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WATER SURFACE PROFILE OF THE TRAPEZOIDAL PERMEABLE SILL WITH SHARP-CRESTED WEIR ON THE UPSTREAM SLOPE

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ABSTRACT

The aim of the study was to analyse the possibility of using dimensionless coordinates in order to determine the typical shape of the overflow stream at the gabion sill, as well as identify the flow zone therein and evaluate the characteristic dimensions of the profile.

The analysed weir consists of a permeable part filled with natural stone material, and a solid part in the form of sharp-crested weir on sloping upstream face. The shape of the upper profile of the stream has been determined along with its parameters. Three flow zones at the length of the crest sill were identified: the free flow zone, the inlet wave zone and the sill part, which is free of water.

The water flow rate influences the formation of water stream profile flowing over the tested sill. The full correlation dependence of variables was obtained in the analysis. The obtained results can be used in the design of this type of field structures.

Keywords: gabion sill, sharp-crested weir, stream shape

INTRODUCTION

Water structures are divided according to their functions, mode of operation, type of construction, material used and computational hydraulic conditions. The choice of the type of water structure used is influenced mainly by its purpose, whereas its construction depends on topographical, hydrological, hydraulic, and geological conditions as well as operational requirements. River sills (thresholds) are structures whose aim is to stabilize, strengthen and secure the bottom of the watercourse. These structures are situated across the channel of the watercourse, and they typically span its entire width.

Increasingly often, sill structures are made of stone material, reinforced with a woven or welded mesh. Such a sill is a permeable structure, through which water is filtered. At higher flow rates in the channel, water also flows over the sill crest (Akkerman and Konter, 1985). In order to maintain the minimum level of the upper water, permeable sills are installed with screens on the upper embankment, or with watertight walls located in their interior or forming upper overflow (weir) barriers. In the construction of trapezoidal sills, tight screens are laid on the upstream slope. They are inclined to the level of a fixed weir with a sharp edge. The upper edge of the weir on the embankment of the trapezoidal permeable sill determines the level beyond which the water overflows over the crest, and flows into the permeable body of the structure (Bajkowski, 2013). The surface stream affects the body of the sill, filled with aggregate, which is a porous medium, and it flows in a filtering turbulent motion between the aggregate grains through a system of ir-

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regular pores. With an increasing flow rate, the length of the infiltration zone increases, until the flow on the crest reaches the lower edge of the sill, beyond which some water flows into the body, and the rest flows over the sill.

For fixed overflows, the contour shape of the overflow stream depends on the geometry of the sill, depicted by the shape of the weir wall, its width, and the roughness of the edges, as well as the values of hydraulic variables, the flow rate, and the overflow layer height, describing the parameters of the surface stream (Sobota, 1994, Żbikowski et al., 1986). The shape of the upper stream contour on the permeable sills also depends on the geometrical characteristics of grains in the corpus (Bajkowski, 2013).

The article presents an analysis of the results from testing the free water table layout of the stream overflowing over the crest of the embankment weir, and flowing into the permeable sill. The shape of the free stream depends on the elevation of the upper water table, the geometry of the sill, and the parameters of the aggregate filling the body of the structure, which include grain size, material type, and grain placement, determining the surface roughness of the overflow crest.

MATERIAL AND METHODS

In the analyses of the water table system on the tested trapezoidal sill, the values defining the depths of the stream at characteristic points along the stream's length were defined (see: Fig. 1):

- h_k – the initial (inlet) depth of the stream in the final cross-section of the edge of the slope weir (see: No. 2 in Fig. 1), which at the same time constitutes the initial cross-section of the permeable part of the sill (see: No. 1 in Fig. 1);
- h_s – the final (outlet) depth of the free stream in the cross-section below which the wave zone of the stream disturbance appears on the crest (see: No. 4 in Fig. 1);
- h_z – the depth of the stream at the highest point of the water table at the length of the wave zone of disturbance;
- L_k – length of the water inflow zone on the overflow crest, measured from the edge of the inlet cross-section to the point where the stream disappears at the sill surface;
- L_s – the length of the free stream zone (see: No. 3 in Fig. 1) on the section from the inlet cross-section to the place where the bottom of the first wave on the body occurs;
- L_z – the length of the wave zone of disturbance arising on the surface of the crest of the sill.

Measurements of the water table profile were made along the longitudinal axis of the test site, referring the obtained results to the OXY coordinate system, whose OY ordinate is located in the inlet plane of the permeable sill, whereas the slope elevation crest is the location of the OX abscissa (see: Fig. 1).

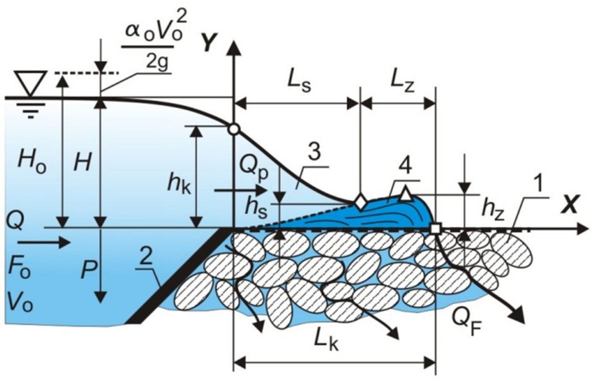


Fig. 1. Overflow stream of permeable sill: 1 – stone permeable sill, 2 – sharp-crested weir on upstream slope, 3 – free flow zone, 4 – wave intake (inlet) zone

Laboratory tests were carried out at The Professor Armand Żbikowski Hydraulic Laboratory of the WULS-SGGW in Warsaw. The test stand consisted of a flume of the following dimensions: 0.203 m wide, 0.40 m high and 4.0 m long. The tested model was a trapezoidal sill with a tight screen on the upper embankment. The slope of both embankments was 1: 1. The sill height equalled P = 0.10 m, the base width was 0.40 m, and the crest width was 0.20 m. The stone part of the sill was reinforced with a 16 x 20 mm hexagonal mesh, with wire thickness of 0.6 mm. The test stand was equipped with automatic electronic measuring devices, connected to the computer system and manual mechanical measuring devices (Bajkowski, 2009).

The sill body was filled with natural aggregate (KO). These were the boulders in the fraction group of 60/80 mm. Specific gravity of the aggregate was

2.60 g · cm^{-3}, the porosity of the body was p = 0.426, and the porosity index equalled e = 0.743 (Bajkowski, 2013, Bajkowski and Jastrzębska, 2012). The grain characteristics of the material that filled the body of the tested physical model of the sill were determined for a reliable analytical sample. To this end, a granulometric analysis was carried out according to direct grain measurement. The determined grain characteristics listed in Table 1 include:

- the actual dimensions:
  - *A* – grain length – the largest dimension determined along the longitudinal axis,
  - *B* – grain width – an indirect dimension determined along the transverse axis,
  - *C* – grain thickness – the smallest dimension perpendicular to the length and width.
- substitute dimensions:
  - D_s – mean diameter as the arithmetic mean of the length, width and thickness of the grain,
  - D_z – volumetric diameter or grain size with the volume of spherical substitute grain.

The geometrical characteristics of the aggregate curve in the aggregate sample were determined by adopting a leading dimension with respect to which the curve was developed. For the listed grain curves according to the grain size *B*, D_s and D_z, the following characteristics were determined:

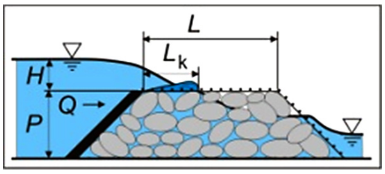
- D_m – effective grain size d_{50}, for which 50% of the sample's weight content has a larger/smaller diameter than the one given,
- D_p – mean grain diameter, calculated as the weighted average of the percentage interval p_i in which the weight percentage of the analysed dimension D_i, is measured,
- C_c – graining coefficient of curvature according to the formula (PN-B-02481/1998),
- C_u – graining coefficient of uniformity (Hazen sorting factor) (PN-EN ISO 14688-1: 2006),
- C_k – graining coefficient of variability according to Knoroz,
- C_d – dominant feature, giving the dominance of grain-size either larger or smaller than the effective diameter d_{50} (Kollis, 1966).

Table 1 lists the characteristics of the grain curves obtained for the sample being tested. These features were calculated for the actual grain curve according to the *B* dimension and for the curves according to the equivalent diameters D_s i D_z. Aggregate used in laboratory tests of gabion construction, selected according to the grain-size fraction, is characterized by grain uniformity. According to the indicated criteria, the material of the sample is single-fraction, with the majority of grains being larger than the effective diameter. Table 2 presents the measurement ranges of basic values, as measured on the model, as well as dimensionless parameters obtained in laboratory tests.

Table 1. Parameters of the grains of stone material filling the sill body

No.	Parameter	Unit	Value		
			Minimum	Average	Maximum
1	2	3	4	5	6
1	*A*	[mm]	67.6	88.5	108.0
2	*B*	[mm]	60.2	68.0	77.2
3	*C*	[mm]	37.7	53.5	68.7
4	D_s	[mm]	57.8	70.0	81.6
5	D_z	[mm]	56.6	67.1	79.4
Geometric features of the grain curves according to the dimension					
			B	D_s	D_z
6	D_m	[mm]	68.75	73.46	68.70
7	D_p	[mm]	69.06	71.79	68.97
8	C_c		1.04	0.97	0.99
9	C_u		1.15	1.18	1.18
			$C_c \cong 1$. $C_u < 6$ – single-sized material		
10	C_k		0.75	0.73	0.68
			$C_k \leq 4 \div 5$ – well-sorted material		
11	C_d		1.09	1.11	1.12
			$C_d > 1$– particles with diameters greater than d_{50} prevail		

Table 2. Parameters of the physical model and ranges of the measured values



No	Parameters	Values		
1	Value	Minimum	Average	Maximum
1	Q ($10^{-3} \cdot m^3 s^{-1}$)	1.745	2.238	2.932
2	H ($10^{-2} \cdot m$)	2.39	3.02	3.70
3	H/L	0.12	0.15	0.18
4	L/H	8.36	6.63	5.41
5	P/H	4.26	3.38	2.76
6	$H/(H+P)$	0.19	0.23	0.27
7	Re	16 463	23 534	31 879

RESULTS

Shape of the upper contour of the stream in the system of dimensional coordinates (x_p, y_p)

The water mirror profiles in the dimensional coordinates (x_p, x_p) of the measurements, as shown in Figure 2, demonstrate the variability of the water table system along the length of the overflow crest. In the area of the tested profile, two characteristic zones were distinguished: one, of free flow and the other, of disturbed (wave) flow. After the water overflows above the embankment, the line of the free water table decreases. In the lower part, the surface stream in the zone of transition into the disturbance zone deflects, and takes the shape of the trough of wave. Below, on the surface of the body, there is a wave zone of disturbances.

The inflow of water masses to the body occurs at the length of the free part and in the area of the wave form of the stream. The disturbance zone caused by the impact of the aggregate that fills the sill body also affects the shape of the lower part of the free water table. This interaction is manifested by the deviation of the free-line mirror at the entrance to the wave inlet zone (see: Fig. 2). The wave front created on the surface of the sill determines the width of the zone of the overflow crest coverage with water. The range of the wave zone of disturbance depends on the grain size parameters of the aggregate, as well as on the arrangement of its surface layer. The diversity of form of the inlet zone on the sills, which were filled with various

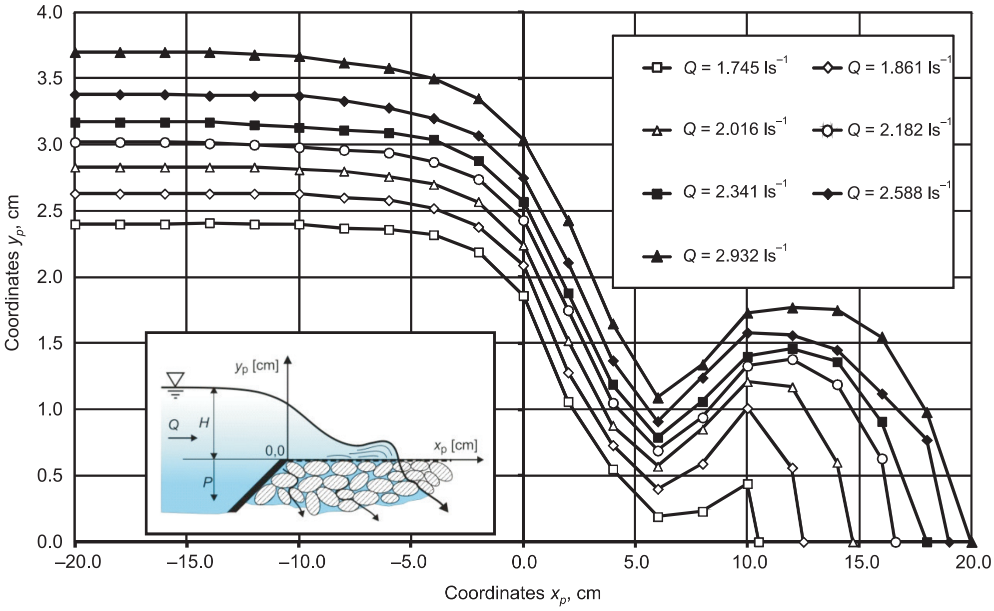


Fig. 2 . Dimensional curves of the free water surface on the permeable sill

Source: own study

aggregates (natural and broken), was observed during the studies carried out by Bajkowski (2013). Furthermore, it is possible for the type and dimensions of the mesh strengthening the body to influence the extent and form of the said zone.

Shape of the upper contour of the stream in the system of dimensionless coordinates (X_b, Y_b)

Dimensionless coordinates ($X_b = x_p/H$, $Y_b = y_p/H$) of the stream contour were obtained by dividing the values (x_p, y_p) of measurement coordinates by the H height of the water head above the overflow crest. By entering the dimensionless coordinates of the upper contour, relative values were obtained describing the ordinates of the characteristic points of the contour. In the dimensionless coordinate system (see: Fig. 3) for the initial free part of the stream, the upper contours for different heights H are arranged close to each other, forming a regular stream shape.

In the field of the graph in Figure 3, as specified by Khan & Steffler (1996), profile of the upper contour of the stream was presented, freely overflowing over a sharp-crested weir tilted at a ratio of 1:1, with a sill height of P = 9.66 cm, depth of the upper water T_g = 27.66 and unit flow rate q = 2252.5 cm$^3 \cdot$ s^{-1}. Khan & Steffler (1996) compared the results of numerical simulations with the outline obtained from previous experimental studies. The authors obtained very good compliance of the measured and calculated outlines. In order to compare the profile of Khan & Steffler (1996) with our own, the authors of the present article introduced the necessary correction (0.5 cm) of the position of point 0.0 of the axis $0X_b$ in the coordinate system, resulting from the shape of the weir wall. The intersection of the profile according to Khan & Steffler (1996) with the contour measured for the permeable sill divides the free stream into two parts: the upper one without affecting the shape of the sill, and the lower structure in which the permeable part of the body makes an impact.

Effective depths of the stream in the system of dimensionless coordinates (X_b, Y_b)

The shape of the upper contour of the tested stream shown in Figure 3 demonstrates that a typical profile of the water table for the contour of the overflow stream in stone steps with upper sealing screens can be obtained only until the location of the wave bottom,

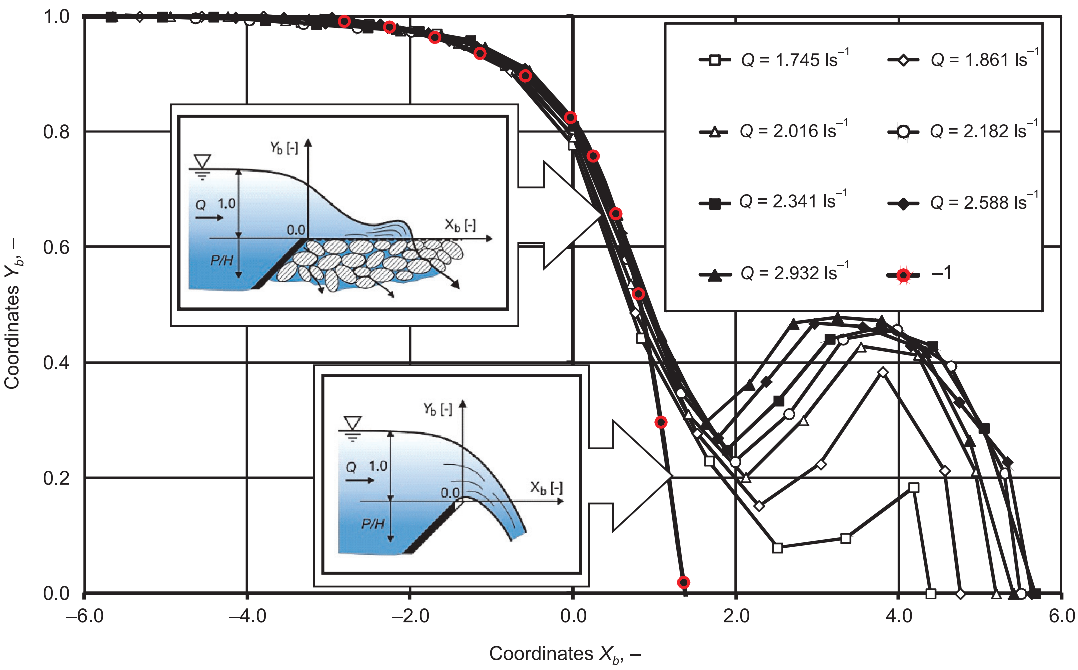


Fig. 3. Dimensionless curves of the free water surface on the permeable sill (own research): Q – according to own research, 1 – according to Khan & Steffler (1996) for sharp-crested weir

situated at a L_s distance from the inlet cross-section. In the section of disturbances, the development of such a shape requires the introduction of an additional reduction parameter, for instance, the grain diameter of the grain of the aggregate, or the length of the defined zone. The dimensionless coordinates of the upper stream contour profile can be used in the design of this type of structure, to determine the width of the sill occupied by the compact overflow stream.

Figure 4 shows the correlation between Y relative fillings at the site of defined contour points, and the X equal the head water H above the overflow crest. The levelling curves are described by a function of the following type:

$$Y = A \cdot X^2 + B \cdot X + C \tag{1}$$

Parameters A, B, C of the function according to the formula (1) for the analysed dimensionless coordinates are listed in Table 3. In the hydraulic calculations of gabion structures partially covered with water, the h_z/H ratio is of the greatest importance. The value of this ratio is the relative pressure influencing the height of the hydraulic losses at the inlet to the structure's body.

Table 3. Parameters of regression curves according to the equation (1)

No.	Parameter values			
	A	B	C	R
1	2	3	4	5
		Depth $h_k/H = f(H)$		
1	– 0.0043	0.0573	0.6687	0.981
		Depth $h_s/H = f(H)$		
2	–0.1092	0.8240	–1.2631	0.998
		Depth $h_z/H = f(H)$		
3	–0.3014	2.0171	–2.8853	0.965
		Distance $L_s/H = f(H)$		
4	0.2228	–2.0285	6.0812	0.999
		Distance $L_k/H = f(H)$		
5	–1.4630	9.7792	–10.7170	0.987

The correlation between the length L_s of the free stream zone and L_k occupied by water the width of the sill, versus the height H of the overflow layer is shown in Figure 5. Curves for individual lengths of L_s and L_k

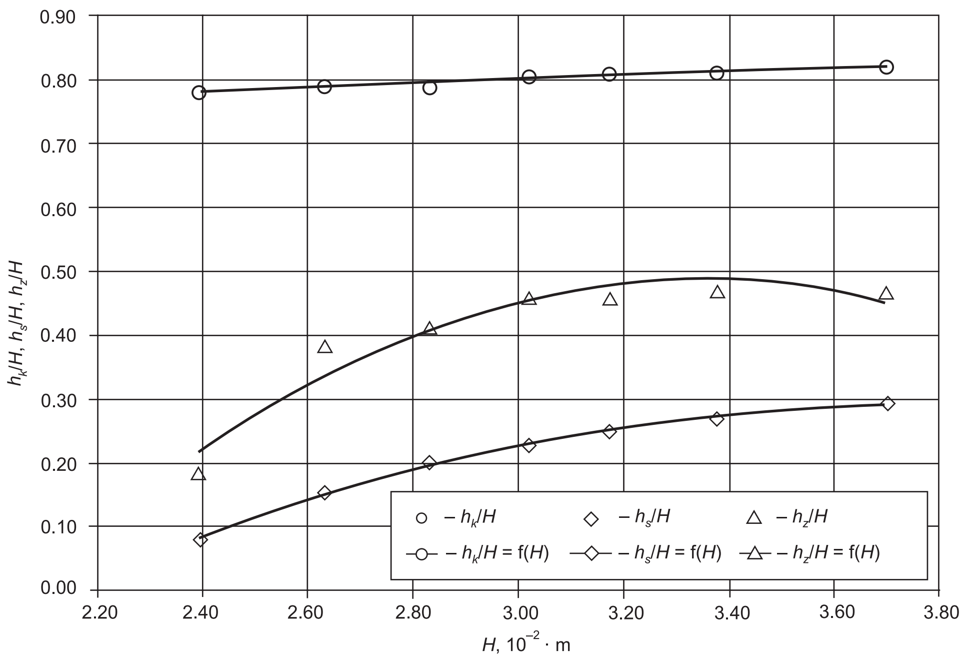


Fig. 4 . Dimensionless water depths on permeable sill

Source: own study

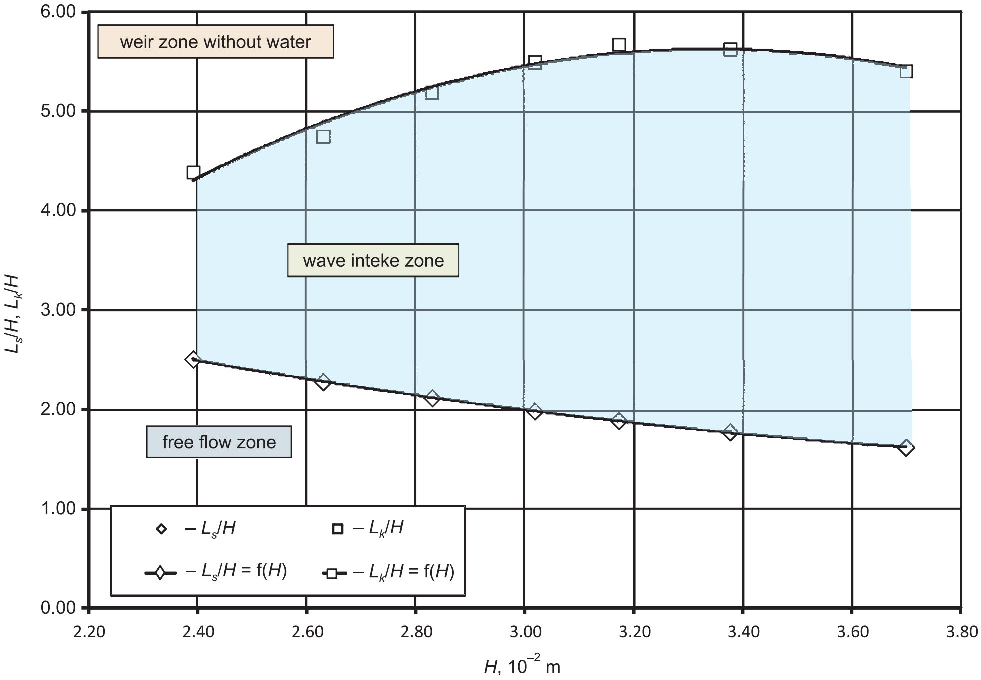


Fig. 5. Ranges of stream zones on the permeable sill

Source: own research

designate three areas within the figure corresponding to the defined zones occurring on the width of the permeable crest: free flow zone, wave intake zone, and the width of the overflow crest that is water-free.

CONCLUSIONS

The stone material filling the body of the permeable sill with a tight screen on the upper embankment changes the shape of the overflow stream in relation to the freely flowing stream over the inclined sharp-crested heir (see: Fig. 3).

In order to describe the shape of the upper stream of the overflow, dimensionless co-ordinates can be used in the initial free flow zone, as shown in Figure 3. Within this zone, the upper undisturbed part of the contour is distinguished, whose shape is approximate to the contour of the flow for an inclined sharp-crested weir, not reinforced with a stone prism.

Below the free flow, an inlet zone of disturbances is formed, in the shape of a surface wave, whose front determines the total width of the body that is covered with water. The structure of the water table in the disturbance zone is influenced by the material that the sill body is made of, and its reinforcing structure.

The relative depths of the flow h_k/H in the inlet cross-section, the h_s/H at the end of the free-flow phase, and h_z/H in the disturbance zone all depend on the elevation of the upper water level above the sill crest. These correlations were described by the parabolic function according to equation (1). The values of R correlation coefficient thus obtained (see: column 5 of Table 3) are greater than 0.9. This means that a very strong correlation was obtained. A similar very strong correlation was obtained for the relative L_s/H length of the free zone and L_z/H of the inlet stream range.

The zone that is distinguished in the contour of the initial part of the stream is characterized by free flow, as evidenced by the large compliance of the water-level system shown in Figure 3 with the outline for the overflow that is not supported by a stone prism. The shape of the lower part of the upper free stream and the water surface profile in the disturbance zone are influenced by the parameters characterizing the body material and the reinforcing structure.

The analyses that we have carried out indicate that in addition to the elevation of the upper water level above the sill, there are also other parameters affecting the shape of the contour of the overflow stream of stone sills with tight upper screens.

REFERENCES

Akkerman, G. J., Konter, J. L. M. (1985). Hydraulic Design Criteria for Rockfill Closure to Tidal Gaps,Vertical Closure Method. Report, M 1741, part IV. Delft: Delft Hydraulics Laboratory.

Bajkowski, S. (2009). System pomiarowo-kontrolny Laboratorium Hydraulicznego SGGW. In: A. Wita (ed.), Bezpieczeństwo zapór – bezpieczeństwo ludności i środowiska, Warszawa: Instytut Meteorologii i Gospodarki Wodnej, 195–203.

Bajkowski, S. (2013). Warunki przepływu wody przez budowle przepuszczalne. Warszawa: SGGW.

Bajkowski, S., Jastrzębska, U. (2012). Badanie wpływu kształtu progu gabionowego na podział przepływu. Przegląd naukowy – Inżynieria i Kształtowanie Środowiska, 58, 263–272.

Khan, A. A. & Steffler, P. M. (1996). Modeling overfalls using vertically averaget and moment equations. Journal of Hydraulic Engineering, 122(7), 397–402.

Kollis, W. (1966). Gruntoznawstwo techniczne. Warszawa: Wydawnictwo Arkady.

PN-EN ISO 14688-1:2006. Badania geotechniczne. Oznaczanie i klasyfikowanie gruntów. Część 1: Oznaczanie i opis. Polski Komitet Normalizacyjny.

PN-B-02481:1998. Geotechnika. Terminologia podstawowa, symbole literowe i jednostki miar. Polski Komitet Normalizacji, Miar i Jakości.

Sobota, J. (1994). Hydraulika. Tom, I, II. Wrocław: Wydawnictwo Akademii Rolniczej.

Żbikowski, A., Bajkowski, S., Batijewski, W., Dąbkowski, S. Z. L., Kubrak, J. i Lipka, W. (1986). Wytyczne wymiarowania przelewów i ich kanałów odprowadzających w budowlach wodno-melioracyjnych. In: H. Okruszko, Obliczenia hydrauliczne przelewów budowli wodno-melioracyjnych. Warszawa: Państwowe Wydawnictwo Rolnicze i Leśne, 9–93.

UKŁAD ZWIERCIADŁA WODY NA TRAPEZOWYM PROGU PRZEPUSZCZALNYM Z OSTROKRAWĘDZIOWYM PRZELEWEM NA SKARPIE GÓRNEJ

ABSTRAKT

Celem pracy była analiza możliwości wykorzystania bezwymiarowych współrzędnych do opisu profilu strumienia przelewowego na progu gabionowym, zdefiniowanie stref przepływu na jego długości oraz ustalenie wartości charakterystycznych wymiarów profilu.

Analizowany przelew składał się z części przepuszczalnej wypełnionej naturalnym kruszywem oraz nachylonego przelewu ostrokrawędziowego na skarpie górnej trapezowego progu. W ramach badań wyznaczono kształt górnego obrysu strumienia oraz jego parametry. Na szerokości korony progu wydzielono trzy strefy: strumienia swobodnego, falową strefę wlotową oraz cześć progu wolną od wody.

Kształt profilu strumienia przepływającego ponad badanym progiem zależy od natężenia przepływu. W analizach uzyskano pełną zależność korelacyjną analizowanych zmiennych. Uzyskane wyniki mogą być wykorzystane w projektowaniu takiego typu budowli terenowych.

Słowa kluczowe: próg gabionowy, przelew o ostrej krawędzi, kształt strumienia