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MODELLING OF FLOW CAPACITY AND MASS TRANSPORT IN COMPOUND CROSS-SECTION CHANNEL

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Abstract: The influence of the surface roughness and the trees on discharge in a compound channel has been presented. A considerable part of the paper is devoted to the analysis of the distribution of small-sized floating particles. A defined number of the floating particles were released into a turbulent stream in such a way as to allow their trajectories to be traced with video cameras (the authors made use of the Particle Image Velocity). Based on the measurements of the solid particles spacing, turbulent diffusion coefficients have been determined, which characterize the capacity of a stream and intensity of the spread of particles.

1. INTRODUCTION

Carrying out hydrometric measurements in conditions of a river freshet is both difficult and dangerous. Therefore, information on the flow capacity of the streamway and the hydraulic aspects of freshets is gathered from tests performed in a laboratory setting. Such tests make it possible to reiterate the experiments, as well as to employ highly precise methods of velocity measurement. On the basis of such tests, the flow capacity of the channel and its stream capacity were determined in this study.

In the hydraulic laboratory of the Environmental Engineering at Warsaw University of Life Sciences, a concrete rectilinear channel was built, with the height of 16 m, width of 2.1 m, compound cross-section and the designed longitudinal gradient of the main channel, as well as of the overflow area, of 0.5 ‰. The channel flow capacity was measured in conditions of two different roughness properties and two different arrangements of trees inserted in the overflow area. The stream capacity was examined by means of PIV (Particle Image Velocimetry) visualization. Turbulent diffusion coefficients were determined, which are typically used for the description of stream capacity.

2. METHODOLOGY AND SCOPE OF SURVEY

The survey was conducted in the hydraulic laboratory of the Chair of Hydraulic Engineering and Environment Recultivation at Warsaw University of Life Sciences, in the concrete model of a riverbed rectilinear section of 16 m in length and the upper width of 2.10 m, with symmetric overflow areas and a compound trapezoid cross-section (figure 1). Longitudinal gradient of the main channel and the overflow land was constant and equal to 0.5 ‰. The bottom of the channel and the overflow land was horizontal in the cross-section, and its surface was smoothly float-finished and covered with paint (variant 1). The model of the channel was connected with a closed water cycle in the laboratory, supplied by five pumps with the overall delivery rate of 500 l/s. At the initial section of the channel, there was a row of 30 cm long PVC pipes easing the stream and letting the water into the channel. At the end of the channel there was an adjustable flap used for water level regulation. For the purpose of the main tests, the cross-section in the middle of the stream channel length was assigned, where the measuring apparatus was placed: the measuring trolley with PEMS electroprobe in the shape of an 11 × 33 mm ellipsoid, used for the measurement of horizontal components of velocity, and a needle level gauge for the measurement of depth.

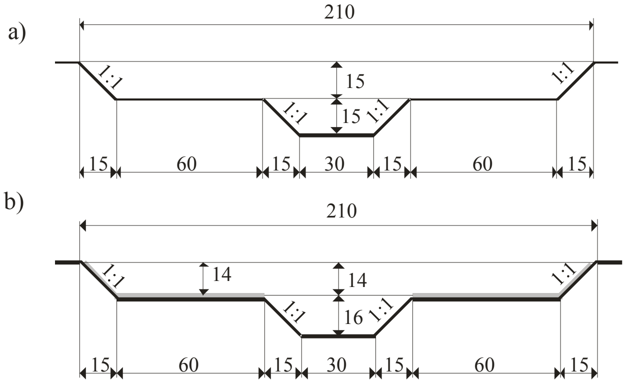


Fig. 1. Cross-section diagrams of the model variants under survey (dimensions in cm):
a) variant 1 – smooth channel, b) variant 2 – channel with the rough surface of the overflow area

The measurement of velocity components in the flow direction perpendicular to the channel axis (*y*) was carried out with the use of PEMS electroprobe at the range of 0–1.0 m/s, with the frequency of 0.1 second and accuracy of 0.01 m/s. The values under survey included the filling ratio in the main channel and in the overflow areas, flow velocity at the cross-section points, temperature and flow rate in the channel. The flow rate was measured by means of a tared circular measuring overfall with a diameter of 540 mm. Free water surface inclination along the channel length was determined on the basis of the differences of the water level in piezometers arranged on the axis of the main channel bottom, at distances of 4 and 12 m from the beginning of channel, and connected to a differential pressure transducer. Both the electroprobe and the transducer were connected to a computer measurement recorder.

The laboratory tests were carried out for four variants of the channel roughness. In variant 1, the whole surface of the channel was smooth (figure 1a). In variant 2, the surface of the overflow area was covered with a layer of terrazzo, which was placed on cement mortar and whose grains had the diameter ranging from 0.5 to 1 cm (figure 1b).

In variant 2.1 (figure 2a), the channel surface was the same as in variant 2, but on the overflow area trees were regularly arranged in 0.10 m × 0.10 m net meshes. In the cross-sections there were 16 trees in 161 sections.

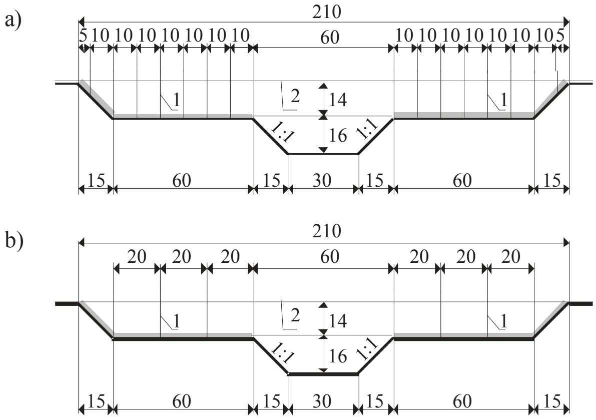


Fig. 2. Diagrams of the cross-sections of variants with trees (dimensions in cm):
a) variant 2.1, b) variant 2.2, 1 – pipes imitating trees, 2 – wooden strips supporting the trees

In variant 2.2 (figure 2b), the channel surface was the same as in variant 2.0, and the trees were inserted into the net meshes with dimensions of 0.20 m × 0.20 m. In the cross-sections, there were 8 trees in 161 sections. The trees were modelled by means of stiff metal pipes, 8 mm in diameter, fastened to the model with the use of wooden beams placed above the channel, perpendicular to its axis. Average Manning's roughness coefficient for the smooth trapezoid channel equalled about 0.011m$^{-1/3}$s, whereas for the rough surfaces of overflow area (variant 2) – 0018 m$^{-1/3}$s for the left and 0.025 m$^{-1/3}$s for the right overflow area. In variant 2, the roughness of the main channel bottom and slopes was the same as in variant 1. The values of absolute roughness of the channel surface were determined from the Colebrook–White equation on the basis of the average velocity values of the flow measured in those parts of the channel. The obtained roughness amounted to k_s = 0.00005 m for the smooth surfaces, k_s = 0.0074 m for the rough surface of the left overflow area, and k_s = 0.0124 m for the rough surface of the right overflow area.

2. CHANNEL FLOW CAPACITY TESTS

The most general way of evaluating the influence of different types of channel development on the channel flow capacity is the analysis of the flow rate curves. On the basis of the measured local velocity values in 77 pions, the flow rates for all the variants under survey were measured, for different depths, and then the flow rate curves were plotted. Figure 3 presents a juxtaposition of flow rate curves for the whole compound channel and its four variants, and also the decrease, in percentage terms, of the overall flow rate in the channel in variants 2, 2.1 and 2.2 in comparison with variant 1.

Both the increase in roughness of the overflow area, as well as the arrangement of trees, caused a significant reduction of the flow rate along the entire section of the channel. A considerable increase of the roughness of the overflow areas (variant 2) resulted in the decrease of the flow in percentage terms with the depth growing, so that in comparison with variant 1, it was by 40% less (*H* = 25 cm), and subsequently, that percentage value decreased.

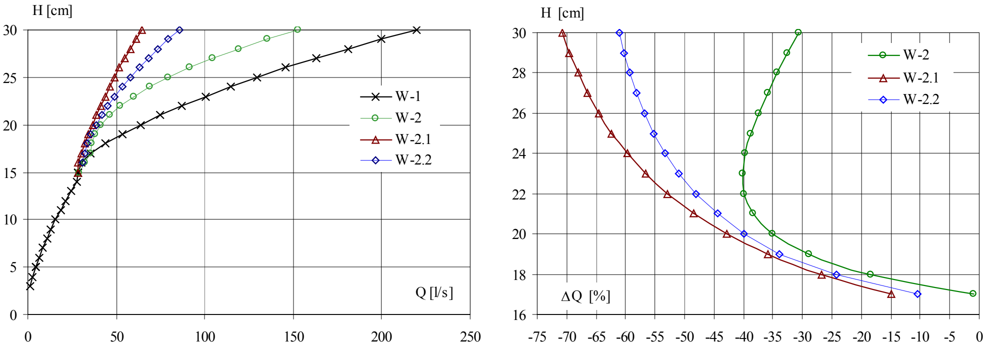


Fig. 3. Flow rate curves in the compound cross-section channel and the reduction, in percentage terms, of flow in comparison with variant 1.
W-1 – variant 1, W-2 – variant 2, W-2.1 – variant 2.1, W-2.2 – variant 2.2

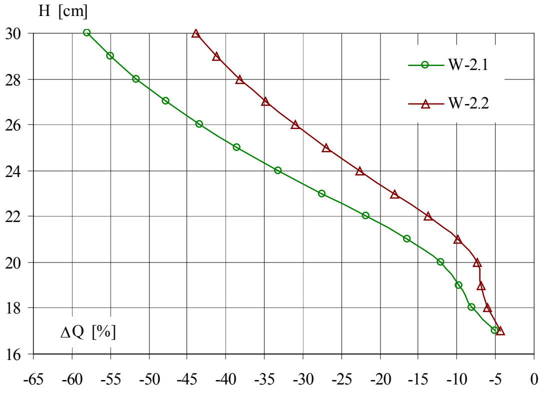


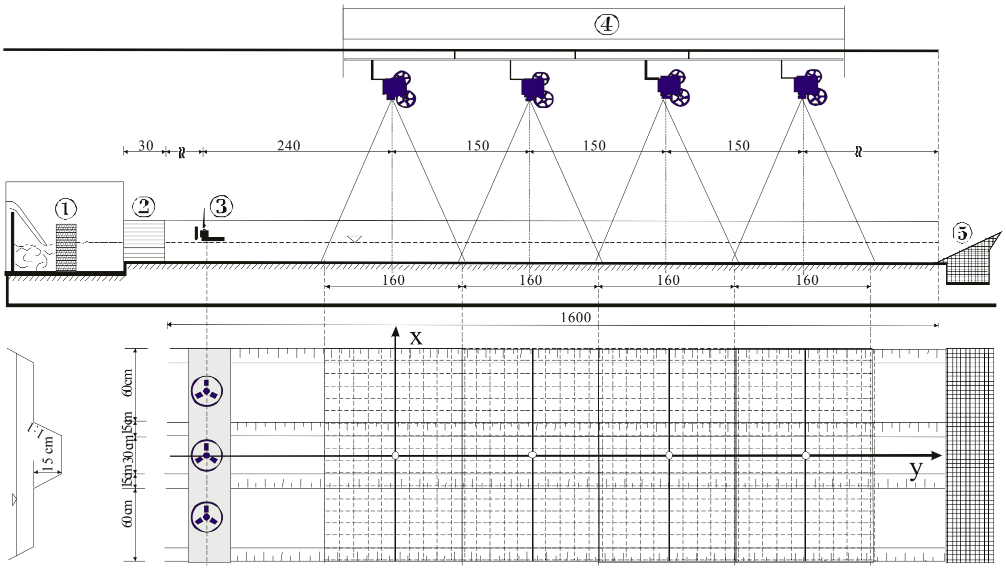
Fig. 4. Percentage decrease of the flow rate in variants 2.1 and 2.2 in comparison with variant 2.
W-2.1 – variant 2.1, W-2.2 – variant 2.2

The insertion of trees in the rough overflow areas brings about the reduction of the active cross-section of the channel by only several percent, whereas the channel flow capacity decreases considerably in comparison with variant 1. In variant 2.1, the difference of the flow rate at $H = 30$ cm was the largest and amounted to 71%, while the active surface of the channel cross-section decreased by 4.9%. In variant 2.2, at $H = 30$ cm, the flow diminished by 61% and the area of the channel active cross-section – by 2.7 %.

Figure 4 shows a percentage decrease of the flow rate in variants 2.1 and 2.2, as compared with variant 2 (rough surfaces of overflow area). The insertion of trees in the overflow areas decreased the flow rate along the whole section of the channel, in variant 2.2 – by 44%, and in variant 2.1 – by 58% ($H = 30$ cm).

3. STREAM CAPACITY EXAMINATION BY MEANS OF PIV METHOD

Stream capacity tests in the compound channel were carried out by means of a video technique, using digital cameras, which made it possible to determine the fundamental parameters characterizing the process of particle transportation in the surface layer of water. For that purpose four cameras were installed at measurement spots. The cameras were fastened in the axis of the channel at the height of 3.10 m so that the four lenses could grasp a 6.40-meter section of the channel. The cameras were located at distances of 2.40 m, 3.90 m, 5.0 m and 6.90 m from the proportioner (figure 5).



1 – overfall with an openwork wall, 2 – calming pipes, 3 – particle proportioner,
4 – the system of four cameras recording the measurement, 5 – a net intercepting the particles

Fig. 5. Diagram of the stand intended for the survey of particle transportation on the water surface

The measurements were carried out for an immobile, point source of the particles. The particles used in the tests were cylinder-shaped and made of plastic (polivinyl chloride, PVC). About 200 particles with the diameter of 8 mm and thickness of 2 mm were prepared. A special proportioner was designed and constructed to lower the particles down to the water surface at programmed regular time intervals.

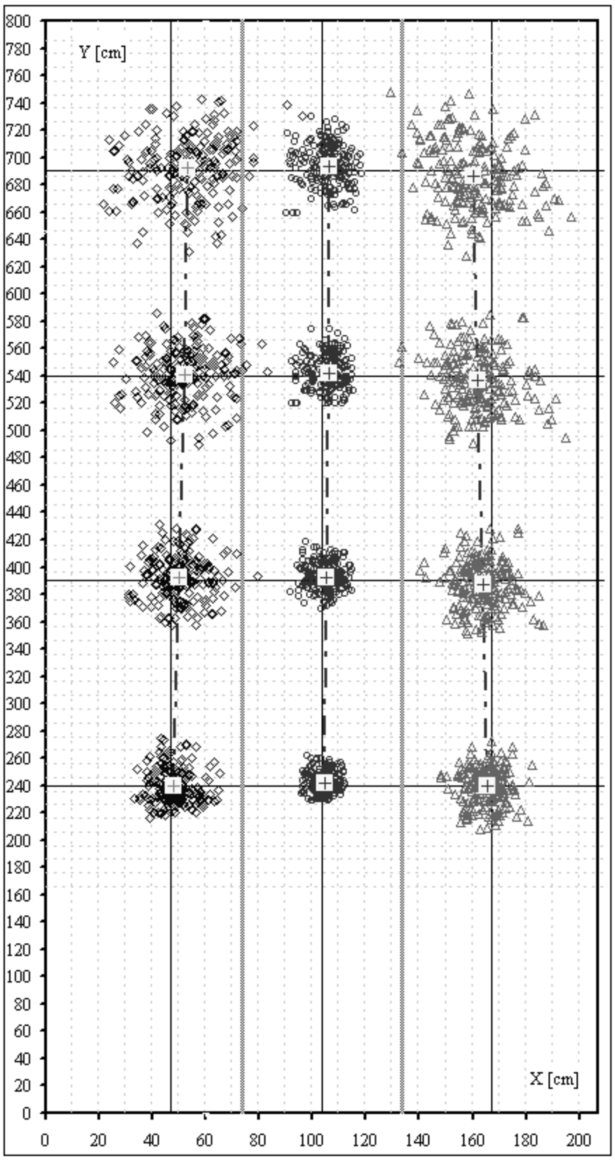


Fig. 6. Registered areas of particle location at the established measurement points

The experiments performed differed in the values of flow ratio in the channel, filling ratio and the average flow velocity. In each location of the proportioner, 195 particles were released (in 3 experiments, 2360 particles were released) [2].

The essential task in the analysis of the filmed material was the determination of coordinates of the location of particles (x_i, y_i) after proportioning time has elapsed from the moment of their release. The coordinates differed from one another due to the turbulent nature of the flow, and their dispersion reflected stream capacity (figure 6). It was assumed that the particle coordinates (x_i, y_i) constitute independent variables and are subject to normal distribution. Detailed information on the properties of the distribution were obtained after the calculation of such estimators as: the gravity center coordinates of the area of particles' location after a selected time, standard deviation, variance, skewness and kurtosis [2].

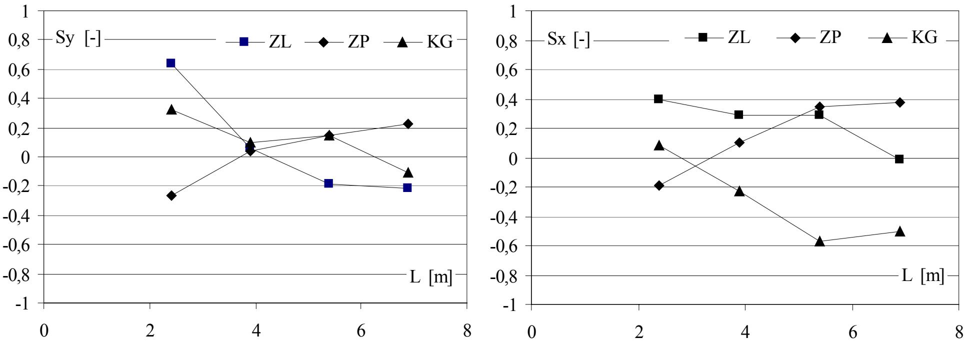


Fig. 7. Variability of skewness values along the channel length
ZL – left overflow area, ZP – right overflow area, KG – main channel

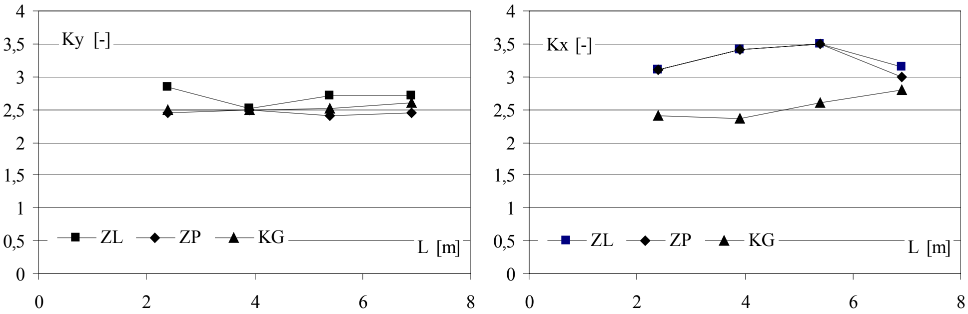


Fig. 8. Variability of curtosis values along the channel length

The calculated values of skewness and kurtosis are given in figures 7 and 8, respectively. On he basis of the diagrams presented it may be concluded that skewness assumes the values close to zero, while kurtosis – the values proximate to "3". It may, therefore, be maintained that the probability density function of the particle coordinates distribution in a given area is very similar to the normal distribution curve (figures 7 and 8). The variability of the skewness values for all the areas bears evidence to minor displacement and shift of the particle gravity center towards the channel axis or suggests the slowing down of particles located at the channel edge. The computed values of skewness and kurtosis differed in certain areas from the values characteristic of normal distribution.

A crucial parameter of flow capacity, determined on the basis of the tests, is the turbulent diffusion coefficient D_i, which describes stream capacity in a homogeneous stationary turbulent flow, and whose relation with the moment of the second order is expressed by equation (1).

The turbulent diffusion coefficient in a homogeneous stationary turbulent flow is linked with the variances of function σ_i^2 of coordinates' probability density in a way described by the equation

$$D_i = \frac{1}{2}\frac{d}{dt}\sigma_i^2 = \overline{u_i'^2}\int_0^\infty R_{ii}(t)dt, \quad i = x, y. \tag{1}$$

For turbulent diffusion coefficients in direction x_i, $dt = \frac{x_i}{u_i}$, therefore,

$$D_i = \frac{1}{2}u_i\frac{d}{dx_i}\sigma_i^2 \tag{2}$$

where u_i – velocity of the particle cloud.

As far as the diffusion of the admixture and the particle cloud in a turbulent flow is concerned, the value of the mass flow per surface area unit in the i-th direction is described by Fick's law

$$\overline{u_i'c'} = D_i\frac{\partial C}{\partial X_i}, \quad i = x, y \tag{3}$$

where C and c' are the average and the instantaneous concentrations of particles in the water volume unit, respectively. The distribution of the concentration of admixture and the particles satisfies the advection-diffusion equation with the turbulent diffusion coefficient D_i defined by equation (1) [1]. The calculated average values of turbulent diffusion coefficients at the section from the source to the area under study (D_i) are shown in figure 9. The values of turbulent diffusion coefficients in the direction of flow increase with the growing distance from the source in the main channel as well as in the overflow area, and the diffusion coefficients are greater in the overflow area than in the main channel (figure 9). This may result from a larger velocity gradient in a transverse direction for the overflow area. It must be stressed that the values of turbulent diffusion coefficients in a transverse direction D_x increase significantly in the overflow areas, while they definitely reduce in the main channel. Such decrease may be caused by the interaction between the streams of water in the main channel and in the overflow areas.

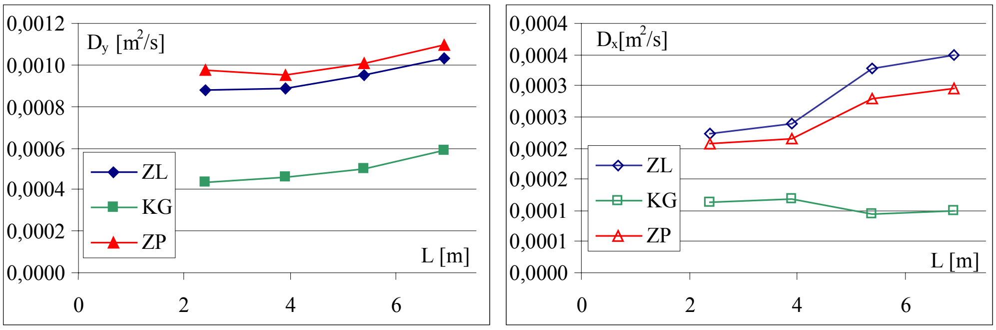


Fig. 9. Changes of turbulent diffusion coefficients as a function of the channel length measured from the particle portioning spot

4. SUMMARY AND CONCLUSIONS

Both the increase in the roughness of the overflow areas, as well as the insertion of trees, resulted in a considerable decrease of the flow rate along the whole section of the channel. The increase in the overflow area roughness brought about the reduction of the flow by 40 %, and the insertion of trees in the same areas caused even a 71% decrease. Static analysis of coordinates' distribution of the particles floating in the compound channel confirms that their distribution is not normal, which may be explained by the intense interchange of stream momentums between the main channel and the overflow areas. Diversification of skewness variation of particle coordinates' distribution in the left and the right overflow area may be caused by differing depth of the flow in those parts of the channel. The diffusion of the particles floating in the compound channel is much larger in the longitudinal than in the transverse direction, and the values of diffusion coefficients in the transverse direction are far greater in the overflow areas than in the main channel. The values of turbulent diffusion coefficients grow as the distance from the source of particles portioning increases, which may account for the presence of an increasing number of vortices.

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