DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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灾害、风险、预测、防治

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Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Forecasting of debris flow processes and control with innovative construction along the Military Georgian Road

G.V. Gavardashvili[1,2]

[1]Georgia National Academy of Sciences, Tbilisi, Georgia

[2]Tsotne Mirtskhulava Water Management Institute of Georgian Technical University, Tbilisi, Georgia, givi_gava@yahoo.com

Abstract. The paper presents the results of theoretical, laboratory and scientific field studies for the purpose of efficient flood protection of the Georgian Military Road.
The erosion coefficients of mountain slopes of erosion-debris flow active right tributaries of Tetri Aragvi catchment have been calculated taking into account the degree of soil and ground surface damage and the class of erosion, as well as the values of turbulent debris flow peak discharge have been determined taking into account the corresponding provision coefficient.
In order to control debris flows in the gorge of the Mleta River, the right tributary of the Tetri Aragvi River, a design of an innovative flood control structure has been presented, with its novelty priority certified by the patent certificate of Georgia No. P2020 7068 B.
After determination of the main hydrological and hydraulic parameters of the Mleta River gorge and hydraulic laboratory large-scale modeling of the flood control dam, a scientific methodology was developed, according to which the structure was designed in the channel of the Mleta River gorge.
From August to November of 2022, the structure was constructed in the bed of the Mleta River gorge, and from April to May of 2023, the structure effectively discharged its function by retaining the debris flow mass in the headrace of the bed of the Mleta River gorge and protected the St. George Church dated by 1879 from destruction.

Key words: *Georgian Military Road, debris flow, debris flow control structure*

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Прогнозирование и контроль селевых процессов с помощью инновационного строительства на Военно-Грузинской дороге

Г.В. Гавардашвили[1,2]

[1]Национальная академия наук Грузии, Тбилиси, Грузия, o.natishvili@gtu.ge

[2]Институт водного хозяйства им. Ц. Мирцхулава Грузинского технического университета, Тбилиси, Грузия

Аннотация. В статье представлены результаты теоретических, лабораторных и научно-полевых исследований с целью эффективной защиты от наводнений Военно-Грузинской дороги.
Рассчитаны коэффициенты эрозии горных склонов эрозионно-селевых активных правых притоков водосбора Тетри-Арагви с учетом степени повреждения почвы и поверхности земли и класса эрозии, а также определены значения пиковых расходов турбулентных селей с учетом соответствующего коэффициента обеспеченности.
Для борьбы с селевыми потоками в ущелье реки Млета, правого притока реки Тетри-Арагви, представлен проект инновационного противопаводкового сооружения, приоритет новизны которого подтвержден патентным свидетельством Грузии № P2020 7068 B.

После определения основных гидрологических и гидравлических параметров ущелья реки Млета и гидравлического лабораторного масштабного моделирования противопаводковой дамбы была разработана научная методология, согласно которой было спроектировано сооружение в русле ущелья реки Млета.
С августа по ноябрь 2022 г. сооружение было построено в русле ущелья реки Млета, а с апреля по май 2023 г. оно эффективно выполнило свою функцию, задержав селевые массы в верховьях русла ущелья реки и защитив от разрушения Георгиевскую церковь 1879 г.

Ключевые слова: *Военно-Грузинская дорога, сель, противоселевые сооружения*

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Introduction

The original route of the Georgian Military Road envisioned a connection between Tbilisi and Vladikavkaz post offices, passing through the post offices along the road.

The lower reaches of the Aragvi River in the area of the Georgian Military Road is low- and middle-mountainous. From Zemo Mleta village there starts high-mountainous relief with mountain-forest, subalpine, alpine, subnival and nival landscape zones changing to mid-mountainous terrain with broad-leaved forests and meadows from Zemo Larsi village [*Chernomorets, 2005*]. The famous Narzani mineral springs are found in the River Bidari valley. Fig. 1 presents a map of the Georgian Military Road compiled in 1913.

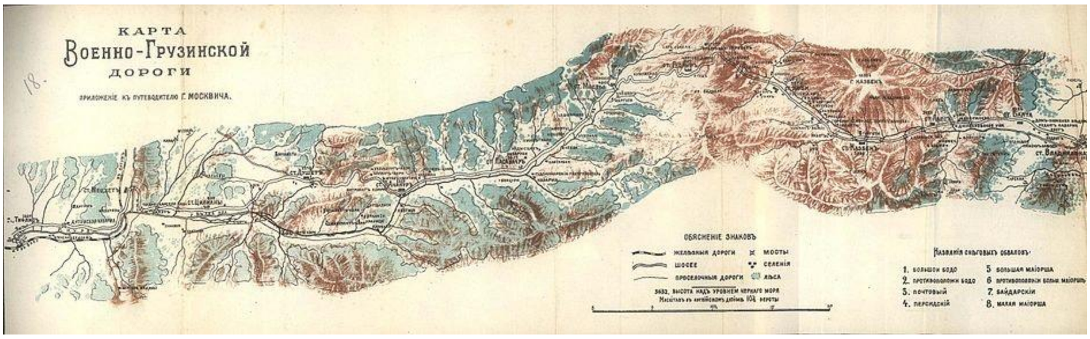

Fig. 1. Map of the Georgian Military Road, 1913

Examples of the recent history of debris flows in the Georgia Military Road corridor and adjacent areas prove that due to frequent debris flows, the potential for decentralization of critical infrastructure in the areas adjacent to their transit corridor has increased significantly causing adverse environmental and, consequently, socio-economic problems.

Since it is impossible to accurately predict the failure of regulating bed structures on the Georgian Military Road due to the diversity of debris flows and their occurrence in different periods, today we have an option of a universal set of measures the utilization of which would significantly reduce the negative impact of natural disasters [*Lin et al., 2009*].

The above is in itself linked to the need for various innovative methods and technologies based on scientific research. In general, most debris flow control structures are a system of complex structural elements, due to which they fulfill such functions as debris flow containment, debris flow transit, debris flow regulation and bank protection from debris flow [*Armanini, Larcher, Odorizzi, 2011*].

Taking into account all the foregoing, the protection of the Georgian Military Road against natural disasters: debris flows, erosion and landslide processes, floods, snow avalanches, etc. has great practical importance as it is the shortest transit highway between Russia and the republics of the South Caucasus (Georgia, Azerbaijan and Armenia)

Forecasting erosion and debris flow processes in the Georgian Military Road corridor

Assessment of erosion processes of mountain slopes is of particular importance to determine the ecological processes on erosion-debris flow mountain rivers in the catchment area of the Mtkvari River [*Gavardashvili, 2011*].

Taking into account the Climate Change, the following natural processes were observed by us: e.g. geographically, there are 4 active river catchment basins fixed in the Aragvi catchment basin, the left tributary of the Mtkvari River: Tetri (Mtiuleti) Aragvi, Black (Gudamakari) Aragvi, Pshavis Aragvi and Khevsuretis Aragvi [*Guide for adaptation to the climate change, 2016*]. Of them, the catchment basin of the Tetri Aragvi is distinguished with the most active erosive-debris flow processes and the catchment basin of the Mletis Khevi River is most active, forming debris flows with peak discharges once in every 4 years in the past. As for now, there are debris flow passages with peak discharges registered in it once in every 4 years. This area is a representative of different catchment basins of the Mtkvari River of an erosive-debris flow type [*Gavardashvili, 2022, Natural Hazards in Georgia, 2011*].

As a result of field scientific research conducted by us in the Mtkvari River basin, an equation by which the erosion coefficient of a mountain slope in relation to time is calculated [*Gavardashvili, 2022*]:

$$E = [0.58 + 1.40(F_1/F_0) \cdot (t/T)^{0.21}], \tag{1}$$

where: F_1 is the eroded area in the river catch basin (km^2); F_0 is the total area of the river catch basin (km^2); t is the time interval (year); T is the period of total observation

The value of the peak discharge of debris flow of various provisions is calculated by the following formula [*Gavardashvili, 2022*]:

$$Q_{\max} = A(34 + 400i)F_0^{0.61}\text{m}^3\text{/s}, \tag{2}$$

where: A is the debris flow discharge coefficient, whose variation, by considering provision coefficient ratio P (%) is given in Table 1.

Table 1. Relationship between the debris flow discharges coefficient (A) and provision coefficient, P (%)

Provision coefficient P (%)	0.1	1	3	5	10	25
Debris flow discharge coefficient A	2.4	1.0	0.7	0.6	0.5	0.3

Using relations (1) and (2), the values of the erosion coefficient of active tributaries of erosion-debris flow type in the catchment area of the Tetri Aragvi River and the peak discharge of debris flows of 1% provision were calculated, the numerical values of which are given in Table 2.

Structural description of the elastic debris flow-regulating barrage

Natural anomalies, debris flows in particular, are of a particular importance for designing efficient engineering solutions. Debris flow is a terrible phenomenon of the natural calamities and the regulation measures are associated with their genesis and dynamics.

The rigidity and structural solutions of the barrages used in practice fail to transform the flow on the pressure surface or redistribute the dynamic force.

By considering the above-mentioned, an innovative structure of the elastic debris flow-regulating barrage was designed by the joint efforts of the scientific workers of Ts.

Mirtskhulava Water Management Institute of Georgian Technical University and NGO Ecocenter for Environmental Protection, with its Know-How approved by the Patent License of Georgia [*Gavardashvili et al.*, *2019*].

Table 2. Basic data of debris flow-type tributaries in the catchment basin of the Tetri Aragvi River

No.	River	Catchment area F_0, km^2	Bed slope *i*	Erosion coefficient *E*	Erosion class, according to Prof. R. Morgan scale	Degree of damage, t/ha per year	1% max. debris flow discharge, m^3/s
1	Mletis Khevi	1,28	0,260	1,13	Fourth	10–50	131,0
2	Tsiskvilt Khevi	1,50	0,251	0,89	Third	5–10	87,0
3	Kotoras Khevi	0,62	0,290	1,62	Fifth	50–100	98,0
4	Arakhvetis Khevi	1,45	0,216	0,96	Third	5–10	109,0
5	Qimbariani Khevi	0,60	0,220	0,95	Third	5–10	70,0
6	Nagvarevis Khevi	6,50	0,247	1,00	Fourth	10–50	387,0
7	Chokhelt Khevi	6,96	0,290	0,95	Third	5–10	550,0
8	Zemo Amirt Khevi	1,87	0,264	0,92	Third	5–10	200,0
9	Kvemo Amirt Khevi	0,96	0,310	0,73	Second	2–5	140,0
10	Chadistsikhis Khevi	1,30	0,360	1,17	Fourth	10–50	141,0

The sections of the elastic debris flow-regulating barrage are made of triangular prisms of the same height inserted in the bed, tight packed with their side faces. The base heights of the prisms increase along the debris flow current and form a springboard. The structure's top is directed against the current and there are elastic ropes stretched between the edges above the prisms connected with one another with the lateral ropes forming pockets between the edges to receive the debris flow mass. This type of barrage allows receiving debris flow smoothly (Fig. 2).

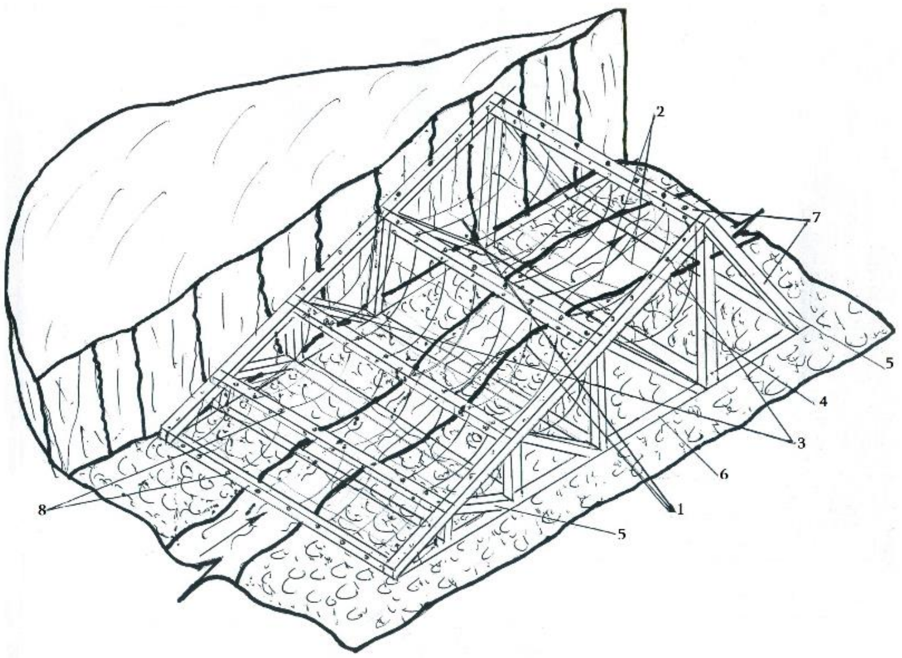

Fig. 2. Debris flow control elastic barrage

Unlike barbed wire structures, the innovation of the elastic barrier is presented in a constructive solution. It is made of triangular prisms connected by stems of equal height, which are placed in the bed of the debris flow.

The construction is presented in the form of sections. The pressure surface hanging in it is made of ropes and has a curved shape of an elastic mesh. According to the current direction, the height of the prism stems increases and it is represented as a springboard.

The size and length of the cross-section of the structure depends on the strength and structure of the debris flow. The structure is shown in Fig. 1. The arrangement of the constituent elements given in № 1 is as follows: Triangular prisms (3), Triangular prism bases (4), Prism base heights (5), Prism grips (6), Attachment holes (7) or nets may be arranged in these places. Hanging hooks – longitudinal (1) and transverse (2) elastic ropes.

Laboratory modeling of the elastic debris flow-regulating barrage

For the sake of laboratory modeling of the elastic debris flow-regulating barrage, a hydraulic duct was selected at the hydraulic laboratory of Ts. Mirtskhulava Water Management Institute of Georgian Technical University with sizes: width: 0,36 m, height: 0,29 m, length: 12 m, duct gradient alteration: 0,01–0,06, [*Natishvili, Gavardashvili, 2019; Natishvili, Gavardashvili, 2015*].

As for the model of the elastic debris flow-regulating barrage, by considering the parameters of the hydraulic duct, they are as follows: length of the model barrage: 0.60 m, width: 0.36 m, maximum height of the barrage: 0.15 m, number of steps: 3, step base length: 0.20 m, sizes of the open-end network to be installed in the elastic pockets: 5–7 mm with the first option, 4–5 mm with the second option and 2–3 mm with the third option.

By considering the above-mentioned, a laboratory model of the elastic debris flow-regulating barrage was made with its general view given in Figs. 3 and 4. Fig. 5 shows the laboratory model of the structure in the hydraulic duct.

Experiments on the laboratory model of the elastic debris flow-regulating barrage will be done during the motion of the turbulent debris flow through the debris flow duct by observing the following parameters of modeling similarity [*Gavardashvili, 2011, Natishvili et al., 2016*.]: the laboratory experiments will be done for debris flow motion through the hydraulic duct for dynamic similarity ($Fr = ident$), geometrical similarity (bed gradient: $i = ident$), drift motion ($V_{water} / V_{sediments} = ident$), bed resistance coefficient (Chezy coefficient $C = ident$).

Fig. 3. Laboratory model of the elastic debris flow-regulating barrage

Fig. 4. Model of the elastic debris flow-regulating barrage in the hydraulic duct


Fig. 5. Debris flow regulation elastic barrage during the laboratory tests

Construction design and building

The dynamic impact of the flow on the innovative debris flow control structure is calculated with the following dependence:

$$P_1 = \frac{\gamma \omega V^2}{g} \; \sin\psi \, f(m) \text{ N/m}^2, \tag{3}$$

where γ is the volume weight of the debris flow (N/m3); ω is the area of the effective cross-section (m2); V is the flow velocity (m/s); φ – angle of internal friction; ψ is the gradient angle to the structure base (0); ψ is the internal friction coefficient and equals to:

$$\psi = tg^2\left(45^0 - \frac{\varphi}{2}\right), \tag{4}$$

where h_0 is the equivalent depth of cohesiveness (m); H is the depth of current (m); a is the coefficient $(1 - h_0)\psi$. $f(m)$ is the coefficient and depends on the rheological properties of the debris flow:

$$f(m) = \frac{16 - \left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2}{\left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2} \tag{5}$$

The innovative debris flow control structure is a bearing frame of a metal structure with steel details. Considering the technical characteristics of the structure, a point foundation was selected for it, and waterproof concrete W8, Class B25, made with Portland cement was used for the foundations. The structure, which is in contact with the ground and the river filtration current, is waterproofed with up-to-date insulating materials. The bearing structure of the anti-debris flow control barrage, as a single spatial system, is designed for permanent and temporary dynamic loads. The calculation was performed with software „Lira Sapr 2019" (License Number 1/7165).

The detail project is developed in accordance with normative documents effective in the territory of Georgia: Concrete and reinforced concrete structures (03.01.-09); Building Foundations (DN 02.01-08); Building climatology (DN 01.05-08); SNiP 2.01.07.85 Loads and Impacts; SNiP II-23-81: Steel structures; SNiP 2.03.11-85: Protection of structures against corrosion. The calculation results are given in Figs. 6 and 7.

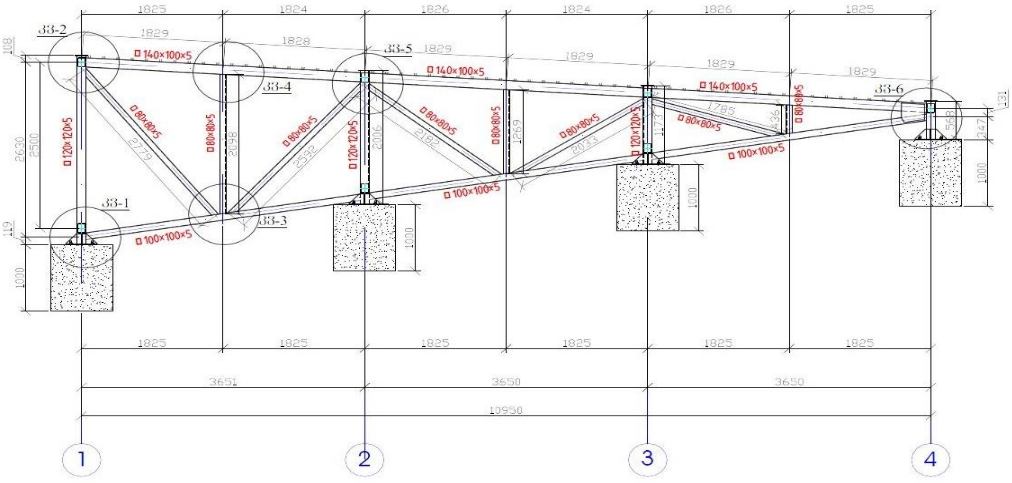

Fig. 6. Longitudinal section of the debris flow regulation

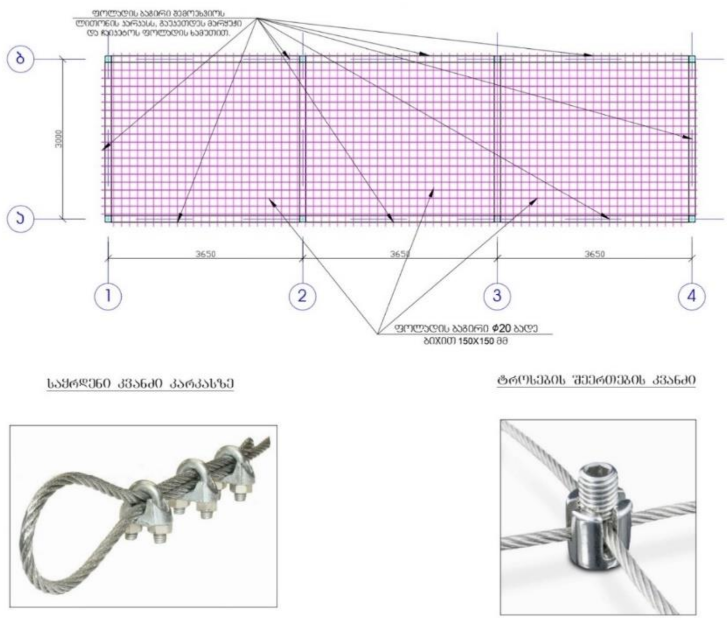

Fig. 7. Construction view in plan and nodes

The volume of solid fractions accumulated in the headrace of the debris flow regulation elastic barrage is calculated as a function of time according to the following dependence:

$$W_t/W_T = \left[0{,}90 + 0{,}10\left(\bar{d}/\Delta\right)^{1{,}51}\right]\ (t/T)^{2{,}34}, \qquad (6)$$

where W_t is the volume of solid fractions retained by the structure at a given moment of time (m^3), W_T is the total volume of fractions retained at the headrace of the structure (m^3); ($W_T = q_{sd}.B.T$), (m^3), B – width of the river bed (m); Δ is the permeability factor of the structure, t is the elementary time period (min), T is the time of complete filling of the structure with sediments in its headrace (min). There are metal cables suspended from the steps of the structure to make the barrage open-end by providing square holes (0.15 x 0.15 (m^2). According to the design data, the structure carries water mass with solid fractions less than 0,15 m to the tailrace, while the solid fractions greater than 0,15 m remain in the headrace of the structure.

Based on the conducted theoretical, laboratory and field studies, in order to regulate the solid fractions in the Mleta riverbed at 1600 m asl, in October of 2022 an experimental model of the debris flow regulation elastic barrage was built by us, and the debris flow formed in May of 2023 filled the first step of the structure with solid fractions. The general view is given in Fig. 8.

a b

Fig. 8. General view of the debris flow regulation elastic barrage regulating solid fractions: structure before (a) and after (b) the debris flow passage

The expedition and field scientific studies and their analysis in the headrace of the elastic debris flow control barrage have yielded the following results: the structure contained the debris flow mass together with solid fractions in the headrace along a 30-m section, the volume of which is 112 m^3, and the height of the debris flow mass at the first step of the structure was 1.0 m (Fig. 9). The weight of the largest stone transported by the debris flow and retained in the headrace of the structure was 1.19 tons. The riverbed slope was 15° in the headrace of the structure before the debris flow passage in the riverbed, and the slope of the longitudinal profile of the surface of the debris flow mass accumulated in the headrace of the structure after the debris flow passage decreased by 4° to 11°.

Fig. 9. General view of the debris flow regulation elastic barrage

Conclusions

Based on the theoretical, laboratory and field scientific studies conducted under the financial support of the grant project of the Shota Rustaveli National Science Foundation of Georgia "Debris flow regulation elastic Barrage" in 2020–2023, the following basic conclusions can be made:

– an innovative design of an debris flow regulation elastic barrage, the priority of which is confirmed by a Georgian patent, has been developed to stabilize mountain riverbeds;
– in order to effectively regulate sediments in riverbeds, laboratory experiments were conducted on the model of the debris flow regulation elastic barrage, when two-phase flows loaded with sediment of different diameters were flowing in the hydraulic channel;
– based on the conducted experiments, the methodology as well as hydrological and hydraulic calculations of turbulent debris flows were worked out and used to develop a working design of the debris flow regulation elastic barrage;
– by using the working design, an experimental structure of the debris flow regulation elastic barrage was installed in the Mleta riverbed in September and October of 2022;
– in May 2023, turbulent debris flow was formed in the Mleta River gorge bed, and the flow affected the experimental model of the debris flow regulation elastic barrage with a dynamic impact force. The structure did not collapse and is operable to date proving its reliability.

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