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# VELOCITY AND TURBULENCE DISTRIBUTION IN UNSTEADY OPEN CHANNEL FLOWS THROUGH AN EMERGENT RIGID STEMS

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## ABSTRACT

Most open channel flows of interest of hydraulic engineers and hydrologists are unsteady. In unsteady flow, some aspects of flow (velocity and depth etc.) are changing in time. But many problems related to unsteady flow have been approximately solved by assuming steady flow or non-uniform flow (for example, constant peak discharges in floodplains without taking the time as a factor). Also, the understanding of vegetated flows under unsteady flow is of primary importance since a new trend on river management consists in restoring rivers and floodplains to their natural form. The present laboratory study focuses on the particular case unsteady flow with combination of highly submerged rigid grass and emergent rigid stems (representing the wood). One hydrograph is passed repeatedly with 100 runs through the rectangular flume using a fixed rigid grass bed with rigid circular stems. Classical hysteresis effect between rising and falling limbs in stage-discharge (h ~ Q) rating curve is illustrated.

***Keywords:*** *open channel flow, emergent rigid vegetation, unsteady flow, laboratory study, velocity profiles, Reynolds stress*

## 1. INTRODUCTION

Flows in the natural rivers and channels are often unsteady. Unsteady flow in open channels allows the flow cross-section to freely change, a factor which has an important influence on the rate of transient change propagation. Accurate knowledge of the velocity distribution in an open channel in unsteady flow is of crucial importance to practicing engineers as it helps in the accurate estimation of erosion, sediment transport apart from the estimation of flood flows. When some obstacles separate the floodplain from the main channel (dyke, dense tree row), the flow in the floodplain can be seen as independent from the main channel flow and thus should be studied in a single channel configuration. Tu (1992) demonstrated that the log-law, in association with Coles' wake law, could be used to describe vertical velocity profiles if the unsteadiness was accounted for the wake parameter. In addition, a parameter was introduced in the formulation of the Clauser parameter that was a function of the relative roughness of the bed and a power law form was introduced for the mean velocity profile. Song and Graf (2002) studied experimentally unsteady flow properties in an open channel with a rough bed. Acoustic Doppler velocity profiler (ADVP) was used to obtain instantaneously the flow profiles. From these measurements, using the Fourier components method, the mean velocities, the turbulence intensities and the Reynolds-stress profile, were obtained. Thirty-three different hydrographs were experimentally investigated. Haizhou & Graf (2010) investigated experimentally on the friction in unsteady open-channel flow over gravel beds. Tognin et al. (2019a) studied the propagation of a solitary wave in the presence of emerging rigid cylinders mimicking the propagation of tsunamis through mangrove forests. Four scenarios were investigated. Specifically, it was observed that the vegetation strongly affects the wave behavior, reducing the wave height proportionally with the vegetation density. During base flow conditions, the vertical velocity profile clearly showed a logarithmic profile in bare soil condition, whereas it turned into a rather uniform velocity distribution in the presence of vegetation. Tognin et al., (2019b) aimed to present a peculiar experimental set up, designed to investigate the interaction between solitary waves and rigid emergent vegetation.

To the authors' knowledge, detail study on velocity profiles and Reynolds stresses under steady flow conditions through rigid vegetation have been found from the previous literature. However, the knowledge on velocity profiles and Reynolds stresses through the rigid vegetation array under unsteady flow conditions is not well investigated. So, the present study investigates a direct measurement of velocity profiles and Reynolds stresses under unsteady flow conditions.

## 2. THEORETICAL CONSIDERATION

### 2.1 Governing equation

The governing equation for unsteady and two-dimensional open-channel flow can be obtained from the Navier-Stokes equation [e.g., see (Leupi et al., 2009, Nezu and Nakagawa, 1993a (IAHR monograph)]

$$\frac{\partial U_x}{\partial t} + \frac{\partial {U_x}^2}{\partial x} + \frac{\partial U_x U_z}{\partial z} = g\,sin\,\theta - \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(\frac{\tau}{\rho}\right) \quad (1)$$

$$0 \cong -g\,sin\,\theta - \frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{\partial}{\partial z}\left(-{u_z}^2\right) \quad (2)$$

$$\frac{\tau}{\rho} \equiv -\overline{u_x u_z} + \nu\frac{\partial U_x}{\partial z} \quad (3)$$

where $U_x$ and $U_z$= mean velocity components, $u_x$ and $u_z$ = turbulence fluctuations in the stream-wise ($x$) and vertical ($z$) directions, respectively; $P$ = mean pressure, $g$ = acceleration due to gravity, $\nu$ = kinematic viscosity, $\rho$ = density of water, and $\tau$ = total shear stress. The mean pressure $P$ is approximately given by the hydrostatic distribution from (2) as follows:

The unsteady flow parameter ($\alpha$) value was also experienced as a long duration flood in the flow with the larger rising time period (say, 2040s). In the present study, the unsteady parameter, $\alpha$ was calculated and found to be $4.87\times10^{-4}$.

## 3. EXPERIMENTAL SETUP AND MEASURING INSTRUMENTS

The experiments were carried out in a 12m long, 0.6m wide and 0.6m deep, rectangular, tilting flume in the Hydraulics Engineering Laboratory (H. E. Lab.) at National Institute of Technology Rourkela, India. A schematic diagram of the experimental setup is shown in Figure 1. Photographs of the experimental set-up and staggered rigid vegetation pattern, H. E. Lab., NITR is shown in Figure 2. A longitudinal slope ($S_0$) of approximately 1.2cm in 10m was set and kept unchanged throughout the experimental program. To get the desired flow depths for the hydrograph, different tail-gate settings with several experimental runs were performed (Khuntia et al., 2018).

**Table 1.** Geometry and roughness parameters for the experimental study

| Sl. no | Item Description | Parameters |
|---|---|---|
| 1 | Channel type | Straight |
| 2 | Geometry of channel section | Rectangular |
| 3 | Channel base width (*b*) | 0.6m |
| 4 | Depth of channel | 0.6m |
| 5 | Bed slope ($S_0$) | 0.0012 |
| 6 | Length of flume | 12m |
| 7 | Length of test channel (*X*) | 10m |
| 8 | Flow condition | Un-steady |
| 9 | Nature of surface bed | Dense rigid grass with rigid vegetation |

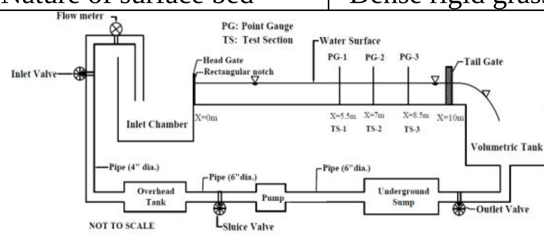


**Figure 1.** A schematic diagram of the experimental setup, NITR

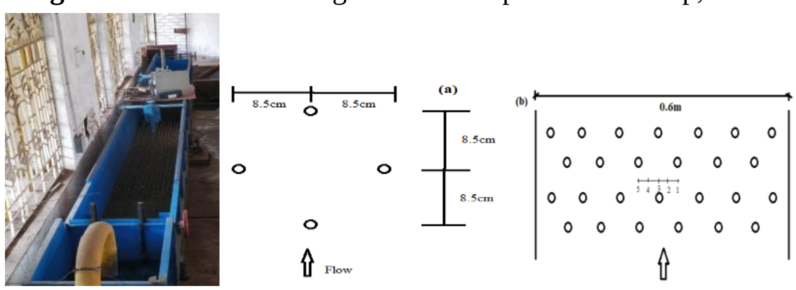


**Figure 2.** Photographs of the experimental set-up and staggered rigid vegetation pattern, H. E. Lab., NITR

## 4. RESULTS AND DISCUSSIONS

A total of 100 hydrographs (i.e., 20 hydrographs repeated at each section) were injected and investigated during the experimental repetition process. The flow and depth hydrographs in an unsteady flow run have been shown in Figure 4. The hysteresis plot of stage-discharge ($h \sim Q$) rating curve between rising and falling limbs is illustrated in Figure 5.

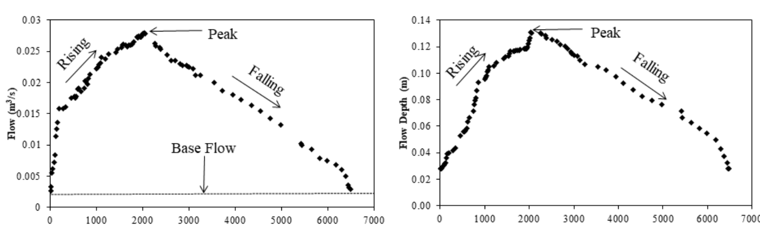


**Figure 4.** Flow and depth hydrograph in an unsteady flow run

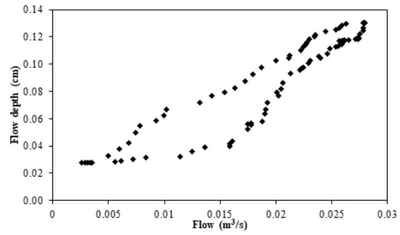


**Figure. 5.** Hysteresis plot of stage-discharge curve

## 4.1 Velocity profiles

Through an array of emergent rigid cylinders, constant velocity distribution was observed except bed region (boundary layer region) and free surface region except location 3 (see figure 6). The location 3 which located at 42.5 mm upstream of the cylinder axis (see figure 2); a local increase in the longitudinal velocity within the boundary layer (resulting in a velocity bulge in the vertical profile) was observed. The velocity bulge has been related to the effect of bed-induced turbulence. From both figures (figure 6), it was also noticed that there is a higher velocity during the rising limb than during the falling limb. This was caused as the flow conveyance was higher during the rising limb than the falling limb

*Longitudinal Velocity profile for Flow depth at 0.07m*

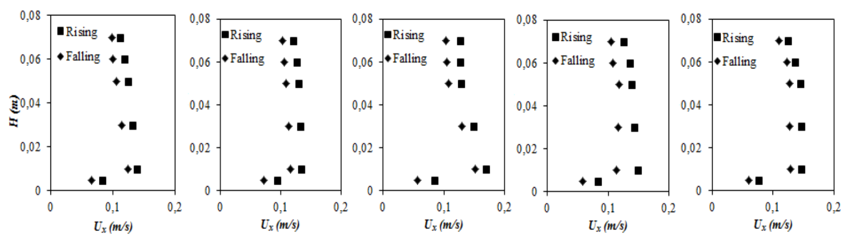


**Figure 6.** Velocity profiles for lower flow depth case (left to right: location 1 to location 5)

## 4.2 Reynolds shear stresses distribution

Through an array of emergent rigid cylinders, it was observed that vertical Reynolds stresses distribution gradually decreased towards the water surface (see figure 8 and 9).

*For flow depth 7cm*

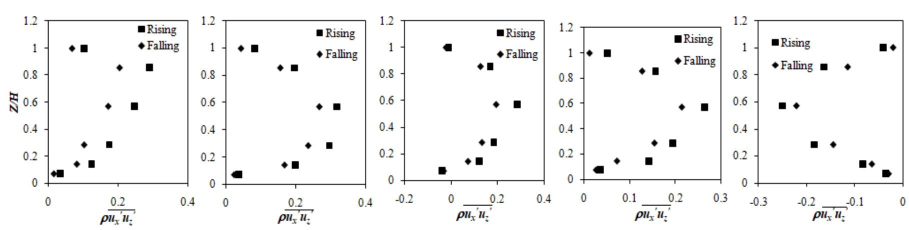


**Figure 7.** Distribution of vertical Reynolds stress for lower flow depth case (left to right: location 1 to location 5)

The positive magnitude of Reynolds stresses were observed except in position 5. The position 5 was influenced by upstream stem and causes negative magnitude of Reynolds stresses. From both figures (figure 7), it was also noticed that there is a higher in Reynolds stress during the rising limb than the falling limb. This was caused the Reynold number was higher during the accelerated limb than the decelerated limb.

## 5. CONCLUSIONS

The following concluding remarks have been drawn from the present study:

1. Experiments have been conducted to investigate the velocity and Reynolds stresses under unsteady flow conditions in open channel over a rough bed with emergent rigid vegetation.
2. In the present study, three unsteadiness parameters (i.e., $\eta$, $\lambda$, $\alpha$) have been considered to characterize the hydrograph.
3. Velocities during the rising limb have been found to be higher as compared to the falling limb cases for the same flow depth. The velocity bulge has been observed at downstream of the stem in both the higher and lower flow depth cases.
4. The Reynolds shear stress, $-\rho\overline{u_x'u_z'}$ values have been observed to be higher in case of rising limb than that of falling limb cases. The values of $-\rho\overline{u_x'u_z'}$ have been found to be decreased and negative magnitude at location 5 which has been influenced by wave induced by the upstream stem.

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