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Private solutions to design an innovative engineering structure for efficient debris flow control

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Abstract: There are hardly any sections in a debris flow channel, where flow movement, except for exceptions, would have a constant hydraulic regime and typical parameters. Therefore, in order to select regulating measures, the urgent means of assessment of the flow regime to totally cover its anomaly is needed. The solution of this question is associated with the full compatibility of laws with soil mechanics and hydraulics. Recently, the engineering problems related to debris flow, based on various considerations, have been realized by integrating the obtained differential equations. Especially important are the possibilities of a debris flow moving regime in prismatic beds described by the system of differential equations of various modifications. If rheological properties are neglected in the above equations, they are completely transformed into differential equations of non-uniform motion of Newtonian fluids. By considering the above-mentioned, the paper gives the calculation methods and practical example of designing an innovative debris flow control barrage, which was realized in the bed of the Mletis Khevi river gorge.

Keywords: prismatic channel, debris flow, elastic barrage, structure, designing

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Introduction

There are hardly any sections of a debris flow channel, where flow movement, except for exceptional cases, has an invariable hydraulic regime and typical parameters. Consequently, in order to select debris flow control measures, the operational

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means of assessing the flow regime, totally dealing with its abnormality and providing full compliance with the laws of mechanics and hydraulics of soils, etc., must be in place (Gagoshidze, 1970).

Today, the engineering problems of debris flows are realized by integrating the available differential equations, based on various considerations. Particularly noteworthy are the capabilities of the modes of debris flows moving through a prismatic bed described by the differential equations of various modifications. If rheological characteristics in the equations are neglected, the equations are completely transformed into differential equations describing the nonuniform motion of Newtonian fluids (Natishvili et al., 1995).

When the bed is prismatic and is described by the corresponding differential equation of flow motion, its particular cases with different assumptions of kinematic coefficient are used. When this coefficient equals to 1, the flow is in a critical state; when this value is less than 1, the flow moves smoothly, and when it is more than 1, the flow motion is turbulent. For all types of differential equations, when the denominator or numerator is not 0 and the pressure derivative value is negative or positive, the depth of flow changes rapidly and continuously and the free surface coordinate decreases in the direction of motion. When considering the problems of debris flow motion, following the flow abnormality, additional special conditions may be used, requiring additional analysis and consideration of classification features (Danelia & Kukhalashvili, 2000).

In case of an irregular steady motion, the depth, effective cross-section, and average velocity of the flow through the channel change in the direction of motion. The flow depths overcome the free surface of the encountered resistance and approach the normal width, i.e., inequality is redistributed all along. Therefore, when evaluating the degree of inequality in any effective cross-section, different criteria must be considered. One such criterion is the kinematic coefficient. Based on the history of the study of the given phenomenon, the dynamics of debris flows is the determinant of the impact on flow on the encountered resistance and the combination of regulation types. It can be used as a methodology for their evaluation and calculation. Based on the above, thorough representation of the debris flow dynamics will allow to accurately solve the problems of their interaction with a structure (Kukhalashvili et al., 2015; Natishvili & Tevzadze, 2011).

1. Private cases of hydraulic calculation of debris flows and research methods

The debris flow differential equation for any duct bed with a non-prismatic shape and rectangular cross-section is as follows (Gavardashvili, 2022):

$$\frac{dh}{dl}=\frac{1}{A}\frac{i-\dfrac{Q\alpha}{g\omega h^3 f(\beta)}-\dfrac{\alpha Qq}{A^2\omega^2 g}}{1-\dfrac{\alpha Q^2}{g}\dfrac{B^3}{\omega^3 A^3}} \tag{1}$$

When the motion through the duct is considered with constant discharge, i.e. $q = \frac{dQ}{dl} = const$

$$\frac{dh}{dl} = \frac{1}{A} \frac{i - \frac{Q\alpha}{g\omega h^2 f(\beta)}}{1 - \frac{\alpha Q^2}{g} \frac{B}{\omega^3 A^3}} \tag{2}$$

where i is the longitudinal gradient of the debris flow bed; A is the coefficient considering the rheological properties of the debris flow mass: $A = \left(1 - \frac{h_0}{h}\right)h$; $f(\beta)$ is the velocity correction coefficient:

$$\left(f(\beta) = \frac{h_0}{h}\left[\left(\left(\frac{h_0}{h}\right)^2 - 1\right) + \frac{1}{3}\left(1 - \left(\frac{h_0}{h}\right)^3\right)\right]\right);$$

Q is the debris flow discharge [m^3/s]; h and B are the depth and width of a debris flow, respectively [m]; ω is the effective cross-section area [m].

By integrating equation (2), a free debris flow surface can be predicted in the direction of motion and a longitudinal profile can be identified (Kruashvili, 2014).

Based on the rheological model, debris flow discharge equals to:

$$Q = \frac{Bih^3 f(\beta)}{\alpha} \text{ [m}^3\text{/s]} \tag{3}$$

Debris flow discharge, expressed by the coefficient of module K, is as follows:

$$Q = K\sqrt{i} \tag{4}$$

By considering equation (4), dependence (2) will be as follows:

$$\frac{dh}{dl} = \frac{1}{A} \frac{i - \frac{K_0}{K}}{1 - y\left(\frac{K_0}{K}\right)} \tag{5}$$

y in equation (5) denotes:

$$y = \frac{QBih^2 f(\beta)}{\omega^2 \alpha A^3} \tag{6}$$

If expressing the debris flow modules with regular and any type of motion by K_0 and K, when the rheological properties do not change, we will gain:

$$\frac{K_0}{K} = \frac{Q_0}{Q} = \left(\frac{h_0}{h}\right)^3 \tag{7}$$

Generally, ratio K_0/K is a composite function and is the function of rheological properties of a debris flow. To integrate equation (5), we can use exponential relationships to describe the relationship between the moduli.

If multiplying the denominator and numerator of the right-hand side of equation (5) by K_0/K, we will gain:

$$\frac{dh}{dl}=\frac{1}{A}\frac{K/K_0-1}{K/K_0-\overline{y}} \tag{8}$$

If introducing notations:

$$\frac{h}{h_0}=\eta,\ \eta=\frac{K}{K_0}=\left(\frac{h}{h_0}\right)^x \text{ and } \eta^x=\left(\frac{h}{h_0}\right)^3,\text{ then } \left.\begin{aligned}\eta_1&=\frac{K_1}{K_0}\\ \eta_2&=\frac{K_2}{K_0}\end{aligned}\right\} \tag{9}$$

As per the notation:

$$d\eta=h_0\,dh \tag{10}$$

By inserting value of equation (10) in equation (8), we will gain:

$$\frac{idl}{Ah_0}=\frac{\eta-\overline{y}}{\eta-1}d\eta \tag{11}$$

By simplifying equation (11), we will gain:

$$\frac{idl}{Ah_0}=\int_{\eta_1}^{\eta_2}d\eta-(1-y)\int_{\eta_1}^{\eta_2}\frac{d\eta}{1-\eta^x} \tag{12}$$

As per equation (10), $\dfrac{dh}{d\eta}=\dfrac{h_2-h_1}{\eta_2-\eta}=a=const=h_0$

By integrating equation (12), we will obtain the following value on section 2-2 distanced by l from section 1-1:

$$\frac{i}{h_0}(l_2-l_1)=\eta_2-\eta_1+\int_{\eta_1}^{\eta_2}\frac{1-\overline{y}}{1-\eta^x}d\eta \tag{13}$$

When special calculations show that value $\overline{y}$ varies within very small limits, by considering important circumstance and taking it out the integration sign when $l_2-l_1=l$, we will have:

$$\frac{il}{h_0}=\eta_2-\eta_1-(1-\overline{y})\int_{\eta_1}^{\eta_2}\frac{d\eta}{1-\eta^x} \tag{14}$$

When the hydraulic exponent of a given duct bed is unchanged, $x = const$ subintegral function of equation (14) can be viewed as a function of η and when the free constant term equals C_0:

$$\int \frac{d\eta}{1-\eta^x} = \varphi(\eta) + C_0 \tag{15}$$

By applying (15) in (14), when $y = \frac{1}{2}(y_1 + y_2)$, $h = \frac{h_1 + h_2}{\alpha}$,

$$\frac{il}{Ah_0} = \eta_2 - \eta_1 - (1-\bar{y})\left[\varphi(\eta_2) - \varphi(\eta_1)\right] \tag{16}$$

Equation (16) is the equation of a free surface of an irregular debris flow motion. It can be used to change the depth along the flow direction. Equation (16) can also be used to select the location of structures in the channel and to predict the potential impact of an expected debris flow (Kukhalashvili et al., 2018).

To calculate value $\varphi(\eta)$ in equation (16) when considering the debris flow problem, the integrand function is divided into rows at different values of η and x, whose value is calculated using the following relationship:

$$x = 3\frac{\log h_0/h}{\log \eta} \tag{17}$$

The obtained equation allows the solving of the practical problems of debris flow regulation, in particular, when the flood depth h_1 or h_2 is given, the second debris flow depth can be found for a section at distance l or vice versa, i.e., when a free surface profile is plotted along the entire length of the duct.

This cited problem applies to the motion of debris flow in case of a positive gradient. As for 0 or negative gradients, such problems are not considered due to the impossibility of their motion.

2. Calculation of the innovative engineering structure to control debris flows

One of the guarantees of the sustainable and stable ecological balance in environmental protection is creating an effective structure, i.e., a type of a building with possible minimal rigidity to the impact force of the flow, with the shape and construction dimensions of its structural elements calculated using concrete methodology. The impact of natural hazards on a structure depends on the degree of their abnormality (Kruashvili et al., 2017).

In addition to the foregoing, when innovative structures are installed in ducts with various types of flows, the structural elements chosen may jeopardize the ability to use the new methodology.

Based on the methodical recommendations, a method to calculate the debris flow regulation barrage is proposed, the novelty priority of which is protected by a patent certificate (Fig. 1).

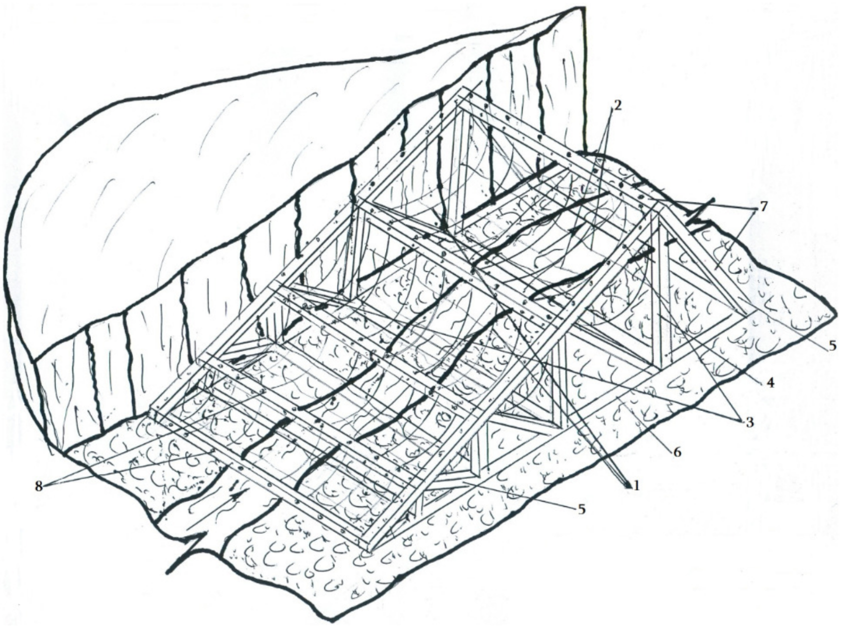

Fig. 1. General view of the innovative anti-mudflow structure (*own research*)

Unlike the existing types, the novelty of the structure is its construction. It is made of triangular prisms of the same height, connected to one another with bases, and installed in the bed of the debris flow duct.

The structural elements of the structure are selected by using completely novel approaches and calculation methods (Esposito et al., 2005). The dynamic impact of the flow on the innovative debris flow control structure is calculated with the following dependence (Natishvili et al., 2016):

$$P_1 = \frac{\gamma \omega V^2}{g} \sin \alpha \, f(m) \ \ [\text{N/m}^2] \tag{18}$$

where γ is the volume weight of the debris flow [N/m^3]; ω is the area of the effective cross-section [m^2]; V is the flow velocity [m/s]; α is the gradient angle to the structure base [°]; $f(m)$ is the coefficient and depends on the rheological properties of the debris flow:

$$f(m) = \frac{16 - \left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2}{\left(\alpha^3 + 4\alpha\sqrt{\alpha}\right)\left(2 + \sqrt{\alpha}\right)^2} \tag{19}$$

α – is the coefficient $\alpha = (1 - h_0/\mathrm{H})\,\psi$, where h_0 is the equivalent depth of cohesiveness [m]; H is the depth of current [m]; ψ is the internal friction coefficient and equals to:

$$\psi = \mathrm{tg}^2\left(45^\circ - \frac{\varphi}{2}\right) \tag{20}$$

where φ is the angle of internal friction.

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, 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-mudflow 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 Figure 2.

Figure 3 shows the plan view and sections of the calculated anti-mudflow control structure, and the installation plan and sections of the steel ropes connections and support nodes on the pressure surface of the structure are given in Figures 4 and 5.

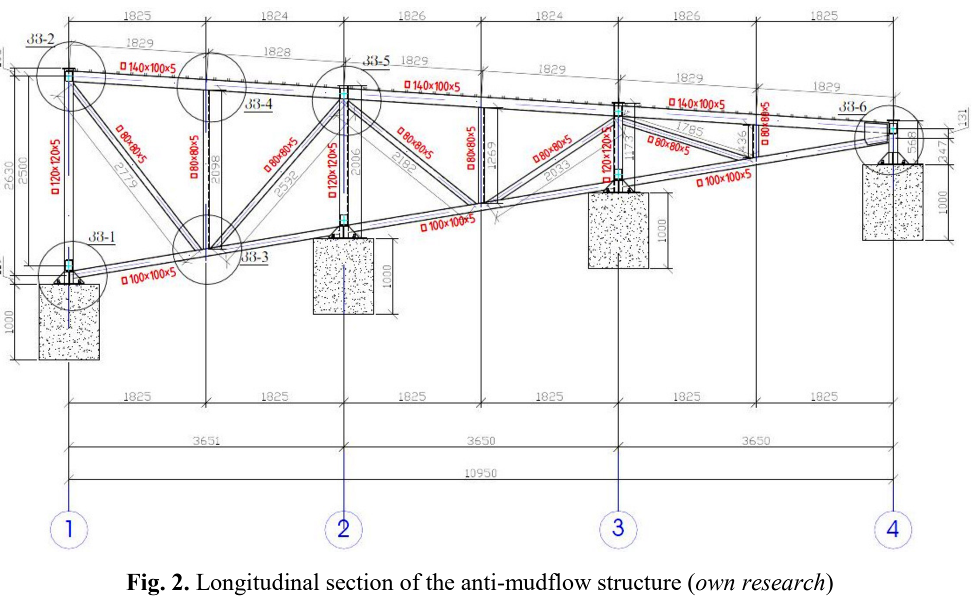

Fig. 2. Longitudinal section of the anti-mudflow structure (*own research*)

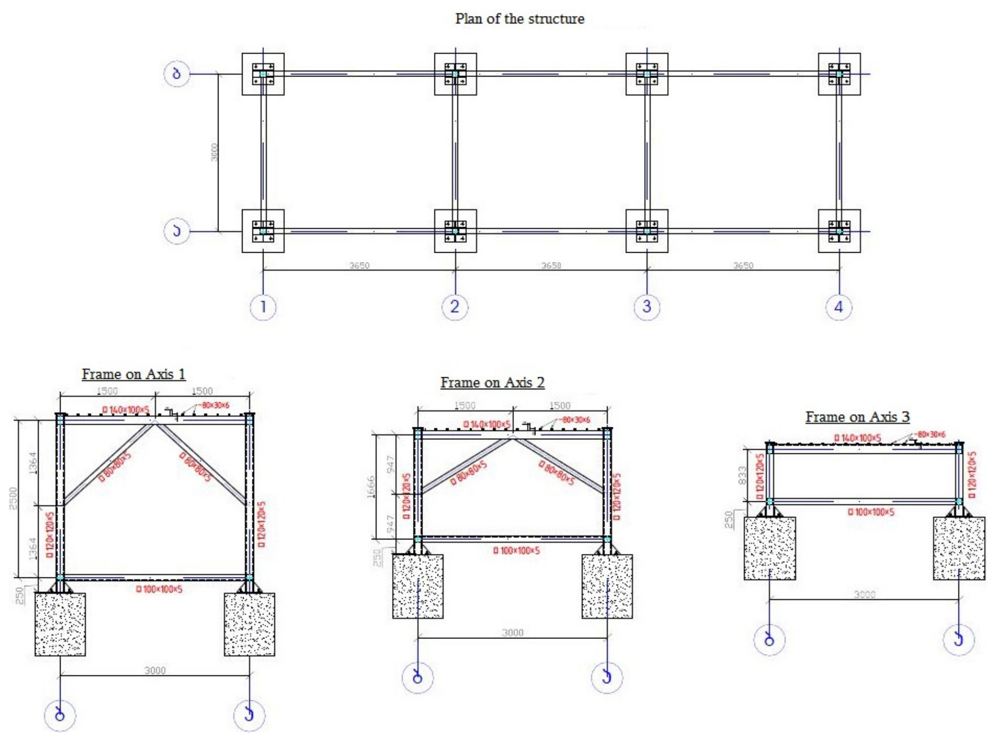

Fig. 3. Plan and sections of the elastic anti-mudflow barrage (*own research*)

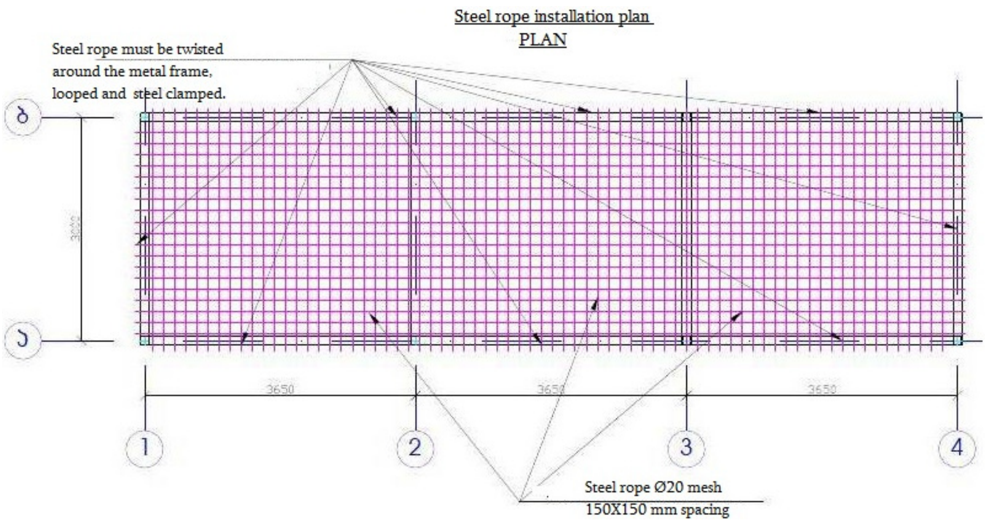

Fig. 4. Plan of the ropes on the pressure surface of the structure (*own research*)

Thus, to effectively regulate the debris flows, private cases of calculation of the debris flow dynamics are given by considering the rheological properties of the debris flows and innovative methodology to calculate the design of the debris flow control barrage.

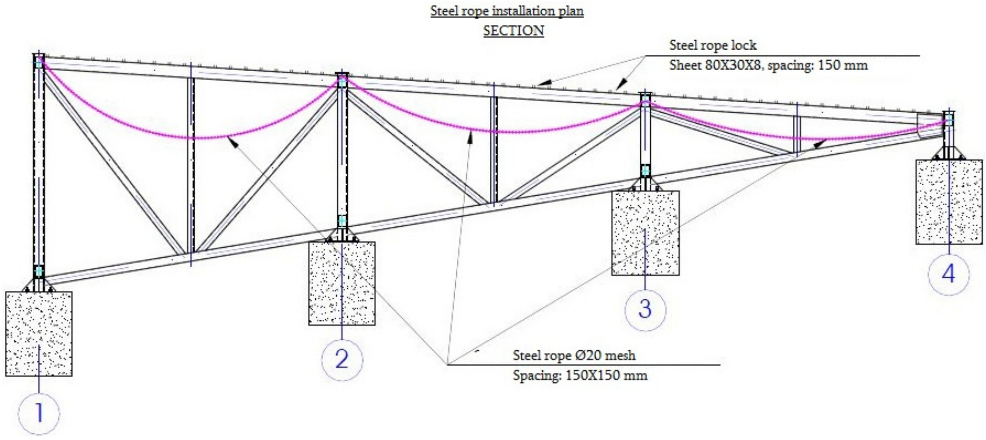

Fig. 5. Plan of the rope installation on the pressure surface of the anti-mudflow structure (*own research*)

3. Results and discussion

Based on the conducted theoretical and field studies, a system of differential equations was solved, and in the case of non-prismaticity of the river bed, calculation relationships were obtained, which are used to calculate the main hydrological and hydraulic parameters of the link gully. The attention in these attitudes is focused on the mainly rheological characteristics of the Debris flow.

Using the obtained results, the methodology has been worked out and a debris flow regulatory elastic barrage has been designed using the "Lira Sapr 2019" program in the construction shed (Fig. 1).

In the process of the theoretical studies, the inclusion of topographic and hydrological parameters of the bed in the equations in the process of designing the construction appeared, which, together with the rheological parameters of the debris flow, required a number of assumptions. Exactly this process became a discussion that arose between the authors of the article and the main donors of the scientific grant.

What is more, the preference of the types of flow generated in the bed of the Mleti river gorge (Dusheti municipality, Georgia), whether turbulent or structural, which determines the dynamic nature of the flow, was discussed. Turbulent or link nature, which determines the dynamic nature of the debris flow, occurs in the first case with the movement of Newtonian flows, and in the second case with Non-Newtonian flows.

Conclusions

The conducted theoretical and field studies are based on the theoretical and field studies accomplished under a grant project of the Shota Rustaveli National Science Foundation of Georgia, as well as on the results of large-scale laboratory modeling conducted at the Hydro-Technical Laboratory of the Tsotne Mirtskhulava Water Management Institute of the Georgian Technical University in 2019-2022.

Taking into account the theoretical studies, the solution of the differential equation of high-concentration cohesive debris flow movement by considering the shape of the river channel and the rheological properties of the cohesive debris flow are considered.

Based on the obtained results and using the finite-difference plan of the structure calculation (with "Lira Sapr 2019" software), the paper gives the methodology to calculate the innovative elastic debris flow control barrage and a practical example of its design realized by considering the hydrological and hydraulic indices of the Mletis Khevi rivebed.

The paper gives the results of the calculation of the innovative elastic debris flow control barrage, namely, its longitudinal, cross sections and structure plan view, as well as the plan of the metal ropes installation on the pressure surface of the structure.

It is planned to construct the elastic debris flow control barrage in the Mletis Khevi rivebed adjacent to the Georgian Military Road (Dusheti Municipality, Georgia) at 1650-1700 m above the Baltic Sea level.

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