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Velocity Distribution in Open Channels with Sand: An Experimental Study

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***Abstract*—**In this study, laboratory experiments in open channel flows over a sand bed were conducted. A porous bed (sand bed) with porosity of ε=0.70 and porous thickness of s′=3 cm was tested. Vertical distributions of velocity were evaluated by using a two-dimensional (2D) Particle Image Velocimetry (PIV). Velocity profiles are measured above the impermeable bed and above the sand bed for the same different total water heights (h= 6, 8, 10 and 12 cm) and for the same slope S=1.5. Measurements of mean velocity indicate the effects of the bed material used (sand bed) on the flow characteristics (Velocity distribution and Reynolds number) in comparison with those above the impermeable bed.

Keywords—Particle image velocimetry, sand bed, velocity distribution, Reynolds number.

I. Introduction

SAND plays a significant role in flow characteristics compared with conditions in rivers with no sand. The presence of sand influences the flow characteristics in open channel flow, such as velocity distribution and Reynolds number. The most important topic in the study of geophysical flows is the form of the velocity distribution.

Flow phenomena and the associated momentum transfer near the permeable bed are encountered in various fields (environmental hydraulics, geophysical fluid dynamics, mechanical engineering, among others). In all problems, the knowledge of the flow interaction above the permeable bed and the momentum transfer in the interfacial region are very important and needed for the water quality aspects of the region.

Initially, Beavers and Joseph [1] used a porous medium with high permeability and laminar flow in a closed channel and found an empirical relationship for the interfacial slip velocity. They noticed an increase of mass flow over a permeable bed in comparison with the fluid flow over an impermeable bed.

The study of turbulent flow near a permeable wall (porous bed) is limited due to the additional difficulties because of the turbulence distributions. The first complete study for the turbulent flow has been realized by [2]. They found analytical results for the turbulent flow characteristics over a porous bed and for the velocity distribution within the porous bed. They found the following law of the wall for the turbulent flow over a porous bed, using a general expression for the shear stress $\overline{uv}$:

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$$\frac{U}{U_*} = \frac{1}{\kappa}\ln\left(\frac{y + z_1}{z_1}\right) + \frac{U_{int}}{U_*} \qquad (1)$$

where U∗ = shear velocity, κ = von Karman constant, z_1 = coefficient dependent on porous characteristics, U_{int}= interfacial velocity. The application of the above equation is rather difficult since the interfacial velocity U_{int} and the von Karman constant must be known. The latter is not necessarily equal to 0.41 due to momentum transfer effects from the fluid to porous region.

Wilson et al. [3] carried out laboratorial experiments to study the effect of flexible vegetation on open channel flow. They used two different forms of vegetation a) flexible rods of constant height and b) the same rods with a front foliage attached. Experimental results revealed that within the plant layer, the velocity profile no longer followed the logarithmic law profile and the mean velocity for the rod/frond canopy was less than half of that observed for the simple rod array. The turbulence intensities indicated that the additional superficial area of the fronts alters the momentum transfer between the within-canopy and surface flow regions. Finally, this research indicated that the plant form can have a significant effect on the mean flow field, and therefore potentially influence riverine and wetland system management strategies.

In [4], results (experimental and computational) for turbulent flow over and within a porous bed have been presented. The simulation has been achieved with the use of rods bundle.

Keramaris and Prinos [5] investigated experimentally the turbulent flow in an open channel with permeable bed. The permeable bed is simulated initially with porous filters and then with flexible vegetation. Measurements of mean velocity and turbulent characteristics (Reynolds stresses) reveal the effect of the material used (filters, vegetation), ε and s′/h on the flow characteristics.

In [6], the effects on the velocity distribution of turbulent flow in an open channel in a half-separated (impermeable and permeable) bed were studied experimentally using a PIV. A grass-like vegetation of 2 cm height was used for the simulation of the half permeable bed (with 3.75 cm width). Velocity is measured on the centreline 3.75 cm above the vegetation for the permeable bed at the corresonding point above the impermeable bed as well as at the interface between impermeable and permeable bed in the mid-plane of the channel. Results show that the presence of half-separated impermeable and permeable bed influences the values of velocity distribution in comparison with situations over permeable or impermeable bed. The comparison with the same experiments when it has transition from permeable to impermeable bed and vice versa shows that there are a lot of differences in velocity distribution.

Finally, in [7], laboratory experiments are used to explore the effect of porous bed on the turbulent characteristics of the flow in an open channel using a PIV. Hydraulic characteristics such as velocity distributions, turbulent intensities and Reynolds stress are investigated. Experiments were carried out, with four types of porous bed with the same porosity ε = 0.70 and the same porous thickness (3 cm): (a) porous filter, (b) rods bundle, (c) grass vegetation and (d) gravel bed. Turbulent characteristics are measured above the porous bed for the same different water heights (h´= 3, 5, 7 and 9 cm) and for the same slope S = 1.5. The results show that the bed type can significantly influence the turbulent characteristics of the flow.

In the present work the characteristics of turbulent flow above a sand bed are studied experimentally with the use of a 2D PIV. Measurements of mean velocity were taken above impermeable and permeable bed. Results show that presence of sand bed influences significant the velocity distribution and Reynolds number of the flow in comparison with similar experiments for impermeable bed.

II. Experimental Setup and Procedure

Experiments were conducted in a channel with 6.5 m length, 7.5 cm width and 25 cm height in the laboratory of Hydraulics in the department of Civil Infrastructure Engineering of Alexander Technological Educational Institute of Thessaloniki, Greece.

Totally eight experiments for the same different total water heights (h= 6, 8, 10 and 12 cm) and for the same slope S = 1.5 were carried out. The porous bed (sand bed) had a porosity of ε=0.70 and porous thickness of s´=3 cm. The water depth above the sand bed was h´= 3, 5, 7 and 9 cm. Reynolds number ($\mathrm{Re} = U_{mean} \cdot h / \nu$), ($U_{mean}$= mean velocity, h= total flow depth and v=kinematic viscosity), ranged between 10000 and 21000 which means that the flow was fully turbulent. The water temperature was approximately constant at 20 ^{0}C.

The morphology of the impermeable and sand bed and the geometrical characteristics of the flow are presented in Figs. 1 and 2 and the characteristics of the experiments are presented in Tables I and II.

The PIV system used for the measurement of the velocity distribution in the flow domain was a two dimensional one consisting of a twin pulsed Nd: Yag lasers (532 nm wavelength, 300 mJ / pulse at 10 Hz), a cross correlation 8bit 1Kx1K CCD camera (Kodak, MEGAPLUS ES 1.0), a synchronizer, a computer, an image acquisition system and a PIV analysis software (Insight 3G).

The laser beams were combined and formed a 1mm wide sheet by using semi-cylindrical optics. The camera image size had 1600x1192 pixel array and the dimension of the velocity field was kept to 291 mm x 214 mm for all the experiments. It means that the resolution of the captured images was typically 5.5 pixel/mm or that the pixel length was 0.1818 mm.

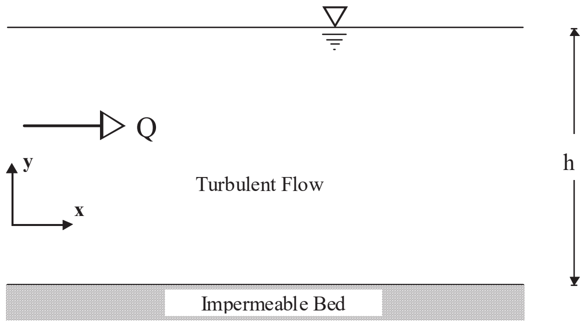

Fig. 1 Geometrical characteristics of the flow above impermeable bed

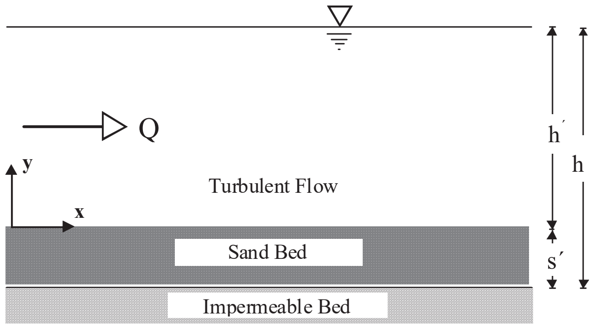

Fig. 2 Geometrical characteristics of the flow above sand bed

TABLE I
Characteristics of the Experiments

Total flow depth h (cm)	U_{mean}(m/s)	Reynolds Number $\mathrm{Re} = \frac{Uh}{\nu}$
6	0.272	16320
8	0.224	17920
10	0.186	18600
12	0.174	20880

Impermeable Bed

TABLE II
Characteristics of the Experiments

ε	s´(cm)	Total flow depth h (cm)	U_{mean}(m/s)	Reynolds Number $\mathrm{Re} = \frac{Uh}{\nu}$
	3	6	0.181	10860
0.70	3	8	0.159	12720
	3	10	0.119	11900
	3	12	0.009	10800

Sand Bed s´=3 cm

The laser was installed above the tank at a distance of 50 cm from the illuminated water free surface, while the camera viewed from an orthogonal direction. Twin images were recorded with a time separation of 2 msec. 200 pairs of images were captured in each experiment. The plane photographs were divided into interrogation spots measuring 32x32 pixels (5.79 mm x 5.79 mm). The experimental apparatus is presented in Fig. 3.

The cross correlation between the interrogation spots determined the mean displacement of the particles and thereof the velocity vector. The cross correlation operation was based on the correlation theorem, stating that the correlation on the spatial domain becomes multiplication on the frequency domain. Adjacent interrogation spots were overlapped by 50%, providing a resolution of about 3 mm. After that calculation, the velocity data were filtered with a signal-to-noise filter, a peak height filter, and global and local filters in order to remove error vectors.

The fluid was seeded with tracer particles which, for the purposes of PIV, were generally assumed to follow the flowdynamics [8]. These particles had size of about 10 μm in clean water. The motion of the seeding particles was used to calculate the velocity profile of the flow. Other techniques used to measure flows are Laser Doppler velocimetry [9]-[11] and Hot-Film anemometry [12], [13]. The main difference between PIV and those techniques is that the former produces two dimensional vector fields, while the other techniques measure the velocity at a point. PIVs use the particle concentration method to identify individual particles in an image and follow their flow; however, tracking particles between images is not always a straightforward task. Individual particles could be "followed" when the particle concentration is low, a method called particle tracking velocimetry, whereas laser speckle velocimetry is used for cases where the particle concentration is high. The distance between two neighbour velocity vectors was 3.00 mm. The experimental uncertainty of the measured velocity with this technique was approximately ± 2% [14].

The measurements were conducted at a 4 m distance from the channel's entrance where the flow was considered fully developed. The full development of the flow was evaluated comparing the velocity distributions above the porous bed in two vertical sections with a 60 cm separation distance. The uniformity of the flow was checked measuring the flow height with point gauges at two cross-sections (4 m between the two sections). The desirable flow height in the downstream section could be controlled using a weir at the channel's outlet. The error of the measured flow depth with the point gauge was ± 0.1 mm.

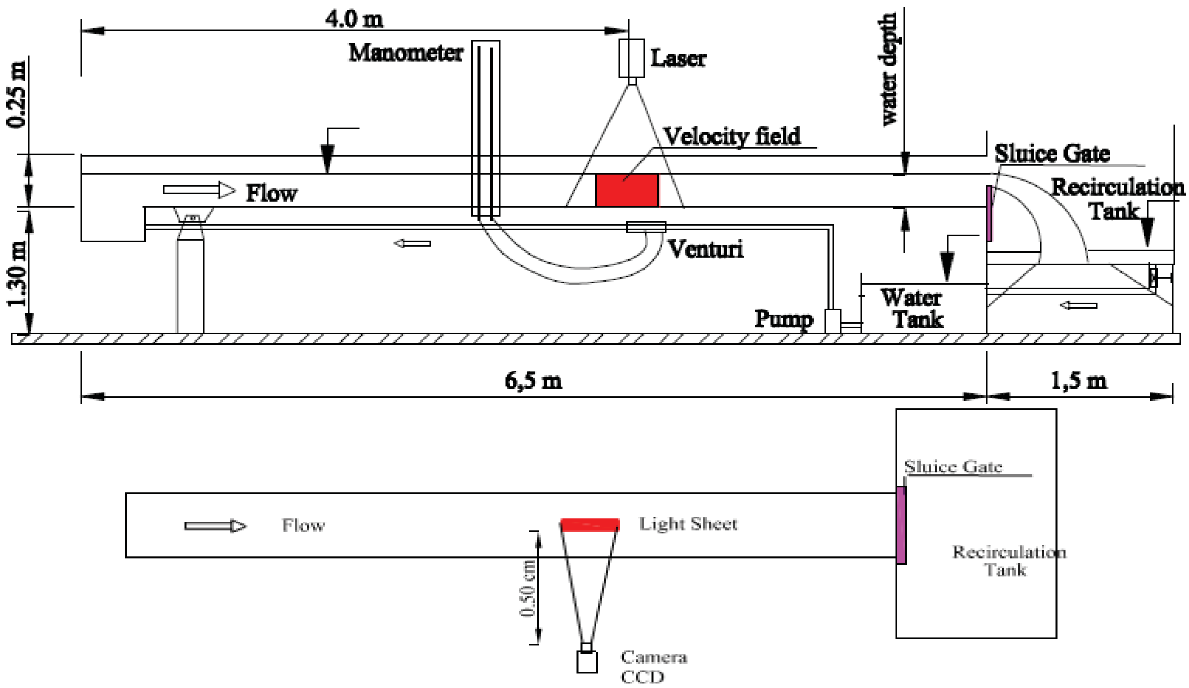

Fig. 3 Experimental apparatus

III. Analysis of Experimental Results

The distribution of the velocity above the impermeable bed is shown in Fig. 4 for all water heights. It is obvious that the velocity increases when the water height decreases. The distribution of the velocity above the sand bed is shown in Fig. 5 for all water heights. It is clear that the penetration of the flow influences the velocities over the sand bed. This penetration reduces the velocities in comparison with the impermeable bed. As seen in Fig. 6, the comparison between impermeable and sand bed for the same water height shows this decrease of the velocities in the case of the sand bed.

From Fig. 5 for sand bed, an approximately zero velocity until h=1cm it is observed. This means that 50% of sand bed behaves as an impermeable bed.

Fig. 7 shows the velocity distribution above the sand bed for $h/s'=2$ and $h/s'=4$ (h: total water heights, s′: porous thickness=3 cm). The logarithmic law for flow over a solid, impermeable bed with depth h is also illustrated. We use dimensionless velocities calculating the friction velocity U_*

($U_* = \sqrt{gRS}$, where S is the slope of the channel and R is the hydraulic radius) and the distance from the interface y with the ratio U_* /v. This normalisation allows us to evaluate the applicability of the logarithmic law for these conditions, using the general expression for the shear stress $\overline{uv}$:

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln\left(\frac{y + z_1}{z_1}\right) + \frac{U_{\text{int}}}{U_*}$$

Velocities are below the logarithmic law line which indicates that velocities above the sand bed are reduced in comparison with the velocities over an impermeable bed. In particular, the velocities are reduced with decreasing h/s´ ratio due to the greater influence of the vegetation on the flow above it.

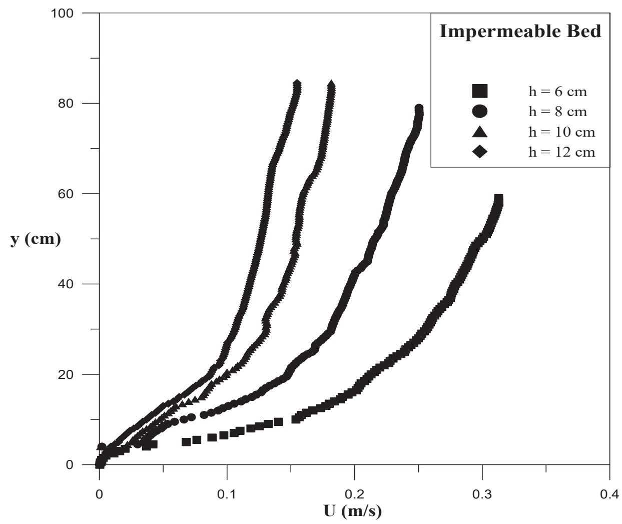

Fig. 4 Velocity distribution for impermeable bed

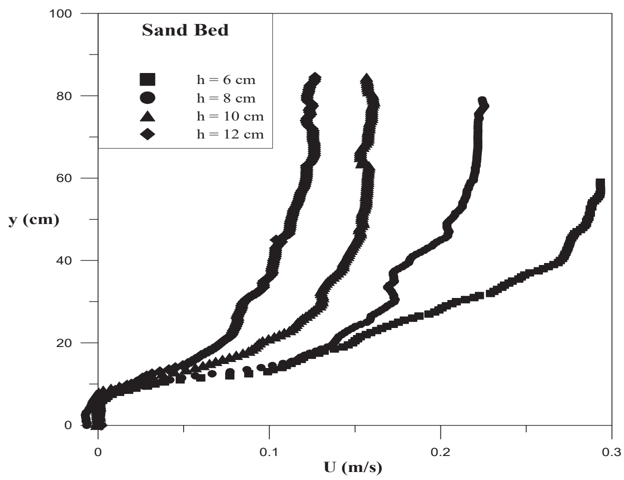

Fig. 5 Velocity distribution for sand bed

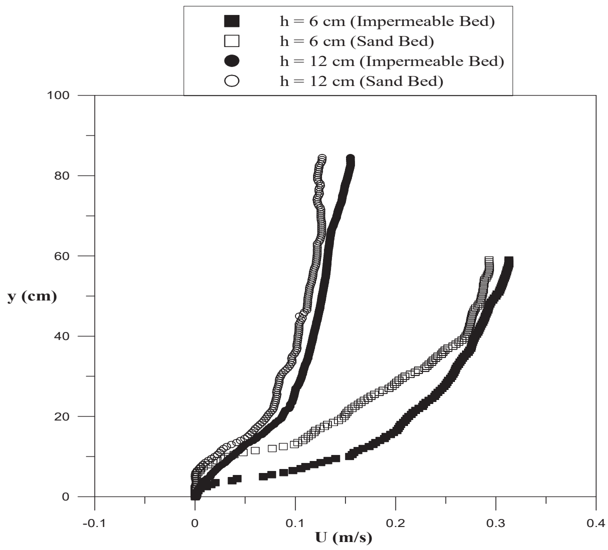

Fig. 6 Velocity distribution for both beds for h=6cm and h=12cm

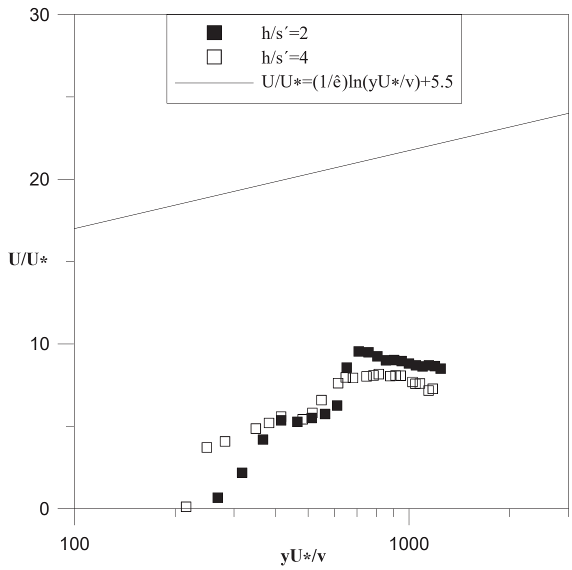

Fig. 7 Dimensionless velocity (h/s´) distribution

IV. Conclusions

In this study, the characteristics of turbulent flow above a sand bed are studied experimentally with the use of a 2D PIV.

The main conclusion of this study is that the presence of sand bed influences significant the velocity distribution and Reynolds number of the flow in comparison with similar experiments for impermeable bed.

The following conclusions can be derived:

- The velocities over the sand bed are lower as regards the velocities over the impermeable bed. This is due to the greater penetration of the flow in the case of the sand bed.
- Approximately zero velocity until h=1 cm for sand bed is observed. This means that 50% of sand bed behaves as an impermeable bed.

- The velocities are reduced with decreasing h/s´ ratio due to the greater influence of the sand bed on the flow above it.

Experiments will continue using several sand bed heights and total water depths; particularly focusing on water depths higher than 12 cm.

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