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FLOW PREDICTIONS IN VEGETATED OPEN CHANNELS

PREDICTIONS DE L'ECOULEMENT DANS DES CANAUX VEGETALISES

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ABSTRACT

Vegetation development in river bed and in the banks, may affect the hydraulic conditions and hydrodynamic behavior of a stream. Understanding flow dynamic within vegetation becomes very important to control floods and the stream ecosystem. The present paper explores the capacity of a model in a two-dimensional code Telemac2D, to predict flow characteristics in vegetated open channel. This model adopted a two-layer approach to determine the mean velocity in vegetated flume using vegetation characteristics. The verification of the programmed model capacity was based on comparison between simulations and measured results derived from the experiences of Keramaris Evangelos (2012), Sergio De Felice (2008) and Le Bouteiller and Venditti (2014). These experiments were conducted with submerged vegetation in a rectangular open channel flow to determine the vegetation effects on flow processes. The comparison shows a good agreement between the simulations results and the measured ones in presence of slopes. This programmed model was more accurate in the case of rigid vegetation than flexible vegetation. In general, the new roughness model could be used to predict the effect of vegetation resistance on flow, which is a very important phenomenon to control river floods.

Key words: Vegetation, hydraulic, floods, two-dimensional code, open channel

RESUME

Le développement de la végétation sur le lit de rivière et sur les bancs, peut affecter les conditions hydrauliques et hydrodynamiques d'un cours d'eau. L'identification et la compréhension de la dynamique de l'écoulement à travers la végétation devient très importante pour contrôler les inondations et l'écosystème des cours d'eau. Ce travail explore la capacité d'un modèle programmé dans un code bidimensionnel Telemac2D, pour prédire les caractéristiques de l'écoulement dans un canal à ciel ouvert au-dessus d'une rugosité produite par la végétation. Cette nouvelle loi de rugosité a adopté l'approche de bicouche pour déterminer l'expression de vitesse moyenne dans un canal végétalisé en utilisant les caractéristiques de la végétation. La vérification de la capacité du modèle programmé s'est basée sur une comparaison entre les résultats simulés et mesurés issus des expériences de Keramaris Evangelos (2012), Sergio De Felice (2008) et Le Bouteiller et Venditti (2014). Ces expériences ont été menées dans un canal à ciel ouvert en présence d'une végétation submergée pour déterminer les effets de la végétation sur le processus de l'écoulement. Cette comparaison montre un bon accord entre les résultats des simulations et celles mesurées avec variation de la pente. Cependant, ce modèle est plus précis en cas d'une végétation rigide. Il pourrait être utilisé pour prédire l'effet de la végétation sur les écoulements, ce qui est très important pour contrôler les crues dans les cours d'eau.

Keywords: Végétation, hydraulique, inondations, code bidimensionnel, canal à ciel.

INTRODUCTION

The presence of vegetation in the rivers could have a significant influence on the velocity distribution and on the water depth. Vegetation influences depends on the flexibility, the stem height and the plants density (Jarvela, 2005; Nepf, 2012; Morri et al., 2015). Generally, vegetation types have been divided into two classes; rigid vegetation typically arborescent and woody plants, and flexible vegetation especially the herbaceous plants (Defina and Boxio, 2005).

Recently, much research has been devoted to understand flow characteristics in vegetated flow using flume experiments with natural or artificial vegetation.

Jarvela et al. (2005) conducted experiments in a rectangular flume to determine the mean velocity profiles, the turbulence characteristics above flexible wheat.

Carollo et al. (2005) analyzed the influence of vegetation density and the vegetation height ration on the velocities profiles over flexible bottom vegetation in a straight flume.

As a consequence, many numerical methods have been developed to describe flow vegetation interactions (Nepf and Vivoni, 2000 ; Baptist, 2003 ; Tsujimoto et al., 1993 ; Shimizu and Tsujimoto, 1994 ; Dunn et al., 1996 ; Augustijn et al., 2011 ; Righetti and Armanini, 2002, Lopez and Gracia, 2001).

Lopez and Garcia, 2001 used a modified turbulence (K- ε) model, they added the drag vegetation force to the momentum equation and to the equation for K and ε to take into account the vegetation effects on flow.

In fact most of the developed relationships adopted a two-layer approach (Klopstra et al., 1997 ; Stone and Shen, 2002 ; Van velzen, 2003 ; Baptist et al., 2007 ; Huthoff et al., 2007 ; Yang et Choi, 2010). This method based on dividing the flow domain into two layers. The first layer through the vegetation called "vegetation layer", the second layer above is called "upper layer". Theses authors used boundary conditions at the interface to much between the two layers. In the vegetation layer, they solved the momentum equation to determine the expression of the velocity and they kept the logarithmic flow velocity. The difference between these descriptions arises from the different assumptions used to determine the shear stress and the turbulent length scale. Some authors used the Boussinesq's eddy viscosity approach and the mixing-length theory to determine the shear stress and the velocity in each layer. The average velocity (U) over the total depth is given by combination between the mean velocity flow inside (U_1) and above the vegetation (U_2) (Klopstra et al., 1997 ; Morri et al., 2014 ; Jarvela, 2005). This velocity was useful to determine the shear velocities and the bed shear stress and to estimate the bed load transport. However, the evaluation of six analytical models derived for predicting flow characteristics in presence of a submerged vegetation (Klopstra et al., 1997 ; Stone and Shen, 2002 ; Van velzen, 2003 ; Baptist et al., 2007 ; Huthoff et al. 2007) using a comparison with experimental data for rigid and flexible vegetations show a best agreement of Huthoff model for the mean velocity prediction (Morri et al., 2015). In this context, this model was included in a two - dimensional software Telemac 2D, to predict flow characteristics in presence of vegetation. The validation of the programmed model was determined according to a comparison between measured results of experimental data flume and the simulated ones.

HUTHOFF MODEL DESCRIPTION

Huthoff et al. (2007) derived an analytical model for flow in presence of submerged vegetation, similar to the model developed by Klopestra et al., 1997. They studied the flow behavior in an idealized form of vegetation and they used a bulk characteristics flow to avoid complications of the shapes and flow oscillations.

In the vegetation layer, Huthoff et al. (2007) proposed an analytic expression of the average velocity in the vegetation layer (U_1) based on the momentum equation. The shear stress near the top of the vegetation layer was added to the balance equation. This shear stress had an effect on the flow velocity in the vegetation layer and caused energy losses in the surface layer and it balances the streamwise component of the gravitational force. The momentum equation was given by the following expression:

$$\tau_{h_p} + \rho g h i = \rho f\, U_1^2 + \frac{1}{2}\rho C_D m D h_p U_1^2 \qquad (1)$$

The shear stress at the interface τ_{hp} is determined using the following equation:

$$\tau_{h_p} = \rho g (h - h_p) i \qquad (2)$$

ρ is the water density (kg/m^3), g is the acceleration gravity(m/s^2), h is the water depth (m), i is the energy gradient, U_1 is the mean velocity in the vegetation layer (m/s), C_D is the drag coefficient, m is the vegetation density (m^{-2}), D is the stem diameter (m) and h_p is the vegetation height (m).

Then the mean velocity is given by the following expression:

$$U_1 = U_{r0}\sqrt{\frac{h}{h_p}} \qquad (3)$$

U_{r0} is the depth-averaged flow velocity in the resistance layer for the emergent resistance elements:

$$U_{r0} = \sqrt{\frac{2bgi}{1 + \frac{b}{32 h_p}\left(\frac{k_s}{h}\right)^{1/3}}} \qquad (4)$$

b is the drag length, it is determined by the following equation:

$$b = \frac{1}{C_D mD} \tag{5}$$

k_s is the roughness height (m)

for $k_s << h$

$$U_{r0} \approx \sqrt{2bgi} \tag{6}$$

In the surface layer, Huthoff et al. (2007) derived the expression of the average velocity by analyzing the shear stress over the vegetation.

Huthoff et al. (2007) used a flow bulk behavior to avoid turbulence intensities complications and to avoid the integration over depth. The analyzing of the shear stress was based on the condition of a constant energy dissipation rate from large to smaller flow scale.

Then the mean velocity in the surface layer was determined by the following expression:

$$U_2 = U_{r0} \left(\frac{h - h_p}{s}\right)^{2/3\left(1-\left(\frac{h}{h_p}\right)^{-5}\right)} \tag{7}$$

Where, s is the separation between the individual resistance elements:

$$s = \frac{1}{\sqrt{m}} - D \tag{8}$$

The average velocity over the total depth (U) is given by combination between the mean velocity flow inside (U_1) and the above vegetation one (U_2):

$$U = \frac{h_p}{h} U_1 + \frac{(h - h_p)}{h} U_2 \tag{9}$$

The expression for the average velocity of the entire flow depth becomes:

$$U = U_{r0} \left(\sqrt{\frac{h_p}{h}} + \frac{(h - h_p)}{h} \left(\frac{h - h_p}{s}\right)^{2/3(1-(\frac{h}{h_p})^{-5})} \right) \tag{10}$$

This analytical model was programmed and included in a two-dimensional code which is Telemac2D in order to investigate the vegetation effects on the longitudinal flow. TELEMAC-2D solves the Saint-Venant equations using finite-elements or finite-volume methods and a computation mesh of triangular elements space based on the solution of the depth-averaged shallow-water equations.

The basic equations of Telemac2D are the 2D Saint Venant equations:

Continuity equation:

$$\frac{\partial h}{\partial t} + U\nabla h + h\nabla U = S \tag{11}$$

Momentum equations

$$\frac{\partial U}{\partial t} + U\nabla U = g\nabla Z + hF + \nabla(h\,\nu_e \nabla U) + \frac{S}{h}(U_s - U) \tag{12}$$

h is the water depth, Z is the free surface elevation, U is the mean velocity , F is the friction force, S is the bottom source term, U_s is source term velocity and ν_e is the effective viscosity .

DESCRIPTION OF THE USED PROCEDURE IN THE LITERATURE

Evangelos (2012) experiments description

The experiments of Evangelos (2012) were carried out in a re-circulating glass walls flume in the laboratory of Hydraulics in the department of Civil Infrastructure Engineering of Alexander, Institute of Thessaloniki, Greece. The flow was released from a tank and delivered by pump through a pipe to the channel.

This channel had a length of 6.5 m, a width of 0.075 m and a deep of 0.25m. The slope of the channel was adjustable by a manual device which attached to a specific indicator. These experiments were conducted with different slopes, a slope of S=2‰, S=4‰ and S=6‰. In the bottom of the channel, artificial flexible vegetation was installed vertically with a length of 3 m. the height of vegetation was 0.05 m with a 0.01 m of diameter. Instantaneous velocity and related properties was measured using the optical method of fluid visualization PIV. A tracer particle was used, to follow the flow dynamics.

Velocimetry (PIV) projected vertically on a planted water column. The measurement point was fixed at 4 meters from the entrance of the channel and above the vegetation. In this point the flow was fully developed. The uniformity of the flow was verified using a point gauge at two cross sections with 4m between the two sections. In the downstream the flow depth was controlled using a weir at the channel's outlet. The initial height of 0.1m is water at a rate of 0.631 / s.

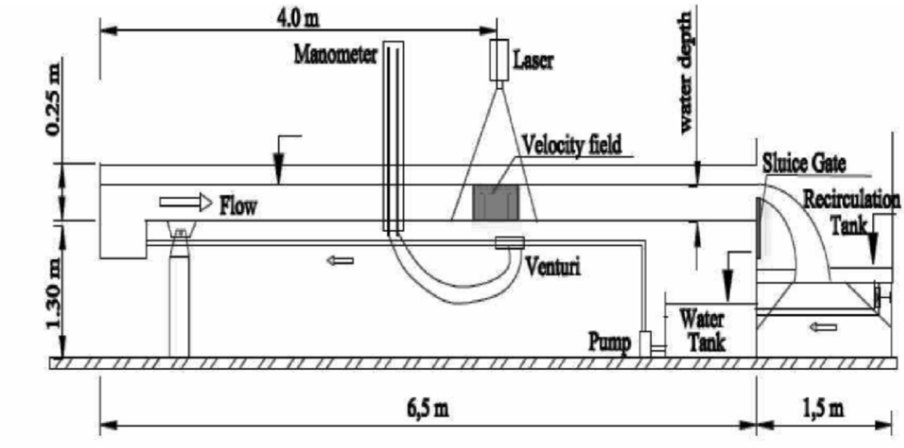

Figure 1: Evangelos (2012) experimental set

Sergio De Felice (2008) experiments description

Sergio De Felice's experiments (2008) were conducted in the laboratory of hydraulic department at the University of Naples Federico II, Italy. The experimental channel was rectangular with a width of 0.4 m, a length of 8 m, and height of 0.4 m (Figure 4.1). Water supply is provided by a centrifugal pump having a maximum flow rate approximately of 60 l/s. This channel operates in a closed circuit. The flow is controlled by a manual valve in the feed pipe. The objective of these experiments is to analyze the flow behavior in the presence of deeply submerged rigid vegetation which is simulated by rigid cylinder. These cylinders were uniformly implanted to the channel bottom and arranged in a rectangular pattern (2.5 x 5 cm^2), with a diameter of 0.004 m and a height of 0.015 m (Figure 2).

The measurements are performed under uniform flow conditions. The velocity was measured with Laser Doppler anemometer. The water level is determined through a calibrated gauge and the flow rates are measured by a triangular weir. The flow rate in this test was 22.6 l/s and water depth is 7.85 m with a slope of 1 %

Figure 2: Sergio De Felice (2008) experimental set

Le Bouteiller and Venditti (2014) experiments description

Le Bouteiller and Venditti (2014) performed an experiment in a rectangular flume with a width of 1m and a length of 12 m. The flume recirculates water using two variable speed pumps. The central section of the flume was covered by submerged artificial vegetation constructed of polyethylene film. The plant density was 800 blades per squares meter of bed. The water discharge

The free surface was measured using three ultrasonic sensors. Flow rate in this experiment equals to 0,04 m^3/s. The water discharge Q in this experiment was 0,04 m^3/s, corresponding to a mean velocity U equal to 0. 28 m/s and a water depth equal to 150 mm. The objective of this experiment was studying the impact of a vegetated patch on the hydrodynamic of flow.

These three experiments were used to verify the capacity of the programmed model for predicting flow characteristics in vegetated open channel.

RESULTS AND DISCUSSIONS

Measured and simulated water depth profiles comparison

The experimental data results were used to validate the programmed model of Huthoff by a comparison between the simulated water depth and the measured data of Evangelos (2012), Sergio De Felice (2008) and Le Bouteiller and Venditti (2014). The following figure shows the comparison between the measured and simulated data corresponding to adimensional water height involving to the vegetation height h_p (m).

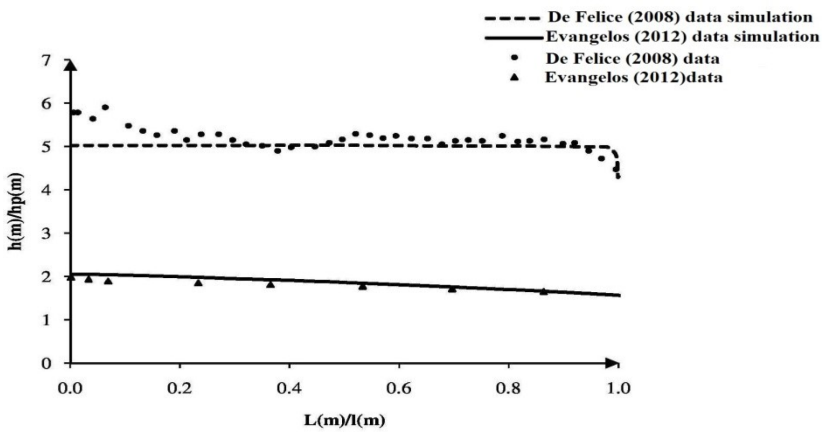

Figure 3: Measured and simulated (with Telemac code) water depth profiles comparison (h : water depth, h_p: vegetation height , L: channel length, l: vegetation length)

From the figure above, we note that the adequacy of the measured and simulated water levels was clearly correct. The simulated water profiles are very close to the measured data of the two experiments. The advantage of this model is the use of vegetation characteristics, such as density, height, spacing and diameter, to determine the vegetation effects on the flow behavior. However, the classical laws of roughness, the Strickler Law, are derived to describe the wall channel and the bottom roughness. They are commonly used to predict the head losses regardless of the form drag across flow. The performance of a classical law depends on the selected roughness coefficient. The Huthoff programmed model is accurate and effective in the case of a deeply submerged and rigid vegetation. In the case of flexible vegetation with low density, the programmed model indicates on offset between the simulated and measured data of Le Bouteiller and Venditti (2014).

This model was performed and validated for rigid submerged cylinder, but it could also be used in the case of flexible vegetation and that is very important in the hydraulic parameters prediction of vegetated flood plain and then for flood managements.

Vegetation effect on the water level with changing of the slope

The aim of Keramaris Evangelos (2012) experiments was to study the vegetation effect on the flow dynamic with the channel slope variation the slope of the channel between 0.2 and 0.6%. The following figures show a comparison between measured water depths of Evangelos (2012) and simulated one with a slope of 0, 2%, 0, 4 % and 0, 6 %:

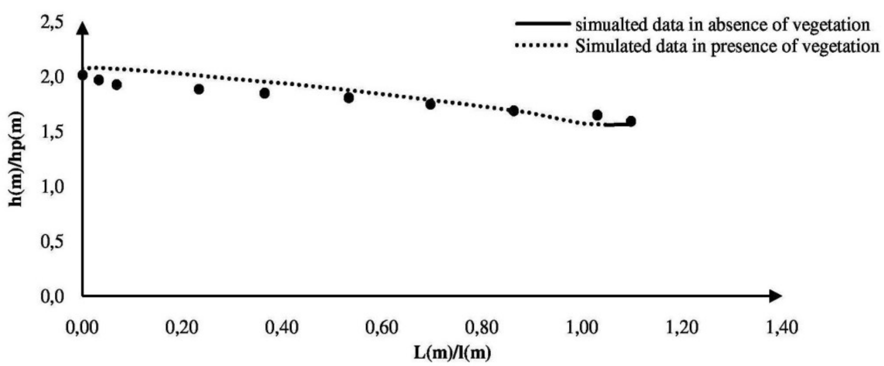

Figure 4: Measured and simulated (Telemac code) water depth (with a slope of a 0,2%)

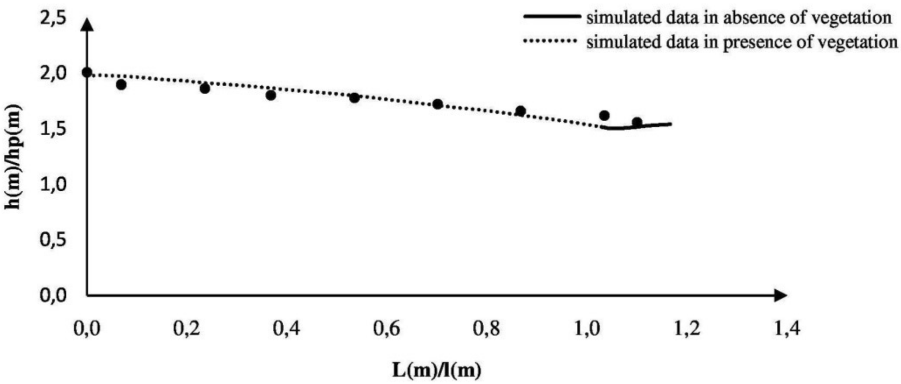

Figure 5 : Measured and simulated (Telemac2D) water depth (with a slope of 0,4%)

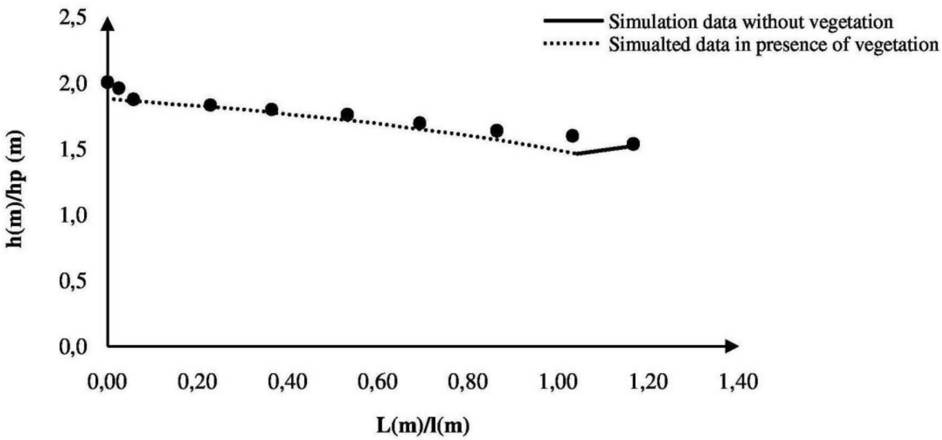

Figure 6 : Measured and simulated water depth (with a slope of 0.6 %)

According these Figures, we can notice the effect of the vegetation on the flow depth. In the vegetation zone the water level was more important than the water level in the zone without vegetation. In the inlet of the vegetation zone, the water is at a maximum, it then reduces slowly (x = 2 cm). This reduction becomes more abrupt and remarkable through the vegetation (x = 10, 60, 100, 200.250). At the end of the vegetation, this variation becomes smaller. The same profile was observed with the different slopes. In this case, the change in the flow characteristics was highly dependent on the vegetation parameters.

Huthoff model, used vegetation characteristics to predict the hydrodynamic flow characteristics by neglecting the bed shear stress, this may explain the good performance in the considered case. This model is not influenced by channel slope variation and that's why, water depth conserved the some profile for the different slopes.

CONCLUSION

The model of Huthoff developed for predicting the flow behavior in the presence of vegetation was included in two-dimensional code Telemac2D, to investigate its capacity for predicting flow characteristics in vegetated open channel. This model adopted a two-layer approach to determine the mean velocity in vegetated flume using vegetation characteristics. The verification of its performance is determined according a comparison between simulations and measured results derived from the experiences of Keramaris Evangelos (2012). This verification shows the model performance in the prediction of the water level in the case of different slopes. Huthoff model was performed and validated for a rigid submerged cylinder vegetation, but it could also be used in the case of flexible vegetation.

In perspective, we will verify the capacity of the programmed model of Huthoff et al.(2007) in the prediction of the hydrodynamic flow through vegetation in a real case

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