Ерозія та руйнування русел річок, фундаментів підтоплюваних інженерних споруд пришвидшується під час стихійних явищ, супроводжуваних значним збільшенням швидкості й змоченого периметру річкових потоків, набуттям рухливості частинками русла. Проаналізовано взаємодію потоку води із окремим каменем циліндричної, сферичної, еліпсоїдної, пірамідальної та іншої конфігурації. Зокрема розвинуто традиційний підхід до визначення силової дії рідини на тверду перешкоду – камінь - для випадку стиснення струменю води й врахування відносної обтічності каменю із заданими геометричними характеристиками: діаметр, об`єм та конфігурація.

Запропоновано використовувати наступні параметри взаємодії потоку води із каменями різних конфігурацій: коефіцієнт стиснення та коефіцієнт обтічності. Отримано аналітичні залежності між граничною швидкістю потоку, яка спричиняє рух каменя, його масою та конфігурацією. Для сферичних гладких каменів ці відношення співпадають із класичними результатами. Запроваджені коефіцієнти типізовано у залежності від конфігурації окремого каменя у таблицях та графіках, що є зручним для використання у розрахунках берегоукріплень. Запропоновано використовувати коефіцієнт форми каменя – відношення дійсної граничної швидкості потоку, що викликає рухливість каменю довільної конфігурації із врахуванням його обтічності – до граничної швидкості потоку сферичного каменю такої ж маси з приведеним діаметром. Коефіцієнт форми слід використовувати як коригуючий множник у розрахунках мінімальної маси каменів для берегоукріплень та у гідротехнічних роботах. Для каменів клиновидної форми значення коригуючого коефіцієнта може в окремих випадках досягати значення 0,170, що вказує на високу ефективність використання таких каменів у порівнянні із сферичними. Крім того запропонований коефіцієнт може застосовуватися для уточнення граничної швидкості потоку води, з огляду на втрату стійкості існуючого берегоукріплення.

Визначено напрями подальших досліджень: аналіз ударної взаємодії конфігуративних каменів із елементами берегоукріплень; визначення параметрів руху водно- каменевих потоків

Ключові слова: річкові потоки, конфігурація каменю, дія потоку на перешкоду, гранична швидкість потоку, берегоукріплення

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ANALYSIS OF INTERACTION BETWEEN A CONFIGURABLE STONE AND A WATER FLOW

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1. Introduction

The multitude of environmental problems at present includes the process of washing out the banks by river flows during floods. This issue is particularly pressing for mountain areas, where during natural disasters water flow in streams increases by tens, and sometimes hundreds, times. The result of riverbed destruction is the formed water-stone arrays that move at considerable speed and further accelerate the destruction of a bank line. The dimensions of stones that are captured by a water flow are in a certain way associated with the speed of its motion. That necessitates that the strength and stability of bank-protecting structures against destruction should be sufficient to interact not only with the water flow, but with a water-stone array with regard to the discrete nature of the load, which is a function of the flow rate and the geomorphological conditions of a riverbed.

Therefore, studying in detail the process of interaction between a water flow and solid obstacles and inclusions is related to those relevant problems that arise in the practice of the construction and effective operation of various river bank-protecting structures. Traditional approaches to solving such problems are based on the application of a classic Izbash formula, which links the volume and density of a stone with the river flow rate limit that can displace such a rock. However, local disturbances that are caused by the compressibility of a water flow, as well as the configuration of a stone, are neglected in this formula. Given the considerable material losses that may arise during destruction of hydroengineering structures, the refinement of results from estimating the structures of such facilities is extremely important. Specifically, it concerns taking into consideration, during such calculations, the structural-rheological features of stones and a water flow specified above.

2. Literature review and problem statement

In modern practice, one of the main techniques to reduce the consequences of disastrous floods for the environment is the protection of the river coastline and foundations of engineering structures by mounds – banquettes made of stones that are large enough, insensitive to the action of the water flow. Paper [1] categorized the structures of banquettes depending on the characteristics of a water flow; however, the configuration of stones from the banquette is not considered. A study into the process of local washouts, reported in paper [2], only partially takes into consideration local disturbance of a water flow, neglecting its capability to be compressed and a pulse action of the water-stone flow, in which the size of a rolling stone could be close to the size of the mound's element.

A problem on the interaction between a river flow and a solid body, a stone, emerged during the design and construction of large-scale hydro-facilities by arranging stone mounds, as it was described in paper [3]; however, the simplicity of engineering assessments, given in this work, does not cover those special features of a material covering the riverbed, associated with their configuration. At the same time, application of numerical methods for calculating the behavior of bottom elements, proposed in paper [4], although it makes it possible to take into consideration the structural features of the examined object, it, however, complicates the application in engineering practice. In study [5], stones are simulated by spheres of reduced diameter, and in [6] – by cylinders. However, the results, obtained in these papers, relate to a limited class of objects, and do not make it possible to analyze the behavior of bottom elements with different configurations. The results reported in paper [7] describe interaction between stones and a water flow, resulting in the formation of vortices of different nature. Still, these results are also far from engineering practice. Features of the simulation of contact interaction between a stone and a liquid medium are given in study [8], but this approach is complicated for the analysis of stones with different physical-mechanical properties. At the same time, taking the mentioned properties into consideration, reported in work [9], does not cover the conditions for contact interaction between various media. Application of results from both papers is complicated for engineering use. Study [10] found a theoretical maximum depth of a washout in the vicinity of bridge supports, but it failed to analyze the minimum size of a strengthening stone, sufficient to protect such a support from the effect of flooding and floods.

It is important for analysis of the interaction between a river flow and the riverbed elements of hydro-engineering structures to study the conditions for long-term successful operation of such facilities. Paper [11] summarized the characteristics of successful and long-time operated hydraulic structures at small hydroelectric power plants in some river basins of Poland; while work [12] reports the systematic study into deformation of a dam's body as a result of the interaction with a river flow at some hydro-engineering facilities in Slovakia, and article [13] substantiated a criterion for the long-term successful operation of such hydro-engineering objects. However, these results do not make it possible to characterize the dependence of the operation duration of a dam on the configuration of stones that underlie these dams.

Summing up the above analysis, we note that existing engineering methods for calculating the size of elements at protective stone mounds, which are important for designing new, highly reliable hydraulic structures, and for protecting existing hydraulic structures from natural phenomena, are imperfect as they do not take into consideration the configuration of stones and the compressibility of water flow. Numerical methods for computing such problems require significant resources when modeling an object, as well as the development of sophisticated software. Thus, it is important to create advanced engineering assessments of the influence of the configuration of individual stones on the maximum speed of a river flow, which is capable of displacing individual stones. The importance of this task is associated with the need to comprehensively refine the size and configuration of stones suitable for protective mounds at hydro-engineering structures that would ensure their long-term successful operation during a period of the projected increase in the rate of a river flow when natural phenomena occur.

3. The aim and objectives of the study

The aim of this work is to determine the impact from the configuration of a stone on a river flow rate limit considering the stability of a bank-protecting structure.

To accomplish the aim, the following tasks have been set:

– to determine the equilibrium limit of a configurable bottom element, a stone, in a water flow based on the cylindrical bottom element in a river flow;

– to devise a procedure for the refined calculation of elements at river bank-protecting structures considering the configuration of stones used.

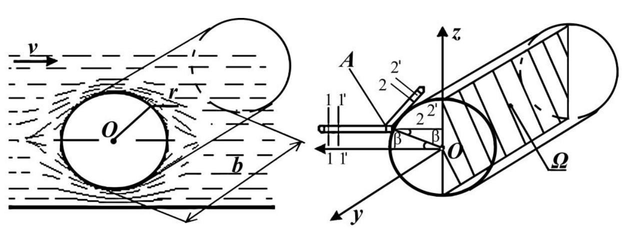
4. Materials and methods to study contact interaction between a solid body and a fluid

Visual analysis of stone detritus that remain at the bottom of riverbeds in mountain river flows (Fig. 1) makes it possible to define certain types of stone configuration (bottom elements) that can be conditionally categorized as follows: cylindrical, spherical, ellipsoidal, parallelepipedal, wedge, pyramidal, etc.

a *b*

Fig. 1. Stone deposits in riverbeds: *a* – River Krushelnitsa, a tributary of the river Stryi (2008); *b* – River Opir, near the village of Tuhlia (2015)

We shall consider a cylindrical bottom element, whose length *b* is large enough compared with radius *r*, which is why the influence of disturbances of a river flow in the vicinity of the ends of the cylinder is disregarded. The depth of a stone immersion is much greater than its radius *r* (Fig. 2, *a*).



a *b*

Fig. 2. General view of a stone: *a* – in a flow; *b* – interaction between an arbitrary elementary jet and a cylindrical stone

We shall consider the bottom element, a stone, to be smooth, and water in a river to be of low viscosity, which is why the processes of vortex formation and viscous friction are disregarded. We introduce the Cartesian O_{xyz} coordinate system so that the *Ox* axis is parallel to the plane of the flow bottom and is directed against the movement of the water flow, the *Oz* axis is perpendicular to it, the *Oy* axis is directed along the axis of the cylinder, point *O* coincides with the center of the weight of the examined cross-section of the cylinder. Applying a standard approach, we shall consider an elementary jet that moves at velocity ν relative to the cylindrical stone, the point of intersection between the axis of the jet and the stone, A, defines the radius of the cross section of the cylinder, inclined to *Ox* at angle β (Fig. 2*b*). When in contact with a stone, a jet compresses in a certain way and then flows around it. Part of fluid in the jet, located between cross sections 1–1 and 2–2, displaces over time Δt to position 1'–1' – 2'–2' and renders the stone a certain amount of movement, whose projection upon the *Ox* axis is $\Delta KP_{11'}$

$$\Delta KP_{11'} = \int_{1'}^{2'} v_x dm - \int_{1}^{2} v_x dm = \int_{2}^{2'} v_x dm - \int_{1}^{1'} v_x dm, \tag{1}$$

where ν_x is the projection of velocity ν on the *Ox* axis, *dm* is the discrete element of mass along the examined elementary jet. At section 1–1' projection $\nu_x=-\nu_1$, at section 2–2' – $\nu_x=-\nu_2 \sin\beta$, where $\nu_1=\nu$ is the jet velocity prior to the impact against the stone, ν_2 – following the impact. As a result of contact interaction, the jet compresses. We introduce magnitude $\varepsilon=\varepsilon(\beta)=\frac{\omega_2}{\omega_1}$ – a jet compression degree, where ω_1, ω_2 is the cross-sectional area of the jet prior and after the impact, respectively. It follows from the equation of a fluid flow continuity that $v_2=\frac{v_1}{\varepsilon(\beta)}$, which is why at section 2–2':

$$v_x = -\frac{v_1}{\varepsilon(\beta)}\sin\alpha.$$

Thus, in (1), the magnitude of the projection of velocity ν_x is constant over the integration sections.

For element *dm*, considering the continuity of a flow: $\omega_2\nu_2=\omega_1\nu$, and the direction of the *Ox* axis

$$\int_{1}^{1'} dm = \rho\int_{1}^{1'} dV = \rho\omega_1\int_{1}^{1'} dx = \rho\omega_1\left(x'_1 - x_1\right) = \\ = \rho\omega_1\frac{x'_1 - x_1}{\Delta t}\Delta t = -\rho\omega_1 v\Delta t,$$

$$\int_{2}^{2'} dm = \rho\int_{2}^{2} dV = \rho\omega_2\int_{2}^{2'} dx = \rho\omega_2\left(\xi'_2 - \xi_2\right) = \\ = \rho\omega_2\frac{\xi'_2 - \xi_2}{\Delta t}\Delta t = -\rho\omega_2 v_2\Delta t = -\rho\omega_1 v\Delta t,$$

where *dV* is the respective *dm* element of the volume, ρ is the density of water, x'_1, x_1 are the coordinates of cross-sections 1–1 and 1'–1' along the *Ox* axis, ξ'_2, ξ_2 are the progressive coordinates of cross-sections 2–2 and 2'–2' along the axis, opposite to the direction of the jet motion after its impact against the stone. In conclusion, we write

$$\Delta K_{11'} = \rho v^2\omega_1\left(1 - \frac{\sin\beta}{\varepsilon(\beta)}\right)\Delta t. \tag{2}$$

In order to determine a change over time Δt in the amount of motion $KP_{\Delta t}$ of all elementary jets that form the flow of fluid, which frontally interacts with a bottom element, we shall integrate expression (2) along section Ω, the cross-section of the stone by the *yOz* coordinate plane (Fig. 2, *b*)

$$KP_{\Delta t} = \int_{\Omega} dKP = \rho v^2 \Delta t \int_{\Omega} \left(1 - \frac{\sin\beta}{\varepsilon(\beta)}\right) d\omega = \frac{1}{3} S_{\Omega} \rho v^2 \Delta t \cdot k_{compr}. \quad (3)$$

where $S_{\Omega}=2br$ is the area of section Ω, k_{compr} is the integrated compression ratio of the flow, determining which requires that function $\varepsilon=\varepsilon(\beta)$ should be assigned, which requires a significant volume of experimental data. In a given notation, we propose the following:

$$\varepsilon(\beta) = \varepsilon = \text{const} = \frac{S_{displ} - S_{\Omega}}{S_{displ}},$$

where S_{displ} is the area of displacement, that is, the area of part of the cross-section of the flow, in which one observes a disturbance caused by the examined stone. Then, for a cylindrical stone

$$k_{compr} = 3 - \frac{1{,}5}{\varepsilon}. \quad (4)$$

According to the theorem about a change in the amount of body movement, applied to the finite part of the fluid flow, the fluid acts on the stone with force

$$F = \frac{KP_{\Delta t}}{\Delta t} = \frac{1}{3} S_{\Omega} \rho v^2 k_{compr}. \quad (5)$$

Its magnitude is decisive for studying the limit of a stone equilibrium in the flow of an actual fluid.

In the course of research, we assumed the bottom element, a stone, to be smooth, and water in a river to be of low viscosity, which is why the processes of vortex formation and viscous friction were neglected. The minimum size of a stone was traditionally determined from the classical solution to a problem for the spherical bottom element of reduced diameter in a river flow.

To generalize the case of a stone equilibrium limit, actual stones were changed for the spherical bottom elements of reduced diameter, which ruled out determining the influence of a stone configuration on its interaction with a water flow.

5. Results of research into the limit of stone equilibrium in a flow of fluid

In order to deal with the first task stated in this work, we consider a cylindrical stone in a flow of fluid that moves along the non-horizontal plane at slope α (Fig. 3). By employing (5), we obtain the following relation for the maximum velocity of a river flow, which shifts the examined stone from its position

$$v = Y_s \frac{1}{\sqrt{k_{compr}}} \sqrt{2g \frac{\rho_s - \rho_w}{\rho_w}} \sqrt{\frac{3V_T}{2S_{\Omega}}}, \quad (6)$$

where $Y_s = \sqrt{f\cos\alpha - \sin\alpha}$ is the coefficient of stability of the stone against the shift (rolling), f is the generalized coefficient of resistance, ρ_s, ρ_w is the density of a stone and water, respectively, V_T is the volume of a stone.

By applying the above-implemented standard approach, we derived a ratio for stones with different configurations. Note that formulae (5) and (6) are universal for all cases; the shape of a stone defined a flow compression ratio k_{compr}. We shall introduce the generalized streamline coefficient for a stone of maximum size in the direction of a flow motion – D

$$Y_{strl} = \frac{1}{\sqrt{k_{compr}}} \sqrt{\frac{3V_T}{2S_{\Omega}D}}. \quad (7)$$

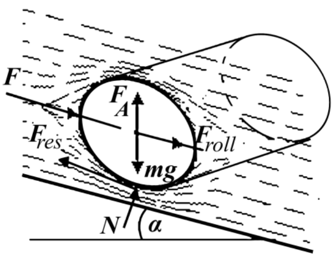


Fig. 3. The limit of a stone equilibrium in a descending flow of fluid: F_A – pushing force, $F_{res} = (\rho_s - \rho_w)\, V_T g f \cos\alpha$ is the resistance force, F_{roll}, N is the rolling force and the normal reaction from a bottom

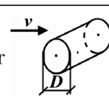
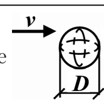
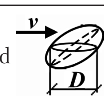
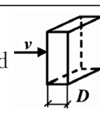
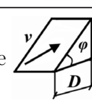
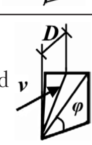
Expressions for the coefficients of compression and streamlining for different types of stones are given in Table 1. An asterisk in the case of an ellipsoidal stone indicates certain simplifications in the derivation of the given relation.

Taking (7) into consideration, formula (6) can be written as follows

$$v = Y_s Y_{strl} \sqrt{2g \frac{\rho_s - \rho_w}{\rho_w}} \sqrt{D}. \quad (8)$$

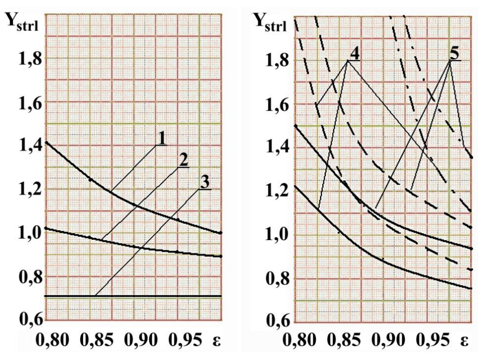
Table 1

Coefficients k_{compr} and Y_{strl} for various configurations of stones

No. of entry	Stone configuration	K_{compr}	Y_{strl}
1	cylinder 	$3 - \frac{1{,}5}{\varepsilon}$	$\sqrt{\frac{3\pi}{8}} \frac{1}{\sqrt{3 - \frac{1{,}5}{\varepsilon}}}$
2	sphere 	$3 - \frac{2}{\varepsilon}$	$\frac{1}{\sqrt{3 - \frac{2}{\varepsilon}}}$
3	ellipsoid 	$3 - \frac{2}{\varepsilon}$	$\frac{1}{\sqrt{3 - \frac{2}{\varepsilon}}}$ *
4	parallelepiped 	3	$\frac{1}{\sqrt{2}}$
5	wedge 	$3\left(1 - \frac{\cos\phi}{\varepsilon}\right)$	$\frac{0{,}5}{\sqrt{1 - \frac{\cos\phi}{\varepsilon}}}$
6	pyramid 	$3\left(1 - \frac{\cos\phi}{\varepsilon}\right)$	$\frac{1}{\sqrt{6\left(1 - \frac{\cos\phi}{\varepsilon}\right)}}$

Note that the streamlining coefficient Y_{strl} depends strongly both on the configuration of a stone and a flow compression coefficient. In particular, for $Y_{strl}=1$, formula (8) coincides with known Izbash formula [3]. This is possible for spherical and ellipsoidal stones in the case of disregarding compression of a flow jets (ε=1), as well as for other types of stones, as it follows from the graphic dependences for a streamlining coefficient Y_{strl}, introduced in this work, on a flow compressibility coefficient k_{compr}, shown in Fig. 4.

The results reported here testify to a significant impact from the configuration of a stone on the maximum flow rate, which causes its rolling or shift: the higher the value for a streamlining coefficient Y_{strl}, the greater the flow rate required to shift a stone, and the more resistant a given stone to the action of a water flow. The highest streamlining indices characterize wedge-shaped stones, which are the most effective for bank-protecting structures. Not much lower are the streamlining indices that characterize pyramidal stones, which are currently most often used in protective mounds at bank-protecting structures in rivers. Stones of other configurations are much more modest in terms of indicators of resistance against the action of a water flow.



a b

Fig. 4. Dependence of streamlining coefficient Y_{strl} on a flow compression coefficient ε: *a* — 1 — spherical and ellipsoidal, 2 — cylinder, 3 — parallelepipedal stones; *b* — 4 — pyramidal, and 5 — wedge-shaped stones; for diagrams 4 and 5: solid lines correspond to Ø=45°, dashed lines — Ø=40°, stroke-dotted lines — Ø=30°

The results obtained could be applied for the purpose of comparative analysis of interaction between river flows and stones of different configurations. In order to quantify such an interaction, it is necessary to reveal the relationship between a river flow rate and the weight of a single stone.

The second task that was set in this work concerns the calculation of elements of protection of riverbanks and flooded supports of engineering structures against the disastrous effect of flooding and floods, which are constructed by using stone mounds. The minimal size of a stone is traditionally determined based on the classic solution to a problem on spherical bottom element of reduced diameter D_{red} in a river flow that moves at velocity v_0

$$v_0 = Y_s \sqrt{2g\frac{\rho_s - \rho_w}{\rho_w}} \sqrt{D_{red}}. \tag{9}$$

Given the geometric considerations and relation (9), the mass of a stone that is displaced by a river flow is

$$m = v_0^6 \frac{\pi\rho_s}{6}\left[\frac{1}{2gY_s^2}\frac{\rho_w}{\rho_s - \rho_w}\right]^3. \tag{10}$$

In practice, formula (10) is employed for the calculation of bank-protecting structures with banquettes made of stone mounds. It is recommended in certain cases [1], in order to determine the reduced diameter of stones, to choose Y_s=1.0 for the case of a small size of the element of a bottom relief in comparison with the size of the stones for bottom obstacles and Y_s=1.5 for close size. When calculating the size of the stones, which block riverbeds, under condition that such stones at the time of work execution are not in contact with the bottom of a flow, one should accept Y_s=0.86–0.9 [1]. The total pattern of dependence of the weight of individual stones on a flow velocity under different conditions for interaction between the flow and a riverbed is given in the form of graphic dependences shown in Fig. 5.

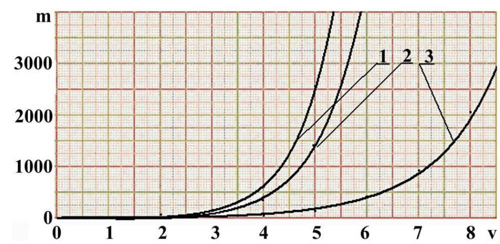


Fig. 5. Dependence of mass *m* (kg) of individual stones that shift after a river flow reaches velocity ν (m/s): 1 — for Y_s=0.9; 2 — for Y_s=1.0; 3 — for Y_s=1.5

In order to determine the influence of a stone configuration on parameters of its interaction with a river flow, we introduce K_{shape} – a stone shape – the ratio of the actual maximum flow velocity ν for a stone of arbitrary configuration (8) to the maximum flow rate $v_0^{sph} = v_0 \cdot Y_{strl}^{sph}$. For a spherical stone of the same mass reduced diameter and taking into consideration its streamlining, here Y_{strl}^{sph} is the generalized streamlining coefficient of a spherical stone from Table 1

$$K_{shape} = \sqrt{3 - \frac{2}{\varepsilon} Y_{strl}} \sqrt{\frac{D}{D_{red}}}. \tag{11}$$

Considering $D_{red} = \sqrt[3]{\frac{6V_T}{\pi}}$, we determined magnitudes K_{shape} (Table 2) from (11) and Table 1. To shift a stone with a shape coefficient K_{shape}<1, a lower flow velocity is required than that for a spherical stone of the equivalent weight, and vice versa – for a stone with a shape coefficient K_{shape}>1. Summing up, we write down an expression for the flow velocity, which displaces a stone of mass m_s with the predefined configuration

$$v = \sqrt[6]{m_s} \sqrt[6]{\frac{6}{\pi\rho_s}} \frac{K_{shape} Y_s}{\sqrt{3 - \frac{2}{\varepsilon}}} \sqrt{2g\frac{\rho_s - \rho_w}{\rho_w}}. \tag{12}$$

We determine the minimum mass of a stone m_s for velocity ν from (12)

$$m_s = \frac{v^6}{\left(K_{shape} Y_s\right)^6} \frac{\pi\rho_s}{6}\left(\frac{3 - \frac{2}{\varepsilon}}{2g}\frac{\rho_w}{\rho_s - \rho_w}\right)^3. \tag{13}$$

This minimal mass m_s correlates with the mass of a non-configurable stone m (10) via the following relation:

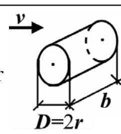
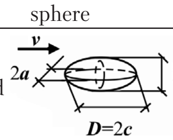
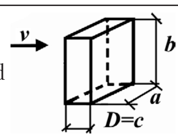
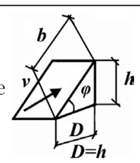
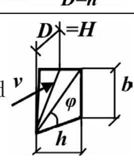
$$m_s = m_0 \cdot \frac{\left(3-\frac{2}{\varepsilon}\right)^3}{\left(K_{shape}\right)^6}. \quad (14)$$

Ratio (14) along with graphic data from Fig. 5 should be used for the calculation of the minimum weight of configurable stones, a stone shape factor K_{shape} is determined based on data from Table 2. Specifically, for stones with the best streamlining, as it follows from Fig. 4, wedge-shaped, in the case ε=1, φ=30°, we determined from table 2 K_{shape}=1,343. Then, we calculate from (14) the adjustment factor for determining the weight of a wedge-shaped stone compared to the weight of a spherical stone, namely $m_s=0{,}170\cdot m$. Using the stones with a different selected configuration must be determined employing the same procedure.

Equation (12) is applied to determine the maximum flow rate, which can cause a loss of stability for a particular existing bank-protecting structure.

Table 2

Values for a shape coefficient K_{shape} for different types of stones

No. of entry	Stone configuration	Kshape
1	cylinder 	$\sqrt[6]{\frac{4}{3}\frac{r}{b}}\sqrt{\frac{3\pi}{8}\frac{3\varepsilon-2}{3\varepsilon-1,5}}$
2	sphere	1
3	ellipsoid 	$\sqrt[6]{\frac{c^2}{ab}}$
4	parallelepiped 	$\sqrt[6]{\frac{1}{6}\frac{c^2}{ab}}\frac{\sqrt{3-\frac{2}{\varepsilon}}}{\sqrt{2}}$
5	wedge 	$\frac{\sqrt{3-\frac{2}{\varepsilon}}}{\sqrt{1-\frac{\cos\phi}{\varepsilon}}}\cdot 0,5\cdot\sqrt[6]{\frac{\pi h}{3b\cdot tg\phi}}$
6	pyramid 	$\frac{\sqrt{3-\frac{2}{\varepsilon}}}{\sqrt{1-\frac{\cos\phi}{\varepsilon}}}\frac{1}{\sqrt{6}}\sqrt[6]{\frac{\pi H}{2b\cdot tg\phi}}$

6. Discussion of results and directions for further research

We have introduced a stone streamlining coefficient, which make it possible to take into consideration the compression of streams in a river flow when determining its velocity limit that shifts a stone. The streamlining coefficient was determined for stones whose configurations are typical for river flows.

A shape coefficient has been introduced, which makes it possible to refine the weight of tones that are shifted by a water flow, depending on the configuration of a stone and its streamlining. Application of the proposed approach implies refining the weight of individual stones that are used to protect the foundations of hydro-engineering facilities against washouts, as in some cases (a wedge-shaped stone) an adjustment factor can accept value 0.170, thereby making it possible to significantly save resources by reducing the weight of individual stones in bank-protecting structures.

The obtained formulae, tabular data, diagrams and a procedure of their application are easy to use by engineering and technical workers; at the same time they make it possible to account, when calculating bank-protecting structures, for the streamlining of stones used and their configurable features.

The results obtained in this work allow us to outline directions for the further research. Motion of a river flow causes shifting the bottom elements, stones, and predetermines forming the flow of a polydisperse water-stone mixture. The dimensions of individual stones in such a flow are smaller than the maximum size assigned by formula (13). The speed of individual stones in the mixture depends on the flow rate, the size of stones, and on the additional pulses, received by stones due to impacts between them and the riverbed elements. As a result of the intensive motion of a river flow part of the stones can obtain the buoyancy in the ascendant turbulent jets of the flow. The movement of a stone in a river flow is characterized by the linear longitudinal displacement and rotating motion around its own center of mass, predetermined by the out-of-center impacts against other stones.

Given this, we consider it relevant to continue studies as follows. First, define parameters for the impact interaction between a rolling stone in a flow, whose size is determined from this study, and the fixed elements of a riverbed or protective banquette mounds for flooded foundations of engineering structures. It is important to run a comparative analysis of the results of such interactions with the effect of protective elements of the riverbed of a river flow without stones. Second, define parameters for the motion of a river polydisperse flow of water-stone mixture considering the distribution of velocities along the perimeter of a living cross-section and the influence of configurations of moving stones, established in this work, on this distribution. That could make it possible to predict the process of bottom detritus formation.

7. Conclusions

1. We have defined parameters for the equilibrium limit of a configurable bottom element, a stone, in a water flow, based on a cylindrical bottom element, which could lead to the buoyancy of such a stone. We have introduced a streamlining coefficient and a stone shape coefficient, which make it possible to refine, during calculation, the size of stones resistant to the action of a river flow. Values for the introduced coefficients are summarized in Table 1.

2. We have devised a procedure for the refined calculation of elements at river bank-protecting structures taking into consideration the configuration of stones used, which implies determining basic size of stones according to Fig. 5, to further specify their mass based on the stone shape coefficients that are given systematically in Table 2.

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