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SHARP-CRESTED WEIRS FORMULA IMPROVEMENT

DOSKONALENIE METOD OBLICZANIA JAZÓW CIENKOŚCIENNYCH

Abstract: Weirs are widespread in hydrotechnical engineering practice as spillway structures in hydroelectric complexes as well as watermeasuring gauges. Sharp-crested weir is the simplest type of all weirs. Such weirs are commonly used as a mean of flow measurement, but they are also of some fundamental interest as well, because their theory forms a basis for the design and computation of spillways that ensure their safe operating conditions. This paper analysis theoretical and experimental approaches of sharp-crested weirs research. Main operating factors and boundary conditions affecting sharp-crested weir hydraulic parameters are determined. It is noted, that many scientists have focused mainly on experimental studies of weirs flow capacity. The absence of theoretical developments that explain the effect of main operating factors and boundary conditions on the weir flow parameters and, as a consequence, determination only of its flow capacity, prompted us to develop a new calculation approach based on energy and momentum conservation principles.

Key words: head, energy, momentum, pressure force, threshold depth, weir discharge coefficient
Słowa kluczowe: ciśnienie, energia, ilość ruchu, siła nacisku, głębokość progowa, współczynnik wypływu jazu

Introduction

Sharp-crested or thin-plate weir is the simplest measuring device widely used in hydraulic laboratories, water use and reclamation industries where highly accurate

discharge measurements are required. Such structures have the advantage that they are less sensitive to the downstream conditions, the channel roughness and the influence of backwater than the velocity–area method for example (Herschy 2009).

Famous scientists have made significant contribution to the theory of sharp-crested weirs computation. M. Castel (D'Aubuisson de Voisins 1834), F. D'Aubuisson de Voisins (Bennett 1852), H. Bazin (1888), M. Hegly (1917), James B. Francis (1883), A. Fteley and F. Stearns (1883), T. Rehbock (1929), K. Kindsvater and R. Carter (1957), H. King (1918), R. Čugaev (1982), K. Kandaswamy and H. Rouse (1957), K. Swamee (1988), H. Afzalimehr and S. Bagheri (2009) and others are among them.

However, we have to admit that, as a consequence of the complexity of the mathematical description of turbulent flow with a free surface, there is no theory for the flow within sharp-crested weir. Various authors in their studies avoid resolving fundamental issues and proceed to solve specific problems by introducing empirical relationships, which have limitations of their use and do not disclose the physical phenomenon of the weir flow. These circumstances complicate the work of engineers and designers. They have to analyse existing methods of calculation to find out the best one for particular conditions. Thus, theoretical studies of the sharp-crested weirs and the development of computational theory are of great practical importance.

History of research investigation

Until 1850s use of sharp-crested weirs as a measurement tool to determine the water flow discharge was very limited. Experiments on research have been performed on small-scale models. They do not take into account the effect of all operating factors and could not provide reliable measurement results.

The first suppressed sharp-crested weirs experiments worth sharing were conducted by French scientists. In 1835 and 1836 M. Castel (D'Aubuisson de Voisins 1834) investigated the weir consisted of a wooden dam, surmounted by a crest of copper 3 mm thickness at the waterworks of Toulouse. Castel erected his apparatus on a terrace in conjunction with the water tower. He received a continuous supply of 37.4 l/s, capable of being increased to 50.1 l/s. The head varied from 3.6 to 7.6 cm. F. D'Aubuisson (Bennett 1852) obtained the following formula, derived from the experiments of Castel for a suppressed weir in m^3/s

$$Q = 1.92LH\sqrt{H + 0.115\,W^2},\qquad(1)$$

where L is the actual length of weir crest, m; H is the observed head, m; W is measured central surface velocity of approach, equal $1{,}2V$, where V is the mean velocity of approach in the approach channel, m/s.

The experiments by J.V.. Poncelet and J.A. Lesbros (1832) were conducted at Metz, in 1827–1836. The experiments were performed on the weir in fixed copper plate, 5.56 feet in length. The head varied from 0.050 to 0.787 feet. In 1846 P. Boileau (Horton 1907) based on their and his own experiments (weir length varied from 0.95 to 5.30 feet, the height was 1.12-2.64 feet and the head varied from 0,19 to 0,72 feet) received the following equation for a suppressed weir in ft^3/s

$$Q = 3.3455 \frac{P+D}{\sqrt{(P+D)^2-D^2}} LD^{3/2}, \tag{2}$$

where P is height of the weir crest above bottom of channel of approach, ft; D is weir head, ft. Boileau afterwards gave a table of corrections varying with the depth, indicating a discharge from 96 to 107% of that obtained with the formula (2).

In 1886-1888 french engineer Henry Bazin (1888) has performed thorough researches of the sharp-crested weir capacity in the side channel of the Canal de Bourgogne, near Dijon, France. Based on the well done experiments in rectangular channels 0.5–2.0 m in width, with the weirs p =0.240–1.135 m high and with the heads up to h =0,60 m he deduced the following equation for the discharge of the sharp-crested weir in m^3/s

$$Q = \mu \left(1 + 0.55 \frac{h^2}{(p+h)^2}\right) lh\sqrt{2gh}, \tag{3}$$

where l is actual length of the weir crest, m; g is acceleration of gravity, m/s^2; μ is a coefficient of weir discharge that depends on the weir head $\mu = 0.405 + 0.003/h$.

M. Hegly (1917), who worked with H. Bazin, specified the weir discharge coefficient as following $\mu = 0.405 + 0.0027/h$, then the discharge in m^3/s

$$Q = \left(0.405 + \frac{0.0027}{h}\right) \left(1 + 0.55 \frac{h^2}{(p+h)^2}\right) lh\sqrt{2gh}, \tag{4}$$

Formula (4) is called Bazin-Hegly formula.

Great contribution to the investigation of the sharp-crested weirs was made by American scientists. The experiments on discharge over thin-plate weirs were conducted in 1848–1852 at the Pawtucket canal and at the Boott Cotton Mills in Lowell (Francis 1883). Based on these experiments, Francis proposed following equation in ft^3/s

$$Q = 3.33 \left[1 + 0.26 \frac{H^2}{(G+H)^2}\right] bH^{3/2}, \tag{5}$$

where b is actual length of the weir crest, ft; G is height of weir crest, ft; H is weir head, ft.

A. Fteley and F. Stearns conducted their experiments on sharp-crested weir discharge in 1877–1879, near Boston and at the private well in Gate House (Fteley, Stearns 1883). The weir length varied from 5 to 19 ft, weir height was from 0.50 to 3.17 ft and the observed heads varied from 0.0735 to 1.6038 ft. Based on their own measurements and recalculation of the James B. Francis experiments, Fteley & Stearns obtained the final formula in ft^3/s

$$Q = 3.31 L H_0^{3/2}, \tag{6}$$

where H_0 is a head corrected for the effect of velocity of approach, $H_0 = H + ah$; H is a weir head, ft; $a = 1.5$ for suppressed weirs and $a = 2.05$ for weirs with end contractions; $h = \alpha V^2/(2g)$ is velocity head, ft.

The King`s Formula is based upon a study of the experiments of Francis, Fteley and Stearn and Bazin. H. King (1918) specified the coefficient of weir discharge and made correction for the effect of velocity of approach, ft^3/s

$$Q = 3.34LH^{1.47}\left(1 + 0.56\frac{H^2}{d^2}\right), \tag{7}$$

where L is length of the weir crest, ft; H is weir head, ft; d is actual depth of the flow upstream from the weir, ft.

International Organization for Standardization ISO 1438:2017 Hydrometry – Open channel flow measurement using thin-plate weirs recommends the Kindsvater – Carter formula (Kindsvater and Carter 1957; Chaudhry 2008; Munson et al. 2013) for the suppressed sharp-crested weir discharge in m^3/s

$$Q = C_e\frac{2}{3}\sqrt{2g}b_e h_e^{3/2}, \tag{8}$$

where C_e is coefficient of discharge; b_e, h_e is effective width and effective head, respectively, m. For suppressed weirs, effective width b_e is equal to the weir crest width b and the effective head is defined by the equation $h_e = h + k_h$, where h is weir head, m; $k_h = 0,001\ m$ is a quantity which compensate the combined effects of viscosity and surface tension. The coefficient of discharge C_e for full-width sharp-crested weirs, has been determined by experiment from the formula

$$C_e = 0.602 + 0.075\frac{h}{p},$$

where p is height of the weir crest, m.

Indian Standards Institution in IS:9108–1979 in addition to Kindsvater – Carter formula (8) recommends to use following equations: T. Rehbock formula; the Swiss Society of Engineers and Architects (SIA) formula and formula of the Institute of Fluid Mechanics of Toulouse (IMTF).

German hydraulician T. Rehbock (1929) suggested next equation for weir discharge in m^3/s

$$Q = C_e\frac{2}{3}\sqrt{2g}bh_e^{3/2}, \tag{9}$$

where $C_e = 0.602 + 0.083\frac{h}{p}$ is a coefficient of discharge, and effective head is $h_e = h + 0.0012m$.

SIA formula for the suppressed thin-plated weir is, m^3/s

$$Q = C\frac{2}{3}\sqrt{2g}bh^{3/2}, \tag{10}$$

where coefficient of discharge C is

$$C = \left(0.615 + \frac{0.000615}{h+0.0016}\right)\left(1 + 0.5\left(\frac{h}{p+h}\right)^2\right).$$

The IMTF formula uses full flow strength $H_0 = h + V_a^2/2g$ for weir discharge determination in m^3/s

$$Q = C\frac{2}{3}\sqrt{2g}\,b\left(h + \frac{V_a^2}{2g}\right)^{3/2}, \qquad (11)$$

where

$$C = 0.627 + 0.0180\left(\frac{h + V_a^2/2g}{p}\right),$$

where V_a is average flow velocity in approach channel, m/s; $V_a = Q/A_a$, where A_a is an area of cross section of approach channel in which the head h is determined, m^2. Equation (11) can be solved by method of iterations.

Acoording to R. Čugaev (1982) for the heads more than $H \geq 0.10\,m$ and $H \leq 2p_в$ the coefficient of discharge can be determined as

$$m = 0.402 + 0.054\frac{H}{p_в},$$

where $p_в$ is height of the weir crest, m, than the discharge can be determined in m^3/s

$$Q = \left(0.402 + 0.054\frac{H}{p_в}\right)\sqrt{2g}\,bH^{3/2}. \qquad (12)$$

K. Kandaswamy and H. Rouse (1957) from Iowa Institute of Hydraulic Research have conducted experimental hydraulic researches of vertical sharp-crested weirs at the end of a horizontal channel for the continuously changing ratio of head to depth of the flow from zero to unity. In their research, they proved the possibility of using T. Rehbock formula to determine the coefficient of discharge in a range of ratios $0 < h/w < 6$ and within the range $0 < w/h < 0.06$ they received the following equation for the coefficient of weir discharge

$$c_d = 1.06\left(1 + \frac{w}{h}\right)^{3/2},$$

where w is height of the weir crest, m, h is weir head, m, then, m^2/s

$$q = \frac{2}{3}c_d\sqrt{2g}\,h^{3/2}, \qquad (13)$$

In the intermediate zone $5 < h/w < 15$ equations (9), (13) fail, the authors note here the smooth growth of the weir discharge coefficient with its maximum value at the ratio $h/w \approx 10$ and its further reduction to $c_d = 1.06$ when there is no weir crest. This range corresponds to the transition from the regime of weir flow to sill flow.

By combining equation (9) and equation (13), and applying the experimental data of K. Kandaswamy and H. Rouse (1957); K. Swamee (1988) and Swamee at al. (2001) obtained the following full-range equation for the coefficient of sharp-crested weir discharge

$$C_d = 1.06\left(\left(\frac{14.14w}{8.15w+h}\right)^{10} + \left(\frac{h}{h+w}\right)^{15}\right)^{-0,1},$$

then, m^3/s

$$Q = \frac{2}{3}1.06\left(\left(\frac{14.14w}{8.15w+h}\right)^{10} + \left(\frac{h}{h+w}\right)^{15}\right)^{-0,1}b\sqrt{2g}\,H^{3/2}. \qquad (14)$$

H. Afzalimehr and S. Bagheri (2009) used the potential flow theory to determine an equation for discharge coefficient of rectangular sharp-crested weirs

$$C_d = 0.409 \left(\frac{P}{h}\right)^{0.541} \left[\left(1+\frac{h}{P}\right)^2 - 1\right]^{0,5},$$

where P is a height of the weir crest above bottom of channel of approach, m and discharge accordingly, m^3/s

$$Q = \frac{2}{3} 0.409 \left(\frac{P}{h}\right)^{0.541} \left[\left(1+\frac{h}{P}\right)^2 - 1\right]^{0,5} b\sqrt{2g}h^{3/2}. \tag{15}$$

S. Bagheri and M. Heidarpour (2009) and Samiee at al. (2016) used equations of flow nappe profiles developed from experimental data and free-vortex theory to determine a relation for discharge coefficient of a sharp-crested rectangular weir with ratios $h/p \leq 9$

$$C_d = 0.324 \, exp(0.94 \, b/B) \, ln\left(1 + \frac{0.73(h/p+3.64)}{exp(1.18b/B)}\right),$$

where $b,\ B$ are width of the weir crest and approach channel respectively, m. Then weir discharge can be obtained in m^3/s

$$Q = \frac{2}{3} 0.324 \, exp(0.94 \, b/B) \, ln\left(1 + \frac{0.73(h/p+3.64)}{exp(1.18b/B)}\right) b\sqrt{2g}h^{3/2}. \tag{16}$$

Evaluation of results & conclusions

The above equations have different designations of physical quantities and different dimension that complicates their analysis. Therefore, in the table 1 these equations are reduced to symbols and dimensions according to the International System of Units for specific discharge $q = Q/b$, m^2/s, where b is the weir crest width, m.

Analysis of the equations given in table 1 revealed, that all given formulas include empirical discharge coefficients. In formulas (1), (3), (4), (8), (9), (10) factor-label method between operative factors is failed. Therefore, considered equations can be used only within the values of variables in the range of conducted experiments. Using these equations for the actual size weirs (extrapolation of their decisions) is questionable.

Based on energy and momentum conservation principles authors proposed a mathematical model that, in distinction from dependences mentioned before, makes possible to calculate the hydraulic sharp-crested weir flow parameters depending on main operating factors and boundary conditions

$$\left.\begin{array}{l} p + H + \dfrac{\alpha_1 q^2}{2g(p+H)^2} = p + \dfrac{h}{2} + \dfrac{\alpha_2 q^2}{2gh^2} + h_w \\[2mm] \alpha_{02}\dfrac{q^2}{gh} - \alpha_{01}\dfrac{q^2}{g(p+H)} = \dfrac{1}{2}(p+H)^2 - \dfrac{P_2}{\rho g b} - \dfrac{P_{\zeta x}}{\rho g b} \end{array}\right\}, \tag{17}$$

where α_1, α_2 are coefficients of kinetic energy; $(p + h/2)$ is high-altitude position of the jet stream axis; h_w is weir head losses; α_{02}, α_{02} are velocity coefficients; P_2 is piezometric pressure force in section of the overflow wall; $P_{\zeta x}$ is flow contraction resistance force caused by abrupt vertical contraction of the flow and its transformation to the nappe. The design circuit of such weir is shown in the fig. 1.

Equations suggested for specific discharge determination

Zależności zalecane do określenia konkretnego zużycia

Author	№ of equation	Design equation	Operating range
F. D'Aubuisson	(1)	$q = 0.435H\sqrt{2g(H + 0{,}035(1.2V)^2)}$	
P. Boileau	(2)	$q = 0.417\left(\dfrac{p + H}{\sqrt{(p + H)^2 - H^2}}\right)\sqrt{2g}H^{3/2}$	
H. Bazin	(3)	$q = m\left(1 + 0.55\dfrac{H^2}{(p+H)^2}\right)\sqrt{2g}H^{3/2}$, where $m = \left(0.405 + \dfrac{0.003}{H}\right)$	$H/p \le 1.75H$ $> 0.05\ mp$ $> 0{,}2\ mb > 0{,}2\ m$
Bazin – Hegly	(4)	$q = m\left(1 + 0.55\dfrac{H^2}{(p+H)^2}\right)\sqrt{2g}H^{3/2}$, where $m = \left(0.405 + \dfrac{0.0027}{H}\right)$	$H/p \le 1.75H$ $> 0.05\ mp$ $> 0.2\ mb > 0.2\ m$
James B. Francis	(5)	$q = 0.415\left(1 + 0.26\dfrac{H^2}{(p + H)^2}\right)\sqrt{2g}H^{3/2}$	
A. Fteley & F. Stearns	(6)	$q = 0.413\sqrt{2g}H_0^{3/2}$, where $H_0 = H + 1.5\dfrac{\alpha V^2}{2g}$	
H. King	(7)	$q = 0.416\left(1 + 0.56\dfrac{H^2}{(p + H)^2}\right)\sqrt{2g}H^{1.47}$	
Kindsvater – Carter	(8)	$q = \dfrac{2}{3}\left(0.602 + 0.075\dfrac{H}{p}\right)\sqrt{2g}H_e^{3/2}$, where $H_e = H + 0.001\ m$	$H/p \le 2.5H$ $> 0.03\ mp$ $> 0.10\ mb > 0.15\ m$
T. Rehbock	(9)	$q = \dfrac{2}{3}\left(0.602 + 0.083\dfrac{H}{p}\right)\sqrt{2g}H_e^{3/2}$, where $H_e = H + 0.0012\ m$	$H/p \le 1.0\ 0.03 \le H \le 0.75\ m\ p > 0.10\ mb > 0.30\ m$
SIA	(10)	$q = \dfrac{2}{3}m\left(1 + 0.5\left(\dfrac{H}{p+H}\right)^2\right)\sqrt{2g}H^{3/2}$, where $m = \left(0.615 + \dfrac{0.000615}{H+0.0016}\right)$	$H/p \le 1.0;\ 0.025 \le H \le 0.8\ m;\ p > 0.3m$
IMTF	(11)	$q = \dfrac{2}{3}m\sqrt{2g}(H + h_0)^{3/2}$, where $m = 0.627 + 0.0180\left(\dfrac{H+h_0}{p}\right), h_0 = \dfrac{\alpha V^2}{2g}$	$H/p < 2.5;\ H > 0.03\ m;\ p > 0.1\ m;\ b > 0.2\ m.$
R. Chugaev	(12)	$q = m_0\sqrt{2g}H^{3/2}$, where $m_0 = 0.402 + 0.054(H/p)$	$H \ge 0.10\ m,$ $H/p \le 2.0$
K. Kandaswamy, H. Rouse	(13)	$q = \dfrac{2}{3}\left(1.06\left(1 + \dfrac{p}{H}\right)^{3/2}\right)\sqrt{2g}H^{3/2}$	$H/p \ge 15$

K. Swamee	(14)	$q = \frac{2}{3} m_0 \sqrt{2g} H^{3/2},$ where $m_0 = 1.06 \left(\left(\frac{14.14 p}{8.5 p + H} \right)^{10} + \left(\frac{H}{p + H} \right)^{15} \right)^{-0.1}$	$0 < H/p < \infty;$ $H > 0.03\ m;\ b > 0.15\ m$
H. Afzalimehr	(15)	$q = \frac{2}{3} 0.409 \left(\frac{p}{H} \right)^{0.541} \left[\left(1 + \frac{H}{p} \right)^2 - 1 \right]^{0.5} \sqrt{2g} H^{3/2}$	$0 < H/p \leq 8;$ $H > 0.03\ m;\ b > 0.15\ m$
S. Bagheri	(16)	$q = \frac{2}{3} m_0 \sqrt{2g} H^{3/2},$ where $m_0 = 0.324\, exp(0.94\, b/B) \cdot$ $\cdot\ ln \left(1 + \frac{0.73(H/p + 3.64)}{exp(1.18\, b/B)} \right)$	$0 < H/p \leq 9;$ $H > 0.03\ m;\ b > 0.15\ m$

Note: H = weir head; p = height of the weir crest above bottom of channel of approach

In order to determine unknown boundary conditions (piezometric pressure force in section of the overflow wall P_2, flow contraction resistance force $P_{\zeta x}$) and weir head losses h_w special theoretical and experimental investigations in glass-sided-tilting-flume were conducted (Khlapuk et al. 2015; Korniichuk et al. 2017). Based on them, adequate computing dependences were obtained. The adopted design of the weir model enabled following experiments conditions: relation between main operating factors H/p ranged from 0,11 to 9,0; Reynold number R from 17954 to 764797 that corresponds to wholly turbulent flow and Froude number F from 0,003 to 0,930 that corresponds to lower flow regime.
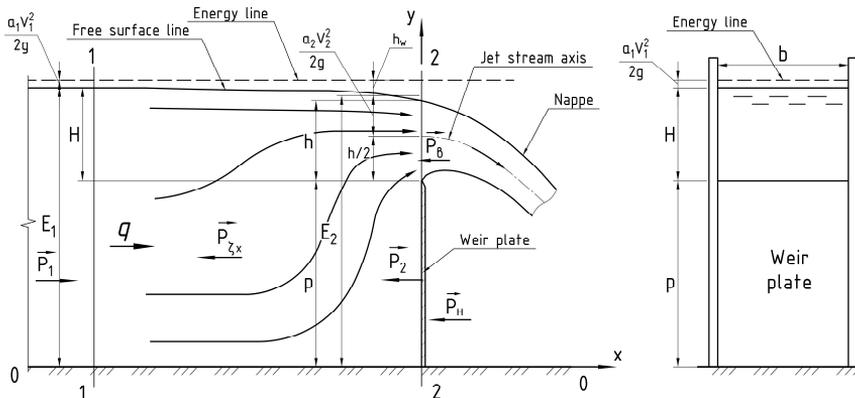

Fig. 1. Rectangular, sharp-crested weir geometry
Ryc. 1. Schemat przelewu cienkościennego

Result of mathematical model (17) are weir head losses, piezometric pressure force in section of the overflow wall, flow contraction resistance force, threshold depth and high-altitude position of the jet stream axis, specific weir discharge.

Utilizing equations, recommended in table 1, specific discharges were calculated. To compare them with specific discharge calculated with mathematical model (17) weir discharge coefficients were calculated with the use of well-known formula

$$m_0 = \frac{q}{\sqrt{2g} H^{3/2}}. \tag{18}$$

Substituting in the formula (17) heads and specific discharges calculated with the equations presented in table 1 corresponding coefficients of discharge m_0 are obtained and graphs between the discharge coefficient m_0 and the relative height H/p for 1,0 m weir height are plotted in Fig. 2. The graphs shown in Fig. 2 are indicated by the numbers of formula numbers according to Table 1. This figure also shows the graph calculated for the proposed mathematical model (17) (position 17).

Analysis of the weir discharge coefficient graphs $m_0 = f(H/p)$ shows a significant deviation within different authors` research results, that points out the lack of knowledge in the field of sharp-crested weir research. Besides most of equations are applicable for the ratio of operating factors less than $H/p < 2.0$. Use of these dependencies to calculate the actual size weirs is questionable.
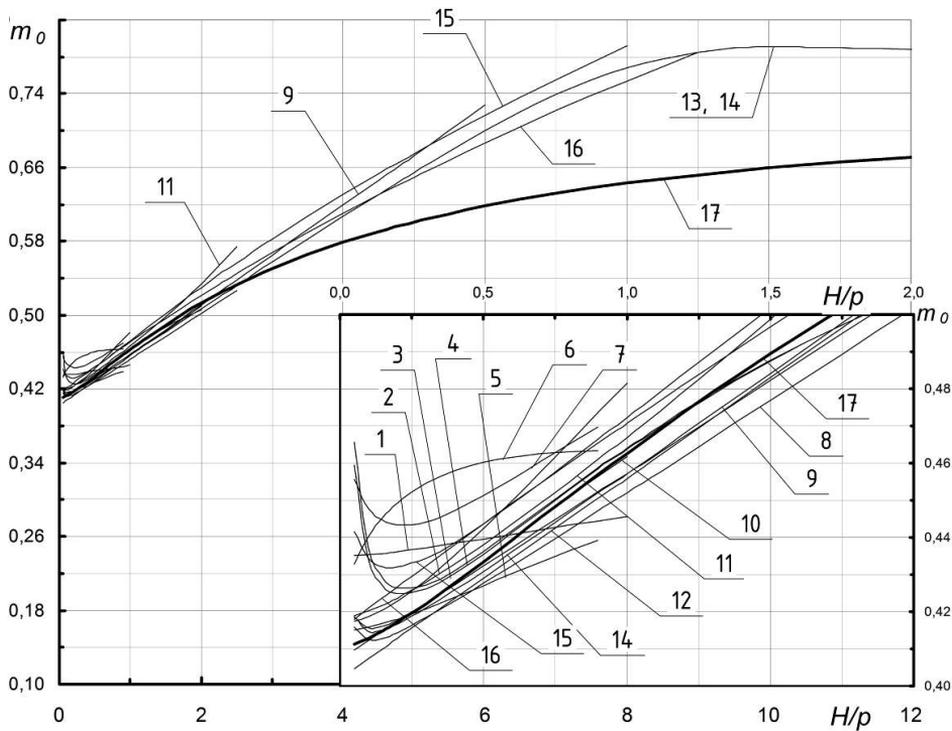

Fig. 2. Dependency graphs $m_0 = f(H/p)$
Ryc. 2 Wykresy zależności $m_0 = f(H/p)$

1 – F. D'Aubuisson; 2 – P. Boileau; 3 – H. Bazin; 4 – Bazin – Hegly; 5 – James B. Francis; 6 – A. Fteley, F. Stearns; 7 – H. King; 8 – Kindsvater – Carter; 9 – T. Rehbock; 10 – SIA; 11 – IMTF; 12 – R. Chugaev; 13 – K. Kandaswamy, H. Rouse; 14 – K. Swamee; 15 – H. Afzalimehr; 16 – S. Bagheri; 17 – present study

The proposed mathematical model makes it possible to calculate sharp-crested weir flow capacity in a wide range of main operating factors, using the generally accepted energy conservation principles. Also, it makes possible to determine the boundary conditions of the flow, head losses and threshold depth.

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Summary

The methods to determine discharge capacity of the sharp-crested weirs and the calculated dependencies based on them are analyzed. In most cases empirical weir discharge constants are used to calculate the discharge. These constants are obtained while investigating small-scaled sharp-crested weirs models in short range of operative factors. Herewith, scale effect of the transition from the models of the weirs, for which discharge constants were obtained, to the real structures is not taken into account. Discharges calculated by different dependencies, for the same conditions, can vary considerably among themselves.

The developed mathematical model will improve sharp-crested weirs calculation methods on the bases of general accepted energy conservation principles without using empirical discharge constants.

Streszczenie

W artykule poddano analizie metody określania przepustowości jazów cienkościennych oraz zależności wyliczane na ich podstawie. W większości przypadków do tego rodzaju obliczeń wykorzystuje się empiryczne stałe przepustowości uzyskiwane na podstawie badania niewielkich modeli jazów cienkościennych, w odniesieniu do małego zakresu czynników operacyjnych. Metoda taka nie uwzględnia efektu skali – przejścia od modeli jazów, dla których uzyskano stałe przepustowości, do rzeczywistej konstrukcji. Przepustowości obliczane na podstawie różnych zależności, dla tych samych warunków, mogą się więc między sobą znacznie różnić.

Opracowany model matematyczny, opierający się na ogólnie przyjętej zasadzie zachowania energii, pozwoli udoskonalić metody obliczeniowe stosowane w przypadku jazów cienkościennych bez odwoływania się do empirycznych stałych przepustowości.