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Experimental Study of Mean Velocity Distributions in Open Channels with Emergent and Submerged Vegetation

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This study aims at experimentally revealing the mean flow characteristics in a straight channel and a meandering channel, both of which are partially covered by emergent and submerged rigid model vegetation. The special emphasis is placed on the development of mean velocity and momentum transfer process between the flow and the vegetation elements. Velocity measurement is carried out by electromagnetic velocimetry not only in fully developed regions but also in developing regions. The measured mean velocity distribution in fully developed region is found to show good agreement with those of previous studies for straight channel flows. Flow visualization is concurrently performed to measure the evolution process of large scale eddies at the interface region in both cases.

Key Words: *Vegetated open channel, mean velocity distribution, momentum transfer, straight channel, meandering channel.*

1. Introduction

Rivers and streams are usually in close association with vegetation. This vegetation can occupy nearly every geomorphic position within the fluvial environment. Vegetation in and near streams are subjected to varying flow stages that can inundate vegetation during high flow events or leave it exposed during low flow events. Emergent vegetation occurs commonly along the banks of rivers and artificial channels, both naturally and by design for erosion control and habitat creation. Importantly, riparian vegetation can play a critical role in the physical, ecological, and hydraulic functions of streams and rivers. Vegetation can affect the transport of water, sediment, and nutrients both within the channel and to or between the riparian zones. These interactions can greatly impact water quality and ecological functionality within river corridors. Vegetation can modulate the pace and characteristics of river morphology.

Natural rives are mostly meandering. The effect of marginal vegetation on flow resistance has been investigated for straight channels whereas little is known of the effects for meandering channels under either inbank or overbank flow conditions[1]. The insight into flow distribution in straight as well as meandering main channels and the neighboring vegetated area is indispensable in river management. Secondary flow is an important hydraulic parameter. Bathurst et al.[2] defined secondary flow as a flow normal to that in the longitudinal flow direction. Secondary currents distort the longitudinal velocity pattern and boundary shear stress distribution and are therefore important. They affect the flow resistance, sediment transport, bed and bank erosion and in turn influence the channel morphology[3]. Open channel flows with emergent vegetation are characterized by complex flow structures due to the presence of shear layer at the interface between the main channel and the vegetated area. In the flow with submerged vegetation shear layers are produced at the interface of vegetation zone not only in the spanwise direction but also in the vertical direction, generating large vortices there. Nepf[4] observed that vegetation alters the turbulence structures through additional shear production near the vegetation height and wake production behind individual vegetation elements. Flood flow significantly interacts with vegetation and reduces the carrying capacity of discharge. It also generates low-velocity zones where fine particles containing nutrients are deposited. In case of compound meandering rivers Toebes and Sooky[5] firstly performed the mean velocity measurement. Ishigaki et al.[6] investigated the flow structure with experimental results of flow visualization and bed shear measurement in a meandering compound channel. Three-dimensional flow structure was studied by Jayaratne[7] in both straight and meandering compound channel. Muto et al. [8] also investigated the three-dimensional flow structure based on velocity measurements in a meandering channel with overbank flow. Most of these investigations have been carried out based on straight and meandering compound channel. But few studies have been carried out to investigate the flow structure in fully developed as well as developing stages of partially vegetated straight and meandering channels.

The present study investigates partially vegetated open channel flow in both submerged and emerged conditions in straight and meandering channels. This type of phenomena has been observed in rives during flood situation. The special emphasis is placed on mean velocity distribution and momentum transfer between the flow and the vegetation elements not only in fully developed region but also in developing regions. The experimental data presented in this paper will be useful for the validation of numerical models.

2. Laboratory Measurements

The measurements were carried out in both straight and meandering channels. In this study two cases of experiment were carried out: a shallow water case where vegetation was emergent (Case A1 for a straight flume and Case A3 for a meandering one) and a deep water case with fully submerged vegetation (Case A2 for a straight channel and Case A4 for a meandering one). The experiments were conducted in a straight rectangular flume whose length and width are 22.0m and 1.82m, respectively. The channel has closed water supply system. Water is transported from downstream reservoir to the upstream reservoir by means of pipeline. In the flume there is an electric motor driven tailgate to obtain the uniform flow by adjusting the water surface slope through raising or lowering the tailgate. Vegetation zones were prepared on either side of the channel. The length of vegetation zone is 11.0m. The vegetation is idealized with wooden rigid cylinders of 3mm diameter. Three mean velocity components were measured by two-component electromagnetic current meters (both L-type and I-type) and water depth by water level gauges at the frequency of 10Hz. The diameter and the height of the electromagnetic probe are 4mm and 18mm respectively. The electromagnetic field generated by the probe is not affected by the model vegetation as the distance between the adjacent model vegetation is large enough (3cm by 3cm) and the model vegetation material is wood. Although electromagnetic velocimetry is unable to precisely measure turbulent quantities, it gives qualitative information on turbulent structures. The *u*-velocity is in x-direction, normal to each cross section (i.e. along the flow direction), *v*-velocity is in the vertical direction, perpendicular to the flow direction and *w*-velocity is in z-direction, parallel to the cross section. The measuring time of velocity and water level fluctuation was 2min and 5min respectively. The measuring devices were mounted on a carriage which can travel along the channel on a rail arrangement. The carriage can be moved longitudinally. An electromagnetic flow meter is installed in the out flow pipe. It is used to fix and measure the discharge.

2.1 Straight Channel

Measurement was carried out in a straight channel at six cross sections to discuss the development of velocity fields in relation to lateral momentum transfer. The Reynolds number, Re=$U_{mean}*h_0/\nu$ was approximately 10,000 and 30,000 for emerged and submerged condition respectively, where U_{mean}=cross-sectional averaged velocity, h_0= uniform flow

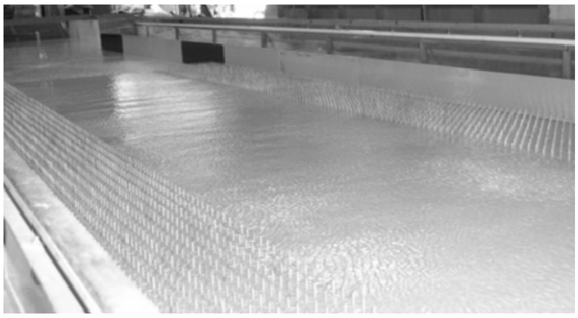

Fig.1 (a) General layout of the straight channel.

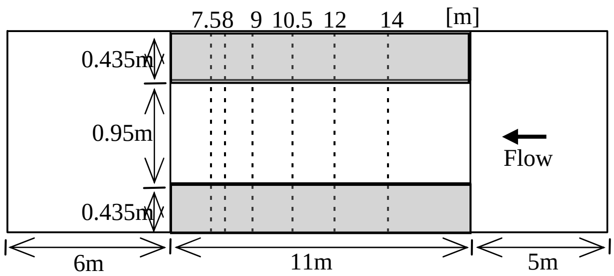

Fig. 1(b) Measurement sections of straight channel depth at downstream, ν = kinematic viscosity. Fig. 1(a) shows the general layout of the experimental flume and Fig. 1(b) depicts the measurement sections. Table 1 summarizes the geometric parameters and the experimental conditions (i_b=bed slope, Q=discharge, B_s=width of vegetation zone, D=diameter of vegetation model, s=distance between the centers of the adjacent vegetation model, H_v= height of vegetation model). The table contains the information of downstream flow conditions for both emerged (Case A1) and submerged (Case A2) flow situations.

2. 2 Meandering Channel

In the meandering channel two flow conditions were considered similar to the straight channel, i.e. shallow water case where vegetations were emergent (Case A3) and deep water case with fully submerged vegetations (Case A4). The straight vegetated flume was converted to a meandering one, keeping the width of the main channel constant that is 0.95m. The measurements were carried out at the downstream section (about 8.35m from the tailgate) over half wave length at the points *S1*=8.35m, *S2*=8.9m and *S3*=9.45m. There are five complete waves along the 11.0m long vegetated zones. The meandering wavelength is 2.2m with the sinuosity of 1.10. The equations of the interface curves are $Z=0.21*\sin(2/l*\pi *x)+0.435$ and $Z=0.21*\sin(2/l*\pi *x)+1.385$. Fig. 2(a) shows the partially vegetated meandering channel and Fig. 2(b) depicts the measurement sections. The channel geometry and the flow conditions are summarized in Table 2.

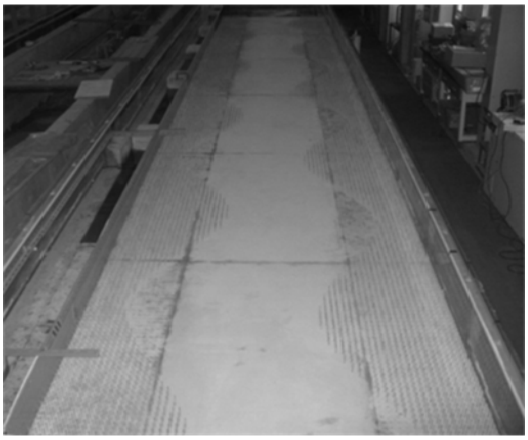

Fig.2 (a) General layout of the meandering channel.

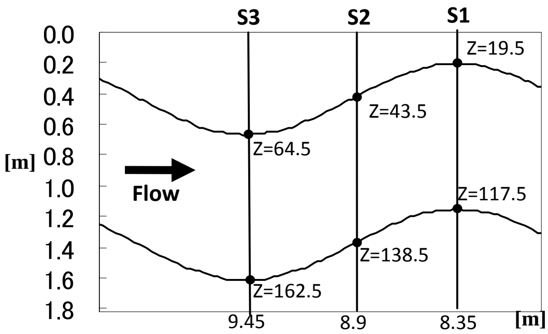

Fig. 2(b) Measurement sections of meandering channel.

3. Experimental results of straight channel

3.1 Mean flow and turbulent stresses

Fig. 3 compares the contours of *u*-velocity and turbulence intensity in x-direction at the downstream zone for emergent vegetation. The measuring section is at X1=7.5m from downstream end. Here, near the interface of the main channel and vegetated zone (Z/H=0, H=flow depth at each measuring section) the contours are nearly vertical, which reveals 2D-structure flow phenomenon.

Table 1 Experimental condition for straight channel

Case	i_b	Q [l/s]	h_0 [cm]	U_{mean} [cm/s]	B_s [cm]	D [mm]	s [cm]	H_v [cm]	Vegetation Condition
A1	1/633	18.5	3.9	26.1	43.5	3.0	3.0	5.0	Emerged
A2	1/633	55.0	7.8	38.3	43.5	3.0	3.0	5.0	Submerged
B1	1/588	／	4.3	27.6	12.0	1.5	2.0	4.6	Emerged
FR4	1/2600	8.9	7.0	33.5	20.0	2.0	2.0	5.0	Submerged

Table 2 Experimental condition for meandering channel

Case	i_b	Q [l/s]	h_0 [cm]	Wavelength(l) [cm]	Amplitude [cm]	B_{smax} [cm]	B_{smin} [cm]	Vegetation Condition
A3	1/633	18.5	4.2	220	22.5	64.5	19.5	Emerged
A4	1/633	55.0	8.3	220	22.5	64.5	19.5	Submerged

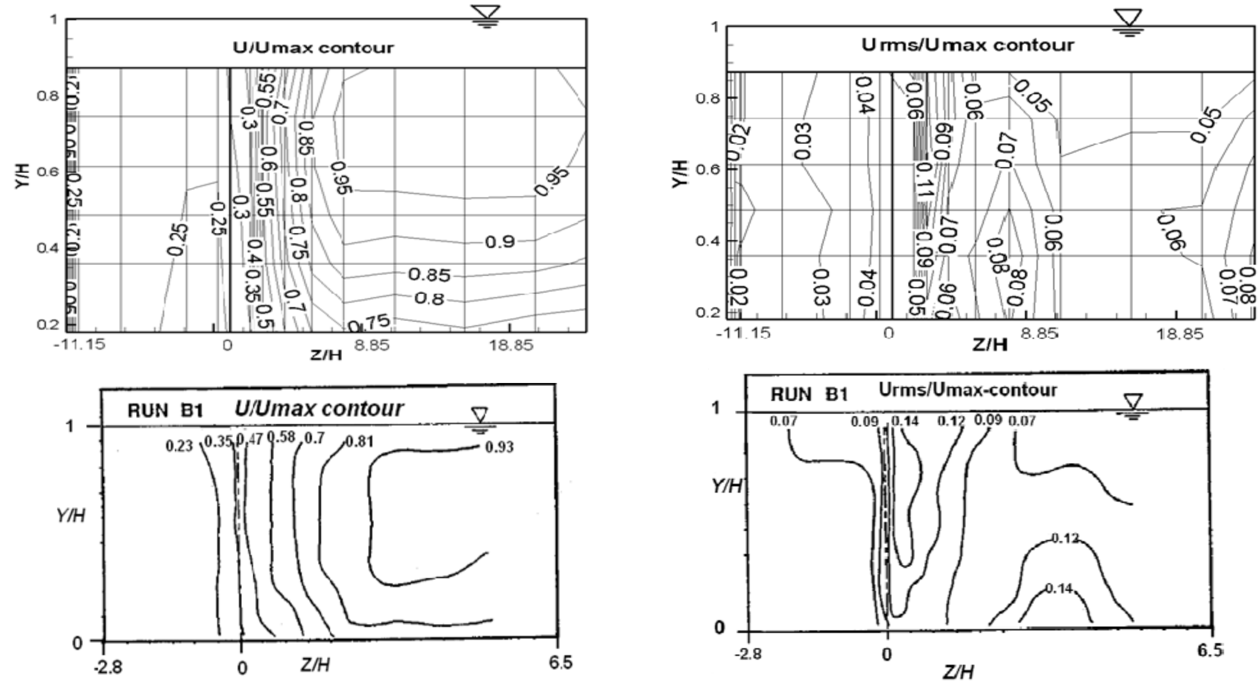

Fig. 3 Contour of mean velocity and turbulence intensity of longitudinal component for emergent case. (up: experimental results by L-probe of Case A1, down: experimental results by Tsujimoto and Kitamura (1994) of Case B1)

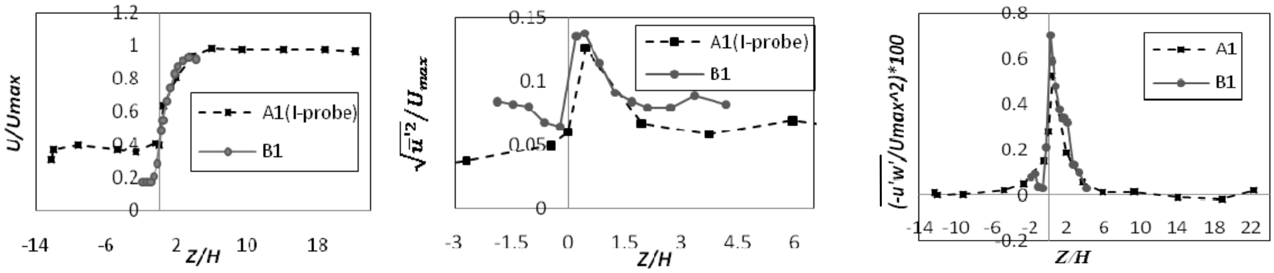

Fig.4 Spanwise distribution of depth-averaged velocity, turbulence intensity and Reynolds shear stress in fully developed zone for emerged condition. (experimental results taken by I-probe of Case A1 are compared with experimental results by Tsujimoto and Kitamura (1994) of Case B1)

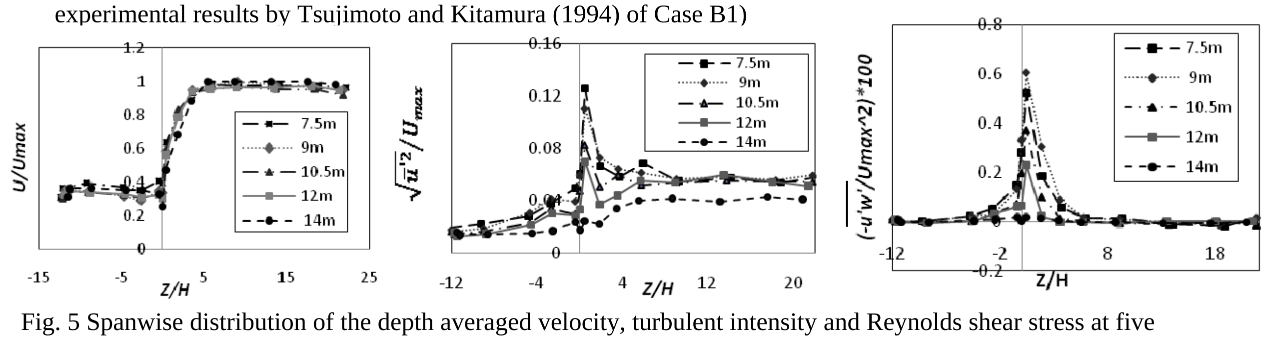

Fig. 5 Spanwise distribution of the depth averaged velocity, turbulent intensity and Reynolds shear stress at five longitudinal positions (measured by I-probe) for emerged condition.

Fig. 4 shows the time-averaged value of the streamwise velocity (U) and its turbulent intensity ($\sqrt{\overline{u'^2}}$) together with Reynolds shear stress in the spanwise direction at the same section X1. It is clearly observed that there is a sharp gradient in the mean velocity at the interface and that the turbulence intensity and Reynolds stress obtain the maximum value there. The experimental results show good agreement with the experimental results of Case B1 by Tsujimoto and Kitamura (1994)[9] at the interface and in the main channel. In vegetated zone, however, mean velocity and turbulent stresses show differences. These differences come from the difference in vegetation density in the vegetated area of the two experiments.

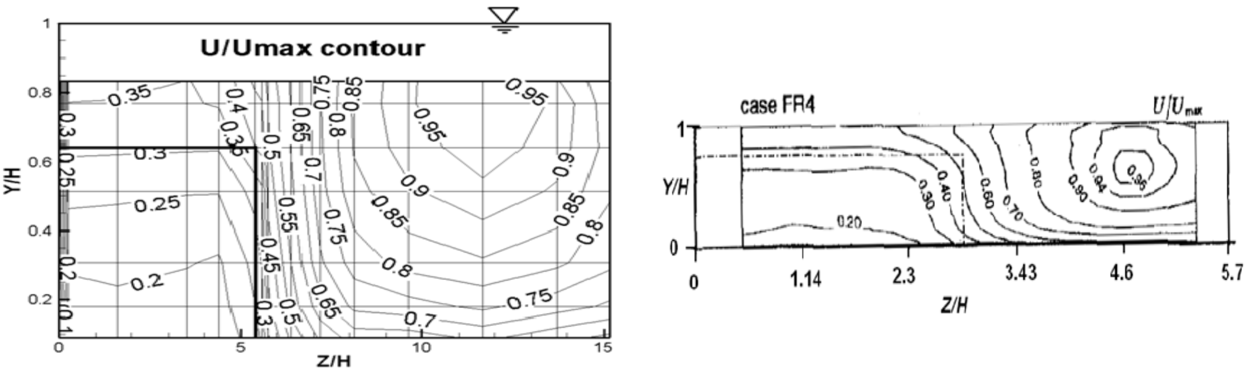

Fig. 6 Contour of mean U-velocity for submerged condition (left: experimental results by L-probe of case A2, right: experimental results by Nezu et al. (2000) of Case FR4).

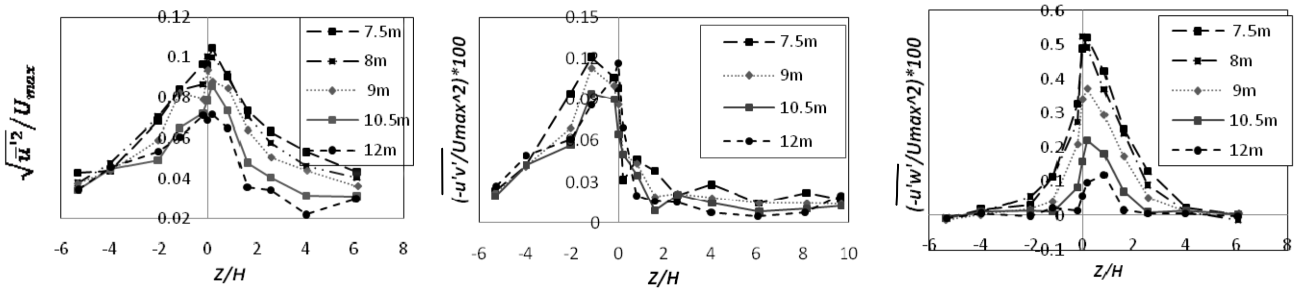

Fig. 7 Spanwise distribution of the turbulent intensity and Reynolds shear stress at five longitudinal positions for submerged condition.

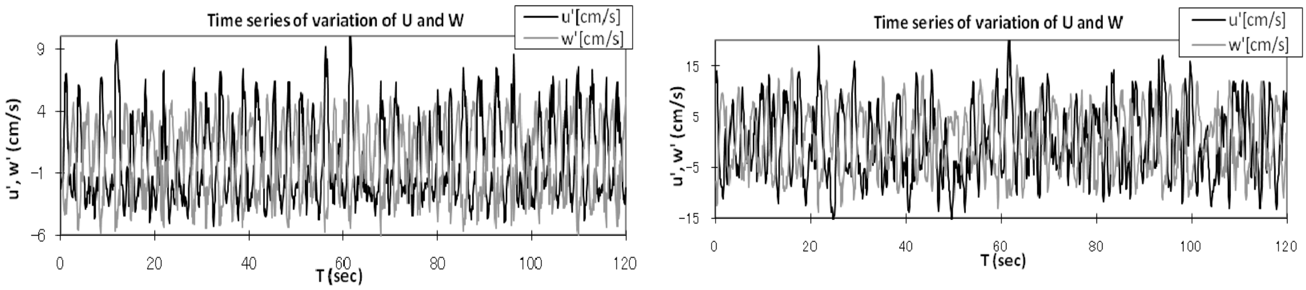

Fig. 8 Time series of velocity fluctuations u' and w' at the interface for emergent (left) and submerged (right) conditions.

Measured velocity in the vegetated area in this study shows a larger value, indicating that the drag due to the vegetation is comparatively small in Case A1.

Fig. 5 explains the development of flow at five different sections from 14.0m to the downstream end at X1. Depth-averaged velocity field shows small difference over the reach while turbulent quantities approach to the equilibrium conditions as the flow goes downstream.

Fig. 6 shows the contour of U-velocity of submerged condition at section X1. The value of U-velocity in the vegetated zone is smaller than that in the main channel and the contour shows almost parallel to the top surface of vegetation. Spanwise change of mean U-velocity in and above the vegetation zone is small which is similar to the emerged condition. The U-velocity above the vegetation zone is greater than the velocity within the vegetation zone, which indicates more 3-D phenomenon than the emergent case. The present experimental results compare well with the experimental data of Case FR4 of Nezu et al. (2000)[10].

Fig. 7 shows the development of turbulence intensity and Reynolds shear stresses in five cross sections at 5 cm above bed. At 7.5m and 8m sections from the downstream end the flow becomes fully developed both in the main channel and the vegetated area with the maximum value at the interface.

3.2 Correlation between water depth and velocity fluctuation

At section X1 the velocity fluctuations and the water level fluctuation have been measured at the interface between main channel and vegetated area. Fig. 8 shows the fluctuation of streamwise velocity u' and spanwise w' for emerged (left) and

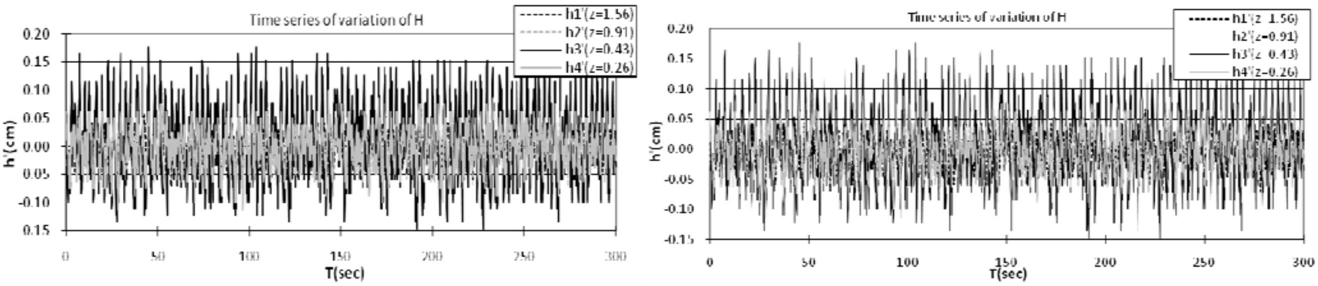

Fig. 9 Time series of water surface fluctuation for emerged (left) and submerged (right) conditions.

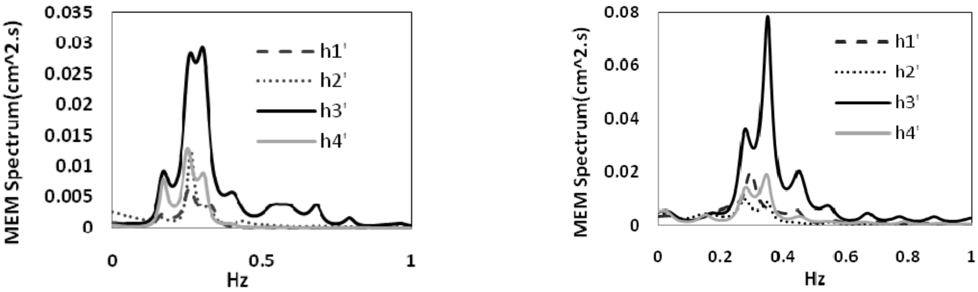

Fig. 10 Spectrum of water level fluctuations at the interface for emerged condition (left) and submerged (right) conditions.

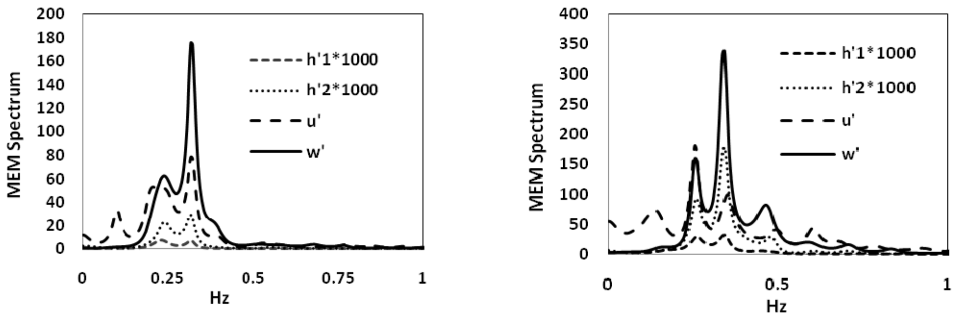

Fig.11 Spectrum of instantaneous velocity components and water level fluctuation for emerged (left) and submerged (right) conditions. [*h1'* and h2*'* are 20 cm away from the interface, *h1'* is at vegetated area and *h2'* is in main channel].

for submerged condition at the top of vegetation stems (right). Over the period 2 min, it can be observed that there is a strong correlation between *u'* and *w'*. Fig. 9 shows the time series of water surface fluctuations *h1'*, *h2'*, *h3'* and *h4'* which are measured at the same time. At the interface (*h3'*), the water level fluctuation is the largest compared to the right vegetation zone (*h1*'), center of main channel (*h2'*) and the left vegetation zone (*h4'*). To obtain the clear picture of the phenomena the spectra have been estimated using MEM with Spectral Analyzer SPCANA Version 4.71. Fig. 10 shows the water level fluctuation at four specified points in the cross section X1 both for emerged and submerged conditions. The amplitude at the interface is the biggest, which implies large vortices flow with their centers at the interface region. Vortices are concentrated near the interface although some eddies move to vegetated area which has been observed through flow visualization. Considering the frequency at the peak (about 0.35 Hz) the diameter of the vortex has been found about around 55cm and 90 cm for emergent and submerged cases respectively. The vortex size differs quite significantly from upstream to downstream. Fig. 11 indicates the instantaneous velocity components at the interface (*u'* and *w'*) and the water level fluctuations. It shows that the spanwise velocity component *w'* has the maximum amplitude at interface and the water level fluctuation in the main channel is prominent over the vegetated zone. Thus spanwise velocity fluctuation is the dominant phenomenon accompanied by large vortices at the interface of main channel and vegetated zone, leading to lateral momentum transfer.

3.3 Momentum transfer

Fig. 12 shows the momentum transfer at the interface due to depth-averaged Reynolds shear stress non-dimensionalized by $U_{max.}$ The lateral momentum transfer obtains the maximum value at near 7m, 7.5m and 8m sections where the flow fully develops as explained in the previous sections for both emergent and submerged cases. Fig. 13 explains the vertical

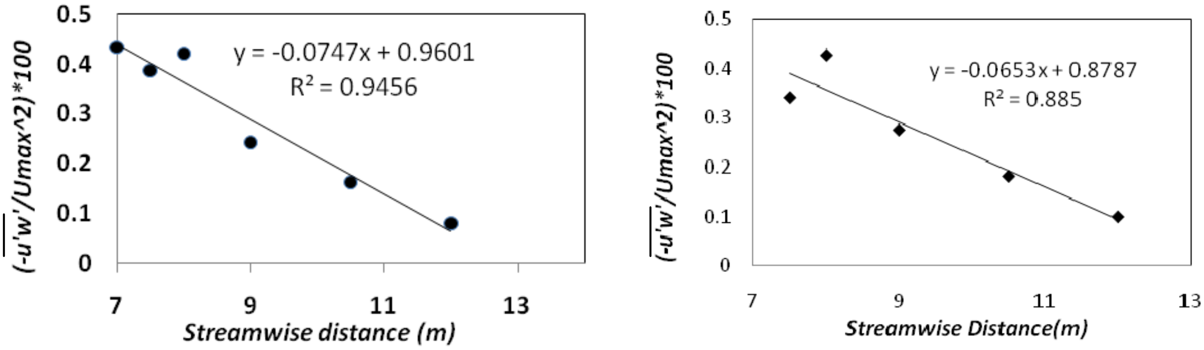

Fig.12 Development of momentum transfer in streamwise direction for emerged (left) and submerged (right) conditions.

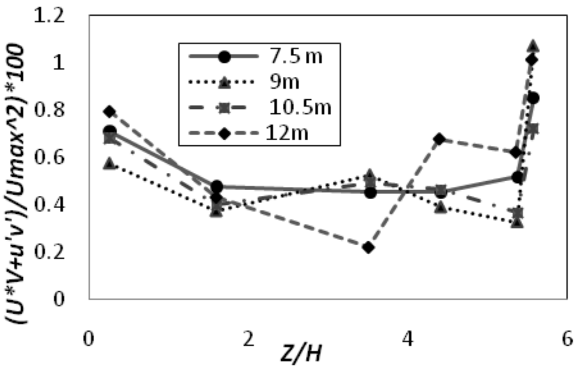

Fig. 13 Vertical momentum exchange at the top of the vegetation layer and its development.

momentum exchange at the top of the vegetation layer in submerged condition at four measuring sections. The vertical momentum exchange shows larger value at the interface and near the side wall than the middle vegetation zone due to large V-velocity and small Reynolds stress.

4. Experimental results of meandering channel

4.1 Mean flow and turbulent stresses

Flows in meandering channel show complex behaviors. Fig. 14 and Fig. 15 show the longitudinal mean velocity profile, turbulence intensity ($\sqrt{u'^2}$) and Reynolds stress along spanwise direction for emergent (A3) and submerged (A4) cases respectively. It is noted that the velocity shows little difference in the main channel. The velocity gradient is

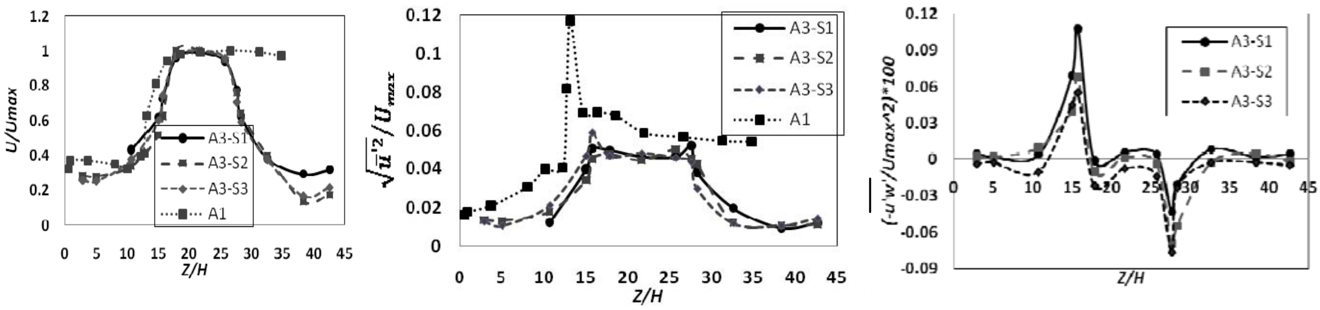

Fig. 14 Distribution of mean velocity, turbulence intensity and Reynolds stress at 3.2cm above from bed under emerged condition.

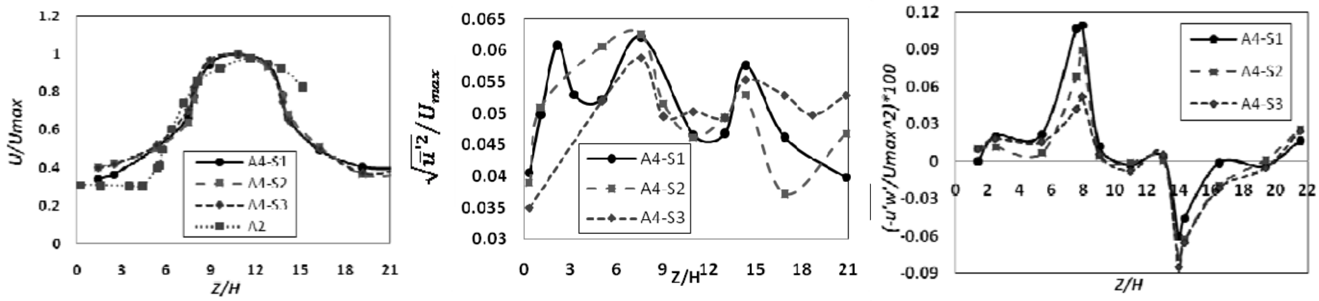

Fig. 15 Distribution of mean velocity, turbulence intensity and Reynolds stress at 5cm above from bed under submerged condition.

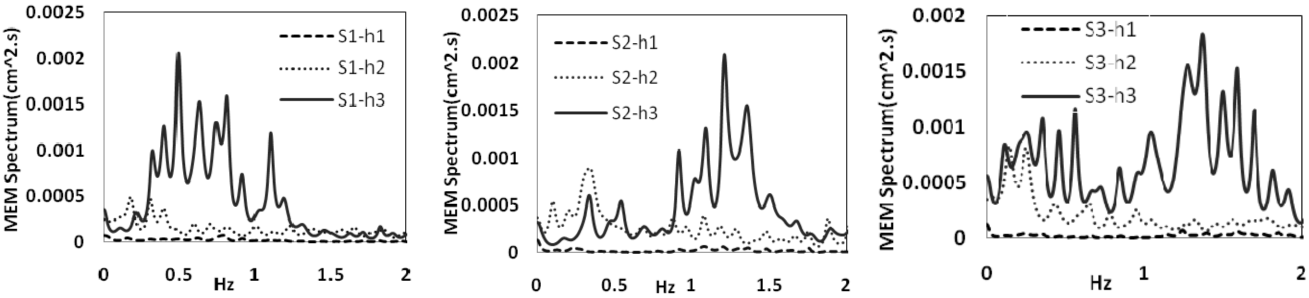

Fig.16 Spectrum of water level fluctuations for emerged condition at three different positions.

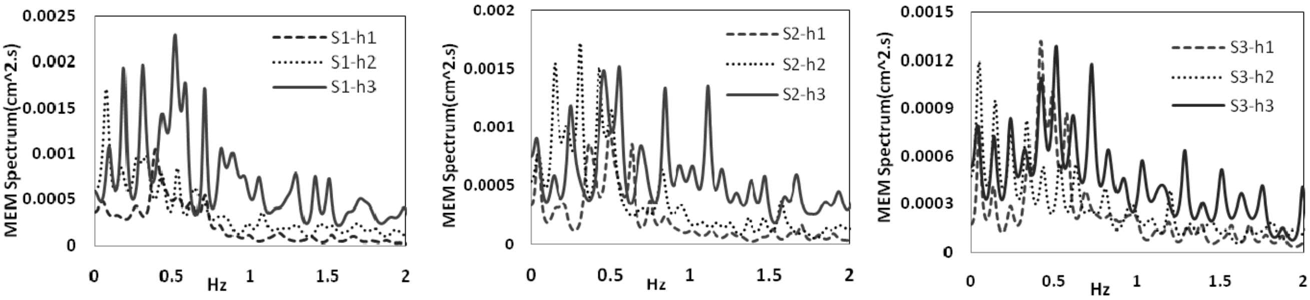

Fig. 17 Spectrum of water level fluctuations for submerged condition at three different positions.

comparatively smoother in meandering channel than the straight channel where velocity sharply increases at the interface of main channel and the vegetation zone. In straight channel strong shear layer can be observed and vortices gradually develop until fully developed situation comes whereas in meandering channel the geometry is relatively complex and difficult for vortices to grow. Hence in straight channel both the turbulent intensity ($\sqrt{\overline{u'^2}}$) and the Reynolds shear stress obtain large values compared to those in meandering channel. It has been observed that for both emergent and submerged case the maximum positive and negative values of Reynolds stresses occur at the same position of the flume, i.e. at the interface of main channel and the vegetated zone, which indicates the two outer apex of the left and right vegetation zone (considering half wave length). The shear becomes dominant and the strongest along the outer peak in the main channel. The turbulent intensity ($\sqrt{\overline{u'^2}}$) of emerged condition has much regular pattern than the submerged one. In emerged condition the turbulence intensity becomes the maximum along two outer apex where *Z/H*=15.4 and *Z/H*= 28, i.e. around 0.65 m and 1.17 m from the left channel side wall respectively. For submerged condition along the outer apex of the wave in the both side of the channel, ($\sqrt{\overline{u'^2}}$) takes the maximum value while along the inner apex ($\sqrt{\overline{u'^2}}$) gradually increases and becomes maximum at the interface point of the inner apex of the vegetation zone and the main channel. In meandering channel for emerged and submerged condition at the interface (which shows the maximum value) the value of turbulence intensity ($\sqrt{\overline{u'^2}}$) is decreased by about 50% compared to the straight channel and Reynolds shear stress by about 80%. For emerged and submerged conditions the calculation data has been taken for 3.2 cm and 5 cm from bed respectively.

4.2 Water level fluctuation

Water level fluctuations data have been taken along *S1*, *S2* and *S3* sections at the point 0.66 m, 0.91 m and 1.61 m from the left side wall of the channel. Fig. 16 and Fig. 17 show the water level fluctuations for emerged and submerged condition respectively. In the figures the *h1*, *h2* and *h3* denote the water level fluctuations at the point of 1.61 m, 0.91 m and 0.66 m from the left side wall of the flume. Water level fluctuations show much complicated trend in submerged case than the emerged condition. Through spectrum analysis no clear peak has been obtained in submerged condition. In both cases water level fluctuation at the point 0.66 m i.e. *h3* shows dominancy. For both submerged and emerged conditions the water level fluctuation at the interface and in the vegetation zone obtains the maximum amplitude. In emerged condition the frequency showing the peak amplitude keeps increasing from *S1* to *S3*. At the inner peak of *S3* position the peak amplitude occurs at the highest frequency. It is due to the flow mixing phenomenon. The impact of flow mixing has been observed in greater extent near the inner apex of the curve than the outer apex in the flume. It is recommended to observe the Fig. 2(b) for better understanding of the phenomenon.

4.3 Momentum transfer

Fig. 18 shows the lateral momentum transfer in Case A4 along the flow direction with the depth-averaged Reynolds shear stress non-dimensionalized by U_{max} at the interface over the half measuring wave length at the top of the vegetation zone,

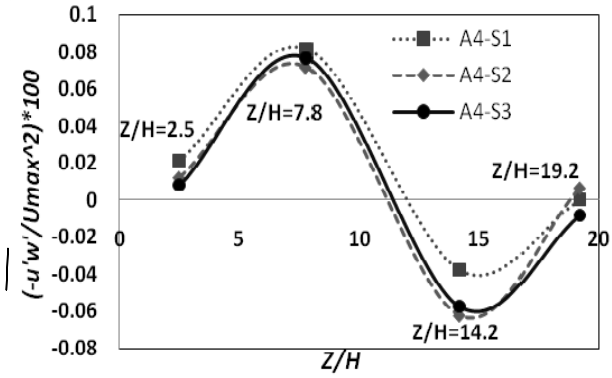

Fig. 18 Lateral momentum transfer for submerged condition in meandering channel.

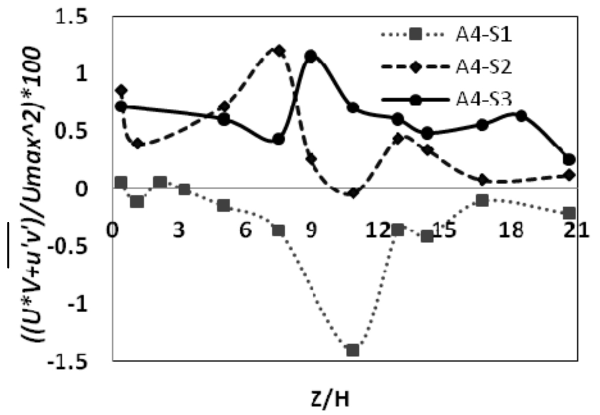

Fig.19 Vertical momentum exchange for submerged condition at the top of the vegetation layer in meandering channel.

that is 5cm above the bed. In case of meandering channel along the outer apex (*Z/H*=7.8) of the left bank of flow direction, maximum positive momentum transfer has been observed. On the other hand along the outer apex of the right bank (*Z/H*=14.2) of the flow direction the maximum negative momentum transfer has been observed. Along the two inner apexes (*Z/H*=2.5 and *Z/H*=19.2) the momentum transfer shows comparatively smaller value which is due to the flow through vegetation zones. Model vegetation retards the momentum transfer within the vegetation zone. Similar phenomenon has been observed in the straight channel. Fig. 19 reveals the vertical momentum exchange in the spanwise direction (Case A4). Its shows a very complex observable fact. At the center of the channel *S1* and *S3* shows opposite signed momentum exchange. In section *S1* the momentum exchange at the center is negative on the other hand in section *S3* it is positive. Same type of situation can be observed in emergent case in meandering channel.

5. Conclusion

The present experimental work has been carried out with a partially vegetated open channel without flood plain for both straight and meandering channel. This type of flow phenomenon is observed in the rivers during flood. In the experiment the effect of vegetation on the flow has been studied and the main findings can be summarized as follows.

1) The aquatic vegetation dramatically changes the velocity profile within and above the vegetated zone. The velocity gradient has sharply increased at the interface of the vegetated zone and the main channel in the straight flume than the meandering one due to the simple channel geometry.
2) Channel has diminutive secondary current. The Reynolds shear stress and the turbulence intensity in the longitudinal direction have been found comparatively much smaller in meandering channel than the straight one.
3) The water level fluctuation at the interface of the main channel and the vegetated zone has been found maximum in straight channel. In case of meandering channel the maximum fluctuation has been observed in the interface and vegetated zone.
4) Vertical momentum exchange for meandering channel at the top of the vegetation layer shows a complex trend which is much simple and has regular pattern in straight channel. In meandering channel the momentum transfer at the outer apex of the wave shows maximum value in form of positive and negative. In straight channel the momentum transfer of flow between the vegetated zone and the main channel increases along downstream which increases the size of the vortex.

References

1) James, C. S. and Myers, W. R. C., Conveyance of meandering channel with marginal vegetation, *Proceedings of the Institution of Civil Engineers. Water, Maritime and Energy,* Vol.148, pp.97-106, 2001.
2) Bathurst J. C., Thorne C. R., and Hey R. D., Secondary Flow and Shear Stress at River Bends., *Journal of hydraulics Division,* ASCE, Vol. 105,No. 10, pp. 1277-1295, 1979.

3) Ismail, Z. and Shiono, K., The effect of vegetation along cross-over floodplain edges on stage-discharge and sediment transport rates in compound meandering channels, *Proceedings of the 5th WSEAS International Conference on Environment, Ecosystems and Development*, Venice, Italy, pp.407-412, 2006.
4) Nepf, H. M., Drag, turbulence, and diffusion in flow through emergent vegetation, *Water Resour. Res*, 35(2), pp. 479–489, AGU 1999.
5) Toebes, G. H., and Sooky, A. A., Hydraulics of meandering rivers with floodplains, Journal of the Waterways and Harbors Division, *Proceedings of the American Society of Civil Engineers*, 93, WW2, pp.213-236,1967.
6) Ishigaki, T., Muto, Y., Takeo, N. and Imamoto, H., Fluid mixing and boundary shear stress in compound meandering channel. *27th Congress of IAHR*, San Fransisco, USA, pp. 763-768, 1997.
7) Jayaratne, B.L., Three-dimensional flow structure in straight and meandering compound channel and planning of desirable river configuration, *Ph.D. Dissertation*, University of Tokyo, Japan, 1998.
8) Muto, Y., Shino, K., Imamoto, H., Ishigaki, T., Three-dimensional flow structure of overbank flow in meandering channels, *Journal of Hydroscience and Hydraulic Engineering*, JSCE, 16(1), pp.97-108, 1998.
9) Tsujimoto, T., Kitamura, T., Experimental study on mechanism of transverse mixing in open-channel flow with longitudinal zone of vegetation along side wall. *Journal of Hydraulic, Costal and Environmental Engineering*, JSCE, No. 491/II-27, pp.61-70, 1994.
10) Nezu, I., Onitsuka, K., Iketani, K., Correlation between water-surface fluctuations and velocity fluctuations in vegetated open-channel flows. *Annual Journal of Hydraulic Engineering*, JSCE, Vol. 44, 2000.

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