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Turbulent Kinetic Energy and Budget of Heterogeneous Open Channel with Gravel and Vegetated Beds

OP Folorunso

Department of Civil Engineering, Ekiti State University, Ado Ekiti, Nigeria

ABSTRACT

Turbulent kinetic energy (TKE) and budget are indispensable hydraulic parameters to determine turbulent scales and processes resulting from various and different natural hydraulic features in open channels. This paper focuses on experimental investigation of turbulent kinetic energy and budget in a heterogeneous open channel flow with gravel and vegetated beds. Results indicate the turbulent kinetic energy (TKE) value over gravel region of the heterogeneous bed remains approximately constant with flow depth. The highest turbulent kinetic energy was calculated for flexible vegetation arrangement compared to the rigid vegetation. The estimation of the turbulent kinetic energy budget shows the higher values of turbulence production recorded over the flexible vegetated bed, consequently, the dissipation rate exhibits faster decay of turbulence kinetic energy over the vegetated bed in comparison to the gravel bed.

***Corresponding author**

OP Folorunso, Department of Civil Engineering, Ekiti State University, Ado Ekiti, Nigeria. E-Mail: ftobex@ymail.com

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Introduction

The modified turbulent kinetic energy (K) in vegetated flow assumed to be steady can be expressed as [1]:

$$\frac{D\langle k\rangle}{Dt} = 0 = P_s + P_w + T_t + T_p + \varepsilon \qquad (1)$$

where Ps, is the shear production, P_w, the wake production, T_t, turbulent transport, T_p, pressure transport, and ε the dissipation. In a fully developed flow, the largest terms are the shear turbulent production P_s and dissipation ε. Under equilibrium conditions, these terms tends to be in balance and under non-equilibrium conditions, turbulent kinetic energy is transported either through turbulent transport T_t, or pressure transport T_p. Example of turbulent kinetic energy budget is showing in Figure 1 [1].

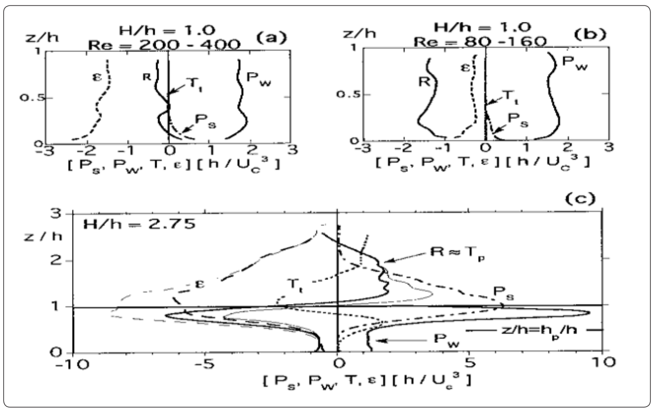


Figure 1: Turbulent Kinetic Energy for Emergent and Submerged Conditions [1].

Turbulent Intensity and Kinetic Energy

The magnitude of turbulence can be quantified using the turbulence intensity, i.e,

$$I_x, I_y, and\ I_z = \frac{\sigma_x}{U}, \frac{\sigma_y}{U}, and\ \frac{\sigma_z}{U} \qquad (2)$$

Where σ is the standard deviation of the velocity fluctuation. Experimental observations in open channel flows have shown that the turbulence intensity will be greater near the channel boundary where turbulence is being generated, and decrease with depth away from the boundary towards the free surface [2]

Turbulence Kinetic Energy (K)

With turbulence being transferred by the turbulent kinetic energy (K), the K relates the mean kinetic energy per unit mass of fluid with the turbulent eddies; this is characterized by the three dimensional turbulence intensities. The turbulent kinetic energy $\frac{1}{2}(u'^2 + v'^2 + w'^2)$ was obtained on the basis of the turbulence intensity values along the streamwise, lateral, and vertical directions.

Material and Methods

The experiments were conducted in 22mm long rectangular re-circulating flume of width B=614*mm* 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 130*mm* width to depth ratio (*B/H*) 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 ($0 \leq {}^{y}/_{B} \leq 0.5$), the interface occurs at (${}^{y}/_{B}=0.5$), and the vegetated region extends over ($0.5 \leq {}^{y}/_{B} \leq 1.0$), wherey 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 2 shows the bed configuration for EXPT1 and EXPT2 [4-10].

Figure 2: Bed Configuration for EXPT1 and EXPT2

Results and Discussion

Figures 3 and 4 show the lateral distribution of the turbulent kinetic energy for CRS3. Figure 3 shows that the maximum value of turbulent kinetic energy (K) occurs near bed (${}^{z}/_{H} \leq 0.2$) over the vegetated zone. For depths greater than ${}^{z}/_{H} \cong 0.2$, the turbulent kinetic energy value reduces towards the free surface. However, the TKE value over gravel region in EXPT2 remains approximately constant with flow depth (Figure 4). The highest turbulent kinetic energy was calculated for flexible vegetation arrangement compared to the rigid vegetation [11-20].

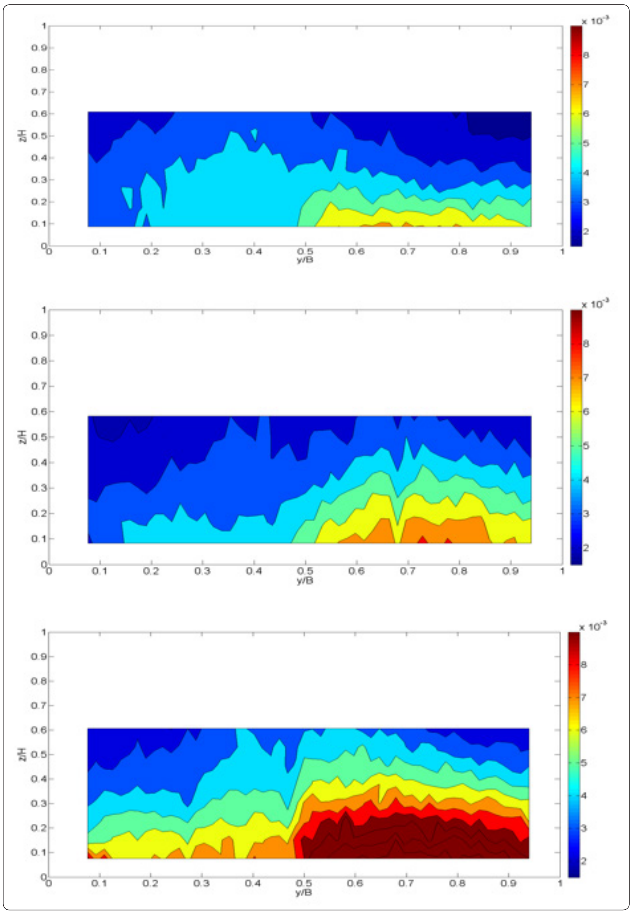


Figure 3: Lateral Disribution of Turbulent Kinetic Energy (K) at CRS3 EXPT1

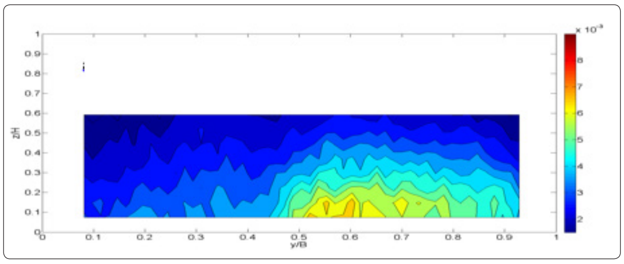
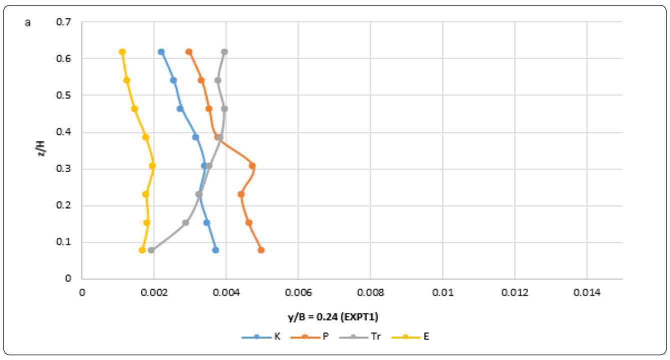


Figure 4: Lateral Disribution of Turbulent Kinetic Energy (K) CRS3 (bottom) EXPT2

Turbulent Energy Budget

To clarify further the structure of turbulence in the flow, the turbulent energy terms were explored using the velocity data to explain the relative significance of the processes that control the turbulent flow. The turbulence kinetic energy was obtained as described in the introduction, the vertical turbulence transport (vertical flux) was obtained as $T_r = \frac{\partial w' K}{\partial z}$, the turbulence production $P = -\overline{uw}\frac{\partial U}{\partial z}$ and dissipation $E = \nu\left(\frac{\partial U}{\partial z}\right)^2$ where ν is the kinematic viscosity [3]. Figure 5 and Figure 6 show the turbulence terms for the flow, with the values normalized by the depth of flow. Both the turbulence production and the turbulence kinetic energy attained maxima near the bed, and decrease towards the free surface (Figure 5 and Figure 6). In contrast, the turbulence transport T_r tends to increase towards the free surface when compared with other turbulence terms; this indicates the transport of the near bed turbulent energy towards the free surface. Similar mechanisms have been observed by others [3]. Hence, in this region, *Tr* serves as source of turbulence compensating for reduced turbulence production at the free surface. However, it should be noted that the high turbulence intensity near the bed over the vegetated region (Result not presented) in EXPT1 indicates an inflection point; this becomes an essential source of turbulence generation hence enhancing turbulence production and kinetic energy over the vegetated bed relative to gravel bed. It can be observed that the higher values of turbulence production are recorded over the vegetated bed in EXPT1 (Figure 5b). However, comparison with turbulent intensity shows that this is enhanced by the vertical velocity fluctuating component of the flow. Turbulence production over the vegetated bed in EXPT2 is comparable to the turbulence production over the gravel bed with similar magnitude of production terms (Figure 6a and 6b). The dissipation rate exhibits faster decay of turbulence kinetic energy over the vegetated bed in comparison to the gravel bed (Figure5and6) [21-40].



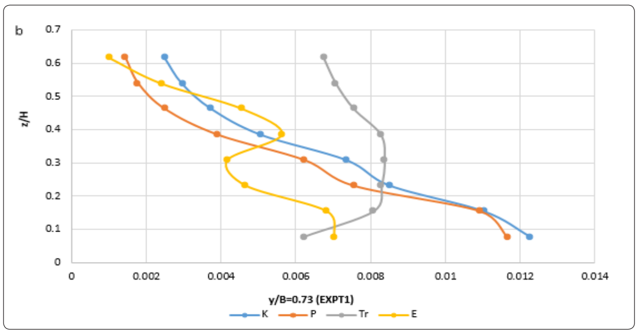


Figure 5: Vertical Distribution of the Turbulent Energy Terms (EXPT1): (a): Gravel Bed (b): Vegetated Bed

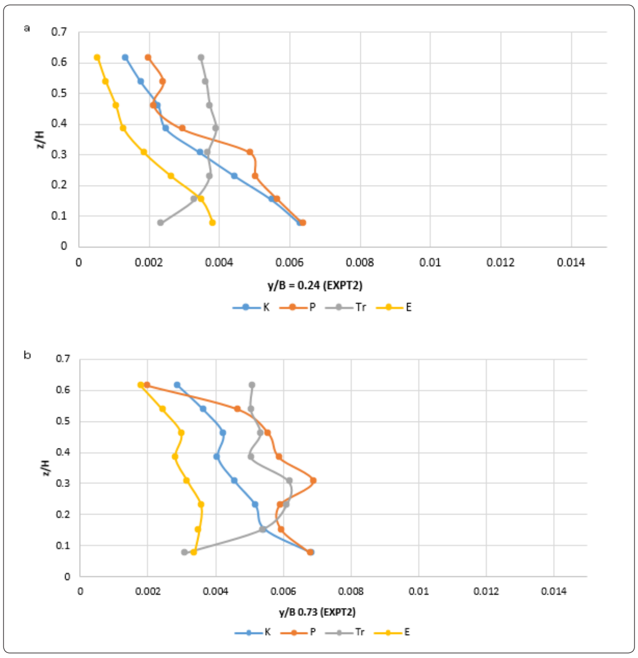


Figure 6: Vertical Distribution of the Turbulent Energy Terms (EXPT2): (a): Gravel Bed (b): Vegetated Bed

Conclusion

It is concluded from the current research work that the maximum turbulence production and kinetic energy attained maxima near the bed due to shear, and decreases towards the free surface. However, the near bed turbulent energy is transported towards the free surface hence tends to increase turbulent transport T_r towards the free surface when compared with other turbulence terms [41-51].

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