated as 1m$^{-1}$.

We consider that the frequency of flood event by typhoon occurrence is one time per one month. For example, the hydrograph with $Q=1,381m^3$/s can be expressed in Fig.9. Discharge graph of Fig.9 consists of flood events and normal discharge seasons. And during normal discharge seasons, only braided channel was occurred (see Fig.13) so that we skip computation of the normal discharge season to reduce the CPU time. But the vegetation is still growing during normal discharge (37m$^3$/s), therefore, we consider the discontinuous vegetation growth rate in Fig.9.

The value of the vegetation growth function rapidly increases (30 $\times$ 24 times larger) during the compressed normal discharge season (1 hour) to consider the vegetation growth for 1 month at each normal discharge season.

\textbf{(5) Sediment transport model}

To calculate the sediment transport of the bedload, we used Ashida and Michiue formula\textsuperscript{28}), which is described as
\[ q_b = 17 \tau_e^{3/2} \left( 1 - \frac{\tau_c}{\tau_e} \right) \left( 1 - \sqrt{\frac{\tau_c}{\tau_e}} \right) s_g d \]  
(5)

where, \( q_b \): sediment discharge flux, \( \tau_c \): dimensionless critical tractive force, \( s_g \): specific gravity of sediment, \( d \): mean diameter of the sediment particle, \( \tau_e \): dimensionless tractive force, \( g \): gravitational acceleration.

(6) Slope failure model

A slope failure model is employed for this study, consistent with several researchers\(^{29}30\). Slope failure occurs when bed slope among four neighbor cells becomes steeper than the angle of repose of the bed material after bed scouring. A slope failure model in which bank slope adjustment is set to be milder than the angle of repose and the volume of failure is set equal to the volume of deposition. A slope failure equation can be expressed as follows:

\[ \Delta \zeta_0 = \frac{L(\tan \theta - \tan \varphi)}{1 + \frac{A_0}{A_1}} \]  
(6)

\[ \Delta \zeta_1 = -\frac{L(\tan \theta - \tan \varphi)}{1 + \frac{A_0}{A_1}} \]  
(7)

where \( \theta \): current bed slope, \( \varphi \): angle of repose, \( L \): grid cell width, \( \zeta_0 \) and \( \zeta_1 \): bed elevations at two adjustment cells, \( \Delta \zeta_0 \) and \( \Delta \zeta_1 \): bank and bed elevation changes, and \( A_0 \) and \( A_1 \): the width of two adjustment cells. In this study, angle of repose is 0.58 (= tan 30\(^\circ\)) because almost riverbed consists of the sand, which angle of repose (\( \varphi \)) is around 30\(^\circ\). (deg).

(7) Secondary flow model

We employed a non-equilibrium model to consider the lag between the secondary flow and streamline curvature. In this model, the transport of depth-averaged vorticity in the streamwise direction is calculated with the vorticity transport equation. The streamwise vorticity is associated with the secondary flow of the first kind. Therefore, we can solve the effect of development of secondary flows depending on time and space. The velocity near the bed is evaluated by this secondary flow model and the direction of the bedload transport is estimated using the present secondary flow model with Hasegawa’s equation\(^{31}\). We also apply the equilibrium secondary flow model for comparison, in which the streamwise vorticity equation is not solved and just estimated well-developed secondary flow with Engelund model. The result of each model may show different tendency, especially, in the sharp meandering channel such as this study area. Therefore, it is necessary to evaluate carefully the adequacy of the models for secondary flows.

(8) Simulation conditions (Case 1 and Case 2)

All of cases, fixed vegetation is considered because, for at least 10 years, fixed persisting vegetation has been observed on the same location, and has influenced the river flow and river bed deformation (Fig.10).

In addition, as the initial condition, the bed of the computational domain for all cases are assumed as a laterally flat and streamwisely sloped (0.00159). After the computation, the simulated bed shape is compared with the present river survey data. As for the diverse flood events, we also consider four different discharges: total averaged discharge (37 m\(^3\)/s), averaged annual maximum discharge (1,381 m\(^3\)/s), and half/twice (drought/extreme) the averaged annual maximum discharge (690 m\(^3\)/s / 2,762 m\(^3\)/s).

We applied the aforementioned two types of secondary flow models, the equilibrium and the non-equilibrium models to evaluate the sensitivity for development of point-bar. We performed two cases of computations. In Case 1, only fixed vegetation is considered and the dynamic vegetation growth is neglected. We considered vegetation growing and fixing in Case 2.

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(a) study area (2003 year)

(b) fixed vegetation area

Fig. 10 Fixed vegetation area
a) Case 1: Diverse flood events without vegetation growing

Case 1 is a series of computations under diverse flood events without vegetation growing. Various flood events shown in Fig. 11 are considered. The main properties of each simulation are listed in Table 1, in which, Run-0 is the observation data for comparison with other simulations. Run-1 does not consider a flood event though it assumes only the constant input discharge as 37 m$^3$/s (normal discharge in this study area).

<table>
<thead>
<tr>
<th>No.</th>
<th>Peak discharge (m$^3$/s)</th>
<th>Flood duration (hr)</th>
<th>Flat or surveyed bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-0</td>
<td>-</td>
<td>-</td>
<td>Surveyed</td>
</tr>
<tr>
<td>Run-1</td>
<td>37</td>
<td>1 month</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-2</td>
<td>690</td>
<td>112</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-3</td>
<td>1,381</td>
<td>150</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-4</td>
<td>1,381 (Equilibrium)</td>
<td>150</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-5</td>
<td>2,762</td>
<td>188</td>
<td>Flat</td>
</tr>
</tbody>
</table>

Fig. 11 Annual hydrograph without vegetation growing

Table 2 Simulation types depending on discharge with vegetation (Case 2)

<table>
<thead>
<tr>
<th>No.</th>
<th>Peak discharge (m$^3$/s)</th>
<th>Flood duration (hr)</th>
<th>Flat or surveyed bed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-6</td>
<td>37</td>
<td>1 month</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-7</td>
<td>690</td>
<td>112</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-8</td>
<td>1,381</td>
<td>150</td>
<td>Flat</td>
</tr>
<tr>
<td>Run-9</td>
<td>2,762</td>
<td>188</td>
<td>Flat</td>
</tr>
</tbody>
</table>

b) Case 2: Diverse flood events with vegetation growing

Case 2 is a series of computations under diverse flood events with vegetation growing. Various flood events shown in Fig. 12 are considered in the present computations. The main properties of each simulation are listed in Table 2.

We also consider the vegetation growing. This vegetation growing may be changed by flood event so that we can compare the influence of vegetation effect. Vegetation growing is assumed as constant and continuous until the finish of a flood event.

5. RESULTS AND DISCUSSIONS

(1) Comparison of secondary flow models

We compared the results of two types of simulations by equilibrium and non-equilibrium models with 1,381 m$^3$/s flood event as shown Fig. 13 (Run-3 and Run-4).

Basically, two results show similar tendency, but the result with the equilibrium model (Run-4) is relatively unstable and generates a smaller point-bar. The secondary flow of the first kind is induced by the curvature of the streamline. There is a lag between the streamline curvature and the development of the secondary current. The equilibrium model neglects the lag. On the other hand, non-equilibrium model (Run-3) is able to calculate the delay of development of secondary current behind the streamline curvature.

The point bar generated by the equilibrium model is too short. The reason is that the secondary flow effect suddenly disappears just downstream the curved region with the equilibrium model. On the other hand, the non-equilibrium model can consider the persistence of the secondary flow due to inertial effect at downstream region of the curved region. For these reasons, all other simulations hereafter employed the non-equilibrium secondary flow model.
In addition, in Run-0 (Fig.13(a)), surveyed topography shows smooth point-bar and riverbed. Since the distance of survey interval is around 20m in the cross section and 100m in the longitudinal section, small bed fluctuations may be smoothed away.

Moreover, this computational domain is trimmed at the beginning of second meandering channel. In the observation data, the low channel locates near inner bank at the end of this domain, conversely, in other simulation results, this low channel locates near the outer bank. Probably, the difference is caused by the inlet boundary conditions. Since we focus on the point-bar and other topography in the middle of meandering channel, this difference was neglected.

(2) Results of diverse flood events without vegetation growing (Case 1)

In Run-1, during the constant input discharge, 37m$^3$/s (normal discharge), the point-bar was not generated on the middle of the inner bank after 30 days’ simulation as Fig.14(a). It can be explained that the point-bar would not be generated without influence of flood events because the amount of erosion is not enough to develop the point-bar under the normal discharge. On the contrary, we confirmed the generation of a braided channel under the constant normal discharge. Tal and Paola (2010)$^{32}$ suggested that, in the numerical simulation, development of braided channel requires the initial perturbation of discharge due to lateral dynamic effect, but braided channel occurred without any perturbations in this study, because the computational domain is sharply meandered.

Under diverse flood events, both the point-bar and mid-channel bars were generated (Run-2~Run-5). As Fig.14(a)~(g), the point-bar area is different among each flood event, because diverse factors such as flow velocity, peak discharge, water level rising time and water level falling time, etc. are able to affect the sediment transport and create a point bar with different features. If the discharge increases, not only erosion but also sediment movement becomes active, whereas, if discharge decreases, the velocity of sediment movement also decreases. Then the deposition increases on the riverbed. If peak discharge becomes larger, the tractive force increases, which may increase the erosion.

Moreover, because of increase of the time for falling water level, the deposition time also increases. The phenomena also affects the sediment transport depending on the discharges 690~2,762m$^3$/s (Fig.14). If the peak discharge increases, the strength of the secondary flow becomes larger and increases the sediment transport in the transverse direction.

(3) Results of diverse flood events with vegetation growing (Case 2) and comparison with Case 1

As Fig.14, vegetation growing influences the development of the braided channel because vegetation disturbs the flow path and increases the velocity near the vegetation area. If vegetation increases due to low discharge flood event, water flows is disturbed by vegetation area. It is also indicated that, if the erosion becomes active, water depth increases$^{5(12)33}$. 
Fig. 14 Elevation change depending on the discharge and vegetation growing
In Run-6–8, the influence of vegetation is strong so that braided channel was developed and submeandering channel was occurred. It means that the vegetation affects the flow characteristics such as increasing velocity, disturbing flow path and so on\(^6\).\(^7\). However, in Run-9 (2,762 m\(^3\)/s), braided channel disappeared and the point-bar was developed. In this case, the influence of vegetation becomes weak due to erosion by strong flood discharge.

Also, at beginning part of point-bar, main channel is narrower than Run-5 (2,762 m\(^3\)/s, No vegetation growing). Because near the vegetation area on the point-bar, flow velocity becomes larger and it causes acceleration of the erosion of the main channel. Moreover, growing vegetation on the edge of the point-bar protects the erosion due to the flood discharge.

To quantitatively compare Case1 and Case2, we introduce the depth and erosion ratio in computational domain using Eq.8.

\[
\frac{\bar{E} \times E_n}{\bar{D} \times D_n} = r \tag{8}
\]

where, \(r\): ratio of erosion and deposition, \(E_n\): the number of eroded grid, \(\bar{E}\): averaged erosion, depth, \(D_n\): the number of deposited grid, \(\bar{D}\): averaged deposited depth. Here, we assume that the sizes of all grid cells are almost same.

Fig.15 shows the result of ratio of erosion over deposition. In case by normal discharge (37 m\(^3\)/s), deposition is dominant so that a point-bar cannot occur. In case with 690 m\(^3\)/s, \(r\) is more than 1. In this case, the point-bar is able to occur. In case with 1,381 m\(^3\)/s, \(r\) of no-vegetation case is larger than the case with vegetation growing, so that a point-bar becomes larger than 690 m\(^3\)/s case. In case by both with and without growing vegetation on 2,762 m\(^3\)/s, the point-bar was stably and smoothly developed than lower discharge cases. Besides, in no vegetation growing cases, the amount of erosion of 1,381 m\(^3\)/s case is greater than that with \(Q=2,762\) m\(^3\)/s. It can be described that in 2,762 m\(^3\)/s case, not only the erosion but also the deposition is more active than 1,381 m\(^3\)/s case, so that \(r\) was decreased at 2,762 m\(^3\)/s case. However, the case with 2,762 m\(^3\)/s with growing vegetation shows lager \(r\) than the case with same discharge without growing vegetation because the erosion increases by water flow near vegetation area\(^6\).\(^7\).\(^15\).

In addition, to verify the effects of discharge on \(r\), we simulated the cases with flood events of 345 m\(^3\)/s and 500 m\(^3\)/s without vegetation growing. As results, \(r\) of 345 m\(^3\)/s case is 0.87, \(r\) of 500 m\(^3\)/s case is 1.09. Fig.16 and 17 show the bed change result. In these simulations, 345 m\(^3\)/s case dominantly shows braided channel and thread channels. 500 m\(^3\)/s case also shows the braided channel, but this case shows relatively concentrated channel than the case with 345 m\(^3\)/s. It can be described that if \(r\) become larger, braided channel can be reduced and width of main channel will be increased so that point-bar can be generated as shown Fig.14(c)–(h).

6. CONCLUSIONS

We studied the effect of vegetation and diverse discharge on the sharp meandering channel. Through this study, we got the conclusions as follows:

1. Case 1 (No vegetation growth)

During the 37 m\(^3\)/s constant discharge (normal discharge), a braided channel can be generated, but a point-bar did not appear. Flood events are necessary to generate the point-bar. In this study, the flood with discharge larger than 690 m\(^3\)/s is necessary to generate the point-bar. And if discharge becomes...
larger, the point-bar occurs more stably. The non-equilibrium secondary flow model can reproduce the point bar longer due to the delay of development of secondary current behind the curvature radius.

2. Case 2 (with vegetation growth)

Vegetation growth can lead to make mid-channel bars and braided channel. And if the discharge of flood event is smaller, the influence of vegetation becomes stronger, and then the flow paths are disturbed by vegetation. It leads to generate the braided channel.

To generate point-bar, erosion is important factor. If the amount of erosion is larger than the deposition, point-bar is able to be occurred in this study area. In contrary, if the amount of the erosion is less than the deposition, development of braided channel and thread channel is dominant.

In this study, the development of topography was reproduced only considering the three times of flood events. In the future work, the effects of the number of flood events should be considered.

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