The different impact of rods bundle in an inclined open channel in comparison with other permeable beds

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Abstract: In order to experimentally investigate the impact of rods bundle in an inclined open channel, a series of laboratory experiments were performed to investigate the different impact between rods bundle and other permeable beds. In the other cases the permeable bed is simulated using two different types of vegetation: a) grass vegetation and b) gravel bed. All the permeable bed (rods bundle, grass vegetation and gravel bed) have the same thickness \( h_v = 5.5 \text{cm} \) and the same porosity \( \varepsilon = 0.75 \). Laboratory experiments were used for the calculation of the turbulent velocity profiles. The measurements were obtained using a two-dimensional (2D) Particle Image Velocimetry (PIV). Measurements of velocity were taken for inclined channel for three different slopes \( S \) (\( S = 1\% \), \( 3\% \) and \( 5\% \)), for the same three different heights \( h' \) over the permeable bed (\( h' = 2.0 \text{cm}, 3.0 \text{cm} \) and \( 4.0 \text{cm} \)) and for the same discharge (\( Q = 1.0 \text{t/s} \)). The results indicate that the presence of rods bundle impact with different way the velocity distribution in comparison with other permeable beds. Also results showed that the presence of rods bundle in inclined open channels influence significantly different the turbulent characteristics of the flow (turbulent intensities and turbulent shear stresses) in comparison with other permeable beds (grass vegetation or gravel bed).

Key-Words: Turbulent Flow, Experimental Analysis, Particle Image Velocimetry, Permeable Bed, Velocity Distribution, Turbulent Intensity, Turbulent Shear Stress.

1 Introduction
Vegetation is an important component of aquatic ecosystems and it is important to analyse many physical processes involved in the ecosystem at different spatial and time scales.

Previous studies report turbulence data obtained from hot-film anemometry (Antonia and Krogh [1], Prinos et al. [2]), laser Doppler anemometry (Tachie et al. [3], Bergstrom et al. [4], Balachandar and Patel [5]) or acoustic Doppler velocimetry (Lopez and Garcia [6], Hurther and Lemmin [7], Nikora and Goring [8]).

Stephan and Gutknecht investigated the resistance of submerged flexible aquatic vegetation on the flow. They described the flow resistance of the natural macrophytes used by means of equivalent sand roughness and they found out that the latter as well as the zero plane displacement of the logarithmic velocity profile were of the same order of magnitude as the mean deflected plant height and increased with increasing plant height [9].

Bigillon et al. investigated experimentally the turbulent characteristics of open-channel flows under transitionally-rough wall conditions. Vertical distributions of the velocity, turbulent intensities and vertical flux of turbulent kinetic energy were investigated using a PIV over a transitionally-rough fixed bed. Results were further compared with those obtained for smooth, rough and transitionally-rough walls. The results are in good agreement with those previously obtained on smooth walls and provide further evidence that PIV can be applied successfully to investigate turbulence in open channel flows over a rough bed [10].

Pechlivanidis et al. investigated experimentally the turbulent characteristics of open-channel flow using Particle Image Velocimetry. Results show that velocity over the vegetation region is a function of the vegetation height and the total flow depth; velocity decreases as the vegetation height increases. In addition, we show that velocities above the vegetation region are much lower than velocities above an impermeable bed. This is due to the turbulent shear stresses and the existence of turbulence in the vegetation region, which reduce the mean velocity above the vegetation region [11].

The width of the channel is only 7.5cm but it doesn’t influence the magnitude of the velocities. Keramaris et al. carried out experiments to investigate the impact of lateral walls on the velocity profile in an open channel with 7.5cm wide.
Results from these experiments showed that the lateral walls influenced the velocities at a distance limited to 0.4cm from the walls. This result indicates that the wall doesn't influence the instantaneous velocities in the central area of the channel where the velocity measurements are usually conducted. The impact of the lateral walls on the flow dynamics in the rest of the channel is negligible [12]. Nyantekyi-Kwakye et al. investigated experimentally the effects of bed roughness on the turbulence characteristics of shallow open channel flows. The mean velocities and Reynolds stresses for the two smooth cases were observed to be weakly dependent on Reynolds number. The effect of bed roughness was observed to penetrate into the outer layer of the boundary layer. The results show that bed roughness significantly increased the skin friction coefficient, wake parameter, boundary layer parameters, as well as the mean velocity, Reynolds stresses and the energy budget terms. A two-point correlation analysis showed that the coherent structures were also significantly modified by bed roughness [13].

Finally in the study of Keramaris and Pechliyanidis 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 2-D Particle Image Velocimetry (PIV). PIV is an optical method of fluid visualisation that is used to obtain instantaneous velocity measurements on a plane of a flow field. A grass-like vegetation of 2cm height was used for the simulation of the half permeable bed (with 3.75cm width). Velocity is measured on the centreline 3.75cm above the vegetation for the permeable bed at the corresponding 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 on velocity distribution [14].

In this study, in order to experimentally investigate the impact of rods bundle in an inclined open channel, a series of laboratory experiments were performed to investigate the different impact between rods bundle and other permeable beds. In the other cases the permeable bed is simulated using two different types of vegetation: a) grass vegetation and b) gravel bed. All the permeable beds (rods bundle, grass vegetation and gravel bed) have the same thickness hv=5.5cm and the same porosity ε=0.75.

Laboratory experiments were used for the calculation of the turbulent velocity profiles. The measurements were obtained using a two-dimensional (2D) Particle Image Velocimetry (PIV). This optical method of fluid visualisation is used to obtain instantaneous velocity measurements related properties in the fluids. The PIV method assumes that the particles of a fluid faithfully follow the flow dynamics; hence the motion of these seeding particles is used to calculate the dynamic characteristics of the flow.

The measurements were conducted at a 12X10cm² region in a distance of 4m from the channel’s entrance, where the flow is considered fully developed. The uniformity of the flow was checked measuring the flow depth with point gauges at two cross-sections (2m distance between the two regions). The total discharge was estimated using a calibrated venture apparatus. Measurements of velocity were taken for inclined channel for three different slopes S (S=1‰, 3‰ and 5‰), for the same three different heights h‘ over the permeable bed (h’=2.0cm, 3.0cm and 4.0cm) and for the same discharge (Q =1.0t/s).

The results indicate that the presence of rods bundle impact with different way the velocity distribution in comparison with other permeable beds. Also results showed that the presence of rods bundle in inclined open channels influence significantly different the turbulent characteristics of the flow (velocity distribution, turbulent intensities and turbulent shear stresses) in comparison with other permeable beds (grass vegetation or gravel bed).

2 Experimental Procedure
In total, twenty seven (27) experiments were carried out in a laboratory of Hydraulics in the department of Civil Infrastructure Engineering of Alexander Technological Educational Institute of Thessaloniki, Greece. The channel (figure 1) has a length of 6.5m, width of 7.5cm and height of 25cm. Hydraulic characteristics were measured for three different slopes S (S=1‰, 3‰ and 5‰), for the same three different heights h‘ over the permeable bed (h’=2.0cm, 3.0cm and 4.0cm) and for the same discharge (Q =1.0t/s). The experiments were performed to investigate the different impact between rods bundle and other permeable beds. In the other cases the permeable bed is simulated using two different types of vegetation: a) grass vegetation
and b) gravel bed. All the permeable bed (rods bundle, grass vegetation and gravel bed) have the same thickness \( h_v = 5.5 \text{cm} \) and the same porosity \( \varepsilon = 0.75 \). The total flow depth \( h \) was 7.5, 8.5, 9.5 cm. The experimental apparatus is presented in Figure 1. The geometrical characteristics of the flow are presented in Figure 2a (for rods bundle bed) and 2b (for other permeable bed). The characteristics of the experiments are presented in Table 1.

Table 1. Characteristics of Experiments

(i) Rods Bundle

<table>
<thead>
<tr>
<th>Slope</th>
<th>0.001</th>
<th>0.003</th>
<th>0.005</th>
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</thead>
<tbody>
<tr>
<td>U_{mean}</td>
<td>0.187</td>
<td>0.213</td>
<td>0.236</td>
</tr>
<tr>
<td>h=7.5cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_{mean}</td>
<td>0.174</td>
<td>0.201</td>
<td>0.221</td>
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<tr>
<td>h=8.5cm</td>
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<td></td>
<td></td>
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<tr>
<td>U_{mean}</td>
<td>0.165</td>
<td>0.191</td>
<td>0.209</td>
</tr>
<tr>
<td>h=9.5cm</td>
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</table>

(ii) Grass Vegetation

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<th>0.005</th>
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<tbody>
<tr>
<td>U_{mean}</td>
<td>0.216</td>
<td>0.246</td>
<td>0.262</td>
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<tr>
<td>h=7.5cm</td>
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</tr>
<tr>
<td>U_{mean}</td>
<td>0.200</td>
<td>0.228</td>
<td>0.247</td>
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<tr>
<td>h=8.5cm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>U_{mean}</td>
<td>0.187</td>
<td>0.211</td>
<td>0.232</td>
</tr>
<tr>
<td>h=9.5cm</td>
<td></td>
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</table>

(iii) Gravel Bed

<table>
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<th>0.003</th>
<th>0.005</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_{mean}</td>
<td>0.226</td>
<td>0.257</td>
<td>0.271</td>
</tr>
<tr>
<td>h=7.5cm</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>U_{mean}</td>
<td>0.208</td>
<td>0.237</td>
<td>0.255</td>
</tr>
<tr>
<td>h=8.5cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_{mean}</td>
<td>0.192</td>
<td>0.219</td>
<td>0.241</td>
</tr>
<tr>
<td>h=9.5cm</td>
<td></td>
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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 291mm x214 mm for all the experiments. It means that the resolution of the captured images was typically 5.5pixel/mm or that the pixel length was 0.1818mm. 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 2msec. 50 pairs of images were captured in each experiment. The plane photographs were divided into interrogation spots measuring 32x32 pixels (5.79mmx5.79mm).

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. Correlation made use of the FFT. Adjacent interrogation spots were overlapped by 50%, providing a resolution of about 3mm. 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 flow dynamics. These particles had size of about 10 μm in clean water. The motion of the seeding particles was used to calculate the velocities in magnitude and phase. The distance between two neighbour velocity vectors was 3mm. The experimental uncertainty of the measured velocity with this technique was approximately ± 2% [15].

The processing algorithm maintains a spatial displacement accuracy of less than approximately 0.1px, so that the spatial displacement error is on the order of less than 2.5% for a particle displacement of four pixels. The error associated with temporal variations in the laser pulse synchronization due to the jitter of the electronics is negligible since it is several orders of magnitude smaller [16, 17].

The measurements were conducted at a 4m distance from the channel’s entrance where the flow is considered fully developed. The full development of the flow was evaluated comparing the velocity distributions above the vegetation in two vertical sections with a 60cm separation distance. The uniformity of the flow was checked measuring the flow depth with point gauges at two cross-sections (4m between the two sections). The desirable flow depth 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 ± 0.1mm. The total discharge was measured at the channel’s outlet using a triangular tank. The measurements were made at the mid-plane of the flow channel. Individual experiments are performed and were observed that the two side walls influence the measurements for only 0.2 cm along the wall. With a mechanism in the entrance of the open channel the channel slope is defined from S = + 0.1 to S = - 0.1.

3 Analysis of Results

The current analysis aims to identify the influence of the impact of rods bundle in an inclined open channel and to investigate the different impact between rods bundle and other permeable beds. Figure 3 shows the influence of the kind of bed ((a) rods bundle, (b) grass vegetation and (c) gravel bed) on velocity distribution for the same slope (S=3‰) and the same flow depth (h=7.5cm). The presence of rods bundle influences significantly the velocities when compared with the other permeable beds. Also the velocities over the rods bundle are lower as regard the velocities over the other two permeable beds. This is due to the greater penetration of the flow in the case of the rods bundle as regards the penetration for the grass vegetation and gravel bed. In addition, results for porous bed show a region of approximately zero velocity until 1.5cm inside porous bed. This result shows that 50% of the porous bed behaves like an impermeable bed in all cases.

The influence of the inclined bed is important to the turbulent intensities. We use dimensionless velocities using the friction velocity $U_*$:

$$U_* = \sqrt{\frac{\tau_0}{\rho}}$$

where $\tau_0$ is the shear stress

$$\tau_0 = \mu \frac{\partial U}{\partial y}, \ \mu \text{ is the dynamic viscosity and } \rho \text{ is the water density}. \text{ In figure 4 the distribution of turbulence intensity } u'/U_*, \text{ within the flow depth (} u'/U_* \text{ vs } y/h, \text{ with } u' = \sqrt{u^2} \text{ and } \overline{u^2} = \text{ turbulent normal stress in the flow direction) is presented for the same slope (} S=1\% \text{) and the same flow depth (} h=9.5cm \text{). In the same figure the semi-empirical curve of the distribution of the turbulence intensity in the flow depth for flow above impermeable bed is shown, as given by the relationships of Nezu and Nakagawa [18].}

The relationships (Nezu and Nakagawa [18]) are:

$$\frac{u'}{U_*} = 2.30 \exp\left(-\frac{y}{h}\right)$$

$$\frac{v'}{U_*} = 1.27 \exp\left(-\frac{y}{h}\right)$$

$$\frac{-u'v'}{U_*^2} = 1 - \left(\frac{y}{h}\right)$$

Figure 4 show that the kind of bed influences significantly the variation of the longitudinal turbulent intensity $u'/U_*$. As regards the porous beds, the presence of the permeable bed influences significantly the variation of the turbulent intensity $u'/U_*$. Especially for $y/h<0.5 \text{ (} y \text{ : distance from the bed})$ the turbulent intensity $u'/U_*$ for the porous bed (in all cases) is increases in regard to the impermeable bed due to the high turbulence which propagate the presence of porous bed. The presence
of rods bundle influences more than grass vegetation and gravel bed the variation of the longitudinal turbulent intensity $u'/U_*$. This is due to the greater roughness of the rods bundle in comparison to the grass vegetation and gravel bed which is observed near the interface. For the case $y/h>0.5$ the turbulent intensity $u'/U_*$ for porous beds it is almost equal in regard to the impermeable bed near the free surface due to the fact that the presence of the permeable bed doesn’t influences the turbulent intensity $u'/U_*$ away from the bed.

In figure 5 the distribution of the vertical turbulent intensity $v'/U_*$ within the flow depth $y/h$ is shown for both horizontal and inclined impermeable bed. Also, in this case, the presence of the porous bed influences significantly the variation of the turbulent intensity $v'/U_*$. The same results are observed for $y/h<0.5$ and for $y/h>0.5$.

The distribution of turbulent shear stress $uv$ in the flow depth $(\frac{-u'v'}{U_*})$ vs $y/h$ is shown in figure 6. A satisfactory agreement between the experimental results and the theoretical equation $\frac{-u'v'}{U_*} = 1 - \left(\frac{y}{h}\right)$ is observed for all cases (rods bundle, flexible vegetation and gravel bed). The kind of bed doesn’t influences the turbulent shear stress $uv$.

Figure 3. The effect of the kind of porous bed on the velocity distribution. Flow depth and slope are constant and equal to 7.5cm and 3‰ respectively.

Figure 4. Distribution of the turbulent intensity $u'/U_*$ in the flow depth $y/h$

Figure 5. Distribution of the turbulent intensity $v'/U_*$ in the flow depth $y/h$
4 Conclusion

In this study in order to experimentally investigate the impact of rods bundle in an inclined open channel, a series of laboratory experiments were performed to investigate the different impact between rods bundle and other permeable beds. In the other cases the permeable bed is simulated using two different types of vegetation: a) grass vegetation and b) gravel bed. All the permeable beds (rods bundle, grass vegetation and gravel bed) have the same thickness $h_v=5.5\text{cm}$ and the same porosity $\varepsilon=0.75$. The measurements were obtained using a two-dimensional (2D) Particle Image Velocimetry (PIV).

The following conclusions can be derived:

(a) The velocities over the rods bundle are lower as regard the velocities over the other two permeable beds. This is due to the greater penetration of the flow in the case of the rods bundle as regards the penetration for the grass vegetation and the gravel bed.

(b) Results for porous bed show a region of approximately zero velocity until 1.5cm inside porous bed. This result shows that 50% of the porous bed behaves like an impermeable bed.

(c) The kind of the bed influences significantly near the impermeable bed the variation of a) longitudinal turbulent intensity $u'/U_*$ and b) vertical turbulent intensity $v'/U_*$. Turbulent intensities (longitudinal and vertical) for the porous bed (in all cases) is increases in regard to the impermeable bed due to the high turbulence which propagate the presence of porous bed.

(d) The presence of rods bundle influences more than the other porous beds the variation of: a) longitudinal turbulent intensity $u'/U_*$ and b) vertical turbulent intensity $v'/U_*$. This is due to the greater roughness of the rods bundle in comparison to the grass vegetation and gravel bed which is observed near the interface.

(e) A satisfactory agreement between the experimental results and the theoretical $-\frac{u'v'}{U_*} = 1 - \left(\frac{y}{h}\right)$ is observed for all cases (rods bundle, grass vegetation, gravel bed). The kind of bed doesn’t influence the turbulent shear stress $uv$.

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