Effect of a Weir-Type Obstruction with Different Geometric and Hydraulic Conditions on Flow Structure in an Open Channel

SHAHID ALI*, USMAN GHANI**, AND ABID LATIF***

RECEIVED ON 09.12.2013 ACCEPTED ON 19.03.2014

ABSTRACT

This paper presents results from an experimental study which was conducted at Technical University Delft, Netherland. The research was made on obstructions resembling weirs in an open channel. This weir-type obstruction was a representative of groyne/dike in a natural channel. The experimentation was performed in the laboratory for different values of inflow (25 l/sec and 40 l/sec), weir with and without vegetation and with different leeward slopes of the weir (1:4 and 1:7). The results were obtained for Reynolds normal stresses, longitudinal and vertical velocities. A comparison was made between the results of 1:4 and 1:7 leeward slope ratios. The data was collected with a LDA (Laser Doppler Anemometer). The vegetation was modeled with vertical circular rods placed over the crest of the weir. The blockage area due to this vegetation was 25% of the total area. The velocity data was gathered at around ten locations both at upstream and downstream the weir to get an insight into the flow structure. The results have been presented in the shape of vertical profiles both for velocities as well as Reynolds stresses at different locations of the channel.

Key Words: **Reynolds Normal Stresses, Laser Doppler Anemometer, Weir, Vegetation, Velocity Profiles.**

1. INTRODUCTION

Floods have always remained very important in the history of mankind. Severe flooding has caused huge losses to both property and human life as well. Such floods happen every year in different parts of the world. Pakistan is also too much prone to extreme flooding. Such catastrophic events have happened in Pakistan in recent past a number of times (2010-2012). This natural calamity causes huge loss to the economy of Pakistan and other countries of the world. Research into flooding under different hydraulic and geometric conditions has been a field of immense research for decades. Among these conditions include research conducted on meandering channels [1-2], channels with different bed roughness materials such as gravel [3-5], sediments (mobile and immobile), presence of vegetation both within the main channel and on the flood plains [6-7] etc. There are rivers with converging and diverging floodplain shapes. Sometimes rivers do have confluences with bed discordance.

One important possible feature of floodplains is the presence of a groyne/dike in the floodplains. These types of obstructions act as a hindrance in the flow path. The flow phenomenon might become more complicated due to the existence of vegetation on these

* Senior Engineer, Pakistan Atomic Energy Commission, Islamabad.
** Assistant Professor, Department of Civil Engineering, University of Engineering & Technology, Taxila.
*** Assistant Professor, Department of Civil Engineering, University College of Engineering, Bahauddin Zakirya University, Multan.

obstructions. The major role of these obstructions is the enhanced resistance to water flow i.e. the water will face more surface resistance. The following Fig. 1 is showing a weir-type obstruction existing in a natural channel.

A lot of research has been performed on vegetation and weir-like obstructions. Among these include the studies conducted by various researchers on emergent and submerged flexible and stiff vegetation on flow characteristics such as; Kouwen, et. al. [8] performed a laboratory work with the help of polyethylene plastic strips to simulate vegetation and established a relationship for average velocity. Kouwen and Fathi-Moghadam [9] investigated resistance caused by flexible vegetation. Li and Shen [10] formulated a principle for calculation of resistance of flow due to rigid vegetation, whereas Freeman, et. al. [11] studied different configurations for vegetation which can exist in natural channels. Many studies focused on velocity profiles and turbulent characteristics of vegetated channels [12-15]. Kutija and Hong [16] showed that the relationships formulated for stiff vegetation can also be applied on flexible vegetation by including the bending behavior of vegetation stem with the help of a cantilever beam theory. Similar methods have been proposed by Thompson and Roberson [17] and Manz and Westhoff [18]. Sargison and Percy [19] studied the flow resistance on broad crested weirs. They used different upstream and downstream slopes (2H: 1V, 1H: 1V and vertical in various combinations) during their work. They concluded that discharge coefficient is more affected by the upstream slope as compared to downstream slopes. Tanino and Nepf [20] attempted to calculate flow resistance by quantifying the drag developed by an array of cylinders.

To the knowledge of the authors, although a lot of work has previously been done on these types of obstructions and vegetation, however none of these studies had considered the combined effect of vegetation and weirs on flow structure. For developing this understanding, an experimental work has been performed in the laboratory under different hydraulic and geometric conditions. The objective of this research work is to perform a detailed understanding of complicated turbulent flow structure behind the non-vegetated and vegetated weir-type obstructions. Vertical profiles of velocity components and Reynolds stresses have been presented in the study.

2. EXPERIMENTAL WORK

The experimentation has been performed at Delft University of Technology, Netherlands. A detailed description of the work is available in Ali, et. al. [21]. A brief description of the work is given below.

Fig. 2 shows the flume used during this work. The length of the channel was 14m, its width was 0.4m and depth was 0.4m. It was a glass-walled flume with a horizontal bed. The bed was made rough with sediments of sizes 5 and 8mm. The water inflow was controlled with the help of a valve while a gate was installed at the end of the channel to maintain the depth of flow in the channel. The flow had a Reynolds number of 10^4. Fig. 3 shows the modeled weir and cross-sectional view of the weir crest with vegetation installed over it. Fig. 4 represents the side view of weir with different leeward slopes used in this study. The data was collected with the help of LDA at approximately ten locations as shown in Fig. 5. Fig. 6 represents the mutual distance between successive points of velocity measurements along the depth of the flow. LDA provided the instantaneously velocity values at these points. The mean and turbulent velocity components as well as Reynolds normal and shear stresses were calculated from these observed values of instantaneously velocities. The calculation of water depth was performed with a rail mounted point gauges. Two inflow values were used. Table 1 show values of flow variables which were maintained during the experimentation.

FIG. 1. AN OBSTRUCTION ACTING AS A VEGETATED WEIR

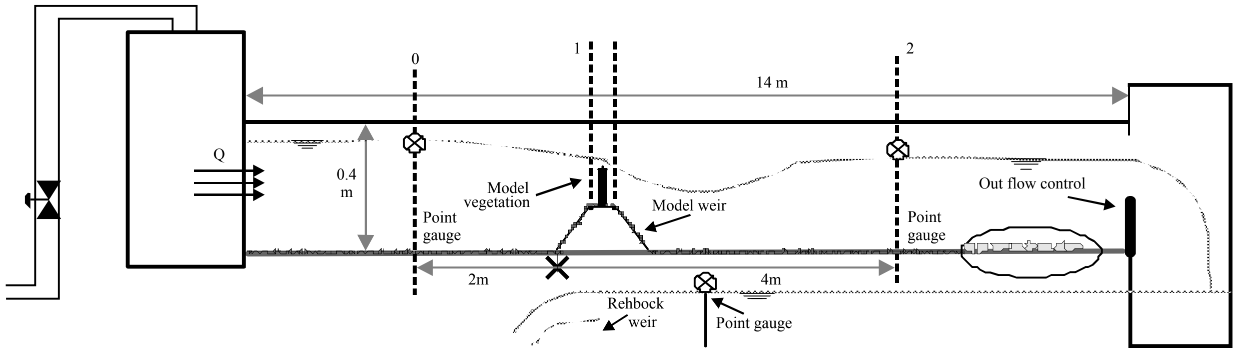

FIG. 2. A VIEW OF THE FLUME USED IN THE EXPERIMENTATION

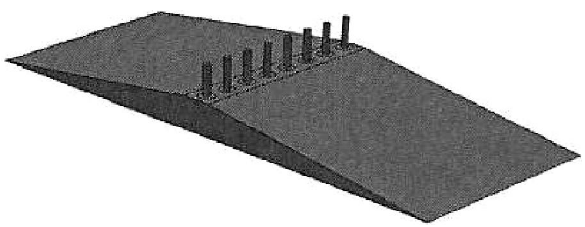

FIG. 3 (A). A 3D VIEW OF MODELLED WEIR AND VEGETATION IN THE CHANNEL

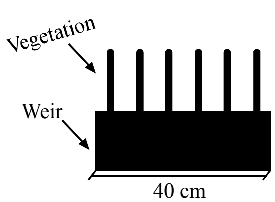

FIG. 3(B) CROSS-SECTIONAL VIEW OF THE WEIR CREST

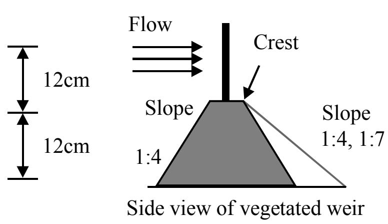

FIG. 4. WEIR WITH DIFFERENT LEEWARD SLOPES 1:4 AND 1:7

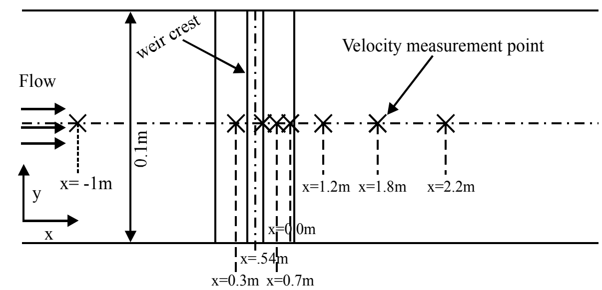

FIG. 5. LOCATIONS OF VARIOUS POINTS ALONG THE LENGTH OF THE CHANNEL SELECTED FOR DATA COLLECTION

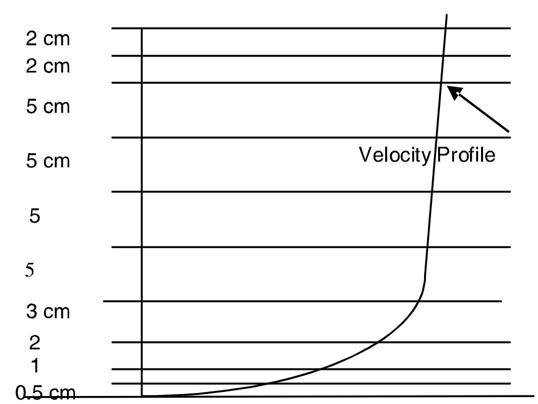

FIG. 6. MUTUAL DISTANCE ALONG THE DEPTH OF THE CHANNEL BETWEEN SUCCESSIVE POINTS OF VELOCITY MEASUREMENTS

TABLE 1. EXPERIMENTAL CONDITIONS FOR VEGETATED WEIR WITH DOWNSTREAM SLOPE 1V:4H

Vegetation Type	Inflow (m^3/sec)	Fr Over the Crest of Weir	Depth of Flow (m)		
			Before the Weir Crest	Over the Crest	After the Weir Crest
Weir without vegetation	0.025	0.25	0.32	0.185	0.313
	0.04	0.40	0.32	0.18	0.317
Weir with vegetation	0.025	0.25	0.35	0.20	0.345
	0.04	0.40	0.35	0.189	0.339

3. RESULTS AND DISCUSSION

The results have been presented for velocity components, Reynolds normal and shear stresses for the modeled weir with a leeward slope of 1:7. u, and w are velocity components in stream-wise and vertical directions respectively. Vertical velocity was taken as positive when directed upward. Results also include Reynolds normal stresses for a leeward slope of 1:4. Results are presented for two discharge values i.e. 25 and 40 l/sec. The velocity values were normalized by average stream-wise velocity (u_o), Reynolds stresses were normalized by u_o^2 and flow depth was normalized by weir depth Δ. In all the cases a comparison has been made between vegetated and non vegetated cases keeping discharge and leeward slope constant.

3.1 Flow Characteristics of Weir with Downstream Slope of 1:7

Fig. 7(a) is showing the primary velocity profiles at different positions along the channel for the two cases i.e. vegetated and non-vegetated weirs. In this diagram u/u_o represents normalized stream-wise velocity whereas z/Δ shows normalized depth of flow with reference to weir height (Δ). The velocity profiles downstream of the weir crest shows that there is no recirculation flow zone because of mild leeward slope (1:7). In this situation the energy head loss also decreased due to absence of recirculation zone behind the weir. Fig. 7(b) represents vertical velocity profiles for leeward slope 1:7. It shows that at locations 3 and 4 there is a negative vertical velocity profile (downward velocity was taken as negative) from bottom to top. The region downstream of the crest is expansion and if there is no flow separation zone, then vertical velocity should be negative. In case of flow separation zone, the vertical velocity should be positive in lower region and it should be negative in upper region.

The turbulence generated fluctuations in velocity components are represented by Reynolds shear and normal stresses. A detailed understanding of these stresses is vital for an in depth knowledge of the flow behavior. Over here, an attempt has been made to explore and understand the distribution patterns of these Reynolds shear and normal stresses at different critical locations both upstream and downstream the weir in the channel.

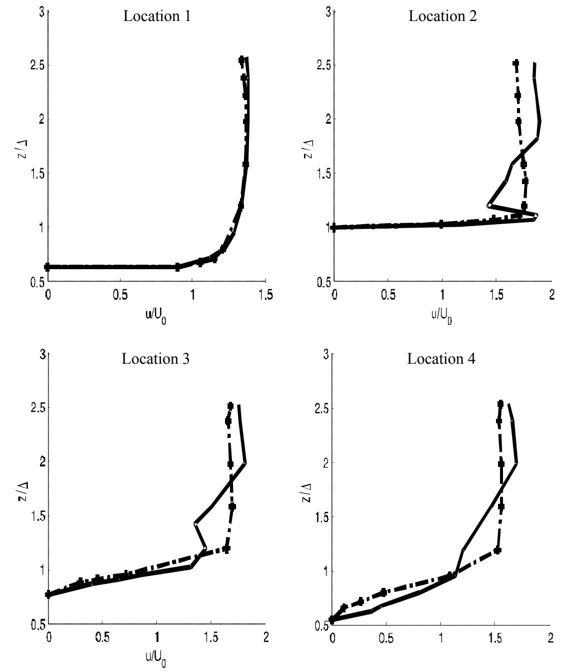

FIG. 7(A). PRIMARY VELOCITY RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [*u/u_o represents normalized stream-wise velocity whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)*]

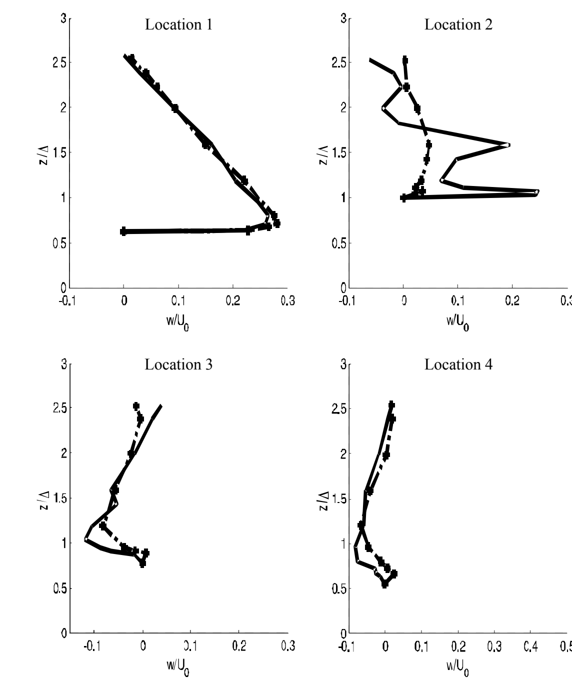

FIG. 7(B). VERTICAL VELOCITY RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [*w/u_o represents normalized vertical velocity whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)*]

Fig. 8 (a-c) shows Reynolds shear and normal stresses for vegetated and non-vegetated weir cases. As mentioned above these stresses depend upon velocity variations, now as the velocity components are showing much fluctuations over the weir crest close to bed and in the mid depth regions, so Reynolds shear stress also have high values close to bed and in the middle regions, while it decreases as we move upwards. This is more prominent in case of normal stresses. It has also been noticed that maximum normal and shear stresses occurred at location 2. This happened in case of vegetated weir. For non vegetated case, the location of maximum value varied from case to case. The high Reynolds shear stresses at location 2 indicate that at this location there are significant velocity gradients. Similarly for vegetated case, Reynolds normal stresses uu" and ww" (Fig. 8(b-c)) are significant in certain regions over the depth of the flow due to high fluctuations in those regions. Generally speaking Reynolds stresses are very small at upstream of weir but these are significant at downstream side of the weir.

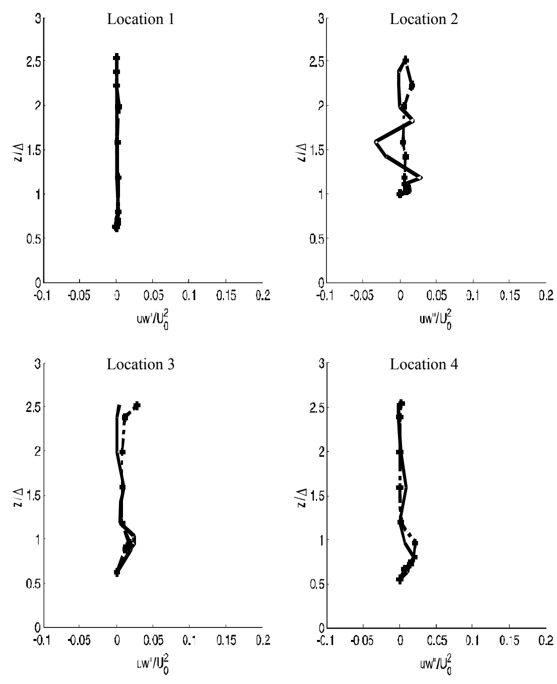

FIG. 8(A). REYNOLDS SHEAR STRESS RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [uw"/u_o^2 represents normalized Reynolds shear stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

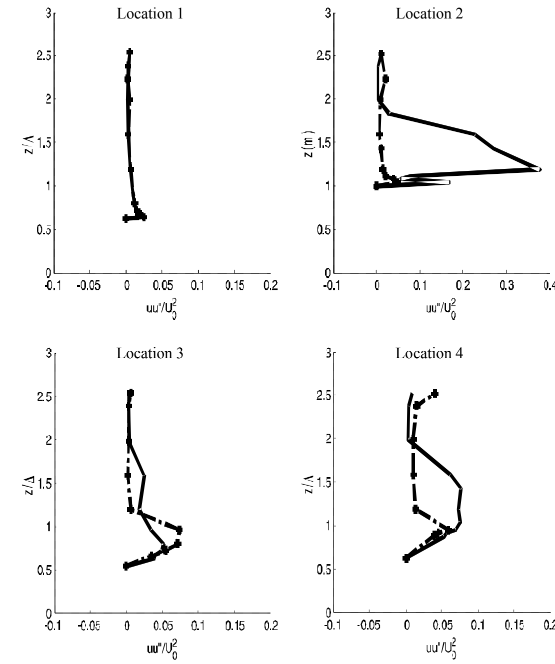

FIG. 8(B). REYNOLDS NORMAL STRESS (UU) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [uu"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

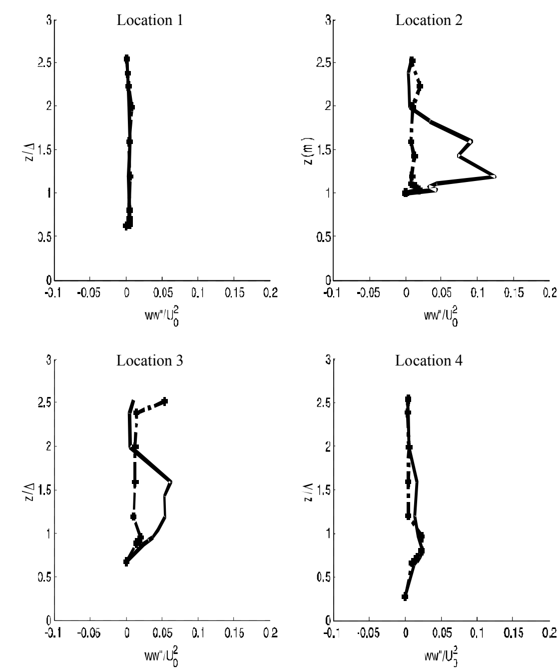

FIG. 8(C). REYNOLDS NORMAL STRESS (WW) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [ww"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

3.2 Flow Characteristics of Weir with Downstream Slope 1:4

The Figs. 9-10 shows the results for Reynolds normal stresses for steep slope case of 1:4. Two discharges (25 and 40 litre/s) have been used. The Reynolds normal stresses are important for a detailed study of different flow features. These stresses are representing the turbulence part of instantaneous velocities which are comprised of mean and fluctuating components. Results are shown for both vegetated and non-vegetated cases. In case of uu normal stresses (Fig. 9(a)), the variation is too much over the crest and close to downstream side of the weir. However away from the slope the fluctuation mitigates as the situation returns to normalcy. The stress values and fluctuation intensities are high in case of longitudinal Reynolds stresses (uu) than vertical Reynolds stresses (ww) as given in Fig. 9(b). The Fig. 10(a-b) shows results for 40 l/sec discharge values. It is evident from these diagrams that Reynolds stress patterns are similar as those observed in case of 25 l/sec.

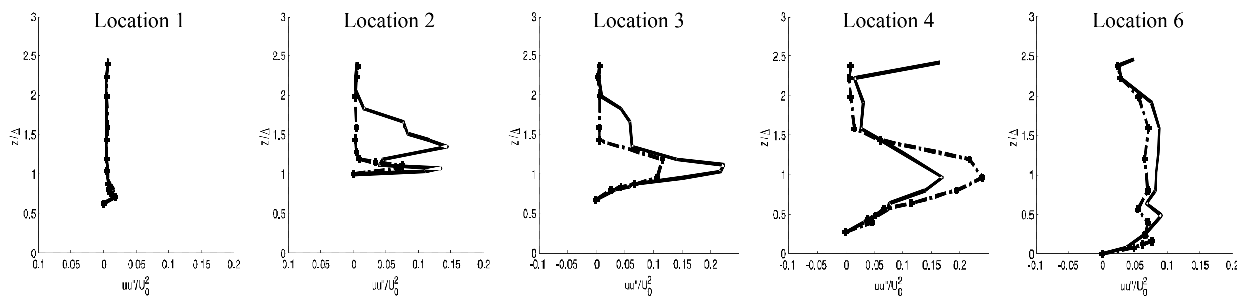

FIG. 9(A). REYNOLDS NORMAL STRESS (UU) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=25 L/SEC) [uu"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

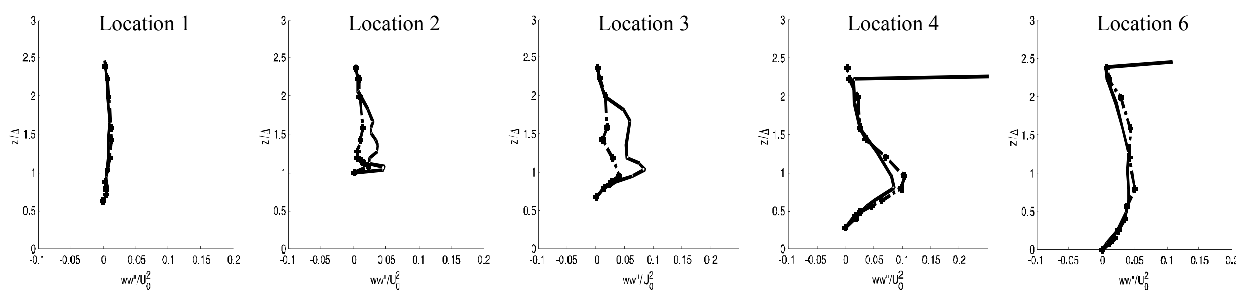

FIG. 9(B). REYNOLDS NORMAL STRESS (WW) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=25 L/SEC) [ww"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

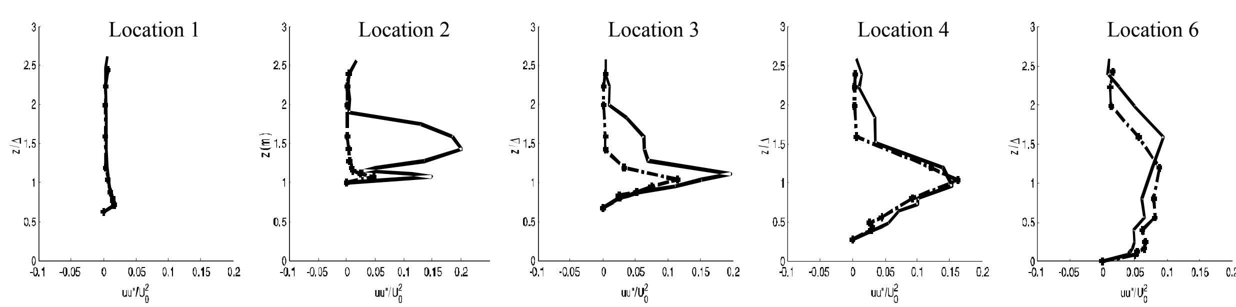

FIG. 10(A). REYNOLDS NORMAL STRESS (UU) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q= 40 L/SEC) [uu"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

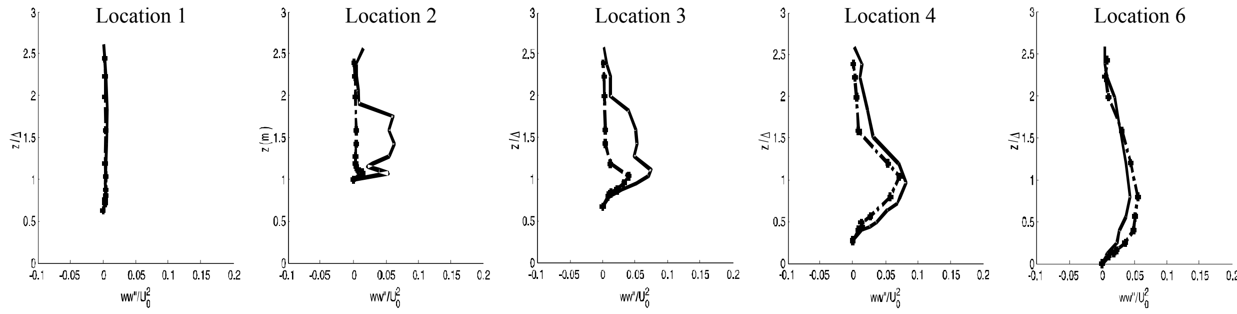

FIG. 10(B). REYNOLDS NORMAL STRESS (WW) RESULTS OVER VARIOUS POSITIONS (NON-VEGETATED CASE SHOWN BY DOTTED LINE AND SOLID LINE INDICATES VEGETATED CASE WITH Q=40 L/SEC) [ww"/u_o^2 represents normalized Reynolds normal stresses whereas z/Δ shows normalized depth of flow with reference to weir height (Δ)]

4. CONCLUSIONS

The results have been presented from experimental work performed at Delft University of Technology, Netherland. Weir type obstructions with different slopes were employed to get their impact on flow characteristics. It was observed that presence of vegetation over the crest of weir considerably disturbs the flow patterns. In most of the cases, the Reynolds normal stresses were found to be maximum over the crest of the weir. Although in some cases of steep slope (1:4), high normal stress values were also noticed at downstream locations. As far as discharge intensity is concerned, both the values showed similar pattern of Reynolds stresses and velocity fluctuations but the magnitude of stresses was found to be dependent on flow intensity.

ACKNOWLEDGEMENT

This work was conducted at Delft University of Technology, Netherland. The first author is highly acknowledged to Higher Education Commission, Pakistan for providing funds to carryout this research work in Netherland.

REFERENCES

[1] Stoesser, T., Ruether, N., and Olson, N.R.B., ''Calculation of Primary and Secondary Flow and Boundary Shear Stresses in a Meandering Channel'', Advances in Water Resources, Volume 33, pp. 158-170. February, 2010.

[2] Afzalimehr, H., and Singh, V.P., ''Influence of Meandering on Estimation of Velocity and Shear Velocity in a Cobble-Bed River'', Journal of Hydrologic Engineering, Volume 14, pp. 1126-1135, USA October, 2009.

[3] Qin, J., and Ng, S.L., ''Estimation of Effective Roughness for Water-Worked Gravel Surfaces'', ASCE Journal of Hydraulic Engineering, Volume 138, pp. 923-934. USA, October, 2012.

[4] Pagliara, S., and Chiavaccini, P., ''Flow Resistance of Rock Chutes with Protruding Boulders'', Journal of Hydraulic Engineering, Volume 132, pp. 545-552, USA, June, 2005.

[5] Lawless, M., and Robert, A., ''Three-Dimensional Flow Structure Around Small Scale Bed Forms in a Simulated Gravel-Bed Environment'', Journal of Earth Surface Processes and Landforms, Volume 26, pp. 507-522, September, 2001.

[6] Sanjou, M., Nezu, I., Suzuki, S., and Itai K., ''Turbulent Structure of Compound Open Channel Flows with One-Line Emergent Vegetation'', Journal of Hydrodynamics, Volume 22, pp. 577-581, October, 2010.

[7] Zang, M., Li, C.W., and Shen, Y., ''Depth-Averaged Modeling of Free Surface Flows in Open Channels with Emerged and Submerged Vegetation'', Applied Mathematical Modelling, Volume 37, pp. 540-553. January, 2013.

[8] Kouwen, N., Unny, T., and Hill, H.M., ''Flow Retardance in Vegetated Channels'', ASCE Journal of Irrigation and Drainage Division, Volume 95, IR2, pp. 329-342. USA, Septmber, 1969.

[9] Kouwen, N., and Fathi-Moghadam, M., ''Friction Factors for Coniferous Trees along Rivers'', ASCE Journal of Hydraulic Engineering, Volume 126, No. 10, pp. 732-740. USA, October, 2000.

[10] Li, R.M., and Shen, H.W., ''Effect of Tall Vegetations on Flow and Sediment'', ASCE Journal of Hydraulic Division, Volume 99, No. 5, pp. 793- 814. USA, May, 1973.

[11] Freeman, G.E., Rahmeyer, W.H. and Copland, R.R., ''Determination of Resistance due to Shrubs and Woody Vegetation'', Technical Report, ERDC/CHL, TR-00-25, US Army Engineering Research and development Centre, Vicksburg, MS, 2000.

[12] Baptist, M.J., ''Modeling Floodplain Bio-Geomorphology'', Delft University Press, Delft, 2005.

[13] Nepf, H.M., and Vivoni, E.R., ''Flow Structure in Depth-Limited, Vegetated Flow'', Journal of Geophysical Research, Volume 105, No. C12, pp. 28547-28557, USA, 2000.

[14] Liu, D., Diplas, P., Fairbanks, J.D., and Hodges, C.C., ''An Experimental Study of Flow through Rigid Vegetation'', Journal of Geophysical Research, Volume 113, USA, 2008.

[15] Neary, V.S., ''Numerical Solution of Fully Developed Flow with Vegetative Resistance'', Journal of Engineering Mechanics, Volume 129, No. 5. pp. 558-563. USA, May, 2003.

[16] Kutji and Hong, ''Determination of Flow Resistance Caused by Non-Submerged Woody Vegetation'', Journal of River Basin Management, Volume 2, No. 1, pp. 61-70, IAHR, 2004.

[17] Thompson and Roberson, "Hydraulics of Board-Crested Weirs with Varying Side Slopes", Journal of Irrigation and Drainage Engineering, No. 2, pp. 115-118. USA, January, 2009.

[18] Manz, Westhoff, V.D., and Mark, C.F., ''A Semi-Analytical Model for form Drag of River Bed Forms'', University of Twente, Netherlands, 2009.

[19] Sargison, J.E., and Percy, A., ''Hydraulics of Board-Crested Weirs with Varying Side Slopes'', Journal of Irrigation and Drainage Engineering, Volume 68, No.1, pp. 115-118. USA, January, 2009.

[20] Tanino, Y., and Nepf, H.M., ''Laboratory Investigation of Mean Drag in a Random Array of Rigid Emergent Cylinders'', Journal of Hydraulic Engineering, Volume 134, No. 1, pp. 62-73. USA, January, 2008.

[21] Ali, S., Ghani, U., and Arif, S., ''Estimation of Flow Resistance Due to Embankments and Spur Dikes During Floods'', Mehran University Research Journal of Engineering & Technology, Volume 32, No. 3, Jamshoro, Pakistan, July, 2013.