NUMERICAL MODELING OF VEGETATED FLOW BY CONSIDERING PHYSICAL VEGETATION CHARACTERISTICS

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ABSTRACT

The impact of climate change has increased the frequency of extreme floods, necessitating a more precise analysis of flood level changes. A problem arises because the frequency of floods increases with the rapid increase in the number of dry days. The inflow of vegetation not only has an impact on flood levels, but also on the river system in general, including the effect of velocity decrease on sediment transport. Therefore, it is necessary to carefully analyze the changes in flow caused by vegetation and utilize the results for flow analysis. However, accurate analysis of the effects of vegetation is difficult because they are influenced by numerous factors including vegetation species, range, density, and form. In addition, it is difficult to immediately identify the effect of vegetation on the flow because existing studies are mainly based on the reproduction of two-dimensional images or laboratory research. Therefore, in this study, a two-dimensional numerical model was used for a more accurate estimation of flow resistance in a stream-scale channel. To this end, theoretical flow resistance estimations using relations proposed by Chezy and Baptist are compared with the velocity measured by Acoustic Doppler Velocimetry (ADV). This can be used to estimate vegetation flow resistance more accurately for application to the numerical model for flow resistance.

Keywords: Flow Roughness, Flow Velocity, Numerical Calibration, Stream-scale Experiment, Vegetated Channel

1. INTRODUCTION

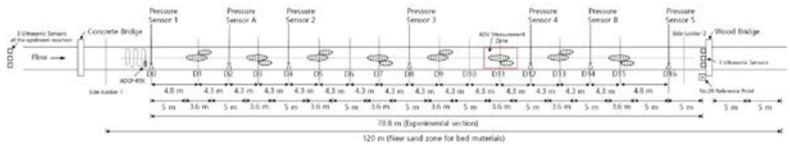
Vegetation is an important factor in flow resistance and water level determination. Further, it plays a critical role in the physical, chemical, and biological processes of river systems (Aberle and Järvelä, 2013). Flow–vegetation interactions are known to affect sediment and solute transport, river topography, and ecology (Gurnel, 2014). Vegetation is generally used to artificially stabilize riversides, support the diversity of vegetation species, and serve as a buffer for riverbanks (Bunting et al., 2013). However, across the world, recent years have seen frequent and unpredictable flooding owing to global climate change. The excessive inflow of vegetation into river systems causes flood levels to rise abruptly and inflict damage. Therefore, there is an increasing need for accurately estimating vegetation-induced flow resistance (Jang et al., 2019).
Therefore, this study analyzed the effectiveness of existing flow resistance formulas that consider the vegetation by comparing their results to the measured flow velocity in the stream-scale channel. This result can be used to obtain more accurate flow resistance values in numerical modeling. The results are applied to a two-dimensional numerical model for flow analysis that can estimate vegetation-induced flow resistance.

2. METHODS

2.1 Experiment

Indoor hydraulic experiments to assess the impact of vegetation on natural banks and floodplains are generally limited to small-scale vegetation or only parts of larger crops owing to waterway size constraints. However, such limited experiments cannot precisely analyze the complex flow processes in the vegetation-flow-bed fluctuations observed in nature. Hydraulic experiments that consider the size and shape of actual vegetation using full-scale experimental facilities can explain the vegetation structure more accurately. In particular, the physical characteristics of vegetation can be analyzed more accurately by addressing the limitations of small-scale indoor open channel experiments that cannot properly reproduce the natural form of riverbeds. This includes experiments that use natural bed topography facilities to closely analyze the impact of sediment that flows from upstream and the lower layer of vegetation. This study's approach is considered the most reasonable method for incorporating the spatial and structural conditions of natural vegetation. Investigations on vegetated flows were performed at the Korea Institute of Civil Engineering and Building Technology–River Experiment Center (KICT-REC) in Andong, Korea. The REC can conduct real-scale tests with its three prototype channels (length: ~600 m, width: 11 m) and a large capacity pump facility (maximum flow rate: 10 m^3/s) (Lee et al., 2018) (Fig. 1 (a)). The channel section used was 120 m long with a trapezoidal cross section of 8-m width; the bank slope was 1:1.5 (V:H) and the bed slope was 1/1,000 (Ji et al., 2018) (Fig. 1 (b)). Additionally, the artificial vegetation stem was 75 cm long and 2.3 cm in diameter (Fig. 1 (c)). It had four small branches around the vegetation stem, and the number of leaves distributed among the stem and branches was 485. The leaves had an average length of 7.96 cm, a width of 1.88 cm, and an area of 15.04 cm^2.

(a) Large-Scale Outdoor Flumes (Flow Direction →) (Lee et al., 2018)



(b) Sketch of Vegetation Patches and Measurement Points (Ji et al., 2018)

(c) Vegetation Sample

Figure 1. Study Area and Vegetation Arrangement

For the flow velocity measurement, the MicroADV developed by SonTek was used with a sampling rate of 50 Hz and measuring time of 150s. Eight measurement locations were chosen (see Figure 2). From the inside of the vegetation patch, the instantaneous velocity at six different locations where chosen with 14 vertical points. Time-averaged data were calculated after the instantaneous velocities were filtered out as the correlation values were lower than 50%. Finally, to estimate the depth-averaged streamwise velocity for D10 and D12, a three-point velocity approach was adopted (averaged velocity = ¼ x ($v_{0.2}$ + 2$v_{0.6}$ + $v_{0.8}$)).

Figure 2. Location of the Velocity Profile Measurement

2.2 Delft3D and Flow Resistance

This study used the Delft3D model for flow analysis by considering the vegetation effects. The Delft3D is a numerical modeling suite that is used to investigate hydrodynamics, sediment transport and morphology, and water quality in fluvial, estuarine, and coastal environments. This program enables an overall simulation of the river environment, including flow, sediment transport, waves, water quality, river shape, and ecosystem. It is also designed to be easily usable by experts and non-experts in the field of river science, and is particularly advantageous because it enables communication with developers through Delft3D's framework. Delft3D changes the number of layers to convert two-dimensional and three-dimensional models that approach the mean water depth (Jang et al., 2019).

The bulk roughness coefficient for the section between D2 and D14 was measured using Chezy's equation. In this process, the cross-sectional area was calculated using the time series data for water level measured by the pressure sensors at D2 and D14 and topographical data measured by the total station. Additionally, the Rh at D2 and D14 were calculated in the same manner as the cross-sectional area. Chezy's coefficient was measured for the baseline channel and the case with the vegetation patch. Also, existing relations that quantify the vegetation resistance were applied to estimate the flow resistance for two-dimensional numerical modeling. The most representative of existing relationships that consider the vegetation are those proposed by Baptist et al. (2007), Västilä and Järvelä (2014), and Luhar and Nepf (2013), which are shown in Table 1. Besides, both the submerged and emergent conditions were considered for these formulas. Of these, the Delft3D model uses the formula proposed by Baptist to determine the flow resistance.

Table 1. Estimation Formulas for Vegetation Roughness

Formula	Baptist et al. (2007)	Västilä and Järvelä (2014)	Luhar and Nepf (2013)
Conditions	Submerged condition (H>h): $C_r = \sqrt{\frac{1}{1/C_b^2 + C_D mDh/(2g)}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{H}{h}\right)$ Emergent condition ($H < h$): $C_r = \sqrt{\frac{1}{1/C_b^2 + C_D mDh/(2g)}}$ If the flow resistance due to bed can be neglected: $C_r = \sqrt{\frac{2g}{C_D mDh}}$	Friction factor of foliage: $f_F'' = 4\frac{A_L}{A_B}C_{D\chi,F}\left(\frac{u_m}{u_{\chi,F}}\right)^{\chi F}$ Friction factor of stem: $f_S'' = 4\frac{A_S}{A_B}C_{D\chi,S}\left(\frac{u_m}{u_{\chi,S}}\right)^{\chi S}$ Friction factor of foliated vegetation: $f_{tot}'' = \frac{4}{A_B}\left[A_L C_{D\chi,F}\left(\frac{U}{U_{\chi,F}}\right)^{\chi F} + A_S C_{D\chi,S}\left(\frac{U}{U_{\chi,S}}\right)^{\chi S}\right]$	Overflow velocity: $U_o = \left(\frac{2gS(WH - wh)}{C_f L_b + C_v L_v}\right)^{\frac{1}{2}}$ In-patch velocity: $U_v = \left(\frac{2gSwh + C_v L_v U_o^2}{C_D awh}\right)^{\frac{1}{2}}$ Depth-averaged velocity: $U = U_o(1 - B_X) + U_v B_X$

3. Modeling Results

3.1 Modeling Conditions

The experimental channel section consisted of seven vegetation patches of artificial willow saplings placed in an alternate bar arrangement (Fig. 1 (b)). A flow discharge of 2.805 m^3/s was calculated with the measured velocity and cross-sectional area in the approach channel section. A downstream water level of 98.76 m and Chezy's flow resistance of 48.17 was set as the boundary conditions. Also, the total length of the section was 120 m and the width was 8 m. Besides, the values of Cd in the relation specified by Baptist et al. (2007) were taken as 1 and 1.5 and compared with the measured water level.
The cross-section was also calibrated from the depth measurement data, following which it was extrapolated using a simple linear equation. By using the measured slope of the bed, we calibrated the measured data and slope such that they matched, as shown in Figure 3.

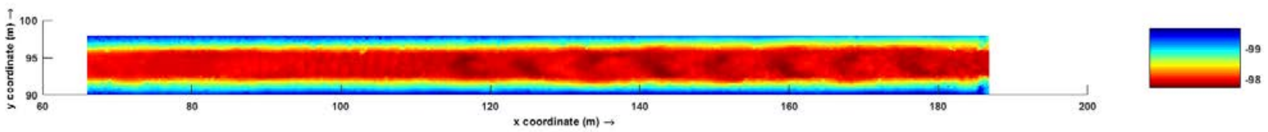


Figure 3. Initial Bed Elevation (m)

3.2 Simulation Results

The results corresponding to each water level applied to the Cd values 1 and 1.5 were compared with the measured water level, which corresponded to the point D11 in the sixth vegetation patch (Fig. 5). According to the measurement, the water level at sensor 1, which was the patch start point, was 98.86 m. Additionally, a value of 98.856 m was measured for a Cd of 1.5 and 98.839 m for a Cd of 1.0. In the downstream, the measured water level was 98.77 m. Then, 98.769 m for both Cd1.5 and Cd1 were simulated. Therefore, Cd1.5 with a difference of 0.004 m in the upstream and 0.001 m in the downstream was more suitable.
When comparing the velocities in the same vegetation patch section (Fig. 6), the simulated depth-averaged velocity was higher than the measured velocity using ADV. The vegetation patch had a difference of approximately 0.35 m/s from the measured velocity, although the pattern of the decrease in flow rate due to vegetation was consistent in the passage. It is possible that the simulated result was a depth-averaged velocity and the measured velocity was within the vegetation patch, thus making it relatively small. Therefore, the flow

velocity in the vegetation patch should be measured and compared in various sections in the vertical and lateral directions. Additionally, the measurement of the surface flow velocity should be discussed.

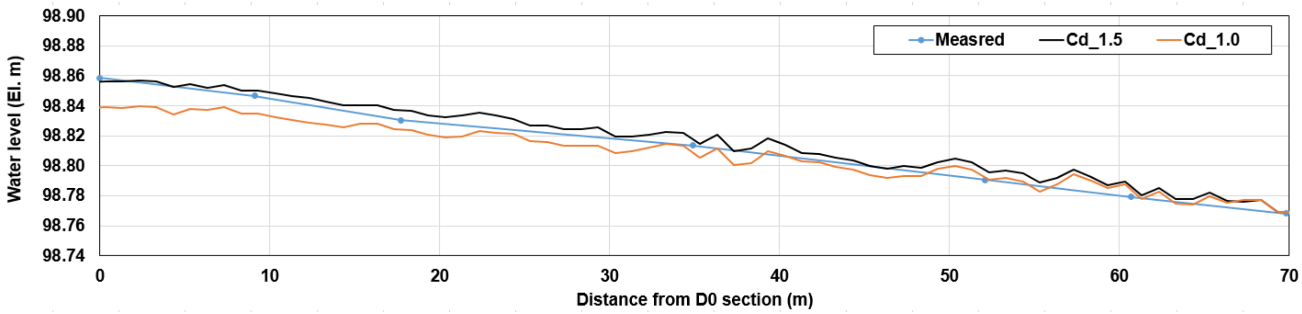


Figure 4. Comparison of Delft3D Results and Measurement of the Velocity (m/s)

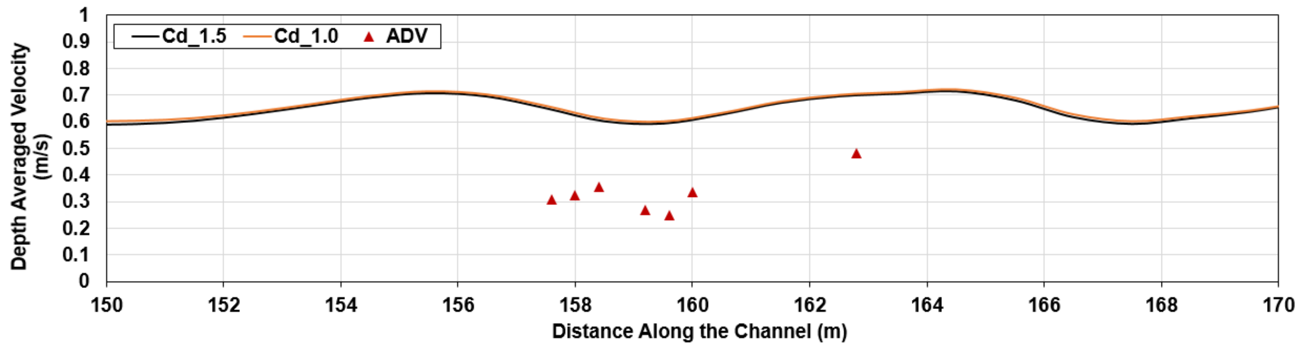


Figure 5. Comparison of Delft3D Results and Measurement of the Velocity (m/s)

4. CONCLUSIONS

In this study, we investigated a method for the numerical modeling of flow resistance due to the vegetation effects. First, the flow velocity was calculated for all sections using the flow resistance coefficient applied to Chezy's formula that incorporates the Cd Value. As a result, when comparing the water level obtained by applying Cd1 and Cd1.5, it was found that Cd1.5 was better matched with the measured water level. Additionally, a velocity that is slightly higher than the measured flow velocity was derived, and it will therefore have to be considered by referring to some existing formulas that take into account the effects of vegetation.

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