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On the Issue of Generation of Hydrodynamic Waves in the Shovi Gorge (Georgia) due to a Collapse on Glacier Tbilisa

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ABSTRACT

The occurrence of a glacial mudflow in the Shovi gorge on August 3, 2023 was caused by a destructive process on the Tbilisa glacier. Based on the existing picture of the spread of the mudflow, it is possible to carry out an analysis regarding the rheological qualities of the water-saturated soil mass that forms its basis. It is also possible to approximately estimate the parameters of various types of hydrodynamic waves, the generation of which was probably possible during the propagation of the debris flow. It seems that such a problem can be satisfactorily solved only in the case of a correct assessment of the values of dimensionless criteria for the flow of debris flow, which are convenient quantitative characteristics that simplify the analysis of the qualitative consequences of applying the principle of hydrodynamic similarity. For example, in the case of approximating the bed of a debris flow with a rectangular channel, you can use the results of well-known analytical solutions obtained under simplifying assumptions that are valid for certain intervals of variation in the Reynolds and Froude similarity numbers. In particular, in the shallow water approximation, in the case of sufficiently large Reynolds numbers, when the fluid flow is highly turbulent, the Froude parameter allows one to fairly correctly simulate changes in the flow regime that occur as a result of the generation of hydrodynamic waves. The negative effects that often accompany the process of propagation of wave disturbances largely depend on the type of these waves. Therefore, in the case of a mudflow in the Shovi gorge, it seems quite realistic, for example, the generation of the so-called rolling hydrodynamic waves, which could well have been among the probable causes that determined the catastrophic scale of the tragic event.

Key words: *glacier, debris flow, hydrodynamic waves, Reynolds number, Froude number*

Introduction

A glacial debris flow descending from any glacier can be represented either as a heterogeneous liquid or as a water-containing solid mass moving in a mountain gorge or on a flat area (Fig. 1). The occurrence of a glacial mudflow in the Shovi gorge on August 3, 2023 was caused by a destructive process on the Tbilisa glacier. When analyzing the probable causes of this phenomenon, the lack of sufficient observational data seems obvious. Therefore, it is impossible to unambiguously judge the nature of the processes that took place on this glacier over the past decades and predetermined the catastrophic event, which has tragic consequences. Therefore, at this time, it is only possible to approximately imagine a fairly complete picture of the spread of the mudflow along the gorge of the Bubistskali and Chanchakhi rivers, which are an integral part of the Shovi gorge.

Glacial flow in Shovi gorge.

In any case, the movement of the glacial flow obeys the laws of hydrodynamics, in particular, the Navier-Stokes equation. Known that, depending on the viscosity properties, the liquid medium may belong to the usual Newtonian, or to the so-called rheological fluid (Bingham fluid). In particular, pure water is a Newtonian fluid, but a debris flow, which is a mixture of water with solid particles and ice fragments, is considered a suspension.

Fig. 1. a) general view of Shovi disaster, b) debris-flow brake area in Shovi valley

Such a medium belongs to the class of viscoplastic (pseudoplastic) Bingham fluid with a characteristic coefficient of plastic viscosity: $\eta \approx /10^9 - 10^{10}/$ Pa.s. Unlike water, Bingham fluid always has an initial shear stress τ_0, which is in the functional dependence $\tau = f(\beta)$ on the deformation rate $\beta = (\frac{\partial \xi}{\partial t})$, where ξ is the magnitude of linear deformation. The nature of this dependence qualitatively changes from nonlinear to linear with increasing parameter β. In this case, pseudoplastic viscosity is transformed into dynamic viscosity, i.e. Bingham fluid acquires the qualities of an ordinary Newtonian fluid. Therefore, for the shear stress the following equation becomes valid:

$$\tau = \tau_0 + \eta\beta. \qquad (1)$$

Among the special qualities of a Bingham fluid that distinguishes it from a Newtonian fluid, one should highlight its ability to maintain a spatial structure after braking on a solid surface. However, the immobile state can only last up to a certain point. It may be disrupted due to the appearance of any factor causing the movement of the viscoplastic medium [1]. In particular, such a factor usually turns out to be an increase in the angle of inclination of the fluid flow channel to the horizon φ. In this case, the shear force of the viscoplastic mass can exceed the force of surface friction with the bottom of the channel. For example, according to information received from direct eyewitnesses of the catastrophic event in Shovi, the mudflow in the lower part of the Shovi gorge acquired sufficient viscoplastic qualities necessary for its braking after collapsing on the glacier Tbilisa for about 20-25 minutes.

It is known that for mathematical modeling of the movement of a liquid medium, certain sets of dimensionless hydrodynamic parameters are used, to estimate the value of which the coefficient of dynamic viscosity of the liquid is the cornerstone characteristic. In an ordinary liquid, the coefficient of dynamic viscosity determines the degree of turbulence of the flow, i.e. its value may vary depending on the flow regime. In the case of a viscoplastic suspension, the dynamic viscosity coefficient is transformed into a plastic viscosity coefficient. Consequently, until a mudflow with suspended solid particles retains the qualities of an ordinary liquid, the distribution of the solid fraction of the mudflow along the channel of movement will largely depend on dynamic viscosity.

Mudflow with variable rheology.

The movement of a heterogeneous fluid in a gravity field along an inclined channel approximating a river bed is a physical analogue of the spread of a mudflow along a mountain gorge. The mathematical problem of studying various fluid flows is associated with solving the Navier-Stokes equation. In general, such an operation is impossible. Therefore, simplifying assumptions that are valid for a specific problem are usually used. This method often allows one to obtain a completely correct analytical solution, valid when postulating certain qualities of a moving liquid medium. One of these areas of research is turbulent flows in channels of various geometries and associated hydrodynamic instabilities that generate periodic wave processes. It is known that waves arise in both ordinary and rheological fluids. For example, the flow of liquid of any rheology in channels at sufficiently large angles of inclination of its bottom can become unstable, as a result of which waves of various types can be generated. An important parameter of these waves is their amplitude, i.e. height, which only in some special cases can be determined analytically by solving the well-known Burgers equation [2]. However, for a general idea of the process of propagation of waves similar to those that probably occurred in the mudflow in the Shovi gorge, one can use a more simplified analysis based on the well-known solutions of shallow water equations [3]. In this approximation, in the case of fluid motion in a rectangular channel, after the standard transformation of the Navier-Stokes equations and the continuity of the medium to a dimensionless form, two similarity numbers appear: the Reynolds number and the Froude number. These dimensionless criteria are determined using the hydrodynamic parameters of fluid flow and the linear characteristics of the channel [4]. The Reynolds number determines the flow regime, which for a rapid fluid flow will necessarily be turbulent. In this case, in an ordinary liquid, depending on the value of the Froude number, various waves can be generated. In a viscoplastic medium, which has a different rheology, wave motions can be no less diverse than in an ordinary liquid. For example, in a mixing inhomogeneous fluid, waves arise as a result of the development of instability due to a velocity shift in layers with different densities. A similar effect can also arise due to a restructuring of the flow structure in a rheological fluid, when inhomogeneous layers with large velocity and density gradients appear in it. In any case, the presence of such textures in a liquid medium allows us to simplify the problem of mathematical modelling of waves by introducing a certain small parameter, which is the ratio of the channel depth to the wavelength and serves as a quantitative criterion for the validity of the shallow water approximation. Although such a model significantly simplifies the equations of hydrodynamics, mathematical complications may arise associated with the nonlinearity of waves, the manifestation of which obviously depends on the rheology of the liquid.

At sufficiently large Reynolds numbers, the nonstationary equations of shallow water in a one-dimensional approximation, when moving on an inclined plane with turbulent fluid friction at the bottom of the channel, have the form [5]

$$\frac{\partial}{\partial t} h + \frac{\partial}{\partial x}(hu) = 0,$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^2 + \frac{gh^2}{2}\cos\varphi\right) = gh\sin\varphi - C_w\ u^2, \qquad (2)$$

where h, u - are the average depth and velocity of the fluid; g - acceleration of free fall force; φ – channel inclination angle; C_w - is the friction coefficient, which for simplicity is considered constant. The first equation means the continuity of the medium, the second determines the movement in an inclined channel.

After the standard transition to dimensionless variables and flow parameters, the system of equations (2) takes the form [4]

$$\frac{\partial}{\partial t} h + \frac{\partial}{\partial x}(hu) = 0,$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial x}\left(hu^2 + \frac{h^2}{2}\right) = \alpha h - u^2 \quad , \qquad (3)$$

where $\alpha = tg\varphi/C_w$ — is the only dimensionless parameter that determines the flow. If the movement of a uniform fluid flow in a channel with a normal depth h_0 is realized, then the Froude number of such a flow will be determined by the parameter α associated with the Froude number: Fr= $\sqrt{\alpha}$.

In the shallow water approximation, the Froude number makes it possible to classify hydrodynamic waves, the generation of which is possible at sufficiently large Reynolds numbers, when the flow is highly turbulent. In particular, in the case of approximating a debris flow bed with a rectangular channel, one can use the results of well-known analytical and numerical solutions obtained for certain types of hydrodynamic waves. To do this, let us estimate the characteristic intervals of change in the values of the indicated hydrodynamic similarity numbers: Reynolds number Re=$\frac{u_0 d}{\eta}$, where u_0 is the characteristic velocity value, d is the channel width, η- is the kinematic viscosity coefficient; Froude number Fr=$\frac{u_0}{\sqrt{g h_{0} \cos\varphi}}$, where h_0 – is the normal (characteristic) channel depth. It has been proven that the flow in the channel becomes unstable at Fr > 2 (α > 4). For example, the characteristic speed of the mudflow and the parameters of the Shovi gorge: u_0= /10-20/ms^{-1} ,d= /40-60/m, h_0 =/8-10/m, α=5^0. For water containing an admixture of solid particles, η≈/1-10/10^{-6} m^{2}s^{-1}. Consequently, we will have characteristic intervals of change in the indicated dimensionless parameters of hydrodynamic similarity: Re≈/4-12/ 10^7 and Fr≈/1-2.2/. The large Reynolds number means that the degree of turbulation of the flow in the main part of the Shovi gorge was critically high. It is also likely that the local value of the Froude number in some places of the gorge could go beyond the characteristic interval, for example, due to a change in the depth of the flow or a decrease in its speed. There is also no doubt that at times the mudflow changed its rheological properties under the influence of various factors that actively influenced the movement of the medium. This effect could probably be especially noticeable in the last, widest section of the gorge, where the viscous plastic nature of the mudflow was fully appeared. In this place, the distribution of the mudflow mass was completely similar to the movement of a viscous plastic medium with a low (≈20%) water content. Particularly interesting is the question of the nature of wave motions, the spectrum of which can be represented by the results of some solutions to the shallow water equations, as well as by data from laboratory experiments [4]. In this case, the Froude number is obviously the parameter that serves as a quantitative criterion that distinguishes between different types of long hydrodynamic waves, the generation of which is possible in the shallow water approximation [13]. Thus it is obvious that the generation of waves of various types is directly dependent on the value of the Froude number. Let us consider this issue in more detail, for which we can use the following classification:

1) $0.3 \le Fr \le 0.5$. This range of Froude number values for the case of a mudflow propagating along the Shovi gorge is unlikely. It is more typical for a channel of finite depth, along the bottom of which a liquid flows with a higher density than in the surface layer. It is known that with such a flow structure in a non-uniform fluid, can be generated so-called gravitational (density) waves;
2) $0.9 < Fr < 1.1$. According to the Kadomtsev-Petviashvili equation, for such Froude numbers, when the influence of factors of linear dispersion, nonlinearity and spatial effects is balanced, the generation of solitons (solitary waves) is possible. The probability of the existence of such a balance necessary for the emergence of solitons, as well as the conditions necessary for the generation of gravitational waves, is probably quite low. However, despite the stringency of the condition, it is impossible to completely exclude the possibility of the propagation of solitons and, especially, gravitational waves during a catastrophic phenomenon in the Shovi gorge;
3) $Fr \le 2$. For such Froude numbers, according to the shallow water equations, as a result of the effect of turbulent friction between the mudflow mass and the bottom of the channel is possible generation so-called linear rolling waves. For waves of this type, the critical value is Fr=2, which determines the threshold for the development of linear instability and a noticeable increase in the wave amplitude;
4) $Fr > 2$. At a sufficiently large Fr, a nonlinear stage of increasing flow instability develops in the liquid. This case corresponds to a certain critical depth of the channel in which the hydrodynamic pattern of a turbulent flow arises. In highly turbulized liquids, so-called depression waves, as well as rolling waves with hydraulic jumps, which contribute to a change in flow regime from supercritical to subcritical;

5) 2 < Fr < 6. In a turbulent flow, a modulation effect of traveling packets of nonlinear rolling waves, averaged within certain spatial and temporal scales, may occur. Such a specific wave effect in the Shovi gorge could arise in those places where there was a sharp increase in the value of the local Froude number.

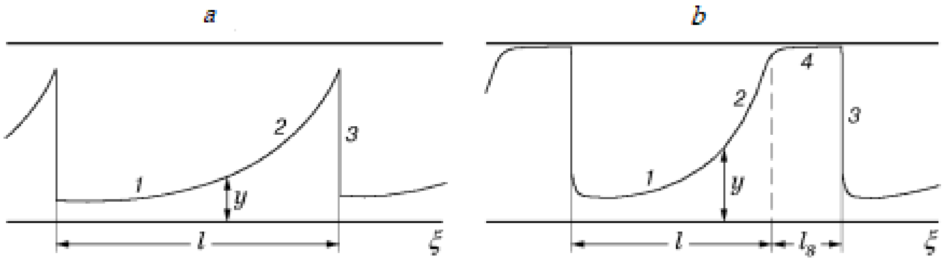

Fig.2. rolling waves

It is obvious that among the considered waves of various types, from the point of view of reconstructing the picture of the propagation of the mudflow in the Shovi gorge, rolling waves are of the greatest interest. In [4], the solution to the system of equations (3), depending on the variable $\xi = x - Dt$ (D - wave speed), is considered. A feature of such wave solutions is the presence of a smooth section of the wave trajectory, indicating the transition between subcritical flow and supercritical flow (sections 2, 1 in Fig. 2a). This site is determined relative to the coordinate system moving at wave speed D and indicates the presence of a hydraulic jump (section 3 in Fig. 2a), which converts the supercritical flow into a subcritical one. Therefore, an important parameter characterizing rolling waves is their critical depth y, at which the determinant of the system of equations (3): $\Delta = h - (u - D)^2$, becomes zero. Hence, when $h = y$, $u = u_c$ when the condition is

$$\Delta_c = y - (u_c - D)^2 = 0 \qquad (4)$$

the equations of stationary waves take the form

$$h(u - D) = y(u_c - D),$$

$$\frac{\partial}{\partial \xi}\left(h(u - D)^2 + \frac{h^2}{2}\right) = \alpha h - u^2 = F. \qquad (5)$$

Of physical interest are waves propagating to the right ($D > u > 0$). In the vicinity of the critical depth, the determinant (Δ) changes sign (site 4 on Fig. 2,b). A necessary condition for the existence of a continuous solution to the second of equations (5) is that the right-hand side vanishes at $h = y$

$$\alpha y = u^2 \qquad (6)$$

Due to condition (4), (6) as well as the condition $D > u_c$, the following expressions are valid

$$u_c = \sqrt{\alpha y}, \qquad D = y^{1/2}\left(1 + \sqrt{\alpha}\right), \qquad u = D - y^{3/2}/h = y^{1/2}\left(1 + \sqrt{\alpha} - 1/z\right), \qquad (7)$$

From expression (5) it follows that the value $\frac{\partial h}{\partial \xi}$ is a function of the variable z, where $z = h/y$.

$$\frac{\partial h}{\partial \xi} = \frac{F}{\Delta} = \left(\alpha z^2 - \left(1 + 2\sqrt{\alpha} - {}^{1}/_{z}\right) + 1\right)/(z^2 + z + 1)\,. \qquad (8)$$

Thus, in a coordinate system moving with speed *D*, the flow downstream from the critical point should be supercritical ($\Delta < 0$), and upstream - subcritical ($\Delta > 0$). This requirement follows from the stability conditions of a hydraulic jump that transforms a supercritical flow into a subcritical one.

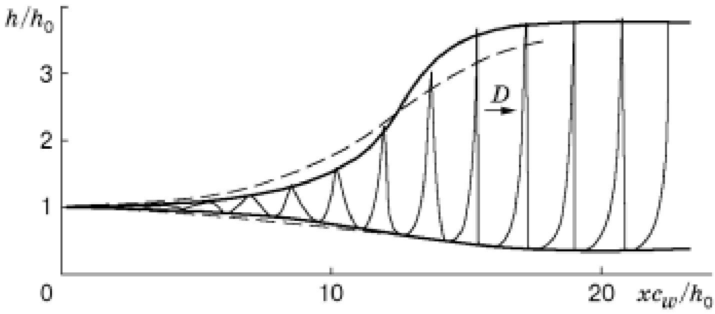

Fig.3. results of numerical calculations on the evolution of a rolling wave packet

As an example of what can happen to a wave packet as the Froude number increases, we can use the result of numerical simulation. Figure 3 corresponds to the theoretical picture of the evolution of a packet of modulated rolling waves when Fr=5. According to a computer experiment, the generation of waves in a flow of inhomogeneous fluid occurred as a result of a nonlinear increase in small disturbances, the initial amplitude of which was ≈1% of the normal channel depth h_0. The maximum amplitudes that were recorded in the corresponding laboratory experiment turned out to be significantly less than the theoretical ones [4]. Nevertheless, the qualitative nature of the growth in the amplitude of the wave packet, which initially had an exponential character, was confirmed. However, after the traveling wave passed a certain distance, the increase in amplitude stopped. It turned out that for a developed turbulent flow the average values of the minimum depths satisfy the inequality: $\frac{xC_w}{h_0} \leq 10$. It is believed that Small disturbances grow exponentially along the channel until the wave parameters reach the boundary of the hyperbolicity region of the system of shallow water equations, after which the growth of the wave amplitude stops and the flow becomes quasiperiodic. The thick lines show the distribution of the average values of the maximum and minimum wave depths along the channel over many periods. Note that the average values of the minimum wave depth in a developed flow, determined in a laboratory experiment and as a result of non-stationary numerical calculations, are in good agreement. At that time, the corresponding experimental values of the maximum amplitude turned out to be significantly less than the analytically determined theoretical amplitudes. Therefore, it was concluded that equations (1) do not convey the true structure of waves during their breaking, i.e. in case of hydraulic jumps.

Conclusion

Thus, during the propagation of the mudflow in the gorge of the Bubistskali and Chanchakhi rivers, which are an integral part of the Shovi gorge, hydrodynamic waves of various types could exist. In the range of values of the Froude hydrodynamic similarity number corresponding to the mudflow bed in the Shovi Gorge, the generation of traveling rolling waves, the height of which could reach several meters, should be considered most likely. The appearance of solitary waves (solitons), as well as the so-called gravitational waves were unlikely, but the possibility of their generation in places where local conditions were suitable cannot be ruled out. In the lower, widest section of the Shovi gorge, in the so-called zone cottages, the movement of the mudflow mass was hydrodynamically similar to the movement of the ice mudflow in the gorge of the Genaldon River, which occurred after the collapse on the Kolka glacier in 2002 [6]. In particular, despite the huge difference in the initial volumes of glacial mudflows that descended from the Tbilisa and Kolka glaciers, the thickness of viscous plastic sediments in the last flat areas of their distribution, taking into account the difference in covered areas, turned out to be comparable. Obviously, this is due to the same type of braking of the viscoplastic debris flow at the stage of its final stop, which is also indicated by a decrease in wave amplitudes within /1-3/ m (Fig.1b)

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მყინვარ თბილისაზე ჩამოქცევის გამო შოვის ხეობაში (საქართველო) ჰიდროდინამიკური ტალღების წარმოქმნის საკითხთან დაკავშირებით

ზ. კერესელიძე, ნ. ვარამაშვილი

რეზიუმე

2023 წლის 3 აგვისტოს შოვის ხეობაში მყინვარული ღვარცოფის გაჩენა თბილისის მყინვარზე მომხდარმა დამანგრეველმა პროცესმა გამოიწვია. ღვარცოფის გავრცელების არსებული სურათიდან გამომდინარე, შესაძლებელია ანალიზი ჩატარდეს მის საფუძველის, წყალით გაჯერებული ნიადაგის მასის, რეოლოგიურ თვისებებთან დაკავშირებით. ასევე შესაძლებელია დაახლოებით შეფასდეს სხვადასხვა ტიპის ჰიდროდინამიკური ტალღების პარამეტრები, რომელთა წარმოქმნა, სავარაუდოდ, შესაძლებელი იყო ღვარცოფული ნაკადის გავრცელების დროს. როგორც ჩანს, ასეთი პრობლემა დამაკმაყოფილებლად შეიძლება გადაწყდეს მხოლოდ ღვარცოფული ნაკადის უგანზომილებიანი კრიტერიუმების მნიშვნელობების სწორი შეფასების შემთხვევაში, რაც მოსახერხებელი რაოდენობრივი მახასიათებლებია, რომლებიც ამარტივებს მსგავსების პრინციპის გამოყენების ხარისხობრივი შედეგების ანალიზს. ჰიდროდინამიკური მსგავსება. მაგალითად, ღვარცოფული ნაკადის კალაპოტის მართკუთხა არხით აპროქსიმაციის შემთხვევაში, შეიძლება გამოყენებული იქნას ცნობილი ანალიტიკური ამოხსნების შედეგები, რომლებიც მიღებულია გამარტივებული დაშვებებით, რომლებიც მოქმედებს რეინოლდსის და ფრუდის მსგავსების რიცხვების ცვალებადობის გარკვეული ინტერვალებისთვის. კერძოდ, მეჩხერი წყლის მიახლოებისას, საკმარისად დიდი რეინოლდსის რიცხვების შემთხვევაში, როდესაც სითხის ნაკადი ძალზე ტურბულენტურია, ფრუდის პარამეტრი საშუალებას იძლევა საკმაოდ სწორად მოახდინოს დინების რეჟიმის ცვლილებების სიმულაცია, რაც ხდება ჰიდროდინამიკიური ტალღების წარმოქმნის შედეგად. უარყოფითი ეფექტები, რომლებიც ხშირად თან ახლავს ტალღური შეშფოთებების გავრცელების პროცესს, დიდწილად დამოკიდებულია ამ ტალღების ტიპებზე. ამიტომ შოვის ხეობაში ღვარცოფის შემთხვევაში საკმაოდ რეალისტურად ჩანს, მაგალითად, ე.წ. მგორავი ჰიდროდინამიკური ტალღები,

რომლებიც შეიძლება იყოს იმ სავარაუდო მიზეზთა შორის, რომლებმაც განსაზღვრეს ტრაგიკული მოვლენის კატასტროფული მასშტაბები.
საკვანძო სიტყვები: ყინვარი, ღვარცოფი, ჰიდროდინამიკური ტალღები, რეინოლდსის ნომერი, ფრუდის ნომერი.

К вопросу о возникновении гидродинамических волн в ущелье Шови (Грузия) в результате обвала ледника Тбилиса

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Резюме

Возникновение гляциальной сели в ушелье Шови 3.08.2023 года было вызвано разрушительным процессом на леднике Тбилиса. По имеющейся картине распространения селя, можно провести анализ относительно реологических качеств водонасыщенной грунтовой массы, составляющей его основу. Можно также приблизительно оценить параметры различных типов гидродинамических волн, генерация которых вероятно была возможна в процессе распространения селевого потока. Представляется, что такая задача может быть удовлетворительно решена только в случае корректной оценки величин безразмерных критериев течения селевой массы, являющихся удобными количественными характеристиками, упрощающими анализ качественных следствий применения принципа гидродинамического подобия. Например, в случае аппроксимации русла селевого потока прямоугольным каналом, можно воспользоваться результатами известных аналитических решений, полученнннных при упрощающих допущениях, справедливых для определенных интервалов изменения чисел подобия Рейнольдса и Фруда. В частности, в приближении мелкой воды, в случае достаточно больших чисел Рейнольдса, когда поток жидкости является сильно турбулентным, параметр Фруда позволяет достаточно корректно моделировать изменения режима течения, происходящие в следствие генерации гидродинамических волн. От типа этих волн в значительной степени зависят негативные эффекты, часто сопровождающие процесс распространения волновых возмущений. Поэтому, в случае селевого потока в ушелии Шови, вполне реальной представляется, например, генерация т.н. катящихся гидродинамических волн, которые вполне могли оказаться среди вероятных причин, определивших катастрофические масштабы трагического события.

Ключевые слова: ледник, селевой поток, гидродинамические волны, число Рейнольдса, число Фруда.