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Chezy's Resistance Coefficient in a Rectangular Channel

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Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

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ABSTRACT

The Chezy's resistance coefficient plays an important role in the calculation of the normal depth in the open channels. When using the Chezy's relationship for the calculation of the normal depth, the main unknown parameter of the problem is the Chezy's coefficient. There is no explicit and complete relationship for the evaluation of the Chezy's resistance coefficient. Current relations are either implicit or do not take into account all the parameters that influence the flow, such as channel slope or kinematic viscosity. Most of them do not apply to the whole domain of turbulent flow because the kinematic viscosity is not taken into account. For these reasons, one affects arbitrarily a constant value for Chezy's resistance coefficient as a given data of the problem, in most practical applications. This arbitrary choice is not physically justified because the Chezy's resistance coefficient must be calculated according to the parameters that influence the flow, especially the normal depth sought. The purpose of this paper is to show how to calculate the Chezy's resistance coefficient in a rectangular channel, using the minimum of practical data. In this article, it is expressed the dimensionless Chezy's coefficient in order to give it a general validity character. The expression of this dimensionless coefficient is deduced from the comparison between the Chezy's relationship and the general formula of the discharge valid for all geometric profiles. The detailed study of this relationship gives interesting results. It is clearly demonstrated that the dimensionless Chezy's resistance coefficient depends on the relative roughness, the aspect ratio of the wetted

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area and the modified Reynolds number. This allows concluding that the obtained relationship is applicable to the entire domain of turbulent flow. The graphical representation of this relationship shows that the dimensionless Chezy coefficient increases with the decrease of the aspect ratio of the wetted area, whatever the value of the modified Reynolds number. This is reflected in the increase of the Chezy's coefficient when the normal depth increases. In addition, the obtained curves intersect the x-axis at points corresponding to the particular case of the narrow rectangular channel, for which the aspect ratio tends to zero. This corresponds to a rectangular channel of small width and large depth. For this particular case, the relationship expresses the dimensionless Chezy coefficient is established, showing the influence of both the relative roughness and the modified Reynolds number. The aspect ratio of the wetted area has no effect.
Through a detailed practical example, it is shown how to calculate the Chezy resistance coefficient in a rectangular channel, from practical data. This calculation depends on the value of the relative normal depth in a rough rectangular channel that is easily determined using the rough model method. A cubic equation is obtained whose resolution is facilitated by the hyperbolic and trigonometric functions.

Keywords: Chezy's coefficient; rectangular channel; energy slope; rough model method; turbulent flow; discharge.

1. INTRODUCTION

The Chezy formula expresses the mean velocity *v* in a steady turbulent flow in open channels as:

$$v = C\sqrt{R_h S} \tag{1}$$

C is the Chezy's resistance coefficient, R_h is the hydraulic radius and *S* is the slope of the channel. Eq. (1) was derived from hydrodynamics theory [1-3]. This formula was used in the construction of channels around the world, from the Panama Canal to the irrigation system of the Central Valley of California.

In the literature, we find no recent relations that express the Chezy coefficient *C*. The most frequently cited are the old formulae of Manning [4], Guanguillet-Kutter [5], Bazin [6] and Powell [7].

Manning empirical relationship expresses the coefficient *C* as follows:

$$C = \frac{1}{n} R_h^{1/6} \tag{2}$$

Where *n* is the Manning's roughness coefficient.

The Guanguillet-Kutter formula expresses *C* in terms of the hydraulic radius R_h, the coefficient of roughness *n* known as Kutter's *n* and the slope *S*. In M.K.S units, this formula is:

$$C = \frac{23 + \dfrac{0.00155}{S} + \dfrac{1}{n}}{1 + \left(23 + \dfrac{0.00155}{S}\right)\dfrac{n}{\sqrt{R_h}}} \tag{3}$$

This relationship does not contain a term relating to the kinematic viscosity. Thus, it can not be applied to the entire domain of turbulent flow. Its application seems to be restricted to the rough domain for which the kinematic viscosity has no effect.

Bazin formula expresses the coefficient *C* as a function of hydraulic radius R_h, but not of the slope *S*. This formula is:

$$C = \frac{87}{1 + \dfrac{m}{\sqrt{R_h}}} \tag{4}$$

Where *m* is a coefficient of roughness whose values are given by a table as a function of the type of the material forming the channel or the conduit. As for the Guanguillet-Kutter formula, Bazin formula contains no terms of kinematic viscosity. It does not therefore apply to the whole domain of turbulent flow.

The Powell formula is more complete as it contains the hydraulic radius R_h, the absolute roughness ε and the Reynolds number R_e. However, this formula is implicit, expressing *C* as:

$$C = -42\log\left(\frac{C}{4R_e} + \frac{\varepsilon}{R_h}\right) \quad (5)$$

According to this relationship, C depends especially on the Reynolds number R_e and therefore on the kinematic viscosity ν. In this relation, there is no term that expresses the influence of the slope S on the coefficient C. Its application seems to be suitable for the entire domain of turbulent flow. It is interesting to note that Powell formula contains the absolute roughness ε which is a measurable parameter in practice. To determine the coefficient C by the Powell formula, it is necessary to use a trial-and-error procedure.

More recently, Swamee and Rathie [8] have attempted to propose a general relationship for Chezy's coefficient C, applicable in the entire domain of turbulent flow and for all shapes of channels and conduits. However, this relationship is implicit, requiring also a trial-and-error procedure especially when the linear dimension of the channel or conduit is not given, or when it comes to compute the normal depth of the flow. Swamee and Rathie suggested for C a logarithmic formula as:

$$C = -2.457\sqrt{g}\,\ln\left(\frac{\varepsilon}{12R_h} + \frac{0.221\nu}{R_h\sqrt{gSR_h}}\right) \quad (6)$$

ν is the kinematic viscosity. Apart from its implicit form, this relationship has the advantage of being very complete. All the flow parameters are included in this relationship.

According to the literature, several tests were performed on corrugated pipes or large scale roughness in channels of non circular cross section that have not led to a convincing formula for Chezy's coefficient.

Among these studies, we can mention those of Streeter [9], Ead and al. [10], Pyle and Novak [11], Marone [12], Perry and al. [13], Naot and al. [14]. More recently, Giustolisi [15] used a genetic programming to determine Chezy's resistance coefficient for full circular corrugated channels. For commercial pipes or artificial channels, the literature does not indicate specific studies. That is why this article is proposed which aims to enrich the bibliography. A simple relationship is proposed for the explicit calculation of the Chezy coefficient in rectangular channel, based on measurable data in practice. This relationship is derived from the general discharge formula proposed by Achour and Bedjaoui [16]. The obtained relationship contains all the parameters that affect the flow, especially the relative roughness, the aspect ratio of the wetted area and mainly the Reynolds number, in such a way that the relationship is applicable in the whole domain of turbulent flow. The Chezy's coefficient relationship is presented in a dimensionless form in order to have a general validity character. It thereby enables to deduce the relationship governing the particular case of the narrow rectangular channel. The graphical representation of the relationship allows us to deduce interesting hydraulic conclusions. The article concludes with an example of practical application in which Chezy's coefficient is calculated from practical data. In this example, the aspect ratio of the wetted area is calculated by the use of the rough model method that has been proven in the recent past by contributing successfully to the design of conduits and channels and to the calculation of normal depth [17-20].

2. HYDRAULICS PROPERTIES

The characteristics of the flow in a rectangular channel (Fig. 1) are in particular:

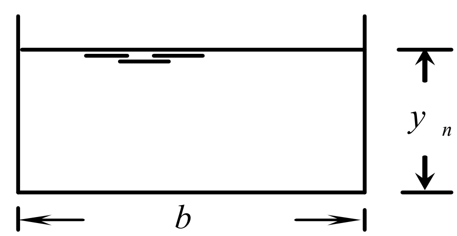

Fig. 1. Flow in a rectangular channel

1. The water area:

$$A = by_n \quad (7)$$

Where b is the width of the channel and y_n is the normal depth.

2. The wetted perimeter:

$$P = b + 2y_n \quad (8)$$

3. The hydraulic radius $R_h = A/P$:

$$R_h = \frac{by_n}{b + 2y_n} \quad (9)$$

Equation (9) can be written as:

$$R_h = \frac{b}{(\eta_0 + 2)} \qquad (10)$$

In which $\eta_0 = b / y_n$ is the aspect ratio of the water area.

3. GENERAL RELATIONSHIP OF CHEZY'S COEFFICIENT

Chezy's relationship expresses the discharge *Q* as follows:

$$Q = CA\sqrt{R_h S} \qquad (11)$$

Where *C* is the Chezy's coefficient and *S* is the slope of the channel. Moreover, in a previous study [16], Achour and Bedjaoui gave a general relationship of the discharge *Q* according to all parameters influencing the flow. This relationship, applicable to all geometric profiles, was established in the whole domain of turbulent flow encompassing smooth, transition and rough regimes. According to Achour and Bedjaoui [16], the discharge *Q* is given by the following formula:

$$Q = -4\sqrt{2g}\, A\sqrt{R_h S}\log\left(\frac{\varepsilon}{14.8R_h} + \frac{10.04}{R_e}\right) \qquad (12)$$

Where R_e is a Reynolds number, *g* is the acceleration due to gravity and ε is the absolute roughness which characterizes the state of the inner wall of the channel. The Reynolds number R_e is governed by the following equation:

$$R_e = 32\sqrt{2}\,\frac{\sqrt{g\,S\,R_h^3}}{\nu} \qquad (13)$$

In which ν is the kinematic viscosity. Inserting Eq. (4) into Eq. (7) results in:

$$R_e = \frac{32\sqrt{2}}{(\eta_0 + 2)^{3/2}}\frac{\sqrt{gSb^3}}{\nu} \qquad (14)$$

Eq. (8) can be rewritten as follows:

$$R_e = R_e^*\varphi(\eta_0) \qquad (15)$$

Where:

R_e^* is a modified Reynolds number expressed as:

$$R_e^* = \frac{\sqrt{gSb^3}}{\nu} \qquad (16)$$

$$\varphi(\eta_0) = \frac{32\sqrt{2}}{(\eta_0 + 2)^{3/2}} \qquad (17)$$

Comparing Eq. (11) and Eq. (12), it is obvious that Chezy's coefficient is such that:

$$C = -4\sqrt{2g}\log\left(\frac{\varepsilon}{14.8R_h} + \frac{10.04}{R_e}\right) \qquad (18)$$

or, in dimensionless form :

$$\frac{C}{\sqrt{g}} = -4\sqrt{2}\log\left(\frac{\varepsilon}{14.8R_h} + \frac{10.04}{R_e}\right) \qquad (19)$$

Taking into account Eq. (10), Eq. (15) and Eq. (17), Eq. (19) is reduced to:

$$C/\sqrt{g} = -4\sqrt{2}\log\left(\frac{\varepsilon / b}{1.165[\varphi(\eta_0)]^{2/3}} + \frac{10.04}{R_e^*\varphi(\eta_0)}\right) \qquad (20)$$

Eq. (20) reflects the fact that the dimensionless Chezy's coefficient $C/\sqrt{g}$ depends on three parameters namely, the relative roughness ε / b, the aspect ratio η_0 and the modified Reynolds number R_e^*. Eq. (20) is the general relationship of Chezy's resistance coefficient in rectangular channel. It can lead to the relation of Chezy's coefficient in narrow rectangular channels by writing that $\eta_0 \to 0$ or $\varphi(\eta_0) = 16$ according to Eq. (20). Thus, Eq. (17) becomes:

$$C/\sqrt{g} = -4\sqrt{2}\log\left(\frac{\varepsilon / b}{7.4} + \frac{0.6275}{R_e^*}\right) \qquad (21)$$

Thus, for narrow rectangular channels, the dimensionless Chezy's coefficient $C/\sqrt{g}$ depends only on two parameters which are the relative roughness ε / b and the modified Reynolds number R_e^*. The aspect ratio η_0 has no effect.

4. VARIATION OF CHEZY'S COEFFICIENT

The graphical representation of Eq. (20) is not easy, but it can be shown, as an indication, its variation for a fixed value of the relative roughness ε / b. This has been performed for different values of ε / b and for Reynolds number R_e^* varying between 10^5 and 10^8. Among all the obtained graphs, those of Fig. 2 and Fig. 3 are representative. Fig. 2 translates the variation of $C / \sqrt{g}$ versus the aspect ratio η_0 and the modified Reynolds number R_e^*, for $\varepsilon / b = 0$ corresponding to a smooth inner wall of the channel. Fig. 3 shows the variation of $C / \sqrt{g}$ versus the aspect ratio η_0 and the modified Reynolds number R_e^*, for $\varepsilon / b = 0.01$ corresponding to a state of the rough inner wall of the channel.

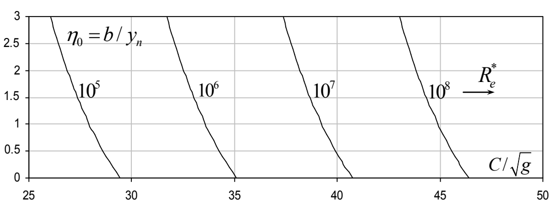

Fig. 2. Variation of $C / \sqrt{g}$ versus η_0 and R_e^*, according to Eq. (20), for $\varepsilon / b = 0$

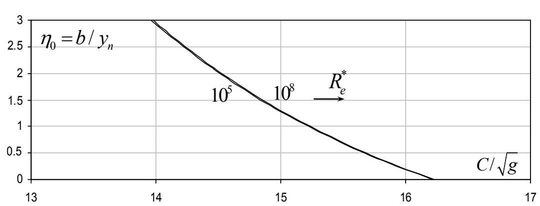

Fig. 3. Variation of $C / \sqrt{g}$ versus η_0 and R_e^*, according to Eq. (20), for $\varepsilon / b = 0.01$

Fig. 2 clearly shows that, for a given value of the modified Reynolds number R_e^*, $C / \sqrt{g}$ increases as η_0 decreases. This means that for a given rectangular channel whose width *b* is known, $C / \sqrt{g}$ increases with the increase of the normal depth y_n. Fig. 2 also shows that $C / \sqrt{g}$ increases with the increase of the modified Reynolds number R_e^*, for a given value of the aspect ratio η_0. The curves of Fig. 2 and Fig. 3 intersect the $C / \sqrt{g}$ axis at points corresponding to the particular case of the narrow rectangular channels for which $\eta_0 \rightarrow 0$. This particular case is governed by Eq. (15).

For the relative roughness $\varepsilon / b = 0.01$, Fig. 3 shows the plot of two curves which are virtually overlapping, corresponding to the modified Reynolds numbers $R_e^* = 10^5$ and $R_e^* = 10^8$. This reflects the fact that the rough turbulent regime is reached for which there is no influence of the modified Reynolds number R_e^*, or the kinematic viscosity ν of the flowing liquid, on $C / \sqrt{g}$. The dimensionless Chezy's coefficient $C / \sqrt{g}$ depends solely on the aspect ratio η_0 and the relative roughness ε / b. This case is governed by Eq. (14), writing that $R_e^* \rightarrow \infty$. Hence:

$$C / \sqrt{g} = -4\sqrt{2} \log \left(\frac{\varepsilon / b}{1.165 \left[\varphi(\eta_0) \right]^{2/3}} \right) \qquad (22)$$

5. COMPUTATION STEPS OF CHEZY'S COEFFICIENT

To calculate Chezy's coefficient, it is necessary that the following parameters are known: the discharge *Q*, the slope *S*, the absolute roughness ε, the width *b* of the channel and the kinematic viscosity ν of the flowing liquid. Considering these parameters, the following steps are recommended to compute Chezy's coefficient:

1. Compute the relative normal depth $\eta = y_n / b$ and deduce the aspect ratio $\eta_0 = b / y_n = 1/\eta$. To calculate the relative normal depth, it is preferable to use the rough model method [16-20]. An example of practical application will be presented in which this method will be presented and detailed.
2. Calculate the value of $\varphi(\eta_0)$ in accordance with Eq. (17).
3. Compute the relative roughness ε / b.

4. Compute the value of the modified Reynolds number R_e^* using Eq. (16).
5. Thus, Chezy's coefficient *C* is worked out with the aid of Eq. (20).

6. PRACTICAL EXAMPLE

Compute Chezy's coefficient *C* for the following data:

$Q = 3.861\ m^3/s$; $b = 2\ m$; $\varepsilon = 0.001\ m$;
$S = 0.001$; $\nu = 10^{-6} m^2/s$

1. The first step is to evaluate the relative normal depth. Use for this the rough model method. The rough model is a rectangular channel of width $\overline{b} = b$, flowing a discharge $\overline{Q} = Q$ under a slope $\overline{S} = S$. It is also characterized by a friction factor $\overline{f} = 1/16$, arbitrarily chosen in the fully rough regime. Consequently, the relative normal depth in the rough model is such that $\overline{\eta} > \eta$. Applying the Darcy-Weisbach relationship [21] to the flow in the rough model, we easily obtain the following equation of third degree in $\overline{\eta}$:

$$\overline{\eta}^3 - \frac{Q^{*2}}{64}\overline{\eta} - \frac{Q^{*2}}{128} = 0 \tag{23}$$

Where Q^* is the relative conductivity, expressed as:

$$Q^* = \frac{Q}{\sqrt{gSb^5}} \tag{24}$$

The discriminant of Eq. (17) can be written as:

$$\Delta = \left(\frac{Q^*}{16}\right)^4 \left(1 - \frac{Q^*}{6\sqrt{3}}\right)\left(1 + \frac{Q^*}{6\sqrt{3}}\right) \tag{25}$$

Eq. (19) shows that two cases arise:

a) $Q^* \geq 6\sqrt{3}$, then $\Delta \leq 0$. The real root of Eq. (17) is:

$$\overline{\eta} = \frac{Q^*}{4\sqrt{3}}\cos(\beta/3) \tag{26}$$

where the angle β is as:

$$\cos(\beta) = \frac{6\sqrt{3}}{Q^*} \tag{27}$$

b). $Q^* \leq 6\sqrt{3}$, then $\Delta \geq 0$. The real root of Eq. (23) is:

$$\overline{\eta} = \frac{Q^*}{4\sqrt{3}}\mathrm{c}\,h(\beta/3) \tag{28}$$

where *ch* is the hyperbolic cosine. The angle β is as:

$$ch(\beta) = \frac{6\sqrt{3}}{Q^*} \tag{29}$$

For the data given in the problem statement, the relative conductivity Q^* is given by Eq. (24) as:

$$Q^* = \frac{Q}{\sqrt{gSb^5}} = \frac{3.861}{\sqrt{9.81 \times 0.001 \times 2^5}} = 6.89112787$$

The relative conductivity so calculated is less than $6\sqrt{3}$, which permits the conclusion that the relative normal depth $\overline{\eta}$ in the rough model is governed par Eq. (28) along with Eq. (29). According to Eq. (29), the angle β is:

$$\beta = a\cosh\left(6\sqrt{3}/Q^*\right) = a\cosh(6 \times \sqrt{3}/6.8911787) = 0.96960721$$

Using Eq. (28), the relative normal depth $\overline{\eta}$ is then:

$$\overline{\eta} = \frac{Q^*}{4\sqrt{3}}\mathrm{c}\,h(\beta/3) = \frac{6.89112787}{4 \times \sqrt{3}} \times ch(0.96960721/3) = 1.04705283$$

The water area $\overline{A}$ of the rough model is:

$$\overline{A} = b^2 \overline{\eta} = 2^2 \times 1.04705283 = 4.18821133\ m^2$$

The wetted perimeter $\overline{P}$ in the rough model is as:

$$\overline{P} = b(1 + 2\overline{\eta}) = 2 \times (1 + 2 \times 1.04705283) = 6.18821133\ m$$

The hydraulic diameter $\overline{D_h} = 4\overline{A} / \overline{P}$ is then:

$$\overline{D_h} = 4 \times 4.18821133 / 6.18821133 = 2.70721933\ m$$

Thus, the Reynolds number $\overline{R_e}$ which characterizes the flow in the rough model is:

$$\overline{R_e} = \frac{4Q}{\overline{P}\,\nu} = \frac{4 \times 3.861}{6.18821133 \times 10^{-6}} = 2495713.09$$

According to the rough model method, the non-dimensional correction factor of linear dimension ψ is related to the hydraulic characteristics of the rough model by the following relationship:

$$\psi = 1.35 \left[-\log\left(\frac{\varepsilon / \overline{D_h}}{4.75} + \frac{8.5}{\overline{R_e}} \right) \right]^{-2/5} \tag{30}$$

Whence:

$$\psi = 1.35 \times \left[-\log\left(\frac{0.001 / 2.70721933}{4.75} + \frac{8.5}{2495713.09} \right) \right]^{-2/5} = 0.76845584$$

Assign to the rough model the new linear dimension $\overline{b} = b / \psi$. This results in the equality of the relative normal depths in the rough model and in the current channel, i.e. $\overline{\eta} = \eta$. For the new linear dimension $\overline{b} = b / \psi$, the relative conductivity is:

$$Q^* = \frac{Q}{\sqrt{gS(b/\psi)^5}} = \frac{3.861}{\sqrt{9.81 \times 0.001 \times (2 / 0.76845584)^5}} = 3.56728326$$

The relative conductivity so calculated is less than $6\sqrt{3}$, implying that the relative normal depth $\overline{\eta} = \eta$ is governed par Eq. (28) along with Eq. (29). According to Eq. (29), the angle β is:

$$\beta = a\cosh\left(6\sqrt{3} / Q^*\right) = a\cosh(6 \times \sqrt{3} / 3.56728326) = 1.73155729$$

Using Eq. (28), the relative normal depth sought is then:

$$\eta = \frac{Q^*}{4\sqrt{3}} \mathrm{c}h(\beta/3) = \frac{3.56728326}{4\times\sqrt{3}} \times ch(1.73155729/3) = 0.60306724$$

The aspect ratio $\eta_0 = b/y_n = 1/\eta$ is:

$$\eta_0 = 1/\eta = 1/0.60306724 = 1.6581899$$

2. According to Eq. (17), one may write:

$$\varphi(\eta_0) = \frac{32\sqrt{2}}{(\eta_0+2)^{3/2}} = \frac{32\times\sqrt{2}}{(1.6581899+2)^{3/2}} = 6.4679344$$

3. The relative roughness ε/b is:

$$\varepsilon / b = 0.001/2 = 0.0005$$

4. According to Eq. (10), the modified Reynolds number R_e^* is as:

$$R_e^* = \frac{\sqrt{gSb^3}}{\nu} = \frac{\sqrt{9.81\times0.001\times2^3}}{10^{-6}} = 280142.821$$

5. Thus, with the aid of Eq. (14), the dimensionless Chezy's coefficient $C/\sqrt{g}$ is:

$$C/\sqrt{g} = -4\sqrt{2}\log\left(\frac{\varepsilon/b}{1.165[\varphi(\eta_0)]^{2/3}} + \frac{10.04}{R_e^*\varphi(\eta_0)}\right)$$

$$= -4\times\sqrt{2}\times\log\left(\frac{0.0005}{1.165\times6.4679344^{2/3}} + \frac{10.04}{280142.821\times6.4679344}\right) = 21.9985195$$

The required Chezy's coefficient *C* is then:

$$C = 21.9985195\sqrt{g} = 21.9985195\times\sqrt{9.81} = 68.9\ m^{0.5}/s \cong 69\ m^{0.5}/s$$

6. This step aims to calculate Chezy's coefficient using the relationship given by the rough model method. According to this method, the Chezy's coefficient *C* is related to the non-dimensional corrector factor of linear dimension ψ by the following simple equation:

$$C = \frac{8\sqrt{2g}}{\psi^{5/2}} \tag{31}$$

Whence:

$$C = \frac{8\times\sqrt{2\times9.81}}{0.76845584^{5/2}} = 68.4529552\ m^{0.5}/s$$

Thus, the relative deviation between the coefficients of Chezy calculated in steps 5 and 6 is about 0.65% only. This means firstly that Eq. (31) is reliable, and secondly the computation step of the relative normal depth η can be avoided. Only the calculation of the relative normal depth $\bar{\eta}$ in the rough model is necessary, as explained in step 1.

7. CONCLUSIONS

Using the general discharge relationship, the expression of the non-dimensional Chezy's coefficient $C/\sqrt{g}$ was established for a rectangular channel. The obtained expression clearly showed that $C/\sqrt{g}$ depends on the relative roughness ε/b, the aspect ratio η_0 of the wetted area and the modified Reynolds number R_e^* characterizing the state of the flow. This in turn depends on the slope S, the width b of the channel and the kinematic viscosity ν. All parameters influencing the flow are represented in the expression of $C/\sqrt{g}$, unlike current relationships. The resulting relationship was presented in dimensionless terms, giving it a general validity character. Its graphical representation clearly showed that $C/\sqrt{g}$ increases with the decrease of the aspect ratio η_0, whatever the value of the modified Reynolds number R_e^*. The obtained curves intersect the x-axis at points corresponding to $\eta_0 \to 0$, reflecting the particular case of narrow rectangular channel. For this case, the expression of $C/\sqrt{g}$ was established, showing the influence of the relative roughness ε/b and the modified Reynolds number R_e^*.

Calculating C requires the determination of the relative normal depth η. We have shown, through a practical example, that this relative depth is easily determined by the rough model method, provided the discharge Q, the slope S, the width b and the kinematic viscosity ν are given.

For future research it would be interesting to apply the rough model method for the calculation of the Chezy's resistance coefficient C in other geometric profiles of open channels.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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