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FLOW VELOCITY FLUCTUATIONS AND TURBULENCE INTENSITY OVER ROUGH BED AND BED COVERED WITH LIGNEOUS WATER PLANTS

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ABSTRACT

Velocity fluctuations and turbulence of velocity in mountain rivers varys when the flow parameters change from free flow conditions to clogged cross-section. The first part of the paper is devoted to extending the description of turbulence intensity distribution in rough flow conditions. In the second part the effect of growth of ligneous water plants in the bed on turbulence intensity is presented.

Key words: river flow, rough bed , ligneous water plant, velocity turbulence intensity

INTRODUCTION

Mountain river flow and velocity fluctuation are determined by hydraulically rough flow conditions where grain Reynolds number ($Re_* = k_s U_* \nu^{-1}$) exceeds 68-70. In this paper an analysis of influence of bed roughness and of plant vegetation on water turbulence intensity distribution is presented. Velocity turbulence intensity distribution varies in free conditions flow i.e. with the bed roughness:

$$t_{rb} = f\,(\text{velocity, viscosity, water specific gravity, bed roughness, flow depth, distance from bed})$$

Introducing plants adds one more "clogging" parameter to the above function. The authors conducted laboratory measurements of velocity fluctuation in rivers with flat bed, rough bed and bed covered with ligneous plants. The velocity fluctuations as well as intensity of turbulence are comparable to exponential distribution. Cardoso et al. [2] give an equation allowing for the determination of turbulence intensity distribution as a function of relative depth and shear velocity:

$$t_{rb}\, U_*^{-1} = D \exp(-\lambda\, y\, Y^{-1})$$

where:

$$t_{rb} = (\text{mean } u'^{\,2})^{0.5}\, U^{-1}$$

and t_{rb} - standard deviation of measured velocity mean value

There are proposed values for D and λ in above equation making possible the determination of turbulence intensity distribution for smooth flow conditions (Re_* from 0 to 5):

D= 2.28 λ = 1.08 acc. to Cardoso et al. [2],
D=2.26 λ = 0.90 acc. to Nezu and Rodi [12],
D=2.30 λ = 1.00 acc. to Nezu [11],
where: D and λ determined empirically.

The authors propose to extend the use of this equation to transition (Re_* from 5 to 70) and to rough ($Re_* > 70$) flow conditions. Re_* above flat bed ranged during the laboratory measurements between 3 and 12, whereas after introducing bed roughness it ranged from 1500 to 15000. Flows for flat bed occurred in the zone of hydraulically smooth and transitional flow, whereas for rough bed it was always rapid flow and hydraulically rough conditions. The introduction of plants caused a dramatic change of the velocity fluctuations and turbulence intensity.

METHODS

Hydraulic flume equipment

The tests were carried out at Hydraulic Laboratory of the Agricultural University of Krakow. The laboratory flume dimensions are 12x0.5x0.6 meters. Bed slopes can be adjusted stepwise between –25.6 and 84.7 [‰]. The flume is supplied by a closed system composed of two tanks (lower and upper) and three pumps working separately. The maximum pump output equals 130 dm^3s^{-1}.

Fixed measuring instrumentation of the flume consists of hydrometric pins, WP300 Merton-Meinecke flow meter (Series 5090154) placed on the pipeline beneath the gate and mated with FM-1D/K frequency converter and by a weir of variable height with helical wheel.

Velocity measurements

The measuring point was equipped with a hydrometric micropropeller. The module KENT MINIFLO of type 265 was coupled with PC computer. During investigations the measurement time was 2 minutes at each level. The number of measuring points on hydrometric vertical ranged between 4 and 20 depending on depth.

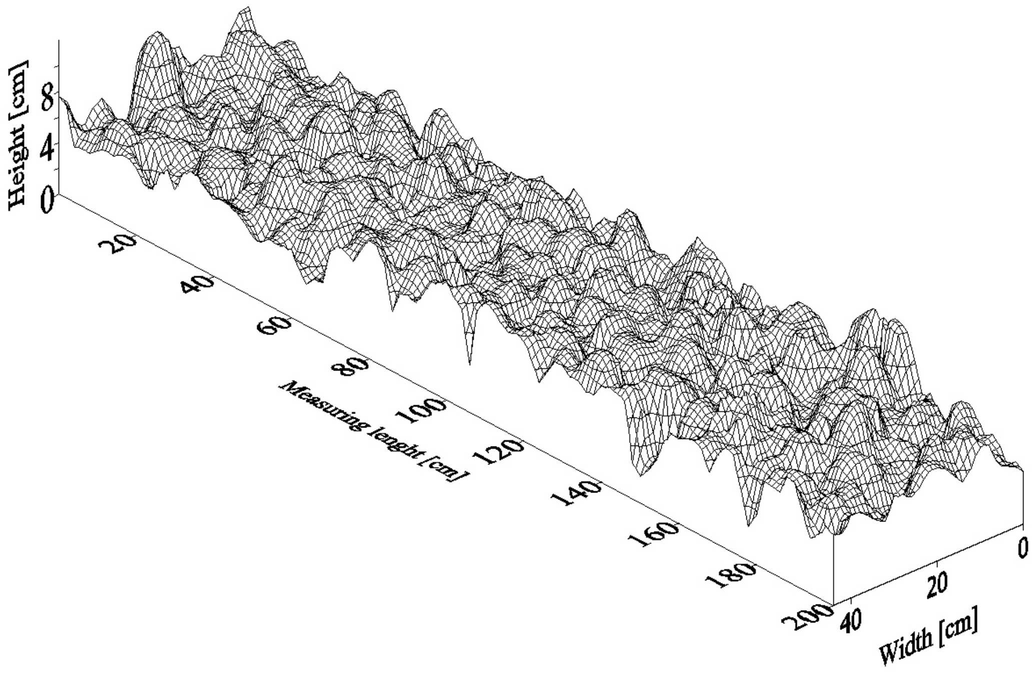
Measurements of bed material roughness height

Bed roughness parameter (K) for artificial and natural grains was determined as a standard deviation of the distance from moving optoelectronic measuring device (DISTANCE PRO I) to the surface of grains resting on the bed [7] [5].

$$K = \sqrt{\frac{1}{n-1}\sum_{n=1}^{N}(h_n - H)^2}$$

The device makes it possible to measure the distance from a liquid or solid surface. The bed area was measured with accuracy 2x2 cm. The measured length was 200 [cm]. Measurements were made on the whole bed width. The bed roughness measurements were done before and after the pass of flow. A sample mesh reflecting the bed roughness is presented in Fig. 1.

Fig.1. Bed roughness determined using Distance Pro I

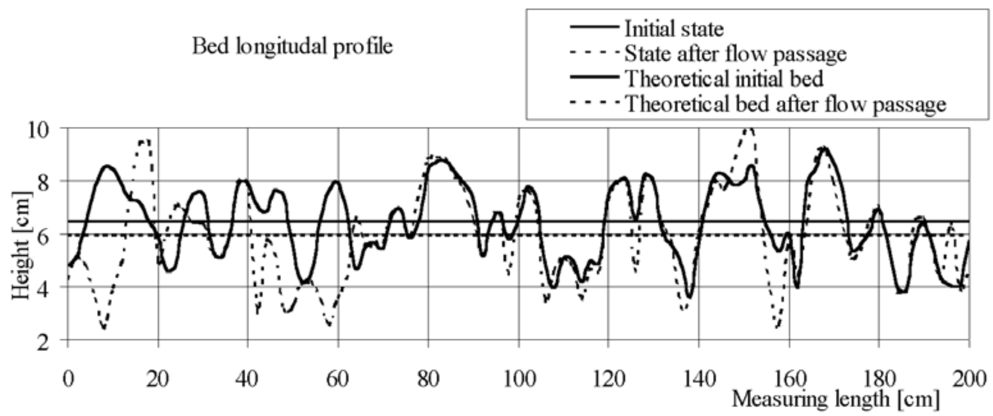


BED CHARACTERISTICS

Bed load granulometry

Results were presented for a flat bed, a bed covered by artificial as well as natural grains and a rough bed with ligneous water plants placed between gravels. In the artificial grain tests, grains were fixed to the bed, which made it possible to exceed incipient motion conditions. The coverage reflected an armoured bed of mountain streams [13]. Small natural grains placed in the hydraulic flume revealed an ability for movement which was registered by DISTANCE PRO I sensor (Fig.2).

Fig.2. Bed longitudal profile



Measurements performed for artificial grains make it possible to determine substitute Nikuradse sand roughness (also called effective roughness height) on the basis of measurements of roughness parameter and shape factor [14].

$$k_s = K(1.926SF^2 - 0.488SF + 4.516)$$

For artificial grains (Fig.3) k_s was determined as a double size of grain height. Value Z presented in Table 1 stands for the percent of substratum coverage by artificial grains, H – stands for the grain height.

Table 1. Characteristics of artificial grains

Grains	H [m]	SF [-]	Z [%]	K [m]	k_s [m]
4A	0.023	0.92	62.6	0.009	0.052
6A	0.032	0.93	68.1	0.012	0.071
8A	0.037	0.97	61.5	0.015	0.087
N	-	0.57	-	0.015	0.071

Where indices:

A – artificial grains of ½ sphere, N – natural grains,
4,6,8 – approximate diameter of sphere base.

Fig.3. View of flume with artificial grains

The effective roughness height for gravelbed is proposed to be $k_s=3.4d_{84}$ [6] or $k_s=2d_{90}$ for sand bedded channels [8]. The level of theoretical bed (y_o) covered with artificial grains was determined at the elevation of flat bed covered by grains, however the set of y_o for natural grains requires a more complicated method. The Nikuradse [10] showed that y_o is related to k_s by $y_o = k_s\ 30^{-1}$. Various methods of calculating the position of theoretical bed line with natural grains can be found in literature [9] $y_0 = (0.5 \div 0.6)d_{max}$.

Bed with ligneous plants

Determining the influence of plant obstacles on the phenomena of water movement makes possible to evaluate discharge changes in the cross-section with vegetation [4]. During hydraulical investigation with vegetation one may use the absolute roughness value k_z, which with vegetation may reach 0.75 m. Dąbkowski and Pachuta [3] state that due to silting, k_z decreases during high water decline. Depending on the kind of plants it is recommended to assume diversified values of substitute roughness:

- for grassy slopes from 0.03 m to 0.05 m
- for slopes covered with bushes from 0.2 m to 0.5 m.

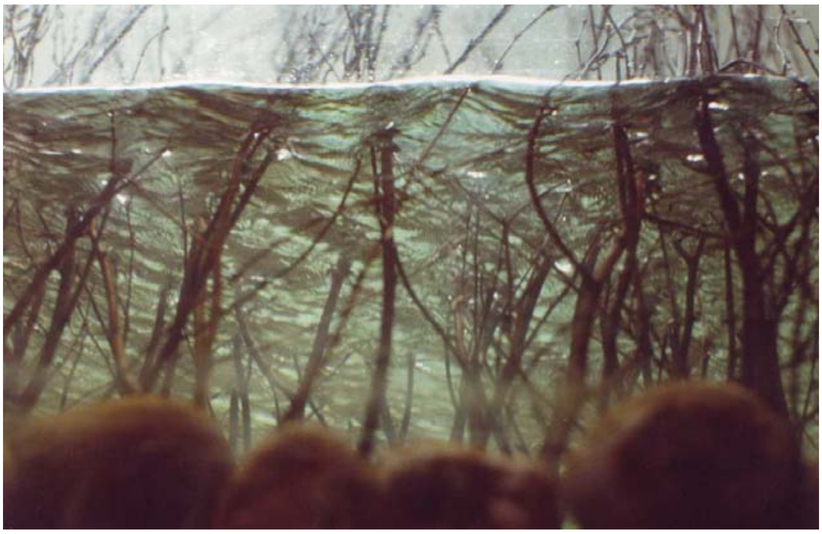
During hydraulic tests with vegetation one considers the factors which most affect flow resistance in overgrown beds. They include [3]:

- plant distribution in the cross- and long-section,
- plant habit (shoot diameters, leaf forms, smoothness of stems, presence of leaves in vertical, etc.)
- mechanical properties of plants (ligneous, springy or limp shoots),
- behaviour of plants (standing or drooping, flow between and above the stems),
- water depth and flow velocity.

In the conducted research the vegetation consisted of dry willow shoots distributed on its bottom according to the established design. The basic plant spacing in one row was 10 cm. Plant rows were placed at the spacing along and across the flume equal to 5 cm. The measurements commenced on the model with rough bed and 180 pieces on square meter plant density and the results were compared with those for the model without vegetation.

Plants occurring in the bed may be divided into low, medium and high. The height of low-growing vegetation is lower than the flow depth, therefore velocity distribution in the vertical remains consistent with the theory of boundary layer. Medium-height and high plants block the cross-section, so as the flow depth in the bed cross-section covered with medium-height and high vegetation increases, the share of local hydraulic losses caused by the overflow of the shoots also grows.

Fig.4. View of flume with ligneous water plants



The classification into low-growing, medium-height and high vegetation should take into account not only the plants themselves (height, density of shoots and stiffness) but also current flow conditions. Plants of high woodiness may be deformed during high water and in consequence behave like soft plants. The tests were conducted for high plants of great lignity (Fig.4). Total stem cross-section area together with the height of the shoots decreases and as a result the average diameter of the plant shoots diminishes with its height.

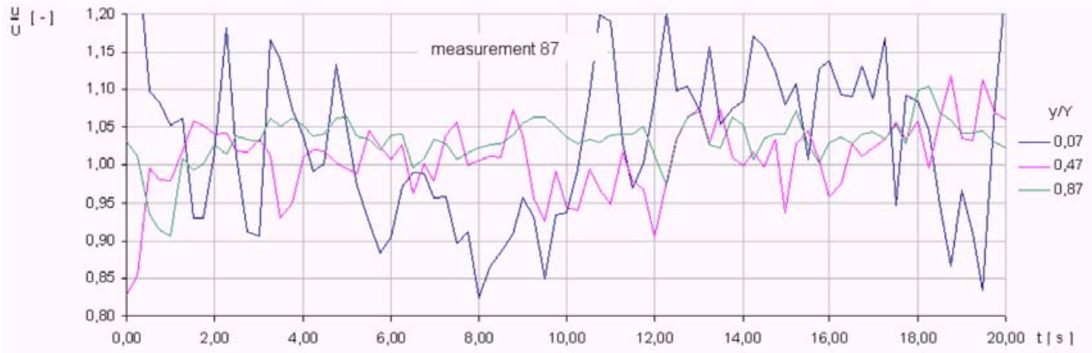
MEASUREMENT RESULTS

Analysis of temporary velocity measurements

Velocity fluctuation reflects flow conditions. Kinetic energy of the flowing water over flat bed has a decisive influence on the course of velocity fluctuation. On fig.5a one can see the effect of internal forces (viscosity), which cause low frequency high amplitude harmonious wave influencing the velocity fluctuations especially apparent at bed (Fr=0.16). When rapid flow appears (Fr=2.11) the only high frequency velocity fluctuation components leave. Due to the increase of kinetic energy of flowing water and the low roughness of the bed the differences between over bed region and upper pats of the flow differs less than for Fr=0.16. Comparing to Fr=0.16, during steep flow over flat bed (Fig.5b) much less fluctuation of velocity is produced. Increasing bed roughness causes the introduction of a new factor responsible for velocity fluctuation. Relative velocity fluctuation increases particularly for rapid flow with roughness (Fig.6) (on Fig.5b u/U ranges in +- 0.2 from average velocity when on Fig.6 u/U=+- 0.6).

Fig.5. Velocity fluctuations of water flowing over flat bed
a) ***Fr = 0.16*****; b)** ***Fr = 2.11***

a)



b)

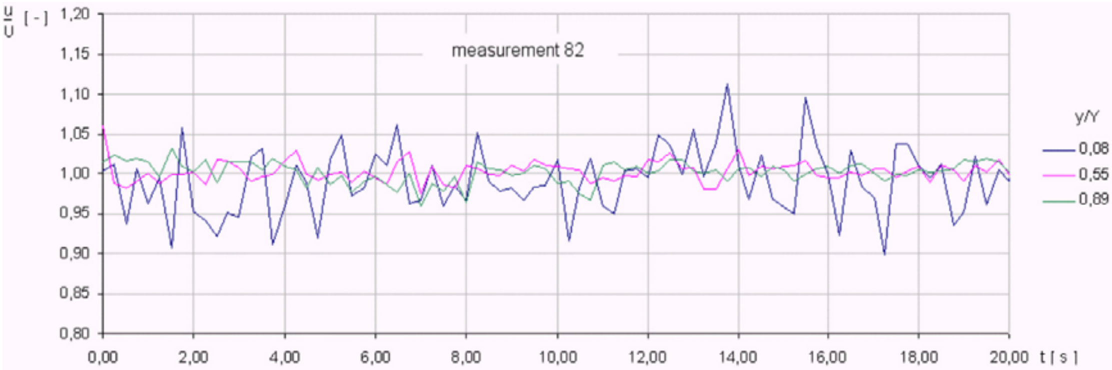


Fig.6. Velocity fluctuations of water flowing over rough bed grain 8A (*Fr = 0.45*)

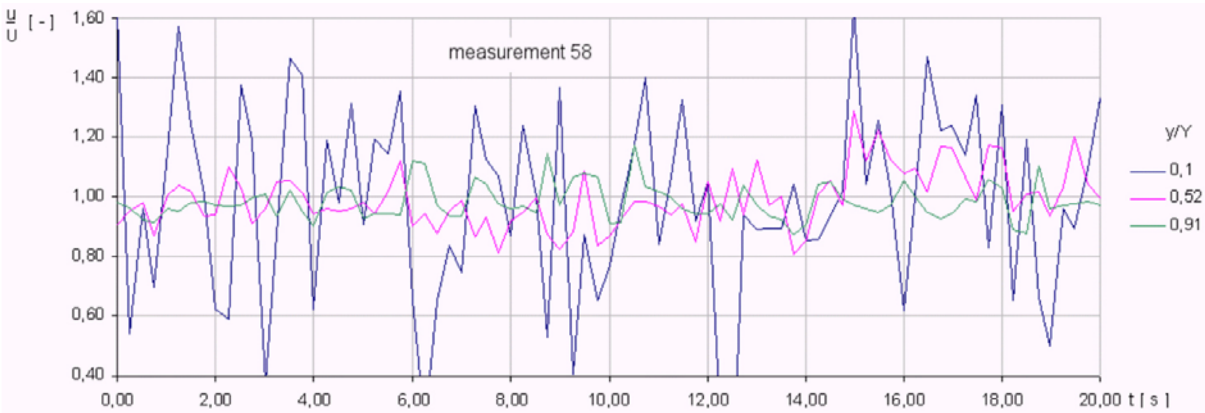
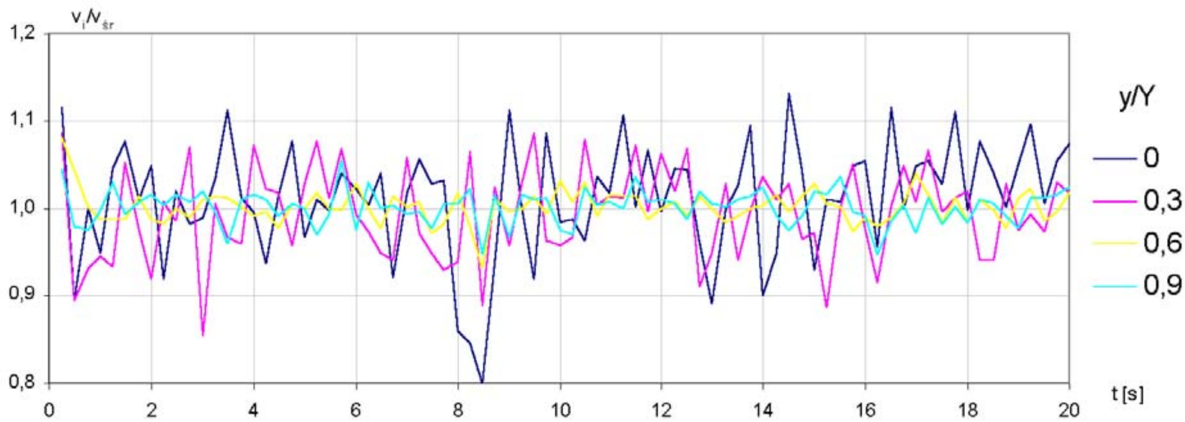


Fig.7. Velocity fluctuations of water flowing over rough bed grain N with plants *Fr = 0.61*

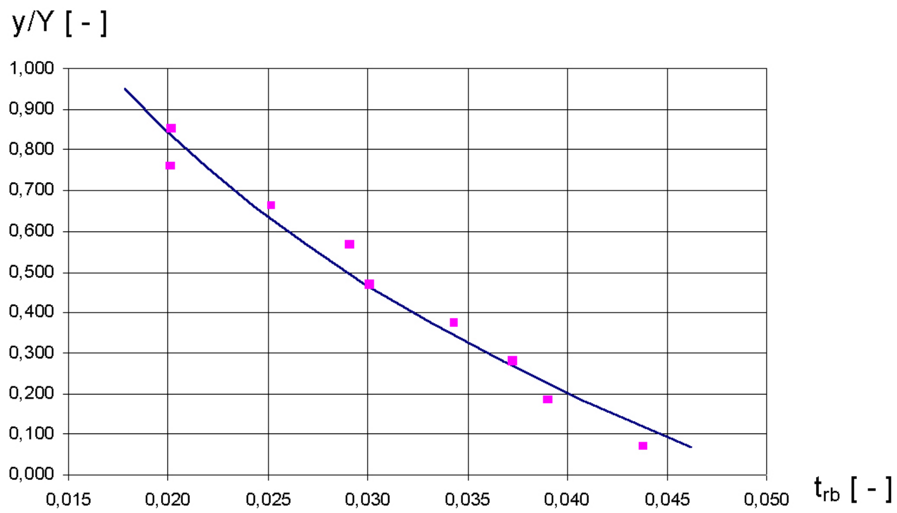


Flow for rough bed with vegetation (Fig.7) is characterised by much smaller velocity fluctuations in the whole flow depth, despite the fact that Reynolds number was described by big values (Re from 5000 to 16000). The influence of bed roughness on the phenomena occurring at some distance from the bed is much diminished. Fig.7 shows also the similarity of velocity fluctuations at various distances from the bed.

Intensity of turbulence

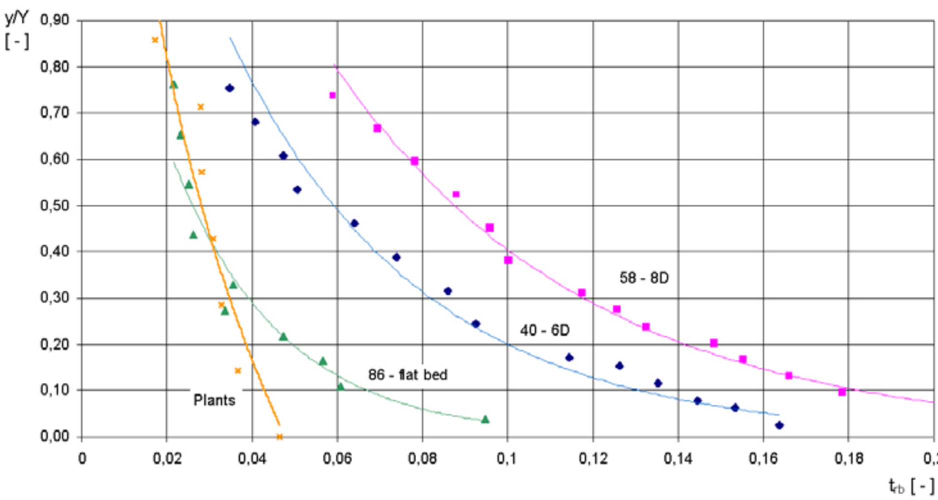
Application of the exponential equation with the parameters proposed by Cardoso et al. [2] allows for a demonstration of measured data for flow over flat bed without vegetation characterised by smooth flow conditions. The flow is described by small Reynolds number values for grains (Re_* from 1 to 4). The distribution of turbulence intensity calculated and presented in Fig.8 is characterised by a correlation coefficient $r^2 = 0.97$.

Fig.8. Profile of turbulence intensity measured and plotted according to function (2)



The influence of roughness on turbulence intensity is demonstrated in Fig.9. Froude number was applied as a flow similarity criterion where distributions measured for varying bed roughness were compiled. The increase in bed roughness from *K* near 0 for flat bed, to 0.124 meters causes a twofold increase of turbulence intensity value in the middle part of the profile (Fig.9). The change of granulometry to grains type 8A, cause threefold increase of the value of turbulence intensity.

Fig.9. Profiles of velocity turbulence intensity at various bed roughness (*Fr ~ 0.43*)



The distribution of turbulence intensity for a bed with vegetation has a completely different character (Fig.9). Turbulence intensity near bed assumes here much lower values, especially in comparison to 8A grain measurements. A weak influence of bed roughness on turbulence intensity distribution in the whole profile is also markedly visible.

Determination of velocity turbulence intensity distribution by exponential formula for flow over rough bed or for rapid flow requires substituting parameters other than given by the authors [2] for smooth flow conditions. Particularly big variability has been noted for small Re_*, i.e. in conditions of smooth and transitional flow. Calculated values of parameters D and λ allow for accurate plotting of trend (r^2 near 0.9 value), which confirms the compatibility of turbulence intensity changes with the course of exponential function [1] [2]. A pair of functions may present variability of D and λ parameters for flat bottom and at roughness k_s less than 0.052 [m] without vegetation:

$$D = 2.34\, Re_*^{0.084},\ \lambda = 0.16 \ln (Re_*) + 1.07$$

Despite the fact that t_{rb} value raises depending on bed roughness and flow parameters (Fig.9) it is difficult to set the proper values of D and λ due to some scatter of the measured turbulence (Fig.10) [2] Table 2. However an analysis of graphs points to an increase in t_{rb} when bed roughness is increased. Altrough the relative roughness (k_s/Y) can be regarded as an important parameter, it is possible to compare the velocity turbulence intensity measured for flow over various bed roughness with the same water depth. Curve 2 (Fig.10) illustrates distributions of turbulence intensity for $Re_*=12$, i.e. in hydraulically transitional conditions. Turbulence intensity distribution for hydraulically smooth flow conditions is presented by curve 1. Series 3 reflect measuring conditions for bed with granulation and series 4 - the situation when vegetation was used for the same roughness.

Fig.10. Specification of mean relative turbulence intensity distributions for different flow conditions

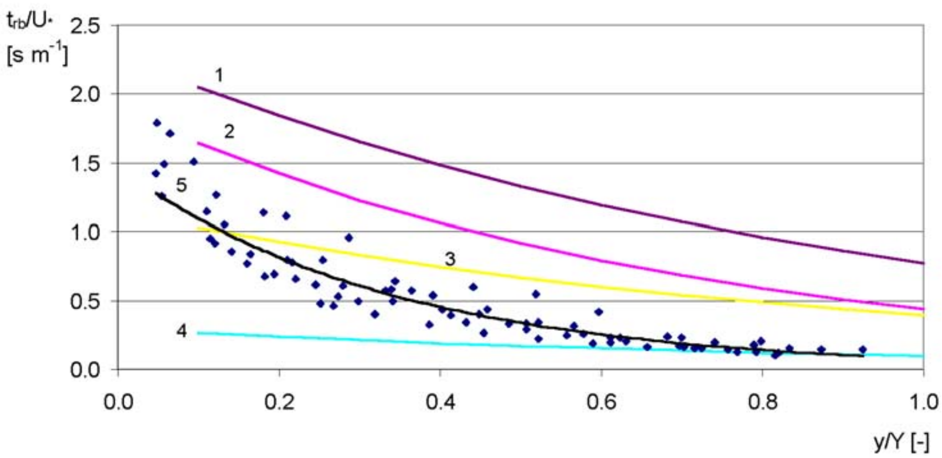


Table 2. Specification of parameters λ and D for exponential equation presented in Fig.10.

Curve No.	1	2	3	4	5
exponential equation parameters	Substratum				
	Flat Re* = 3	Flat Re* = 12	Rough Natural	Rough Plants	Rough Artificial 4A
D	2.28	1.90	1.14	0.29	1.47
λ	1.08	1.47	1.06	1.12	2.93

In flow conditions for flat bed small values of dynamic velocity occur $U^*=0.015$ [ms^{-1}], which is due to the strong influence of internal forces connected with liquid viscosity. This phenomenon causes greater relative velocity turbulences. Increasing the value of Reynolds number for grains causes a change of turbulence intensity to dynamic velocity ratio, which favours a decrease in distribution placement (series 2). Decreased proportion between depth and roughness parameter K in measurements with polyfractional natural and artificial bed material (curves 3 and 5) from one side and hydraulically rough flow conditions from the second side, decreases t_{rb}/U_* values in comparison to hydraulically smooth and transitional flow conditions (curves 1 and 2). The lowest relative turbulence intensity appears in measurements with vegetation (series 4). Variability of the turbulence distribution is also small.

CONCLUSIONS

1. Turbulence intensity is directly proportional to bed roughness and Reynolds number R_{e*}. At the fixed value of Froude number it increases twofold (change of t_{rb} from 0.03 to 0.06) after introduction into the flume of 6A artificial grains and threefold (t_{rb}=0.09) for 8A grains.
2. Research results obtained during flow for small values of Reynolds number for grains (Re_* from 1 to 4) approximate to the distribution for flat bottom described by other authors [2].
3. Turbulence intensity of velocity for free condition flow is described by an exponential distribution and the change of flow conditions concludes the change of D and λ.
4. Bed vegetation disturbs and diminishes the effect of great bed roughness on velocity fluctuation distribution. Consequently, turbulence intensity is balanced on the whole vertical cross-section, and relative values of turbulence intensity decrease fourfold in the whole profile in comparison with the bed free of vegetation.

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