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On the Issue of Modelling the Dynamic Picture of the Spread of a Mudflow in the Shovi Gorge due to a Collapse on the Glacier Buba

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ABSTRACT

Glaciers have always been a potential hazard in the Caucasus region, where mountain canyons are quite densely populated. The processes associated with global climate change occurring everywhere have greatly exacerbated the problem of preventing the population from glacial disasters. For example, there is a sad experience associated with the collapse of the Kolka glacier, which caused a giant ice mudflow in 2002. A similar disaster should include the glacial mudflow from the Buba glacier on 9/3/2023, which resulted in a tragedy with numerous victims at the Shovi resort. Determining the possible place and time of development of such catastrophic events (earthquakes, volcanic eruptions, large-scale floods) has a very low degree of reliability and is problematic, despite the modern level of scientific methods of ground and space monitoring. In particular, there is an obvious need for long-term monitoring and comprehensive diagnostics of the current state of the Caucasus glaciers, taking into account each new experience. It should be noted that there is a paucity of information that allows us to judge the processes that have occurred on the Buba glacier over the past decades. Therefore, hardly anyone could imagine a large-scale virtual picture of the spread of a glacial mudflow along the gorges of the Bubistskali and Dzhandzhakhi rivers, adequate to what it turned out to be in reality. At the same time, in the case of a sufficiently complete database of observation results and its correct analysis, based on the principle of hydrodynamic similarity, there is a possibility of theoretical modeling of probable parameters of a flood or glacial mudflow in any mountain gorge. For example, in the case of the Caucasus region, one can use some of the results obtained by numerical modeling of the Dzhankuat and Kolka glaciers. In particular, these models are quite useful not only for determining probable causes, but also for retrospective analysis of the consequences of destruction on the Buba glacier. First of all. This concerns the process of propagation of hydrodynamic waves in a heterogeneous mudflow. For this purpose, records of seismic equipment are also important, which contain information on the frequency spectrum of acoustic waves generated by the process of destruction on the Buba glacier. Hydrodynamic waves of various types could have existed in the gorges of the Bubistskali and Chanchakhi rivers. In the characteristic range of the Froude similarity number, the most probable is the generation of running rolling waves, the height of which could reach several meters. The appearance of solitary waves (solitons), as well as the so-called gravity waves, was unlikely, but one cannot exclude the possibility of their generation in those places for which local conditions were suitable. In the lower, widest section of the Shovi gorge, in the zone of the so-called cottages, the movement of the mudflow was similar to the movement of the ice mudflow in the Genaldon River gorge after the collapse of the Kolka glacier in 2002. Despite the huge difference in the initial volumes of mudflows that came down from the Buba and Kolka glaciers, the deposit of viscoplastic mass in the last sections of its distribution turned out to be comparable taking into account the spatial scale and the amplitude of the waves in both cases decreased to heights of 1-3 meters.

Key words: *natural disasters, glacier, debris-flow, acoustic waves, viscoplastic.*

Introduction

There is sufficiently comprehensive information on the dynamics of glaciers in the Central Caucasus, suitable for modeling glacial processes that lead to the formation of debris flows, which spread through the riverbeds of mountain rivers, canyons, and mountain valleys. These models are based on two sources: the analysis of results from field morphological studies of glaciers and the observed changes in the landscape that occurred after debris flow events on specific glaciers. In the latter case, particular attention is given to the movement of the rock-ice debris flow, for which hydrodynamic equations are used. Regardless of its location, such a scheme forms the basis for an analytical or numerical model of glacier dynamics. Therefore, to some extent, it is universal, though it may have specific elements in particular cases. Specifically, these are the simulation models for the Djankuat and Kolka glaciers [1,2]. These and similar models can serve as tools for the retrospective analysis of the causes and outcomes of large-scale destructive events associated with glaciers in various regions of the Earth. However, their ability to predict the time and location of a potential disaster is not only limited but also unlikely. Nevertheless, the results of modeling the Djankuat glacier, as well as the disaster on the Kolka glacier, may be useful for analyzing the consequences of the destructive event on the Buba glacier, which caused a catastrophe in the Shovi Gorge. The first model generalizes data from long-term expeditions to the Djankuat glacier. The analytical basis for both models is the hydrodynamic equations. A quantitative assessment of the geophysical parameters of the Djankuat glacier was obtained, which, in terms of linear characteristics, is almost identical to the Buba glacier, located 100 km to the southwest. In the second model, a retrospective picture of the spread of a giant ice debris flow was reconstructed, virtually simulating the catastrophic process on the Kolka glacier in 2002. In particular, this model simulates the conditions for the generation of giant waves that actually spread through the Karmadon and Genaldon gorges. The obtained model parameters for the movement of the debris flow were in agreement with its destructive impact, as determined from satellite and ground-based observations.

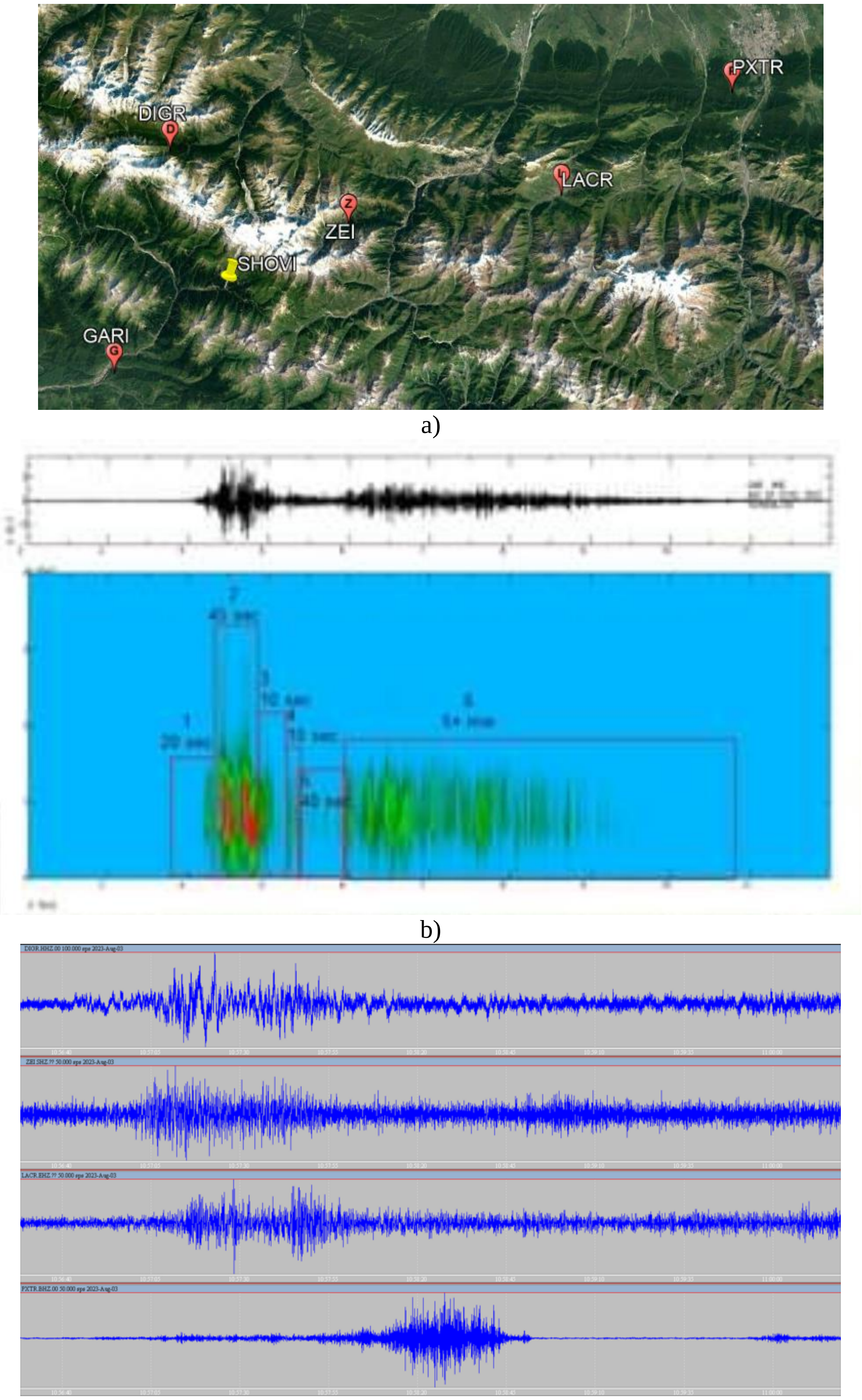
The Event on the Buba Glacier

There are two fairly detailed reports on the disaster at the Buba glacier (Figure 1), caused by the collapse of a glacial debris flow at about 15:03 h on August 3, 2023. The first report was prepared by the National Environment Agency of Georgia [16], and the second was prepared by Swiss specialists [15]. These reports were published a few months after the disaster and have a clear structural similarity, as well as identical main conclusions: the disaster occurred due to the overlap of several natural factors, making it impossible to accurately predict the timing of the event. Given the practical full alignment of the methodology and input data used in both reports for the computer simulation of the disaster, the final part of this work will provide an analysis of the main conclusions from the report prepared by the Swiss specialists.

Fig.1. Buba Glacier (photo by D. Svanadze).

A particularly important element related to the discussed disaster is the recording of seismic oscillations generated by the collapse on the Buba Glacier. Along with the emission of acoustic waves, a powerful glacial debris flow spread through the gorges of the Bubistkali and Dzhandzhakhi rivers. We have records from the seismograph of the Seismic Monitoring Service of Georgia, located in the village of Gari ($42^0 35'12.75''$N, $43^0 27'58.81''$E) adjacent to the district center of Oni, as well as data from four stations located on the northern side of the Caucasus Range, kindly provided by the Seismic Monitoring Service of the North Caucasus (Figure 2c), where the waves, accompanying the destructive process on the Buba Glacier was particularly well recorded. Together, these records provide a clear understanding of the nature of the process that began at about 15:03 h on August 3, 2023 (Figure 2b,c). It is clear that the mechanism for generating and spreading seismic and acoustic waves in the Earth's medium is identical. The boundary between the frequencies of seismic and acoustic waves is somewhat conditional. Specifically, the generation of acoustic waves is always accompanied by the process of destruction of ice clusters of any size and shape. It is accepted that this boundary is near the lower frequencies audible to the human ear. It is believed that above this threshold, seismic wave packets represent the so-called high-frequency trace, the intensity of which decreases with distance according to a nonlinear law. Thus, higher-frequency acoustic waves are formally a continuation of seismic waves. They can be recorded by seismic equipment at distances of up to several dozen kilometers from the epicenter of the earthquake [3]. Spectral analysis of the acoustic radiation from glacial processes is an effective tool for studying structural formations on glaciers. On glaciers in various regions, the method of acoustic emission in the frequency range of 15-20 kHz [4] has been used to diagnose ice movement and ice formation, as well as rockfalls. As a result of these studies, links between the acoustic radiation spectrum and the parameters of dynamic changes in glaciers were identified. Generalizing the results of acoustic studies obtained from several glaciers provided a quantitative estimate of the impact of potential mechanical obstacles on the parameters of ice displacement in the glacier bed, when acoustic effects characteristic of ice destruction were recorded [4,5]. These results demonstrate the effectiveness of diagnostics using acoustic waves not only in cases of smooth ongoing glacial processes but also in cases of spontaneously occurring phenomena, which most often lead to glacier destruction. For example, the recordings in Figure 2b,c, clearly indicate that on the Buba Glacier, with an interval of approximately 3-4 seconds, two destructive events occurred. According to popular opinion, and following the aforementioned reports, these events are more likely related to the fall of a rock mass rather than the breaking of ice from the glacier's tongue. According to eyewitnesses of the event in the Shovi Gorge, the sound wave was the first alarming signal. Additionally, according to eyewitnesses, the powerful effect that typically accompanies the propagation of a shock wave was not felt. Thus, it can be assumed that rockfall or icefall was one of trigger for the destruction process on the Buba Glacier [15,16]. A similar mechanism for a glacial mudflow has been discussed in connection with the Kolka glacier disaster [17]. The paper deals with an 11 m side ice cube, the so-called energetic reference. Was calculated the volume of a rock avalanche (approximately 40,000 m3), falling from a height of about 1 km, which is necessary to melt a 0^0C reference ice cube, which would give us about 1300 cubic meters of water [17]. In the case of Shovi, the height is likely much less, so it is almost certain that there was a theoretical possibility production about of a 10,000 m^3 water, if (0.5 - 1)10^6 m^3 of rock fall occurred simultaneously, which is not yet clear and maybe could be confirmed by an expedition to the disaster site. In that case, it can be hypothesized that the catastrophic event started, for example, due to the rupture of the integrity of the subglacial water reservoir(s) in a certain local area of the glacier. It is likely that the size of this area could have increased sharply within a very short time. This circumstance may be one of the arguments in favour of the hypothesis that, for some reason, whether due to the fall of rock debris or the break-off of ice from the glacier’s tongue, the subglacial water reservoir(s) were emptied. Therefore, it may be justified to assume that information about the linear characteristics that define the volume of the reservoir is present in the acoustic wave frequency spectrum. In this regard, it is worth noting that the lowest frequencies in the infrasound range in the recordings, such as those from the ZEI seismic station, may reflect the natural mechanical vibrations of the Buba Glacier as a unified elastic body. It is known that the spectrum of natural vibrations is related to the linear characteristics of the body, i.e., its size. Typically, natural vibrations occur due to some external trigger. In the case of glaciers, vibrations can be caused by any mechanical reason, such as a seismic shock, a snow avalanche, the collapse of rocks, or the breaking of ice. It is known that in the spectrum of natural mechanical vibrations of an elastic body, the lowest frequency is dominant, and higher frequencies are overtones (harmonics). Usually, the spectrum of acoustic radiation from a vibrating body is discrete, but in the case of complete degeneration, it can become practically continuous. The filling of the spectrum with overtones occurs due to the complex structure and the presence of cavities or heterogeneous-density formations within the body. Such structural features are present in every glacier. Accordingly, each glacier should have a characteristic spectrum of its own acoustic radiation. In calm conditions, this spectrum should primarily reflect the mechanical vibrations of the glacier's internal structures. However, in the presence of a strong external trigger, the entire glacier may also vibrate. Therefore, it is clear that, in most cases, the spectrum of natural frequencies will be relatively high-frequency, as the linear dimensions of even the largest internal heterogeneities of glaciers are typically several times smaller than the size of the glacier. As confirmation of this reasoning, the study [6] provides a broad set of data that determined the characteristic acoustic radiation interval of the natural mechanical vibrations of glacial structures: f = 100-300 Hz. It is clear that the process of spontaneous outflow of water from internal glacier reservoirs must also be accompanied by the emission of acoustic waves in this range. The main frequency of such wave packets should also be linked to the characteristic linear size (volume) of the reservoir.

The lowest frequency in the spectrum of the glacier's natural vibrations should indicate either its slow movement or the oscillation of the glacier as a single body. This bears some resemblance to the emission of seismic waves from the elastic zone of an earthquake’s epicenter. Similar to seismic waves, the emission of acoustic waves from the hypocenter of an earthquake is a quite common phenomenon. Acoustic waves, in this case, propagate not only through the Earth's medium but also through the atmosphere. Therefore, the emission of acoustic radiation in the frequency range of 20-20,000 Hz is used as an indicator of the intensity of glacial processes during monitoring [4].



a)

b)

c)

Fig.2. a) Seismic station layout, b) Gari station (Georgia), c) Records of stations in North Ossetia (Russia) (courtesy of the North Caucasus Seismic Monitoring Survey).

It is evident that this type of noise effect, which emerged after the destruction on the Buba Glacier, reached the resort area in the Shovi Gorge. As mentioned earlier, there may have been water reservoirs under this glacier. Therefore, the delay between two bursts recorded on the seismograms may indicate that there was a rupture or collapse of two reservoirs, separated by ice partitions. Certainly, this assumption is not definitive. Indeed, if there was only one water reservoir, its ice wall could have collapsed first to a certain level. Then, after some delay, the remaining part could have collapsed. In any case, the existence of multiple subglacial water reservoirs is quite plausible. It is likely that clarity on this issue could be provided either by direct examination of the glacier or through satellite observation, i.e., if traces of geomorphological changes in solid structures are found in the area of the glacier tongue.

Thus, the spectrum of the glacier's natural mechanical vibrations can be quite rich. Typically, the texture of a glacier consists of numerous surface and subsurface formations, each with characteristic natural sizes. To generate vibrations corresponding to these formations, a mechanical trigger is needed. Such triggers include seismic shocks, rockfalls, and ice blocks breaking off from the glacier. Additionally, mechanical vibrations—and therefore the emission of acoustic waves—can be triggered by the slow movement of the entire glacier and small local shocks that sporadically occur in the ice field, similar to ice floe collisions during ice drift in rivers. These effects can lead to the development of parametric resonance at a certain natural frequency of the glacier, which would amplify the acoustic emission. As a result, the surface density of the ice and its plasticity may change in certain areas. Laboratory modeling has also shown that the periodicity of wave movements related to the glacier's natural vibrations and its structural components can manifest as periodic secondary textures in the form of bulges and nodes characteristic of standing waves. In the case of their formation, structures with changing ice density could negatively affect the stability of the glacier's surface layer, especially at its boundary, i.e., where the glacier contacts solid rock [7].

Formula (1) represents the simplest relationship between the parameters of the wave.

In the frequency spectrum range, the natural oscillation frequencies of the glacier may include frequencies corresponding to oscillations of subglacial water reservoirs. Their linear parameters, as well as the characteristic sizes of the glacier, are present in the simple expression for the phase velocity of acoustic waves:

$$f_0=v/d, \qquad (1)$$

where f_0 - is the fundamental frequency, v - is the speed of sound in the Earth's medium, and d - is the characteristic linear size of the glacier or its structure. Specifically, in the approximation of harmonic oscillations, all subsequent frequencies in the discrete spectrum of the glacier's natural oscillations can be considered harmonics of its fundamental frequency. However, the approximation of harmonic oscillations is an ideal abstraction for a heterogeneous, dispersive solid medium like a glacier. In reality, the complex form of any oscillating body leads to the emergence of overtones caused by frequency splitting in the harmonic series. In the case of a glacier, due to the superposition of multiple frequencies in the vibration spectrum, a noise background should form, accompanying any glacial process. However, through spectral analysis of peak frequencies, it is possible to judge the degree of disruption in the harmonic oscillation series. It is clear that in a heterogeneous solid medium, particles of rock and ice fragments of different sizes may be present. Therefore, chaotic scattering and degeneration of acoustic waves will occur, contributing to the saturation of the noise background accompanying glacier oscillations. A body of arbitrary geometric shape can have several linear scales. Nevertheless, it can be approximated by some symmetric body. For example, a glacier can be most simply represented as a rectangular parallelepiped. The natural (free) mechanical oscillations of a parallelepiped may be axisymmetric, i.e., the frequency spectrum of its oscillations may include two or three fundamental frequencies, depending on the shape of its cross-section. In reality, to determine the frequency spectrum of free oscillations of a body, formula (1) is too simple. In fact, any elastic homogeneous body, regardless of its shape, must have a dominant fundamental frequency of its natural mechanical oscillations. The specific spatial configuration of such a body, assuming small perturbations in its shape, reflects the nature of the spectrum of its natural oscillations. In this regard, the spectrum of spheroidal oscillations is the simplest, the generation of which occurs with small perturbations of the surface of a homogeneous elastic sphere, a body that has a single linear scale, its radius. Clearly, in a very rough approximation, a glacier can only be abstractly approximated as a sphere, for example, based on the condition of equal volumes. Sometimes, such an approximation can be useful for specific analysis. For example, one can use the analytical formula for the discrete spectrum of natural mechanical oscillations f_n of an elastic spherical body [8]. It was derived using a physical analogy with the natural hydromechanical oscillations of a liquid spherical droplet, which occur due to the effect of surface tension of the droplet [9]. It should be noted that this formula has proven quite effective for modelling the frequency spectrum of natural mechanical oscillations in the elastic zone of moderate-strength earthquake foci. Along with seismic waves, acoustic waves are also generated there, whose frequency spectrum is an extension of the spectrum of lower-frequency acoustic waves:

$$f_n = \frac{V_p}{2\pi R}\left[(n-1)(n+2)n\right]^{1/2}, \; n=2,3,4........., \tag{2}$$

where v - is the longitudinal seismic wave speed, and R is the radius of the sphere. The fundamental oscillation frequency corresponds to n=2.

In the presence of subglacial water reservoirs, as well as cavities and other heterogeneous formations of various sizes and densities, their natural oscillation frequencies will be present in the general spectrum of the glacier's acoustic radiation. The low-frequency part of this spectrum should be associated with the linear characteristics of the glacier as a unified body. Let us demonstrate this with a specific example and estimate the possible discrepancy in the change of the fundamental frequency of the glacier's natural oscillations using formulas (1) and (2). Suppose we have a parallelepiped with sides $a=2.\ 10^3$ m, $b=2.\ 10^2$ m and $c=10^2$ m. The volume of this parallelepiped is $Q= 4.\ 10^7$ m^3. Consequently, the radius of the equivalent sphere with the same volume is $R \approx 2.1\ 10^2$m^3. A typical value for the longitudinal seismic wave speed in the Caucasus region is $V_p \approx 5.\ 10^3$m/sec. Therefore, for each side of the parallelepiped, the frequencies corresponding to formula (1) are: f_{a0} =2.5 Hz, $f_{в0}$= 25 Hz, f_{c0}= 100 Hz. For the fundamental frequency of the sphere equivalent to the parallelepiped, from formula (2), we obtain: $f_2 \approx 11$ Hz. Thus, using formula (1), the fundamental frequency of the natural mechanical oscillations of the model glacier varies in the range /2.5−100/ Hz, which starts with infrasonic frequencies. This range also includes the fundamental frequency of the natural oscillations of the virtual equivalent sphere. In the absence of a mechanical trigger, oscillations of the glacier as a unified body are unlikely. Apparently, for this reason, infrasonic frequencies are outside the typical range of the glacier’s oscillation frequency spectrum, which was determined through statistical analysis: *f*=/100—300/ Hz [6]. For this range, using formula (1) with $V_p \approx 5\ 10^3$m/sec, the average statistical range of linear scale variation is d=/17-50/m. If the reservoirs are approximated as spheres, i.e., the linear scale is equated with the radius, the limiting volumes of the virtual equivalent spherical water reservoirs are $Q_1 \approx 500000$ m^3 and $Q_2 \approx 15000$ m^3. In rough approximation, one can consider that the first of these values is in satisfactory quantitative agreement with the presumed water volume in the debris flow that reached the Shovi Gorge. According to unconfirmed estimates, the volume of the debris mass, in which water accounted for approximately ≈20-30 %,: Q≈ 1500000 m^3. Therefore, if the destruction on the Buba glacier began after the rupture of a subglacial water reservoir, the dominant frequency in the spectrum of acoustic waves generated at that time could have been f≈100 Hz.

Glaciers of the Central Caucasus are well studied

The Djankuat glacier has been the object of careful study for several decades. Therefore, it can be considered a reference for the purpose of identifying general patterns in the dynamic processes occurring on other glaciers of the Central Caucasus. Analysis of morphological changes occurring on glaciers is obviously a traditional tool necessary for identifying empirical relationships between glacier parameters and variable external factors. Undoubtedly, numerical models using observation data can provide a diagnostic picture of glacial processes. The long-term goal of such models, based on hydrodynamic equations, is such a qualitative and quantitative interpretation of observation results, which is necessary for real forecasting of catastrophic events associated with glaciers. Obviously, this is preceded by reliable confirmation of cause-and-effect relationships between various physical factors capable of causing a catastrophic result. An example is the numerical model of the ice mudflow that came down from the Kolka glacier and caused a gigantic catastrophe in the Karmadon Gorge and in the Geraldon River Canyon. In particular, this model, like other similar models, can be useful for analyzing the results of the catastrophic event on the Buba glacier. For this purpose, information on the dynamics of the Djankuat glacier, which has been the object of fairly detailed monitoring for a number of years, is also valuable. There is an obvious similarity in the geophysical characteristics of the Buba and Djankuat glaciers, which are in almost identical climatic conditions. However, field observations have not been carried out on the Buba glacier since the Soviet era. First of all, there are no data on changes in ice thickness that occurred during climate change. At the same time, there is fairly complete information on the Djankuat glacier.

It is assumed that the trigger for the rupture of the subglacial water reservoir on the Buba glacier was a rockfall, There is a possibility that the cause of the destruction on the Buba glacier could be a decrease in the thickness of the ice in the manner noted in the upper part of the Djankuat glacier at altitudes of 3000-3100 m, occurring synchronously with an increase in the area of ice in the nearest area of the glacier bed. As a result of this effect, since this zone is an area of rapid transformation of the pressure field, the local threshold of glacier stability could decrease. A similar effect in sea and lake ice, as well as on rivers, leads to the formation of ice hummocks. Therefore, it cannot be ruled out that a similar phenomenon took place on the Buba glacier. In this regard, the following questions arise: how real is the possibility of the formation and subsequent detachment of a structure similar to an ice hummock from the glacier surface? Was this event impulsive or was it prepared for a certain time? It is impossible not to assume that something similar has already happened many times or will happen in the future on other glaciers, including the Buba Glacier. It seems quite reasonable that the effects of global climate change on glaciers should be especially active in their upper part, where the slope of the relief to the horizon is usually steeper than in the lower sections of the glacier.

Thus, there is a possibility of new destruction on the Buba glacier and a repeated mudflow in the Shovi gorge. Therefore, the most important task is to control the thickness of the Buba glacier, especially in its upper part, which can hardly be done only by satellite observations. For this purpose, the radio sounding method is especially convenient, which highlights the internal structures of the glacier. Accurate data on the thickness of the ice increases the effectiveness of the empirical formula that determines the magnitude of the shear stress in the glacier bed using the difference in height between the top and base of the glacier ΔH [1]

$$\tau = 0{,}005 + 1{,}598\Delta H - 0{,}435\Delta H^2. \qquad (3)$$

$$h = \frac{\tau}{\beta \rho g \sin\alpha} c, \qquad (4)$$

where h- is the thickness of the ice, β - is the coefficient of the cross-sectional shape of the glacier, ρ - is the density of the ice, g - is the acceleration of gravity, α - is the angle of inclination of the surface to the horizontal plane, c - is the coefficient of quantitative correction.

Obviously, the parameters τ and α are variable and depend on the specific parameters of the glacier. The coefficient β depends on the surface friction at the boundary and in the bed of the glacier, i.e. in the area of contact of the glacier with the enclosing medium. The angle α should be averaged over a segment, the length of which is approximately an order of magnitude greater than the ice thickness. It is believed that in this case, model (4) will be in agreement with the approximation of ideal plasticity, the condition of which is the minimization of shear stress. From formula (3) it follows that for large glaciers ($\Delta H > 1.6$ km), the shear stress is on average $\tau \approx 150$ kPa with ± 30% error. For medium glaciers, such as Djankuat and Buba, $\tau \approx 110$ kPa. Formulas (3) and (4) are quite useful, although there is a significant error in quantitative estimates. In any case, they correspond to the general ideas about quasi-stationary processes of glacier parameter changes over a long period of time, comparable to several decades and centuries. A significant error will obviously affect the results of a comparative analysis between new and retrospective data. Probably, this shortcoming can be corrected within the framework of numerical models, the value of which seems undoubted in the process of transition from diagnosing the state of glaciers to predicting the time and place of destructive phenomena.

Glacial flow in the Shovi gorge

Glacial mudflow should be considered either as a heterogeneous liquid or as a water-containing plastic mass. In both cases, the movement of the medium in a canyon or in an open area is subject to the laws of hydrodynamics. It is known that, depending on its viscosity, a liquid medium can be classified as a Newtonian or so-called rheological liquid (for example, Bingham's liquid). Water is a Newtonian fluid, but the mudflow from the Buba glacier, which is a mixture of water with solid particles and ice fragments, is considered a suspension that belongs to the class of viscoplastic (pseudo plastic) Bingham fluid with a plastic viscosity coefficient of: $\eta \approx /10^9 - 10^{10}/$ Pa s. Such a liquid, unlike water, always has an initial shear stress

τ_0, which is in the functional dependence: $\tau = f(\beta)$ on the strain rate: $\beta = (\frac{\partial \xi}{\partial t})$, where ξ - is the linear strain. This dependence qualitatively changes from nonlinear to linear with an increase in the parameter β. During this process, pseudo plastic viscosity is transformed into dynamic viscosity, i.e. the Bingham fluid acquires the qualities of an ordinary Newtonian fluid. In this case, the following equation is valid for the shear stress:

$$\tau = \tau_0 + \eta\beta \qquad (5)$$

Among the special properties of Bingham fluid that distinguish it from Newtonian fluid, of particular importance is its ability to maintain its spatial structure after flow deceleration on a solid surface. This state continues up to a certain point and can be disrupted by the action of some factor, for example, due to an increase in the angle of inclination of the flow channel to the horizon α. In this case, the force required to shift the viscoplastic mass must exceed the force of surface friction. 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.

According to information received from eyewitnesses of the event, as well as as a result of the analysis of numerous television programs, the mudflow in the lower part of the Shovi gorge acquired a viscoplastic character within approximately 20-25 minutes after the collapse on the Buba glacier. Interestingly, in fact, in the same time interval, a picture of the spread of an ice mudflow after the destruction of the Kolka glacier developed. This circumstance allows us to imagine the movement of the mudflow in the Shovi gorge in the image of the movement of the ice-rock mass in its last section in the Genaldon River gorge. According to the principle of hydrodynamic similarity, these two pictures of the mudflow propagation could differ only in the quantitative factor. It is known that in the numerical modeling of the movement of a liquid medium, a standard set of hydrodynamic parameters is used, among which the cornerstone is the coefficient of dynamic viscosity of the liquid. As indicated above, in the case of a viscoplastic suspension, the coefficient of dynamic viscosity is transformed into the coefficient of plastic viscosity. In a normal liquid, its value determines the degree of flow turbulence, i.e. the value of this parameter changes depending on the flow regime. Consequently, until a mudflow with suspended solid particles retains the qualities of a normal liquid, the distribution of the solid fraction along the bed of the liquid will largely depend on its dynamic viscosity. Due to the orographic similarity of the Shovi and Genaldon gorges, despite the huge difference in the volumes of mudflows, the degree of turbulence in both cases can be considered the same. Therefore, in these gorges, one can assume a similarity in the distribution of the solid fraction. This process may also have been influenced by stochastic changes in river beds [10]. Such changes were probably prepared by the active action of a number of geological, geophysical and climatic factors:

- activity of erosion formations in the river beds, in the gorges of which frequent floods are typical;
- increase in solid sediments incomings of rivers, depending on the geological structure of the gorge, geophysical properties of rocks and activity of the liquid component of the mudflow;
- change in turbulent characteristics of the mudflow due to surface and deep erosion of the slopes of the gorge;
- roughness of the river bed and slopes of the gorge, change in its angle of inclination;
- climate change.

Mudflow with variable rheology

The movement of a non-uniform liquid in a gravity field along an inclined channel approximating a river bed is a physical analogue of the propagation of a mudflow along a mountain gorge. The mathematical problem of studying various liquid flows is associated with solving the equations of hydrodynamics. One of the areas is turbulent flows and waves that occur in both ordinary and rheological liquids. The flow of liquid in channels at sufficiently large angles of inclination can become unstable, as a result of which waves of various types can arise in the liquid. An important parameter of the waves is their height, which can be analytically determined, for example, after solving the well-known Burgers equation. However, for a general idea of the process of propagation of waves that arose in the mudflow in the Shovi gorge, one can use only a simplified analysis, without using solutions to specific equations. In particular, after the standard transformation to the dimensionless form of the equation of fluid motion in the channel, two criteria of hydrodynamic similarity appear: the Reynolds number and the Froude number, which are associated with the parameters of the fluid flow and the linear characteristics of the channel [12]. The Reynolds number determines the flow regime, which in case of very strong flow will necessarily be turbulent. In this case, in a normal fluid, depending on the value of the Froude number, various waves can be generated. In a viscous-plastic medium with Bingham rheology, wave motions can be less diverse than in a normal fluid. For example, in a mixing heterogeneous fluid, waves arise due to the development of instability due to a velocity shift in layers with different densities. Also, due to the restructuring of the flow structure, heterogeneous layers with large gradients of velocity and density arise in the rheological fluid. The appearance of such a texture in a liquid flow makes it possible to simplify the problem of mathematical modeling of waves by introducing a small parameter. It is the ratio of the channel depth to the wavelength and is the criterion for the approximation of the so-called shallow water. Although this model significantly simplifies the hydrodynamic equations, complications associated with the nonlinearity of the waves may arise for a rheological fluid. Therefore, such waves in a viscous-plastic fluid are not discussed below.

By means of retrospective analysis it is possible not only qualitatively, but also, to a certain extent, quantitatively to present a hydrodynamic picture of the propagation of a glacial mudflow along the gorges of the Bubiskali and Dzhandzhakhi rivers, which together form the Shovi gorge. For example, based on the tracks in the river beds it is possible to analyze the rheological properties of the water-saturated soil mass, which forms the basis of the mudflow, which allows estimating the probability of generating various types of hydrodynamic waves. This goal can also be achieved by estimating the ranges of dimensionless hydrodynamic numbers in different sections of river beds during the movement of the mudflow mass, which allows applying the principle of hydrodynamic similarity. In particular, in the case of approximating the mudflow bed with a rectangular channel, it is possible to use the results of those analytical solutions based on simplifying assumptions of the shallow water equations. They are valid within certain intervals of change in the Reynolds and Froude similarity numbers. For example, for large Reynolds numbers, when the fluid is highly turbulent, the Froude parameter quite simply characterizes the process of changing the flow regime due to the generation of hydrodynamic waves, the specifics of which are associated with negative effects that often arise as a result of the propagation of wave disturbances. For example, during the propagation of the mudflow in the Shovi gorge, so-called rolling hydrodynamic waves could be generated, which could well have been one of the reasons that determined the catastrophic scale of the glacial mudflow.

In the one-dimensional approximation, at sufficiently large Reynolds numbers, the unsteady shallow water equations, with turbulent fluid friction at the bottom of an inclined channel, have the form [12,13]

$$\frac{\partial}{\partial t} h + \frac{\partial}{\partial x}(hu) = 0, \qquad (6)$$

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial \times}\left(hu^2 + \frac{gh^2}{2}\cos\varphi\right) = gh\sin\varphi - C_w\ u^2, \qquad (7)$$

where h, u - are the average depth and velocity of the fluid; g - is the acceleration of gravity; φ - is the angle of inclination of the channel; C_w - is the friction coefficient, which is assumed to be constant for simplicity. The first equation (1) denotes the continuity of the medium, (2) determines the movement of the fluid in an inclined channel.

After the standard transition to dimensionless variables and parameters, the form of the continuity equation (6) does not change, but equation (7) takes the form

$$\frac{\partial}{\partial t}(hu) + \frac{\partial}{\partial \times}\left(hu^2 + \frac{\mathrm{h}^2}{2}\right) = \alpha h - u^2, \qquad (8)$$

where $\alpha = tg\varphi / C_w$ - is the only dimensionless parameter that determines the flow. If there is a uniform fluid flow in a channel with a normal depth h_0, then the Froude number of such a flow will be determined by the parameter α, related to the Froude number: Fr= $\sqrt{\alpha}$. In the shallow water approximation, the Froude number allows us to classify hydrodynamic waves that can be generated at sufficiently large Reynolds numbers, when the flow is highly turbulent. In particular, in the case of approximating the channel of a mudflow with a rectangular channel, we can use the results of known analytical and numerical solutions obtained for some types of hydrodynamic waves.

Let us estimate the characteristic intervals of change of the hydrodynamic similarity numbers. Reynolds number $\mathrm{Re} = \frac{\mathrm{u_{0\,d}}}{\eta}$, where u_0 is the characteristic velocity value, d is the channel width, η is the kinematic viscosity coefficient. Froude number $\mathrm{Fr} = \frac{\mathrm{u_0}}{\sqrt{\mathrm{gh_{0\,\cos\varphi}}}}$, where h_0 is the normal (characteristic) channel depth. It has been proven that the flow in the channel becomes unstable when $Fr>2$ $(\alpha>4)$. For example, the characteristic velocity of the mudflow and the parameters of the Shovi gorge: u_0= */10-20/m/sec,* d= /40-60/m,

h_0 =/8-10/m, $\alpha=5^0$. For water containing solid particles, $\eta\approx$/1-10/10^{-6}m^2/sec. Therefore, we will have the following characteristic intervals of change of the indicated dimensionless parameters of hydrodynamic similarity: Re≈/4-12/ 10^7 and Fr≈/1-2.2/. The large value of the Reynolds number means that the degree of flow turbulence in the main part of the Shovi gorge was critically high. Such an effect could probably be noticeable in the last, widest section of the gorge, where the viscoplastic nature of the mudflow could be fully revealed. In this place, the movement of the mudflow mass had a complete similarity with the movement of a viscoplastic medium with a small (≈20%) water content. In this regard, the question of the nature of wave motions, the spectrum of which can be presented based on the results of some solutions of shallow water equations, as well as on the data of laboratory experiments, seems interesting [12].

Thus, in the shallow water approximation, the value of the Froude parameter allows us to classify the waves whose generation is most probable in the case of sufficiently large Reynolds numbers. This means that the degree of flow turbulence in the main part of the gorge was critically high. It is also likely that the value of the Froude number in some places of the gorge could go beyond the characteristic interval. For example, due to local changes in the depth of the flow or a decrease in its speed. Therefore, the question of the nature of those wave motions, the spectrum of which can be represented by the results of solving the shallow water equations and data from laboratory experiments, is of particular interest [12]. In this case, the Froude number is a determining parameter that can serve as a quantitative criterion distinguishing between different types of long hydrodynamic waves whose generation is possible in the shallow water approximation [13,14]. Thus, the probability of generating waves of different types depends on the value of the Froude number:

1) $0.3\leq Fr\leq 0.5$. Such an interval of the Froude number for the case of a mudflow in the Shovi gorge is unlikely. It is more typical for a channel of finite depth, along the bottom of which a liquid with a higher density flows than in the surface layer. It is known that with such a flow structure in an inhomogeneous liquid, so-called gravity (density) waves can be generated;

2) $0.9<Fr<1.1$. According to the Kadomtsev-Petviashvili equation, for such Froude numbers, with a balance of the influence of linear dispersion, nonlinearity and spatial effects, the generation of solitons (solitary waves) is possible. The probability of such a balance, as well as the conditions necessary for the generation of gravity waves, is quite low. Nevertheless, despite the rigidity of the mathematical criteria, the probability of soliton propagation in the Shovi gorge cannot be completely excluded;

3) $Fr\leq 2$. In this case, according to the shallow water equations, as a result of the effect of turbulent friction on the channel bottom, so-called linear rolling waves can be generated. For these waves, the critical value is Fr=2, which determines the threshold for the development of linear instability and a noticeable increase in amplitude;

4) $Fr>2$. At a sufficiently large Re, a nonlinear stage of increasing flow instability develops. This case corresponds to a certain critical channel depth, in which a picture of a turbulent flow arises. So-called depression waves appear in the liquid, as well as rolling waves with hydraulic jumps, which facilitate a change in the flow regime from subcritical to supercritical. A feature of such wave solutions is the presence of a smooth section of the wave trajectory, indicating the transition from subcritical to supercritical flow [12] (sections 2, 1 in Fig. 3,a,b).

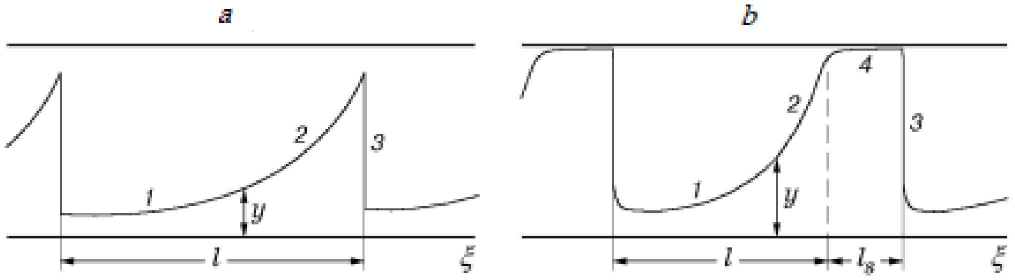


Fig. 3. Rolling waves (V.Yu., Lyapidevsky, V.M. Teshukov. Mathematical models of the propagation of long waves in an inhomogeneous liquid. Novosibirsk, Publishing House SB RAS, 2000, 420 p (in Russian).

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

As an example of what can happen to a wave packet with an increase in the Froude number, we can use the result of numerical modeling when Fr=5. Fig. 4 corresponds to the theoretical picture of the evolution of a packet of modulated rolling waves. They were generated in a flow of inhomogeneous fluid as a result of a nonlinear increase in small disturbances, the initial amplitude of which was ≈1% of the normal channel depth h_0 [12]. The maximum amplitudes that were recorded in the corresponding laboratory experiment turned out to be significantly less than the theoretical ones. Nevertheless, the qualitative nature of the growth of the amplitude of the wave packet, which initially had an exponential nature, was confirmed. However, after the traveling wave has passed a certain distance, the amplitude stops growing. It turned out that for a developed turbulent flow, the average values of the minimum depths satisfy the inequality: $\frac{xC_w}{h_0} \leq 10$, where C_w, is the friction coefficient. It is believed that small disturbances grow exponentially along the channel until the wave reaches the boundary of the hyperbolicity region of the shallow water equation system, after which the wave amplitude stops growing and the flow becomes quasi-periodic. The bold 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, agree well. At the same time, the corresponding experimental values of the maximum amplitude turned out to be significantly less than the analytically determined theoretical amplitudes.

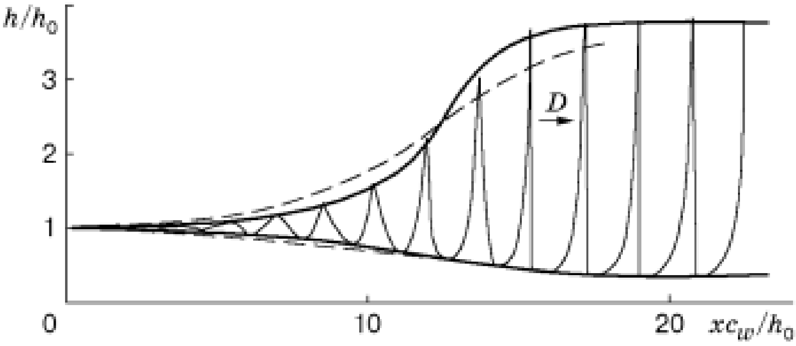


Fig. 4. results of numerical calculations on the evolution of a rolling wave packet (V.Yu., Lyapidevsky, V.M. Teshukov. Mathematical models of the propagation of long waves in an inhomogeneous liquid. Novosibirsk, Publishing House SB RAS, 2000, 420 p (in Russian))

Georgia, Shovi Disaster, Event Analysis. Report №14230941, Zolikofen, November 28, 2023, 42 p.

It was noted above that the reports [15,16] use an almost identical structure, with the exception that the report of the Georgian Nature Agency devotes a lot of space to the general geology and hydrology of the Caucasus Range, which is hardly not directly related to the disaster in the Shovi Gorge. In these reports, the Swiss RAMSS simulation program is used to model the hydrodynamic parameters of the glacial mudflow. Therefore, we consider it sufficient to cite some data and conclusions from [15], which are actually repeated in [16]. It can only be briefly noted that these initial data, as well as the results of modeling the parameters of ice mudflow movement, are to some extent universal, since they also characterize other glaciers and viscous-plastic mudflows. It can be considered that the obvious similarity of the hydrodynamic picture in such cases is the result of the actual identity of the computer programs, which are based on the equations of hydrodynamics and the input initial conditions and boundary conditions, which is obviously a consequence of the general similarity of the orography of mountain canyons and their physical parameters in the Caucasus and in other mountain systems.

Thus, we consider it convenient to present those extracts from [15] that seem especially important:

Estimation of the event volume from August 2023. *"Debris Source Volume, estimation [m^3] Rockfall (release area) ca. 10^6 m^3 Upper channel (periglacial area) ca. (0.5 – 1) 10^6 m^3 ; Middle flat part (above tree line) ca. (0.1 - 0.2) 10^6 m^3 ; Middle and lower channel (below tree line) ca. (0.5 – 0.8) 10^6 m^3 . Total (2 – 3) 10^6 m^3 ."*

Input parameters for RAMMS simulation (August 2023 event). *"The volume that reached the valley is an important input parameter for the debris flow simulation. The parameters for the simulation of the debris flow due to the slope failure on 3rd August 2023 are described in Table 2: Table 2: Applied simulation parameters RAMMS for the reconstruction of the August 2023 event. Dry friction coefficient (Mu) μ [-] 0.05* ***Turbulent friction coefficient (Xi) ξ [m/s²] 1000; Volume [m³] (1.5 - 2.5) 10⁶ . Density: 1,8 10³ kg/m³ ."***

The estimated volume that reached the valley is about 2 Mio. m^3 - max. 3 Mio. $m^{3\,*}$, which corresponds to the volume estimation of NEA. *“.The trigger of the event can only be assumed – there are many uncertainties. But, we assume that the rock mass was "ready to fail" due to the severe weakening of the previous years. With the high temperatures in summer and the maximum melting rate of fissure ice (permafrost), the fissures and cavities in the rock were probably filled with water at this time. It is conceivable that the precipitation on the days before August 3rd, 2023 could have produced a brief overpressure of water in the right place in the rock, causing the rock mass to collapse”.*

**** According to our (Z. Kereselidze, N. Varamashvili) assessments, the maximum volume that reached valley is overestimated by about ≈ 50%.***

Causality of the Process. *“The causality lies in the interplay of the geological disposition (large-scale tectonic structures, fracturing, strong loosening), the local geomorphology (steep glacier and glacier fore field with large debris deposits), the long-lasting, recurring high summer temperatures (climate change with ever higher zero-degree limit in summer and associated strong degradation of permafrost and glacier melt) and the weather on the day of the event (local and strong precipitation intensity). In the following sections, the individual influencing factors are explained, and their interplay explored”.*

We therefore strongly recommend carrying out a disposition analysis to localize the hotspots for such processes*. “Existing methods (e.g. Swiss methodology) can be used for this purpose. For such an analysis, the evaluation of satellite data is a must. Only with satellite data localities with active movements can be evaluated over large areas in an efficient way. Combined with the disposition analysis, the hotspots in the Georgian Caucasus can be evaluated*. Such an analysis should definitely be carried out in a multi-stage process. Then, not all localities with a high risk of collapse are critical for the settlement area. Only with a multi-stage process the areas that are really critical for the settlements can be determined. It has to be discussed to test the methodology and adapted to Georgian circumstances in a small test area with high damage potential”.*

Conclusion

The analysis of the causes of the collapse of the Buba glacier on 3/9/2023 is an ambiguous task. The tragic event that took place in the Shovi gorge was prepared by a number of natural phenomena, probably associated with global climate change. Characteristic signs of this process were noted on the Djankuat glacier, a supporting glacier for the Central Caucasus, which has a certain similarity with the Buba glacier. Therefore, it can be assumed that the dynamic changes on these two glaciers occurred, to some extent, according to a similar pattern. This assumption allows us to use information on the change in ice thickness in the upper part of the Djankuat glacier for extrapolation to the Buba glacier. It cannot be ruled out that this phenomenon caused the formation of ice hummocks on the surface of the glacier, the shift of which was facilitated by the intensive melting process. Along with a possible rockfall, the collapse of ice hummocks in the glacier bed could have triggered the destruction of the intraglacial water reservoir, after which a mudflow spread in the river beds flowing in the Shovi Gorge. The available information about the collapse on the Buba Glacier and monitoring of the changes that occurred in the Shovi Gorge require filling with new data from ground and space observations; In particular, we consider it necessary to check whether the rockfall process was a one-off event or consisted of separate, spaced out in time events. A ground expedition to the Buba Glacier can clarify this.

During the propagation of the mudflow in the gorges of the Bubiskali and Chanchakhi rivers, which make up the Shovi gorge, hydrodynamic waves of various types could have existed. In particular, for the characteristic range of the Froude hydrodynamic similarity number, the most probable is the generation of running rolling waves, the height of which could reach several meters. The appearance of solitary waves (solitons), as well as the so-called gravity waves, was unlikely, but one cannot exclude the possibility of their generation in those places where local conditions were suitable. In the lower, widest section of the Shovi gorge, in the zone of the so-called cottages, the movement of the mudflow mass was similar to the movement of the ice mudflow in the Genaldon River gorge that came down after the collapse of the Kolka glacier in 2002. Despite the huge difference in the initial volumes of glacial mudflows that came down from the Buba and Kolka glaciers, the thickness of viscoplastic deposits in the last flat areas of their distribution turned out to be comparable, taking into account the difference in covered areas. Obviously, this is due to the same nature of the braking of the viscous-plastic mudflow at the stage of its final stop, which is also indicated by a decrease in wave amplitudes within /1-3/ m.

References

[1] Lavrentiev I.I., Kutuzov S.S., Petrakov D.A., Popov G.A. Thickness, subglacial relief and ice volume of the Djankuat glacier. Ice and Snow, No. 4, 2014, pp. 26–342 (in Russian)

[2] Kotlyako V.M., Rototaeva O.V., Nosenko G.V. The September 2002 Kolka Glacier Catastrophe in North Ossetia, Russian Federation: Evidence and Analysis. Mountain Research and Development, т. 24, вып. 1, 2004/02, с. 78–83. ISSN 1994-7151 0276-4741, 1994-7151. doi:10.1659/0276.4741(2004)024[0078:TSKGCI]2.0.CO;2.

[3] Surkov V. V., Pilipenko A. Estimate of ULF electromagnetic noise caused by a fluid flow during seismic or volcano activity. Annals of Geophysics, vol. 58, No. 6, 2015. S0655, doi:10.4401/ag-6767.

[4] Epifanov V.P., Glazovsky A.F., Osokin N.I. Physical modeling of the glacier contact with the bed. Ice and Snow, No. 1 (121), 2013, pp. 43–52 (in Russian)

[5] Yepifanov V.P. Fizicheskoye modelirovaniye rezhimov dvizheniya lednikov. Lod i Sneg, t. 56, № 3, 216, s. 333-34, .doi:10.15356/2076-6734-2016-3-333-344.

[6] Roux P.-F., Marsan D., Metaxian J.-P., O'Brien G., Moreau L. Microseismic activity within a serac zone in an alpine glacier (Glacier d'Argentiere, Mont Blanc, France). Journ. of Glaciology, V. 54. № 184, 2008, p. 157–168.

[7] Epifanov V.P., Sazonov K.E. Wave structures in an ice field and their influence on the strength of salt ice. Ice and Snow, v. 60, no. 4, 2020, pp.624-636, doi: 10.31857/S2076673420040066 (in Russian).

[8] Kereselidze Z., Gegechkori T., Tsereteli N., Kirtskhalia V. Modeling of Elastic Waves Generatedby a Point Explosion. Georgian International Journal of Science and Technology, v. 2, Iss. 2, 2010, p. 155-166, NovaPublishers, https://www.novapublishers.com/catalog/product_info.php?products_id=14264 (in Russian)

[9] Landau L.D., Lifshits E.I. Continuum Mechanics. Moscow, Publishing House of Technical Literature, 1954, 795 p. (in Russian)

[10] Petrakov D.A., Drobyshev D.N., Aleinikov A.A., Aristov K.A., Tutubalina O.V., Chernomorets S.S. Changes in the zone of the Genaldon glacial catastrophe in the period 2002-2010. Earth's Cryosphere, v.17, no.1, 20013, pp.35-46 (in Russian)

[11] Popovin V.V., Petrakov D.A., Tutubalina O.V., Chernomorets S.S. Glacial catastrophe of 2002 in North Ossetia. Earth's Cryosphere, v.7, no.1, 2003, pp. 3-17 (in Russian)

[12] Lyapidevsky V.Yu., Teshukov V.M. Mathematical models of long wave propagation in an inhomogeneous liquid. Novosibirsk, SB RAS Press, 2000, 420 p (in Russian)

[13] Kereselidze Z. A. Varamashvili N. D. Regarding the Spontaneous Mechanism of Atmospheric Whirlwind Generation in Narrow Mountain Canyons. Journal of the Georgian Geophysical Society, e-ISSN: 2667-9973, ISSN: 1512-1127, Physics of Solid Earth, Atmosphere, Ocean and Space Plasma, v. 26(2), 2023, pp. 13 – 21.

[14] Melnikova O. N., Dynamics of channel flow, Moscow: Max Press, Physics Department of Moscow State University, 2006, p. 136 (in Russian)

[15] Georgia, Shovi Disaster, Event Analysis. Report №14230941, Zolikofen, November 28, 2023, 42

[16] Report on the assessment of natural disasters in the Bubistskali River Gorge on August 3, 2023. LEPL National Environmental Agency. Tbilisi 2024, 69 p (in Georgian)

[17] Poznanin V.L., Gevorkyan S.G. The impact mechanism of the preparation of the Kolka glacier to the mudflow accident: the physical processes during the large landslides. Earth's Cryosphere, Vol. XI, No. 2, 2007, pp. 84–91, (in Russian)

ბუბას მყინვარზე ნგრევის გამო შოვის ხეობაში ღვარცოფის ნაკადის გავრცელების დინამიკის მოდელირების საკითხი

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რეზიუმე

მყინვარები ყოველთვის პოტენციურ საფრთხეს წარმოადგენდნენ კავკასიის რეგიონში, სადაც მთის კანიონები საკმაოდ მჭიდროდ არის დასახლებული. გლობალურ კლიმატის

ცვლილებასთან დაკავშირებულმა პროცესებმა, რომლებიც ყველგან ხდება, უკიდურესად გაამწვავა მყინვარული კატასტროფებისგან მოსახლეობის პრევენციის პრობლემა. მაგალითად, არსებობს სამწუხარო გამოცდილება, რომელიც დაკავშირებულია კოლკას მყინვარის ნგრევასთან, რამაც გამოიწვია გიგანტური გლაციალური ღვარცოფი 2002 წელს. ასეთი კატასტროფის კატეგორიაში უნდა შედიოდეს გლაციალური ღვარცოფის გენერირება ბუბას მყინვარიდან 9/3/2023, რამაც გამოიწვია ტრაგედია უამრავი მსხვერპლით კურორტ შოვში. ასეთი კატასტროფული მოვლენების განვითარების შესაძლო ადგილისა და დროის განსაზღვრას (მიწისძვრები, ვულკანური ამოფრქვევები, ფართომასშტაბიანი წყალდიდობები) აქვს საიმედოობის ძალიან დაბალი ხარისხი და პრობლემატურია, მიუხედავად სახმელეთო და კოსმოსური მონიტორინგის სამეცნიერო მეთოდების თანამედროვე დონისა. კერძოდ, აშკარაა საჭიროება კავკასიის მყინვარების ამჟამინდელი მდგომარეობის გრძელვადიანი მონიტორინგისა და ყოვლისმომცველი დიაგნოსტიკის, ყოველი ახალი გამოცდილების გათვალისწინებით. უნდა აღინიშნოს ინფორმაციის სიმცირე, რომელიც საშუალებას არ გვაძლევს ვიმსჯელოთ ბოლო ათწლეულების განმავლობაში ბუბას მყინვარზე მიმდინარე პროცესებზე. ამიტომ, ნაკლებად სავარაუდოა, რომ ვინმეს წარმოედგინა მდინარეების ბუბისწყლისა და ჯაანჯახის ხევებზე მყინვარული ღვარცოფის გავრცელების ფართომასშტაბიანი ვირტუალური სურათი, ადექვატური იმისა, რაც სინამდვილეში აღმოჩნდა. ამავდროულად, თუ არსებობს დაკვირვების შედეგების საკმარისად სრული მონაცემთა ბაზა და მისი სწორი ანალიზი, ჰიდროდინამიკური მსგავსების პრინციპზე დაფუძნებული, შესაძლებელია, მაგალითად, მთის ნებისმიერ ხეობაში წყალდიდობის ან მყინვარული ნაკადის სავარაუდო პარამეტრების მოდელირება. კავკასიის რეგიონის შემთხვევაში, შეგიძლიათ გამოიყენოთ ზოგიერთი შედეგი, მიღებული ჯანკუათის და კოლკას მყინვარების რიცხვითი მოდელირების გამოყენებით. კერძოდ, ეს მოდელები საკმაოდ გამოსადეგია არა მხოლოდ სავარაუდო მიზეზების დასადგენად, არამედ ბუბას მყინვარზე ნგრევის შედეგების რეტროსპექტულ ანალიზისათვის. პირველ რიგში. ეს ეხება ჰეტეროგენულ ღვარცოფში ჰიდროდინამიკური ტალღების გავრცელების პროცესს. ამ მიზნით ასევე მნიშვნელოვანია სეისმური ხელსაწყოების ჩანაწერები, რომლებიც შეიცავს ინფორმაციას ბუბას მყინვარზე ნგრევის პროცესის შედეგად წარმოქმნილი აკუსტიკური ტალღების სიხშირის სპექტრის შესახებ. ბუბისწყლისა და ჭანჭახის ხეობებში შეიძლება არსებობდეს სხვადასხვა ტიპის ჰიდროდინამიკური ტალღები. ფრუდის მსგავსების რიცხვის მნიშვნელობების დამახასიათებელ დიაპაზონში ყველაზე სავარაუდო უნდა ჩაითვალოს მორბენალი მგორავი ტალღების წარმოქმნა, რომელთა სიმაღლემ შეიძლება მიაღწიოს რამდენიმე მეტრს. მარტოხელა ტალღების (სოლიტონების) გამოჩენა, ასევე ე.წ. გრავიტაციული ტალღები ნაკლებად სავარაუდო იყო, თუმცა მათი წარმოშობის შესაძლებლობა იმ ადგილებში, სადაც ადგილობრივი პირობები იყო შესაფერისი, არ არის გამორიცხული. შოვის ხეობის ქვედა, ყველაზე ფართო მონაკვეთში, ე.წ. კოტეჯების ზონაში, ღვარცოფის მასის მოძრაობა მსგავსი იყო 2002 წელს მდინარე გენალდონის ხეობაში კოლკას მყინვარზე ჩამონგრევის შედეგად აღძრული მყინვარული ღვარცოფის მოძრაობისა. მიუხედავად დიდი განსხვავებისა ბუბას და კოლკას მყინვარებიდან ჩამოსული ღვარცოფების საწყის მოცულობებში, ბლანტპლასტიკური მასის გამონატანი, ტალღების სივრცითი მასშტაბისა და ამპლიტუდის გათვალისწინებით, მისი განაწილების ბოლო უბნებში შედარებითი აღმოჩნდა და ორივე შემთხვევაში 1-3 მეტრის სიმაღლემდე შემცირდა.

საკვანძო სიტყვები: ბუნებრივი კატასტროფები, მყინვარი, ღვარცოფი, აკუსტიკური ტალღები, ვისკოპლასტიკური.

К вопросу моделирования динамичекой картины распространения селевого потока в ущелье Шови вследствие обрушения на леднике Буба

З. Кереселидзе, Н. Варамашвили

Резюме

Ледники всегда представляли потенциальную опасность в регионе Кавказа, где горные каньоны являются достаточно густо населенными. Процессы, связанные с глобальными климатическими изменениями, происходящими повсеместно, крайне обострили проблему превенций населения от гляциальных катастроф. Например, имеется печальный опыт, связанный с обрушением ледника Колка, ставшего причиной возникновения гигантской по объему ледовой сели в 2002 году. К разряду подобной катастрофы следует отнести сход гляциальной сели с ледника Буба 9/3/2023 г, в результате которого произошла трагедия с многочисленными жертвами на курорте Шови. Определение возможного места и времени развития подобных катастрофических событии (землетрясения, извержения вулканов, масштабные наводнения) имеет весьма низкую степень достоверности и является проблемным, несмотря на современный уровень научных методов наземного и космического мониторинга. В частности, является очевидной необходимость долгосрочного мониторинга и всестороннего диагностирования текущего состояния ледников Кавказа, с учетом каждого нового опыта. Следует отметить скудность информаций, позволяющий судить о процессах, протекавших на леднике Буба за последние десятилетия. Поэтому, вряд ли кто мог представить масштабную виртуальную картину распространения гляциальной сели по ушельям рек Бубисцкали и Джанджахи, адекватную той, какой она оказалась в реальности. В то же время, в случае наличия достаточно полной базы результатов наблюдений и ее корректного анализа, на основе принципа гидродинамического подобия, существует возможность теоретического моделирования вероятных параметров наводнения или гляциальной сели в любом горном ущелье. Например, в случае Кавказского региона можно воспользоваться некоторыми результатами, полученными при помощи численного моделирования ледников Джанкуат и Колка. В частности, эти модели являются достаточно полезными не только определения вероятных причин, а также ретроспективного анализа, последствий разрушения на леднике Буба. В первую очередь. Это касается процесса распространения гидродинамических волн в неоднородном селевом потоке. Для этой цели также важными являются записи сейсмической аппаратуры, которые содержат информацию о спектре частот акустических волн, генерированных процессом разрушения на леднике Буба. В ущельях рек Бубисцкали и Чанчахи могли существовать гидродинамические волны различного типа. В характерном диапазоне величин числа подобия Фруда наиболее вероятными следует считать генерацию бегущих катящихся волн, высота которых могла достигать нескольких метров. Появление уединенных волн (солитонов), а также т.н. гравитационных волн, было маловероятным, однако нельзя исключить возможность их генерации в тех местах, для которых локальные условия были подходящими. На нижнем, наиболее широком участке ущелья Шови, в зоне т.н. коттеджей, движение селевой массы было подобным движению ледового селя в ущелье реки Геналдон после обрушения на леднике Колка в 2002 г. Несмотря на огромную разницу первоначальных объемов селей, сошедших с ледников Буба и Колки, выносы вязкопластической массы, на последних участках ее распространения, оказались соизмеримы с учетом пространственных масштабов и амплитуды волн в обоих случаях уменьшилась до высот 1-3 метра.

Ключевые слова: природные катастрофы, ледник, селевые потоки, акустические волны, вязкопластика.