INFRASTRUKTURA I EKOLOGIA TERENÓW WIEJSKICH
INFRASTRUCTURE AND ECOLOGY OF RURAL AREAS

Nr 11/2010, POLSKA AKADEMIA NAUK, Oddział w Krakowie, s. 15–22
Komisja Technicznej Infrastruktury Wsi
Commission of Technical Rural Infrastructure, Polish Academy of Sciences, Cracow Branch

Bogusław Michalec, Mateusz Strutyński

DEFINITION OF DIMENSIONLESS COEFFICIENT OF RESISTANCE AND COEFFICIENT OF ROUGHNESS IN CROSS-SECTION OF STREAM WITH LARGE ROUGHNESS ELEMENT

Summary

The results of investigations carried out in the stream Będkówka – a left bank tributary of the Rudawa River are presented in this paper. A stream sector with large roughness element was chosen for investigations. The performed measurements included cross-section leveling and longitudinal leveling of the stream channel, bed load (sediment) sampling, and hydrometric measurements. Cross section leveling included five cross-sections in the 19-m long stream sector; these were located upstream and downstream the large roughness element and in its region. Differentiation of flow velocity in the region of large roughness element and its influence on differentiation of the load granulometric composition in the stream channel was shown. Immediately downstream the large roughness grain zone a fine grain sediment was frapped, its diameter d_{50} was seven to ten times smaller than that of the sediment in bed present in the stream channel.

The dimensionless coefficient of resistance was calculated taking into account the equivalent bottom roughness determined in each of the examined sections by use of Gladki`s formulae.

It was found that the large roughness element in the Będkówka stream caused a change of hydraulic conditions of water flow and, in consequence, the dimensionless coefficient of resistance in the grain section increased by about four times. The coefficient of channel roughness was also determined and it was shown that the coefficient of roughness in the section of large roughness element determined with consideration of the determined dimensionless coefficient of resistance increased on the average in the section of large roughness grain by over 34% in relation to the coefficient of channel roughness.

Key words: stream, large roughness grain, dimensionless coefficient of resistance, coefficient of roughness

INTRODUCTION

Large roughness element present in the stream channel cause a change of hydrodynamic conditions. They change the regime of flow (flow velocity, its rate of discharge and dynamics), continuity of the river (transport and sedimentation), morphological conditions (kind of bottom load, dimensions of the channel and bottom forms).

Large roughness drain may exert essential influence not only on the conditions of hydraulic balance in the flow channel but may also contribute to creation of new habitat conditions for ichtiofauna and macrobentos living in the flow channel. This improves the ecological state of water flow and assures its continuity, which is the requirement of the introduced Water Framework Directive of the European Union. Determination of influence of large roughness element on flow conditions is of crucial importance not only as far as investigations are concerned but also with regard to a proper engineering approach when designing flow channels with large roughness element. Introduction of large roughness element into a stream or a river channel will, without doubt, contribute to a change of hydraulic and hydrodynamic conditions in the zone of grain.

Establishment of changes of these conditions, in dependence on size of large roughness element in relation to surface area of the channel cross section, as well as in dependence on location of grain in this section, or even on water flow rate will permit to elaborate methods permitting to establish the water damming up in the channel, the dimensionless coefficient of resistance and local coefficients of roughness. These parameters especially coefficients of roughness determined for various sizes of large roughness element and conditions of their location in the flow channel can be helpful in designing flow routes, canals and ecological passages for fish in the region of water structures or in realization of engineering works connected with improvement of the ecological state of the watercourse.

The paper presents the results of primary investigations carried out by the authors concerning determination of hydraulic parameters differentiation in the zone of large roughness element influence on water flow conditions. The undertaken investigations aim at determination of dimensionless coefficient of channel roughness in appointed cross-sections of the stream and demonstrating their differentiation caused by large roughness element. Investigations were carried in the Będkówka stream near Cracow.

METHODS

The investigation sector is located on the Będkówka stream at km 4.650 in the locality of Rudawa in the Malopolska Voivodship. This watercourse is a leftbank tributary of the Rudawa River. The total length of the stream is 8.3 km and catchment area is 24.9 km^2. For the investigation, a 50-m sector of the Będkówka stream was chosen. The width of the stream in the investigation sector was 1.5 to 2.0 m. In this part of the stream, in the mid part of the channel, large roughness element of irregular shape occurred; its dimensions were 89 cm – length, 51 cm – width, 41 cm – height. In order to assure precise geodetic measurements cycles a consequent local network of geodetic marks was arranged.

Geodetic survey and hydrodynamic measurements as well as collecting samples of bottom sediment were performed in July 2009. Geodetic survey was done by use of an electronic tachimeter of the type Topcon GT5-226. During this geodetic survey longitudinal and cross-section leveling of the stream channel was done. Cross-section leveling included five cross-sections in the stream sector of the length 19 m and these were located upstream and downstream of the large roughness grain and in its area (Fig. 1). In each of these sections hydrometric measurements of water flow were also performed by use of a OTT Hydrometrie Nautilus C2000 hydrometric current meter. In order to establish the granulometric composition the bottom sediment was sampled from the top layer of the bottom applying a conventional method. Samples were taken upstream and downstream of the large roughness element and around it (fig. 1).

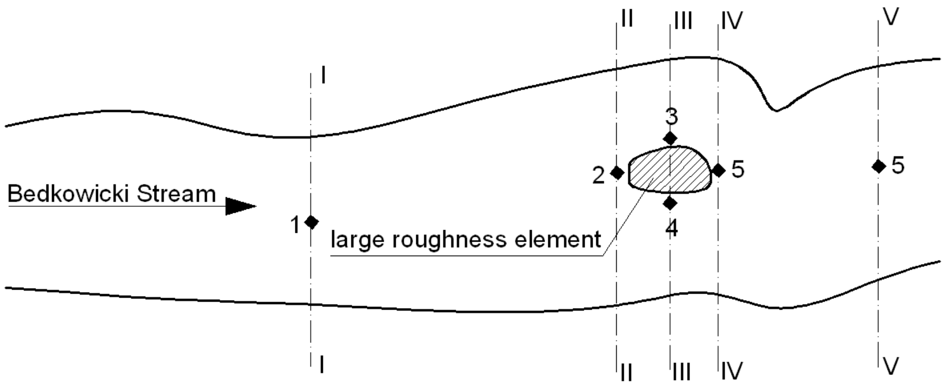

Figure 1. Arrangement of measurement cross sections and points of sediment sampling

Hydraulic parameters of water flow in particular cross-sections such as: cross-section surface area, depth of filling mean velocity of water flow in hydrometric verticals and in the whole cross-section were determined. The Reynolds number for the flow was calculated adopting the coefficient of kinematic viscosity equal to 1.2369 m^2·s^{-1}; for the measured temperature of stream water equaling 12°C. Basic upon the measured flow velocity the total flow was calculated in particular cross sections by use the Harlacher's method [Byczkowski 1996].

The dimensionless Darcy-Weisbach coefficient of resistance in open channels can be calculated from the law of resistance formulated by Colebrook-White for closed channel [Schroeder 1998]. For open channels it is written:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left[\frac{2.51}{\mathrm{Re}\sqrt{\lambda}} + \frac{k_s}{12.2R \cdot f}\right] \tag{1}$$

where:

Re – Reynolds number for water flow [-],
ν – coefficient of kinematic viscosity [$m^2 \cdot s^{-1}$],
k_s – equivalent roughness height [m],
f – coefficient of cross-section shape [-],
λ – dimensionless coefficient of resistance [-].

As given by Kubrak and Żbikowski [1995] the Colebrook-White`s equation established for a uniform flow in closed channels should not be applied for open channel cross sections since it does not take into consideration changeability of the channel cross-section shape and changes of roughness in cross-section. Determining the dimensionless coefficient of resistance in open channel cross-sections the coefficient of the cross-section shape is neglected. Neglecting this coefficient causes changeability of the value the equivalent roughness height for a determined dimensionless coefficient of resistance at small changes of the hydraulic parameter of the cross-section. Considering the fact that the Reynolds number values usually calculated for flows in channels are greater than 25000 a simplified from the formula 1 can be applied i.e.

$$\lambda = \left[-2\log\left(\frac{k_s}{12.84R}\right)\right]^{-2} \tag{2}$$

where denotations are as in formula (1).

The dimensionless coefficient of roughness was determined in each of the appointed cross-sections of the Będkówka stream according to equation (2). Equivalent roughness height was defined as equivalent roughness height of the bottom according to Nikuradse [van Rijn 1984]; this roughness can be determined applying Kamphius', Hey's, Machmood's or Gladki's formulas. Equivalent roughness height of the bottom was determined according to Gladki's formula:

$$k_s = 2.3 \cdot d_{80} \tag{3}$$

where d_{84} defines the diameter of grain constituting together with finer grains 84% of the sample weight content and subsequently the coefficient of roughness was determined from the relation:

$$n = R^{1/6}\sqrt{\frac{\lambda}{8g}} \tag{4}$$

Where

R – hydraulic radius [m],

g – acceleration of gravity [$m{\cdot}s^{-2}$].

INVESTIGATION RESULTS

The bottom slope in the investigated sector of the Będkówka stream, calculated on the basis of geodetic survey was 5‰. It was found that at total water flow in the stream equal 0.14 $m^3{\cdot}s^{-1}$ the mean water flow velocity in cross-section I-I in the Będkówka stream, located 13 meters upstream of the large roughness element was 0.33 $m{\cdot}s^{-1}$ at maximal depth equal to 0.35 m.

In the cross-section II-II located directly upstream of the large roughness element, the depth was 0.33 m and the average velocity decreased to the value of 0.28 $m{\cdot}s^{-1}$. The same value of maximal depth and average water flow velocity was determined in the right-bank part of cross-section III-III, i.e., in the cross-section with large roughness element. In this part of this cross-section the average flow velocity was 0.43 $m{\cdot}s^{-1}$, whereas, in the left-bank part of cross-section III-III, maximal depth was 24 m and the flow velocity equaled 0.35 $m{\cdot}s^{-1}$. In cross-section IV-IV located 0.2 m downstream the grain the average water flow velocity at maximal depth equaling 0.26 m was 0.26 $m{\cdot}s^{-1}$ what was caused by a considerable width of the cross-section. In cross-section V-V the average water flow velocity was 0.25 $m{\cdot}s^{-1}$ and depth of the channel of the downstream equaled 0.25 m.

Granulometric curves of the bottom sediment sampled in the stream upstream and downstream the grain and around it was presented in fig. 2. The bottom sediment, sampled in cross-section I-I located 13 m upstream of the large roughness element (sample No. 1), in cross-section II-II upstream the grain (sample No. 2) and in the right-bank part of cross-section III-III with large roughness element where the main flow concentrated (sample No. 4), does not differ significantly since the mean grain diameters and diameters d_{50} equal respectively: 35.6 m and 12.3 mm in cross-section I-I (sample No 1) 32.5 mm and 8.8 mm in cross-section II-II (sample No 2) and 33.4 and 8.9 mm in cross-section III-III (sample No. 4). Distribution of large roughness element in the channel causes disproportional flow distribution on to the left and right part of the channel in section III-III where the grain occurs. In the left bank part of this section smaller flow velocity prevail which cause load grain sedimentation. The mean grain diameter and the diameter d_{50} of the load in sample 3 equaled respectively 20.7 and 3.3 mm. A considerably greater influence of sedimentation on fine sediment was found in the downstream part of water. In consequence of whirlpool formation on the side of the downstream water of the large roughness element a sand pool 35 cm long was formed. The mean grain diameter and the diameter d_{50} of the sediment sampled from the formed sand pool (cross-section IV-IV sample No. 5) equaled respectively 2.8 m and 1.2 m. Whereas, in cross-section V-V the granulometric composition on the whole width of the section was not so differentiated as in cross-section IV-IV. The mean grain diameter and the diameter d_{50} of the sampled sediment collected from cross-section V-V (sample No 5) equaled respectively 34.8 m and 10.5 m.

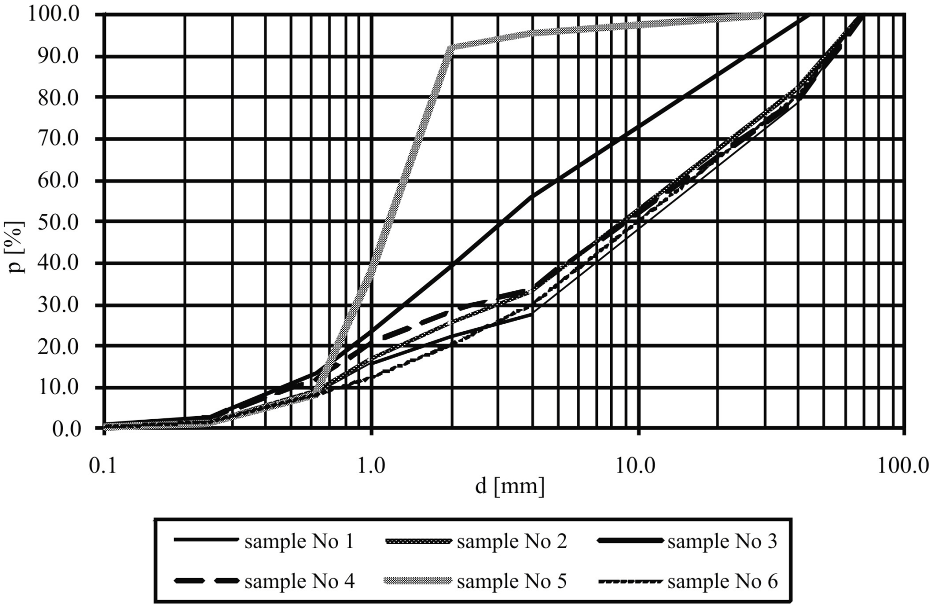

Figure 2. Granulometric distribution of bottom sediment collected in the region of large roughness elements in the stream Będkówka

The measured water flow velocities permitted to calculate the Reynolds number in particular cross-sections of the Będkówka stream. The Reynolds number was within the range 210284 - 97372 assuming the lowest values in the section with large roughness element. Having at disposal granulometric curves of the sediment sampled in the cross-sections, the diameter d_{84} was determined and absolute roughness of the bottom was calculated according to Gladki's formula (3). For sediment samples collected in the main stream current the values k_s were 87.4 mm and 92 mm. Whereas in the left-bank part of section III-III with large roughness element equivalent roughness height of the bottom was

11.5 mm. Variability of the equivalent roughness height of the bottom exerts significant influence on the value of the dimensionless coefficient of resistance λ. Table 1 presents calculation results of the dimensionless coefficient of resistance λ in each of the cross-sections of the stream and of the coefficient of roughness. In the table no calculations for cross-section IV-IV were included since the equivalent roughness height of the bottom was determined on the basis of the granulometric composition of the sediment collected from the formed sand pool. The value k_s determined in this way does not correspond with the equivalent roughness height of the bottom in the whole cross-section.

Table 1. Hydrometric parameters of water flow for the investigated sector of the Będkówka stream established for water discharge Q = 0.14 $m^3 \cdot s^{-1}$

Cross-section		Cross-section area F [m^2]	Average velocity of flow V_{sr} [$m \cdot s^{-1}$]	Equivalent roughness k [mm]	Dimensionless resistance coefficient λ [-]	Roughness coefficient n [-]
I-I		0.43	0.33	92.0	0.112	0.029
II-II		0.50	0.28	87.4	0.100	0.027
III-III	L	0.21	0.31	11.5	0.482	0.057
	P	0.17	0.43	92.0	0.085	0.023
V-V		0.57	0.25	92.0	0.106	0.028

where: L - Left-bank side of cross-section, P - right-bank side of cross-section

The coefficient of screening of this section, defined as the relation of the cross-section without large roughness grain and surface area of the grain at filling corresponding to the flow equaling 0.14 $m^3 \cdot s^{-1}$ equals 27%.

CONCLUSIONS

Occurrence of large roughness element in the flow channel induces changes in hydraulic conditions of water flow and exerts also influence on deformation of the flow channel bottom in the region of the grain. Just upstream the grain there appear local bottom lowering of 6 cm depth. Immediately downstream the large roughness grain in its shade there occur local water whirlpools conductive to sedimentation of fine grain mineral material. The sediment deposited there is characterized by diameter d_{50} which is seven to ten times smaller than the diameter d_{50} of the bedload present in the stream. In consequence of large roughness element distribution in the flow channel distribution of water flows occurs characterized by lower flow velocity in the left bank part of the channel, this being conductive to deposition of fine grain load. In this part of the channel with large grain the bottom load is characterized by a diameter d_{50} from

2.6 to 3.7 times smaller than the diameter d_{50} of the load present generally in other cross-section of the stream channel.

The large roughness grain in the Będkówka stream causes a change of hydraulic conditions of water flow in consequence of it coefficient of resistance in the left bank cross-section of the grain increases over four times. Whereas, in the right bank part of this cross- section characterized by a bigger average velocity the coefficient of resistance undergoes some decrease on the average by 25% in relation to the established coefficient of resistance as compared established with the coefficients of resistance in the other cross-sections of the stream.

The coefficient of roughness in the cross-section with large roughness element established with consideration of the determined dimensionless coefficient of resistance for the left and right part of his cross-section increases on the average in the section with large roughness grain by over 34% in relation to the coefficient of roughness of the stream channel.

REFERENCES

Byczkowski A. 1996. Hydrologia. T. 2, Wydawnictwo SGGW, Warszawa.

Kubrak J., Żbikowski A. 1995. Hydrauliczne warunki przepływu w korytach wielkich wód. [W:] Hydrauliczne i ekologiczne problemy inżynierii rzecznej. Materiały seminaryjne Katedry Budownictwa Wodnego SGGW w Warszawie. B-1-B-14.

Schroeder W. 1989. Gestaltungsmoeglichkeiten einer Renaturierungsstrecke und hydraulische Nachweise. Wasserbau-Mitteilungen der TH Darmstadt, Heft 29.

van Rijn L. C. 1984. Sediment transport. Part II: Suspended load transport. Journal of Hydraulic Engineering, vol.110, No 10. 1613-1641.

Dr hab. inż. Bogusław Michalec
Mgr inż. Mateusz Strutyński,
Katedra Inżynierii Wodnej i Geotechniki
Uniwersytet Rolniczy w Krakowie
Al. Mickiewicza 24/28, 30-059 Kraków
tel. (012) 662-40-23
rmmichbo@cyf-kr.edu.pl
mstrutynski@ar.krakow.pl