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Characteristic of Vertical Reynolds Shear Stress in a Patchy Heterogeneous Open Channel

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ABSTRACT

In turbulent flow, the Reynolds stress provides an understanding of the shear dispersion within the flow. Turbulence can be said to have an effect equivalent to the Reynolds shear stresses and are indicators of turbulence transport. This paper examined the characteristic of vertical Reynolds Shear stress in a patchy heterogeneous open channel using two experimental conditions for flexible and rigid vegetation interaction with gravel bed. The results show the value of vertical Reynolds stress decreases downstream along the channel section and as the distance from change in roughness increases. This is attributed to the effects of the bed roughness configuration (due to the preceding vegetated bed roughness) on the vertical Reynolds stress distribution. However, the position of maximum vertical Reynolds stress is located near bed over the vegetated zone. This provides an indication that the vegetated bed serves as the primary source of turbulence for the flow.

***Keywords*:** Reynolds Stress, vegetation, gravel, patchy, heterogeneous, turbulence, open channel

1. INTRODUCTION

Turbulence can be said to have an effect equivalent to the Reynolds shear stresses and are indicators of turbulence transport. However, Reynolds stresses represent the loss of mechanical energy by the main flow due to its interaction with turbulence (Davidson, 2004).

Considering the velocity to be statistically stationary, the instantaneous velocity can be decomposed into sum of the time averaged and fluctuating components.

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The velocity fluctuating components act to efficiently transport momentum. The RANS equations are derived by substituting the instantaneous velocities in Navier-Stokes Equation (1)

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \rho f_x + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \qquad (1)$$

where: ρ is fluid density, u, v, w are instantaneous velocities in x, y, z directions, t is time, $f_x . f_y , f_z ,$ are body forces, μ is the dynamic viscosity by their mean and fluctuating components:

$$u = U + u' \qquad (2)$$

where: u' represents the fluctuating components (Reynolds, 1895) and taking a time averaged for the x-component: Equation (3):

$$U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \left(\frac{\partial \overline{u'^2}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y} + \frac{\partial \overline{u'w'}}{\partial z}\right) \qquad (3)$$

(corresponding equations also exist for the lateral and vertical directions). Equation (3) is referred to as Reynolds Averaged Navier-Stokes equations (RANS). The RANS equations are primarily used to describe turbulent flows using the Reynolds shear stresses which are one of the important terms in turbulence modelling; these terms represent the effect of velocity fluctuations or turbulence on the mean flow. These are the bracketed parts of the third terms of the RHS of Equation (3) as the normal, lateral and vertical Reynolds shear stresses.

2. MATERIAL AND METHODS

The experiments were conducted in 22mm long rectangular re-circulating flume of width $B = 614mm$ at the University of Birmingham. The channel is supplied from a constant head tank with a capacity of $45{,}500l$ in the laboratory roof. A flow discharges (Q) $(30.0\ l/s)$ with corresponding flow depth (H) of $130mm$ width to depth ratio $\left({}^{B}/_{H}\right)$ of 4.7 achieve subcritical flow condition was investigated. In what follows these experimental conditions are referred to as EXPT1 and EXPT2 respectively. Detailed velocity measurements were made at three cross sections (CRS1, CRS2 and CRS3) at distances of 17.5m, 17.85m and 18.2m respectively downstream from the channel inlet. In the results that follow, the gravel region of the bed extends over $\left(0 \le {}^{y}/_{B} \le 0.5\right)$, the interface occurs at $\left({}^{y}/_{B} = 0.5\right)$, and the vegetated region extends over $\left(0.5 \le {}^{y}/_{B} \le 1.0\right)$, where y is the lateral distance from the left hand side looking downstream and B is the channel width. The streamwise direction x is in the direction of flow. The transverse direction y is perpendicular to x in the lateral direction, while the vertical direction is denoted by z and is perpendicular to the xy plane (positive upwards). The corresponding time average velocity components are U, V, W respectively. Figure 1 shows the bed configuration for EXPT1 and EXPT2.

Figure 1. Bed Roughness Configuration Plan View of Roughness Patches for Experiment One and Two

3. RESULTS AND DISCUSSION

The results of the vertical and horizontal Reynolds stresses (VRS and HRS respectively) are normalized by the theoretical boundary shear stress, $\overline{\tau_b} = \rho g R S_0$, where ρ is the water density, g is the acceleration due to gravity, R is the hydraulic radius and S_0 is the bed slope. The numerically integrated values corresponding to each cross-section are presented in Table 1.

Table 1. Integrated Mean Reynolds stresses and the Mean Boundary shear stress

CROSS SECTIONS EXPT1	$\boldsymbol{VRS_i}$	**CROSS SECTIONS EXPT2**	$\boldsymbol{VRS_i}$
EXPT1CRS1	0.891	**EXPT2CRS1**	0.645
EXPT1CRS2	0.863	**EXPT2CRS2**	0.642
EXPT1CRS3	0.845	**EXPT2CRS3**	0.621

Analysis of the Reynolds stresses for EXPT1 and EXPT2 provides an understanding of the shear turbulence dispersion within the flow. It is shown in Table 1 that the magnitudes of the integrated channel-mean vertical Reynolds stress (VRS_i) are larger in EXPT1 relative to EXPT2 for all the channel cross-sections. It should be noted from Table 1, that the value of the VRS decreases downstream along the channel section with CRS1 having a higher magnitude which reduces as the distance from change in roughness increases. This is attributed to the effects of the bed roughness configuration (due to the preceding vegetated bed roughness) on the vertical VRS distribution.

Figures 2 and 3 illustrate the cross-sectional distribution of the vertical Reynolds stress, whilst Figures 4 and 5 show the vertical distribution of VRS at selected transverse positions. However, the position of maximum VRS is located near bed over the vegetated zone. This again provides an indication that the vegetated bed serves as the primary source of turbulence. Comparison of both EXPT1 and EXPT2 showed a qualitatively consistent distribution of this parameter over the vegetated bed but greater magnitude in EXPT1, with maximum relative vertical Reynolds stress of 0.89 and 0.65 for EXPT1 and EXPT2 respectively.

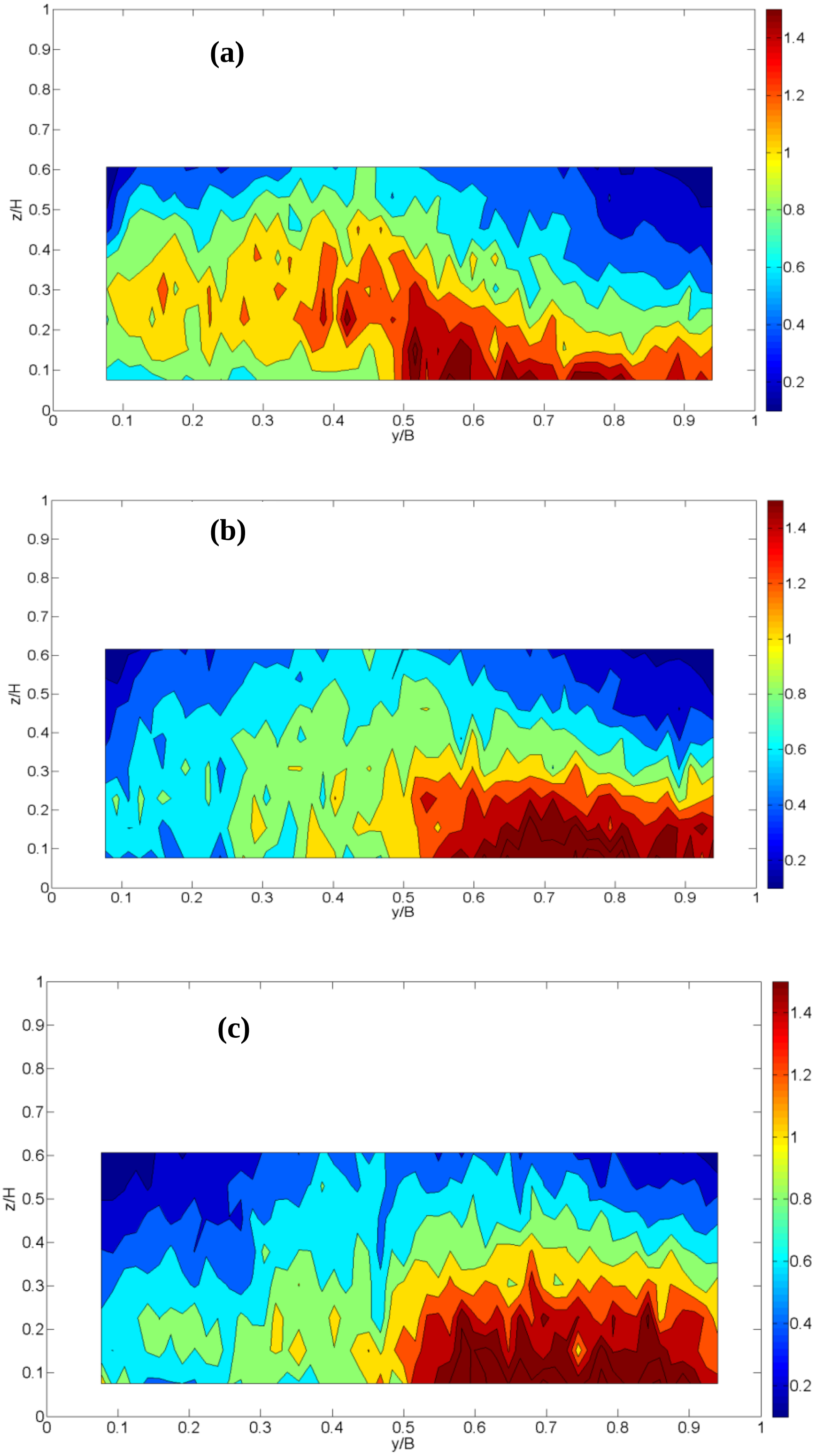


Figure 2. Lateral distribution of vertical Reynolds stress; CRS1 (top) to CS3 (bottom) EXPT1

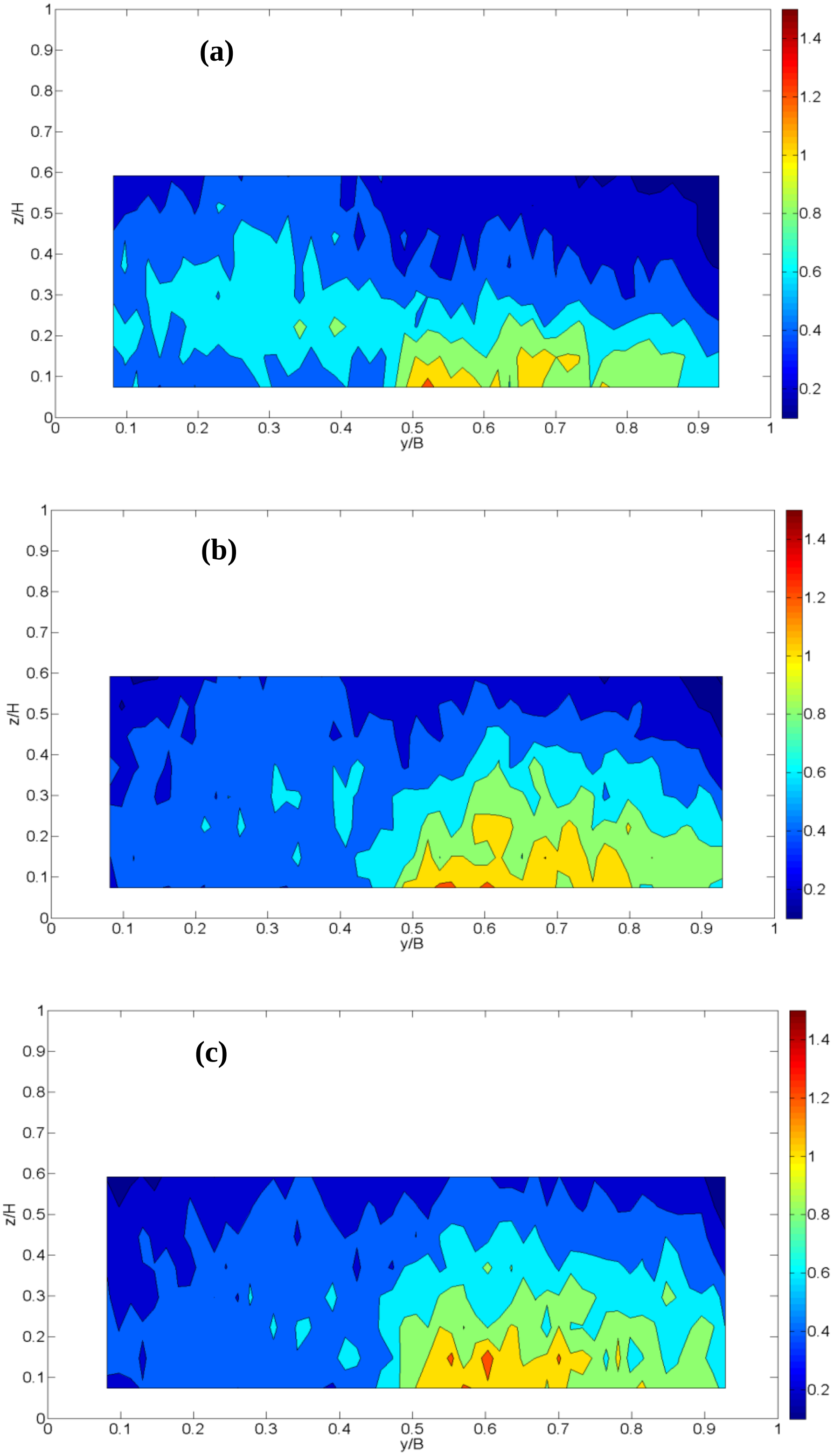
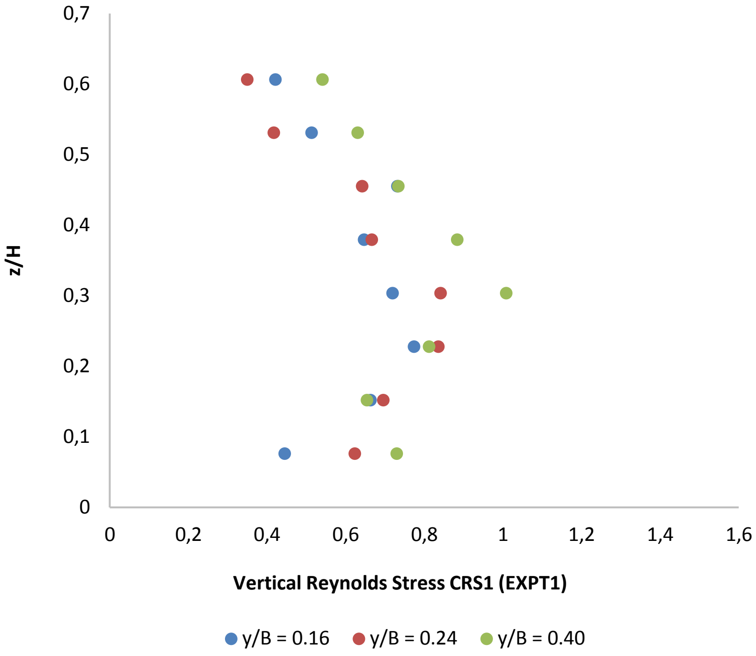


Figure 3. Lateral distribution of vertical Reynolds stress; CRS1 (top) to CS3 (bottom) EXPT2

(a)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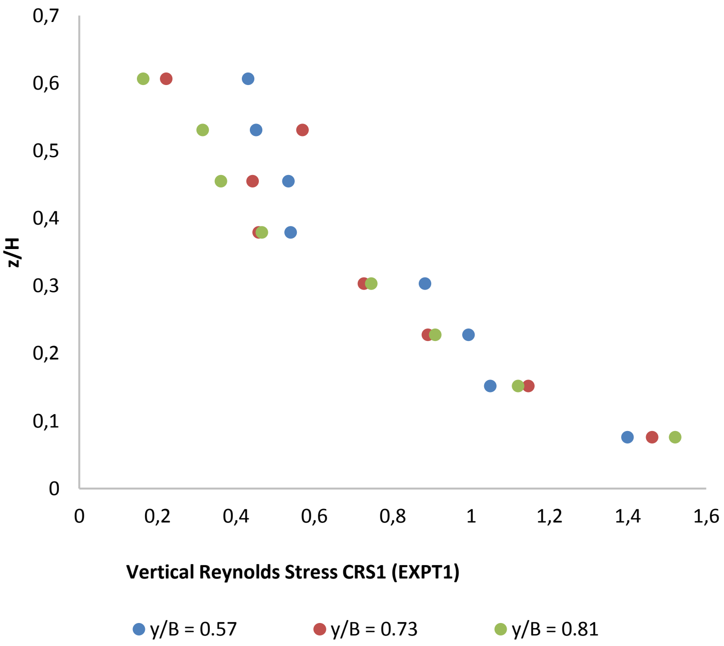
Vertical Reynolds Stress CRS1 (EXPT1)
● y/B = 0.16
● y/B = 0.24
● y/B = 0.40

(b)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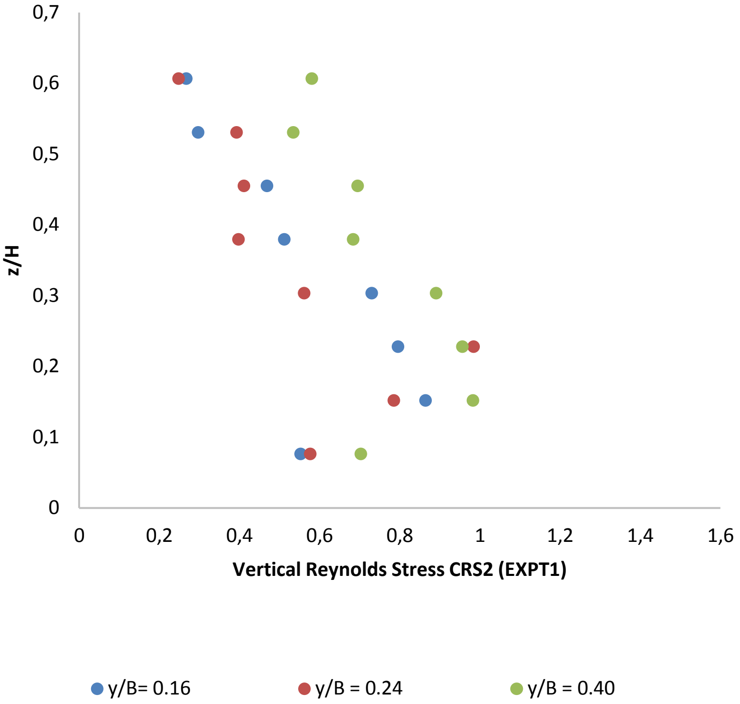
Vertical Reynolds Stress CRS1 (EXPT1)
● y/B = 0.57
● y/B = 0.73
● y/B = 0.81

(c)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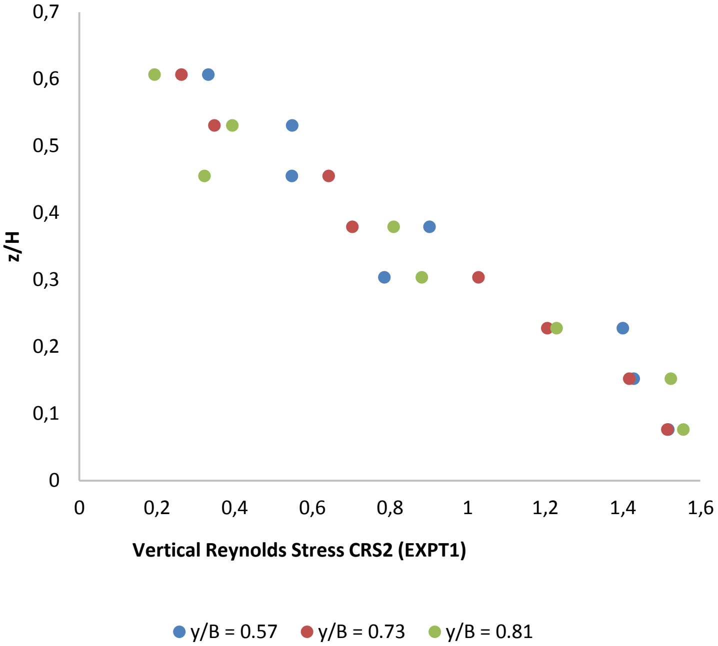
Vertical Reynolds Stress CRS2 (EXPT1)
● y/B= 0.16
● y/B = 0.24
● y/B = 0.40

(d)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Vertical Reynolds Stress CRS2 (EXPT1)
● y/B = 0.57
● y/B = 0.73
● y/B = 0.81

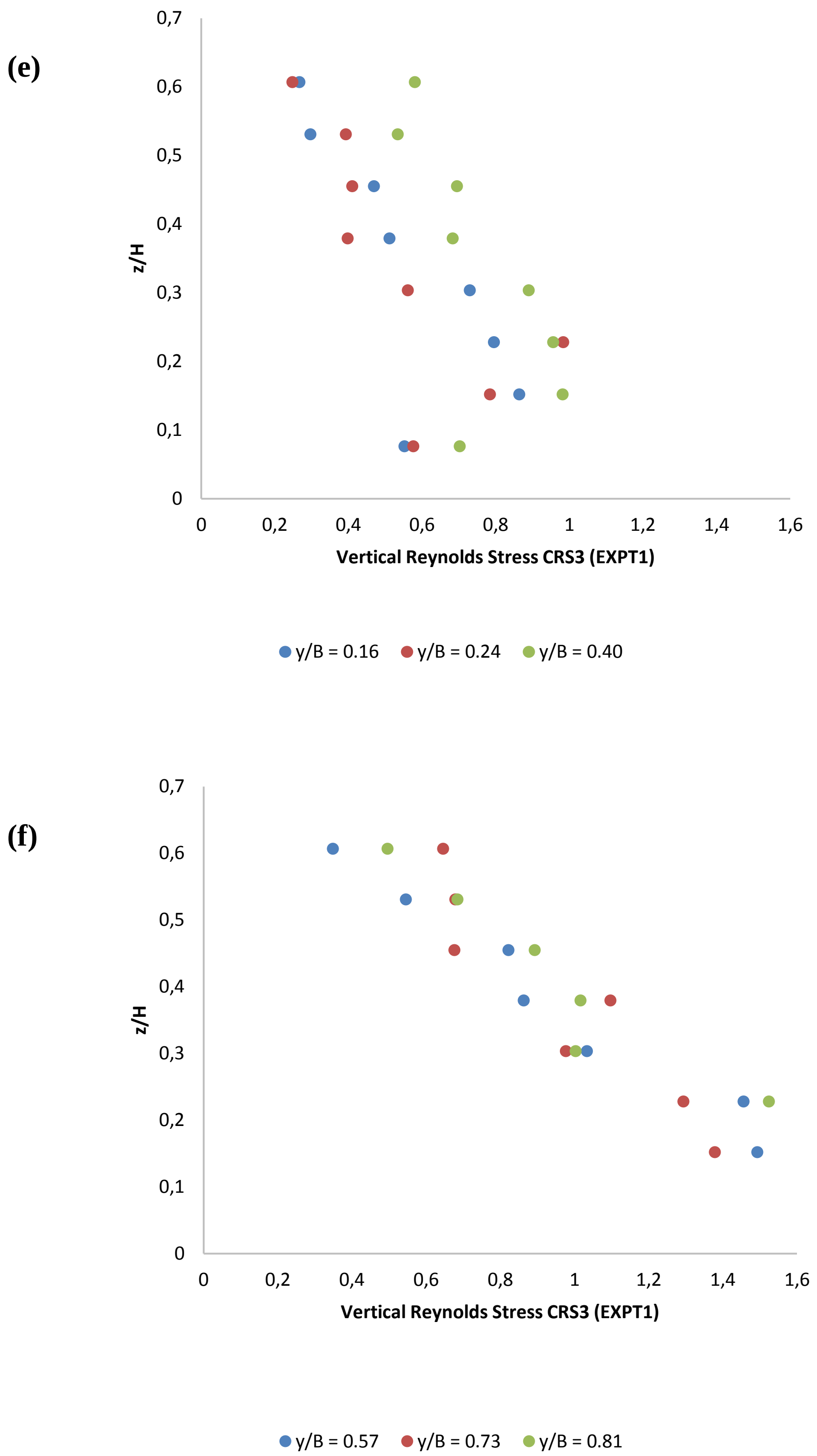
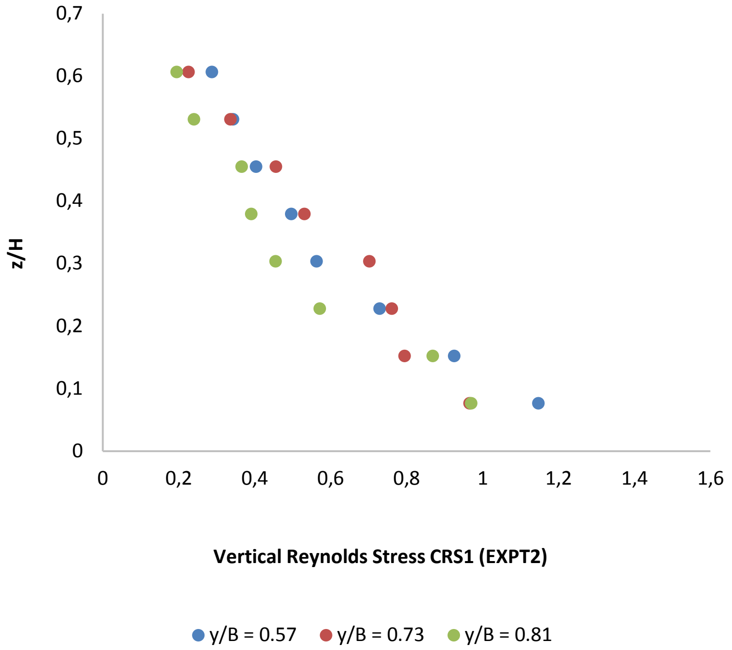


Figure 4. Vertcal distribution of relative verical Reynolds stress by bed region (EXPT1) Gravel (**(a)**, **(c)**, **(e)**) Vegetated region (**(b)**, **(d)**, **(f)**)

(a)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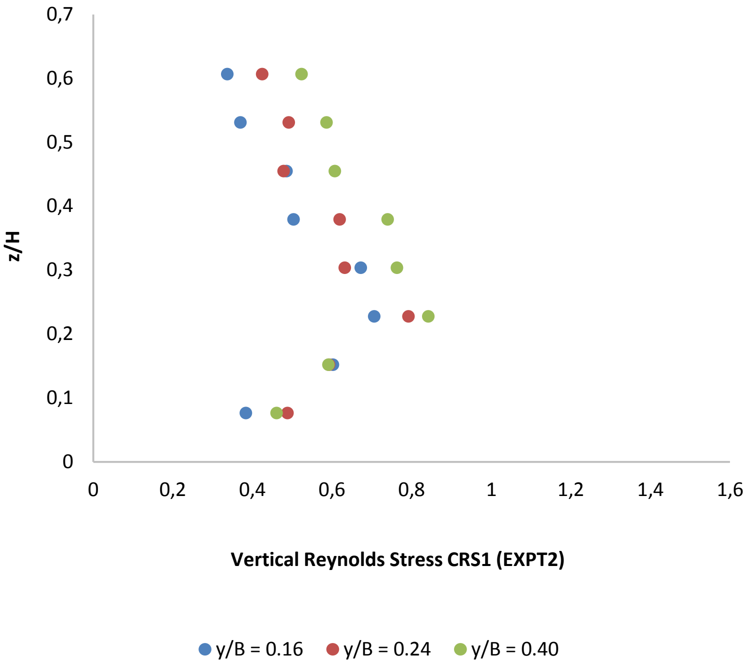
Vertical Reynolds Stress CRS1 (EXPT2)
● y/B = 0.57
● y/B = 0.73
● y/B = 0.81

(b)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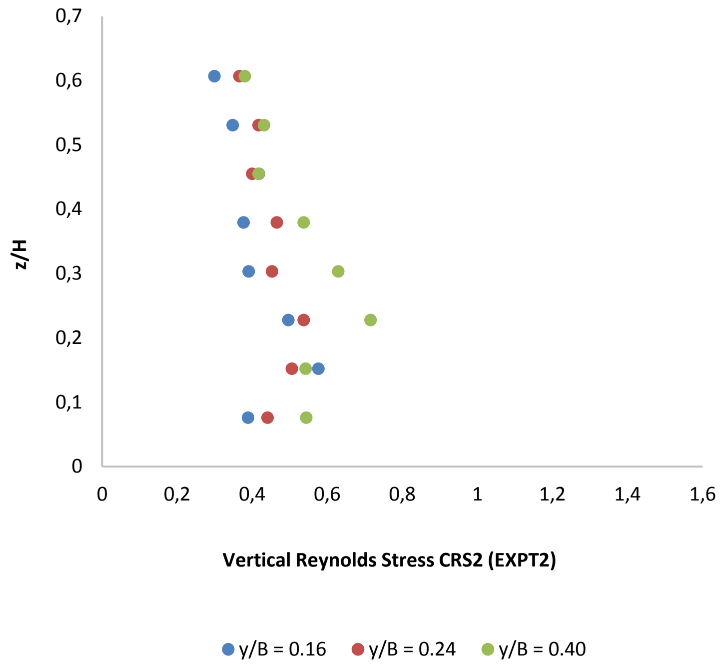
Vertical Reynolds Stress CRS1 (EXPT2)
● y/B = 0.16
● y/B = 0.24
● y/B = 0.40

(c)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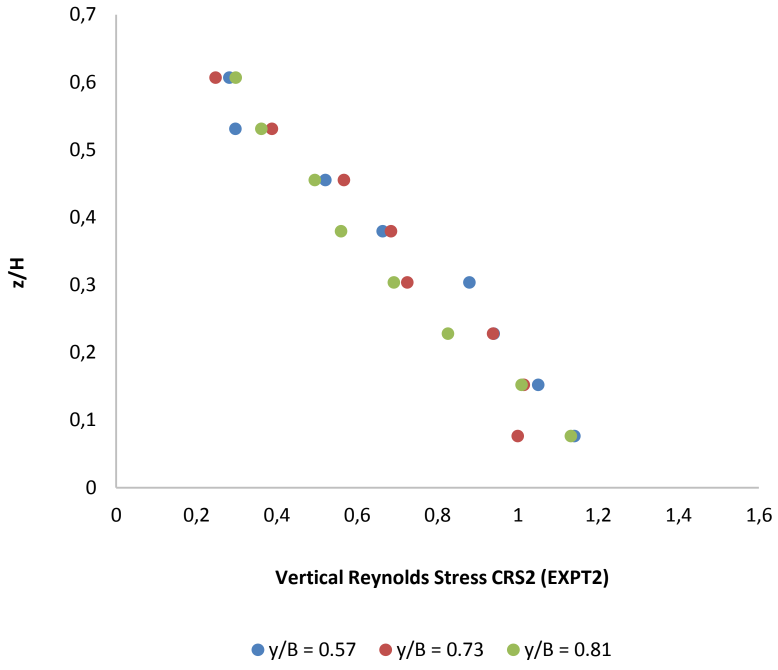
Vertical Reynolds Stress CRS2 (EXPT2)
● y/B = 0.16
● y/B = 0.24
● y/B = 0.40

(d)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Vertical Reynolds Stress CRS2 (EXPT2)
● y/B = 0.57
● y/B = 0.73
● y/B = 0.81

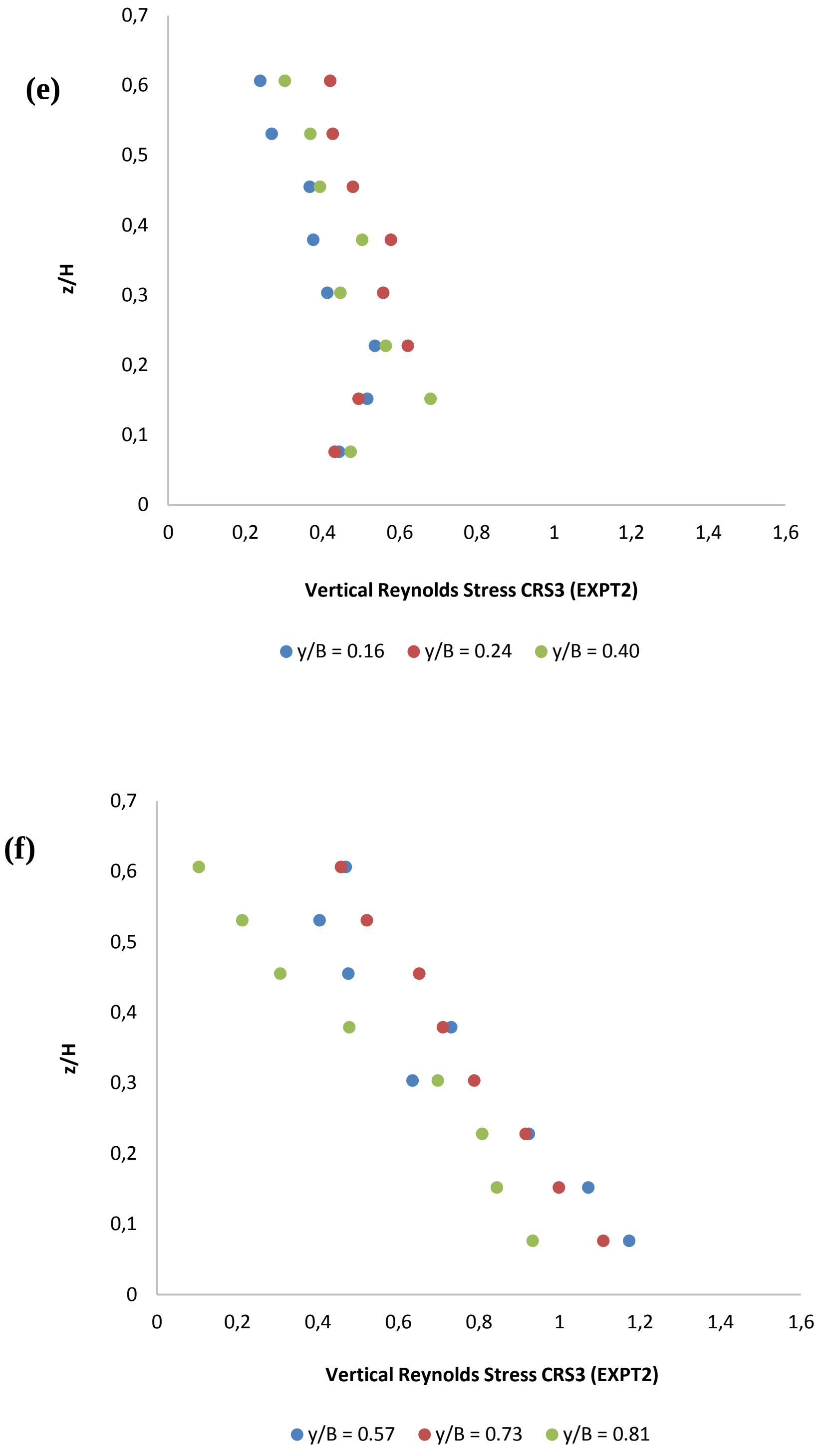

Figure 5. Vertcal distribution of relative vertical Reynolds stress by bed region (EXPT2) Gravel (**(a)**, **(c)**, **(e)**) Vegetated region (**(b)**, **(d)**, **(f)**).

Figures 4 and 5 compares the vertical profiles of the normalised vertical Reynolds stress; Over the gravel bed $\left(0 \leq {}^{y}/_{B} \leq 0.5\right)$, the vertical Reynolds stress has a local maximum above the bed at approximately $\left({}^{z}/_{H} \cong 0.2\right)$, after which it decays approximately in a linear fashion towards the channel bed and the free surface from the maximum point. This is in good agreement with the wall region as defined by (Nezu and Nakagawa, 1993). In this region the vertical Reynolds stress decreases towards the channel bed due to the presence of non-negligible viscous shear stress induced by the bed surface (Nezu and Nakagawa, 1993). Moreover, the near bed momentum transport from gravel bed to the vegetated bed is assumed to have contributed to the reduced value of the near bed vertical Reynolds shear stress over the gravel bed. This is suggested to have contributed to the momentum balance in the near bed flow region (Shiono and Knight, 1991).

Over the vegetated bed, the vertical Reynolds stress is consistently linear over the measured section, with a maximum value located close to the channel bed. This behaviour is consistent with an inflection point in a submerged vegetation which is characterized by a shear layer and confirm the existence of a ‘wake layer’ below the vegetation surface roughness, thus, the effective height of the bed lies below the vegetation roughness crest (Nezu and Nakagawa, 1993).

4. CONCLUSION

The current research demonstrated that vegetation in EXPT1 are dominated by vertical shear. In addition, the current research demonstrates the impact of roughness distribution on turbulence generation, i.e. the flexible vegetation resulted in more vorticity (due to shear) which had an impact on the hydraulic resistance. This in part is related to two-layer flow which arose in the flexible vegetation and the corresponding vertical shear induced therein. In EXPT1, the presence of vegetation promotes vertical shear and the resulting dominance of vertical momentum transport, hence turbulence is enhanced in the vertical direction in EXPT1 over the vegetated bed with an increased near bed value of vertical fluctuation.

References

[1] DAVIDSON, P. A. 2004. Turbulence - an introduction for scientists and engineers. Oxford University Press.

[2] FINNIGAN, J. 2000. Turbulence in plant canopies. *Journal of Fluid Mechanics*, 32, 519-571.

[3] GHISALBERTI, M. 2009. Obstructed Shear Flows: similarities across system and scales. *J. Fluid Mech*, 641, 51-61.

[4] GHISALBERTI, M. & NEPF, H. 2006. The structure of the shear layer over rigid and flexible canopies. *Environmental Fluid Mechanics*, 6, 527-551.

[5] GHISALBERTI, M. & NEPF, H. M. 2004. The limited growth of vegetated shear layers. *Water Resource. Res.* 40, 1-12.

[6] GHISALBERTI, M. & NEPF, H. 2002. Mixing layers and coherent structures in vegetated aquatic flow. *Journal of Geophysical Research-Earth Surface,* 107, 527-551.

[7] HARDY, J. R., BEST, L. J., LANE, N. S. & CARBONNEAU, E. P. 2009. Coherent flow structures in a depth limited flow over a gravel surface: The role of near bed turbulence and influence of Reynolds number. *Journal of Geophysical Research*, 114, 1-18.

[8] HWANG, L. & LAURSEN, E. M. 1963. Shear measurements technique for rough surfaces. *Journal of Hydraulic Engineering,* 89, 19-37.

[9] IKEDA, S., M., K., K. & OHTA 1995. Flow over flexible vegetation and 3-D structure of organized vortex associated with honami. *Journal of Hydraulic, Coastal and Environmental Enginerring,* 515, 33-43.

[10] ISHIGAKI, T., MUTO, Y. & SHIONO, K. 2010. Flow structure and resistance in compound open channel. *Nagare,* 29, 177-186.

[11] JARVELA, J. 2002. Flow resistance of flexible and stiff vegetation: a flume study with natural plants. *Journal of Hydrology* 269, 44–54.

[12] JESSON, M., STERLING, M. & BRIDGEMAN, J. 2010. Turbulent structures in heterogenous channels and their effects on conyeyance. First IAHR European Div. Congress., International Association for Hydro-Environment Engineering and Research (IAHR), Madrid, Spain.

[13] JESSON, M., STERLING, M. & BRIGDEMAN, J. 2013. Modelling flow in an open channel with heterogeneous bed roughness. *Journal of Hydraulic Engineering*, 139, 195-204.

[14] JIMENEZ, J. 2004. Turbulent flows over rough walls. *Fluid Mech*, 36, 173-96.

[15] KOUWEN, N. & UNNY, T. E. 1980. Flexible roughness in open channels. *Journal of Hydraulic Engineering-Asce,* 99, 713-727

[16] LU, S. S. & WILLMARTH, W. W. 1973. Measurements of the structure of the Reynolds Stress in a Turbulent Boundary Layer. *J. Fluid Mech*, 60, 481-511.

[17] LUHAR, M., ROMINGER, J. & NEPF, H. 2008. Interaction between flow, transport and vegetation spatial structure. *Environmental Fluid Mechanics*, 8, 423-439.

[18] MANES, C., POKRAJAC, D., MCEWAN, I. & NIKORA, V. 2009. Turbulence structure of open channel flows over permeable and impermeable beds: A comparative study. *Physics of Fluids,* 21, 125109(1-12).

[19] NAKAGAWA, H., NEZU, I. & UEDA, H. 1975. Turbulence of Open channel flow over smooth and rough beds. *Proceedings of JSCE,* 241, 155-168.

[20] NEPF, H. M. 2012. Hydrodynamics of vegetated channels. *Journal of Hydraulic Research*, 50, 262-279.

[21] NEPF, H. & GHISALBERTI, M. 2008. Flow and transport in channels with submerged vegetation. *Acta Geophysical*, 56, 753-777.

[22] NEPF, H. M. 2004. Vegetated flow dynamics. *Coastal and Estuarine Studies*, 59, 137-163.

[23] NEPF, H. M. & VIVONI, E. R. 2000. Flow structure in depth-limited, vegetated flow. *Journal of Geophysical Research*, 105, 28,547-28,557.

[24] NEZU, I. & SANJOU, M. 2008. Turburence structure and coherent motion in vegetated canopy open-channel flows. *Journal of Hydro-Environment Research*, 2, 62-90.

[25] NEZU, I., SANJOU, M. & OKAMOTO, T. 2006. Turbulent structure and dispersive properties in vegetated canopy open-channel flows. Proceedings of the International Conference on Fluvial Hydraulics, Lisbon, Portugal, 6-8 September 2006

[26] NEZU, I. & ONITSUKA, K. 2001. Turbulent structures in partly vegetated open-channel flows with LDA and PIV measurements. *Journal of Hydraulic Research,* 39, 629-642.

[27] NEZU, I. & NAKAGAWA, H. 1993. Turbulence in open-channel flows. IAHR Monograph, Rotterdam, A.A. Balkema.

[28] NEZU, I. 1977. Turbulence intensities in open-channel flows. *Journal of JSCE,* 261, 67-76.

[29] NIKORA, N. & NIKORA, V. 2010. Flow penetration into the canopy of the submerged vegetation: definitions and quantitative estimates. River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer, 438-444.

[30] NIKORA, V. I. & GORING, D. G. 1998. ADV Measurements of turbulence: can we improve their interpretation. *Journal of Hydraulic Engineering*, 124, 630-634.

[31] OKAMOTO, T. & NEZU, I. 2009. Turbulence Structure and Monami Phenomena in Flexible Vegetated Open Channel Flows. *Journal of Hydraulic Engineering*, 47, 798-810.

[32] RAHMAN, S. & WEBSTER, D. R. 2005. The effect of bed roughness on scalar fluctuations in turbulent boundary layers *Experiments in Fluids*, 38, 372–384.

[33] RAUPACH, M. & SHAW, R. 1981. Turbulence In and Above Plant Canopies *Annual Review of Fluid Mechanics*, 13, 97-129.

[34] REIDENBACH, M. A., LIMM, M., HONDZO, M. & STACEY, M. T. 2010. Effects of bed roughness on boundary layer mixing and mass flux across the sediment-water interface. *Water Resource. Res*, 46, 1-15.

[35] REYNOLDS, O. 1895. Philos. Trans. R. Soc. London. 186, 123-164.

[36] SHIONO, K. & KNIGHT, D. W. 1991. Turbulent open-channel flows with variable depth across the channel. *J. Fluid Mech*, 222, 617-646.

[37] STERLING, M., BEAMAN, F., MORVAN, H. & WRIGHT, N. 2008. Bed-shear stress characteristics of a simple, prismatic, rectangular channel. *Journal of Engineering Mechanics*, 134, 1085-1094.

[38] SUN, X. & SHIONO, K. 2010. Flow characteristics in vegetated compound channel. *Enviromental Hydraulics*, 233-239.