

REVIEW OF MUDFLOW CONTROL BASED ON KNOWN CHANNEL GEOMETRY AND GEOLOGICAL FEATURES IN KAZAKHSTAN

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ABSTRACT: This research addresses the urgent need for improved mudflow protection in high-risk areas. The study aims to develop innovative and effective mudflow protection structures based on mudflow basin classification and dynamics to improve safety and reduce risks in regions exposed to mudflow hazards. Employing methods like analysis, synthesis, comparative analysis, modelling, and engineering methods, the study proposes a solution for mudflow detention in regions where hydraulic structures are impractical. It introduces a scale-based classification system for mudflows, allowing for precise control measures tailored to their dynamic characteristics and volumes. Mathematical modelling provides accurate estimates of mudflow behaviour, accounting for random phenomena. Technical advancements include a newly designed culvert that captures sediment and effectively diverts mudflows. The research also emphasises the importance of environmental considerations to prevent sedimentation and maintain channel cleanliness. The study provides practical value by creating efficient, environmentally sustainable mudflow protection structures, thereby improving disaster prevention, risk reduction, and resource optimization.

Keywords: Sediment, Flood control, Landslide, Geomorphology, Hydrodynamics

1. INTRODUCTION

Research in the field of mudflows is important in the modern world because of climate change, which makes mudflows more likely, and due to risks associated with environmental change and urban development. Technological advances, as well as the possibility of applying new mathematical modelling methods, provide unique tools for more accurate prediction and management of mudflow events. However, existing methods and facilities do not always provide sufficient protection. The problem is also related to the difficulty of predicting and modelling phenomena, such as mudflows, and the need to take into account environmental aspects in the development of protective measures.

Zaginaev, Erokhin, and Omorova argue that the most powerful and dangerous mudflows are formed when highland lakes break out [1]. Mudflows caused by intense rainfall also pose a danger. However, the statistics only include mudflows that pose a threat to economic facilities and the population. Some breakthroughs can alter the debris cone, transfer debris material into the valley, and block the channel, thereby creating favourable conditions for future debris flows. The study did not consider the influence of climatic changes on the frequency and intensity of mudflows. Climate change can significantly affect the intensity of precipitation and snow distribution, which in turn can affect the frequency and extent of mudflow events.

The study conducted by Mirzoeva focusses on the development and application of mathematical models for predicting the stress-strain state of rocks [2]. These models are based on various mechanical approaches that best reflect the specifics of the mining and geological conditions. They also consider the results of instrumental observations of the earth's surface deformation. The equations of motion of a viscous incompressible fluid are used to solve problems related to mudslides and landslides. However, this requires the introduction of additional dependencies linking tangential stresses (τ) to velocity (v). The researcher suggests a widely used Coulomb and Velm formula, believing that this is the most appropriate approach. The study did not consider alternative methods of solving problems related to mudflows, nor did it compare the effectiveness of different models and approaches.

According to Suleyev, Uzbekov, and Sadykova, Kazakhstani seismologists are currently engaged in adapting the procedure for probabilistic hazard assessment to a large amount of available geological, geophysical, and tectonic data in Kazakhstan [3]. The new procedure is being applied within the framework of the National Projects for the development of seismic zoning maps and hazard assessment. The researchers did not address the impact of anthropogenic activities on seismic activity.

Zhilkibayeva, Toktassynov, and Toktassynova believe that mudflow control is best achieved by building barrages, mudflow traps, dams to direct the

flow, and mudslides to protect roads [4]. To allow mudflow to pass through, debris slopes are built as large reinforced concrete trays on supports above the roads. The researchers did not adequately address alternative methods of mudflow control, such as ecological approaches or zoning methods, as well as their environmental impact.

Bexeitov and Abdykalykov argue that Kazakhstan is a leader among other countries in Central Asia and the Commonwealth of Independent States in terms of the scale of mudflow events [5]. In Kazakhstan alone, the direct total material damage could exceed 700 million USD during a mudflow event, omitting human casualties. This study did not consider the potential impact of mudslides on human life and safety. The current study aims to develop effective and innovative debris flow protection structures based on the engineering classification of debris basins and an understanding of debris flow dynamics.

The Research Significance section explains the study's importance in light of the increasing risks posed by climate change and urban development. The Materials and Methods section outlines the key methodologies used during the research. The Results section presents the findings on mudflow dynamics in high-risk areas, along with the classification of mudflows and the effectiveness of different protective measures. The Discussion section explores the implications of these results, comparing them with previous studies and highlighting the practical value of the proposed protective structures. The conclusion section summarizes the main research findings.

2. RESEARCH SIGNIFICANCE

The significance of this study lies in its potential to advance the field of mudflow management amidst increasing climate change and urban development pressures. This study's significance lies in its potential to advance the field of mudflow management amidst increasing climate change and urban development pressures. This study improves the accuracy of mudflow predictions and the effectiveness of protective structures by combining new mathematical modelling methods with engineering classifications of debris basins.

3. MATERIALS AND METHODS

Methods used in the study can be seen in Table 1. Equations of mudflow movement were developed, accounted for hydrodynamic and geological parameters, and the strength characteristics of the slope were determined. The following Eq. (1-12) was used to find the mudflow model.

$$\frac{gu}{gt} + u \frac{gu}{gS} = q \sin \psi - \frac{ku^2}{R} - \frac{L}{2F} \frac{g}{gS} \left(\frac{a_y F^2}{L^2} \right) - f_1 - f_2, \quad (1)$$

where: $F(S, t)$ – cross-sectional area; $L(S)$ – channel

width; $\psi(S)$ – channel slope; $a_y(S, t)$ – projection of the total acceleration of flow particles to the perpendicular to the slope; R – hydraulic radius; S – coordinate along the channel; t – mudflow passage time; $u(S, t)$ – projection of the flow particle velocity to the S-axis; g – acceleration of gravity; k – turbulent friction coefficient; f_1 – Coulomb's force resistance.

Table 1. The key methods

Method	Application
Analysis	Analysis methods were used to examine mudflow hazards around Almaty, studying various geological features like highland lakes, steep slopes, and unstable soils. This involved breaking down complex mudflow formation mechanisms into distinct components to understand their individual impacts.
Synthesis	Synthesis was employed in developing comprehensive anti-mudflow measures by combining multiple protection strategies. This is evident in the integration of preventive measures (like reforestation and terracing) with engineering structures (such as debris dams and channel stabilization systems).
Mathematical modelling	Mathematical modeling was applied to predict debris flow movement, using equations to calculate velocity distributions and flow heights. The model treated mudflow as an incompressible fluid affected by gravity and friction forces, with specific formulas (1-12) describing motion equations and fracture conditions.
Comparative	Comparative analysis was utilized in classifying mudflows into three groups based on their characteristics (flow rates, velocities, volume of outbursts, and debris size). This method helped establish relationships between different mudflow types and appropriate mitigation strategies.
Engineering method	Engineering methods were implemented in designing specific structural solutions, such as the mudflow conduit with its funnel inlet, reinforced bottom, and strategically placed spurs. These designs were developed through practical application of hydraulic principles and structural engineering concepts to create effective mudflow protection systems.

$$\frac{gF}{gt} + \frac{g(uF)}{gS} = qL, \quad (2)$$

where: q – source of the mass.

$$f_1 = \{\mu a(1 + h/L)\}; t_1 = \mu a \rho h < t_*, \quad (3)$$

where: μ – the Coulomb friction coefficient; h – flow height measured along the y-axis; t – tangential stresses.

$$f_1 = \frac{t_*}{\rho h} (1 + 2h/L - t_*/L\mu a \rho); t_1 \geq t_*, \quad (4)$$

where: t_* – the shear strength characteristic of the weakest material involved in friction.

$$f_z = \left\{ -\frac{qu}{F} + a \frac{g\delta}{gS} \right\}, \quad (5)$$

where: δ – the current thickness of the collapsing surface layer of the slope.

$$\xi \rho_0 = (\xi - \vartheta) \rho_1, \quad (6)$$

where: $\xi(S, t)$ – the propagation speed of the fracture front; $\vartheta(S, t)$ – velocity of particles immediately behind the fracture front; ρ_1 – particle density immediately behind the fracture front.

$$\xi \vartheta \rho_0 = \begin{cases} P - P_* \\ 0 \end{cases}. \quad (7)$$

$$\xi = \sqrt{\frac{P - P_*}{\rho_0(1 - \rho_0/\rho_1)}} = \sigma \sqrt{\frac{P - P_*}{\rho_0}}, \quad \sigma = \sqrt{\frac{1}{1 - \rho_0/\rho_1}}, \quad (8)$$

where: σ – a parameter characterising the degree of compaction of the fracture material.

The expression used for pressure:

$$P = \rho(ah + cu^2 \sin \alpha), \quad (9)$$

where: c – empirical constant, $\alpha = \arctg\left(\frac{g\delta}{\delta}\right)$.

Then the following expression is obtained for q :

$$q = \frac{\sigma}{\rho \cos \alpha} \sqrt{(\rho - \rho_*) \rho_0}; \quad \rho \triangleright \rho_*. \quad (10)$$

The solution to formulas 1 and 2 lies in the area between the breakaway line (the tail of the flow) and its front. The model uses the following boundary conditions:

$$F(S_0, t) = 0; \quad u(S_0, t) = 0, \quad (11)$$

at the “tail” end of the stream (S_0) and the front S_f :

$$F(S_f, t) = 0; \quad u(S_f, t) = \bar{u}(S_f, t), \quad (12)$$

where: $\bar{u}(S_f, t)$ – the velocity of the flow front.

In general, the use of a combination of these methods provided a technical solution for improving the performance of mudflow facilities and preventing the negative effects of mudflows.

4. RESULTS

In the Republic of Kazakhstan, the city of Almaty and its environs are primarily considered to be mudflow hazardous areas (Fig. 1). Measures to protect against mudslides were taken primarily around Almaty [1]. When analysing mudflow hazards, it is necessary to address various aspects that require an individual approach to implementing anti-mudflow measures (Table 2). According to research, the most effective measures to combat the formation of

mudflows are the regulation, attenuation, and dispersal of stormwater runoff [1]. This is achieved through reforestation, the development of shrub and grass cover on mountain slopes, terracing, a network of drainage and drainage ditches, and the preservation and development of soil cover. The main measures to protect against glacial targets caused by the breakthrough of moraine-glacial reservoirs include the preventive forced lowering of these reservoirs' levels, the preventive dismantling of unstable moraine accumulations and bridges that could break or collapse during a mudflow period, and the creation of smoke screens that simulate cloud cover over the glacier field.

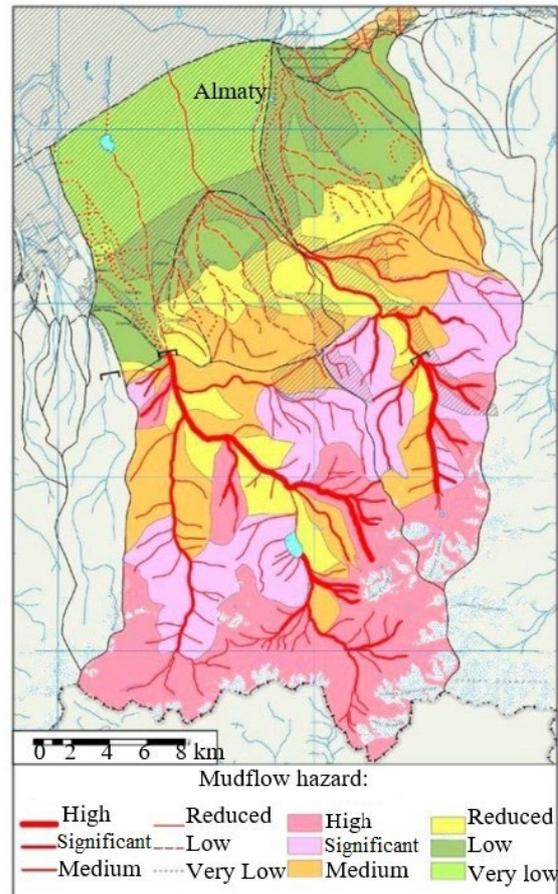


Fig. 1 Mudflow hazard of the city of Almaty and its environs

Mudslides formed during seasonal snowmelt due to intensive meltwater runoff can be prevented by dispersing snowmelt over drainages and areas, which is achieved by blacking out individual snow strips on slopes before the start of intensive spring snowmelt [6]. If mudflows are formed as a result of landslides, sinkholes, and other forms of rock imbalance, the main anti-mudflow measures should stabilise these formations [7-8]. When mudflows happen because of the collapse of moraine fronts, it is important to keep an eye on the condition of dangerous areas,

intramontaine flow channels, and intraglacial flow channels all the time. Glacial mudflows, the main mechanism of formation of which is the thawing of moraine coats covering buried ice or other areas of moraines where floating or sliding [9].

Table 2. Geological features of mudflow-prone areas

Geological feature	Impact on mudflow formation	Recommended mitigation
Highland Lake	High risk of mudflow initiation during lake outbursts	Constructing dams or drainage systems
Steep Slopes	Increased velocity and volume of mudflows	Slope stabilization and terracing
Unstable Soils	Prone to erosion and landslides	Soil reinforcement and erosion control
Loose Debris	High debris content in mudflows	Debris management structures
Permafrost Areas	Seasonal thawing can trigger mudflows	Monitoring and early warning systems

There are two different ways that mudflow protection engineering structures are being developed: building hydraulic anti-mudflow structures to stop mudflows above protected facilities or using engineering to make sure that mudflows can pass through protected facilities without damaging them. Factors of the second group are related to the structure of the mudflow basin itself, its slopes and channels, and soil-botanical features [10-12]. The third large-scale group of factors determines the nature and types of mudflow control measures depending on the quantitative values of mudflows formed in the basin. Three generalised groups can be distinguished in terms of mudflows (Table 3).

Table 3. Mudflow classification and characteristics

Mudflow Type	Flow Rates (m ³ /s)	Velocities (m/s)	Volume of Outbursts (m ³)	Debris Size
Minor	15-20	1-1.5	Up to 2-3 thousand	20-30 cm
Medium Capacity	Up to 100	1.5-3	Up to 30-50 thousand	Up to 1 m
Powerful	Over 100	Over 3	Over 50 thousand	Over 1 m

The fourth group of factors allows for the placement of economic and recreational facilities in the basin, as well as the implementation of engineering measures to prevent contact with traffic routes and mudflow deposition [13]. The main anti-mudflow measures and structures corresponding to the genetic, scale, and other characteristics of the emerging mudflow basins are summarised in Table 4 [1].

The choice of a mathematical model of debris flow movement depends on the problem to be solved. Since the debris flow movement is associated with a mass of random phenomena, the goal was set to obtain some reasonable estimates of debris flow

parameters [14]. The purpose is to calculate the process of debris flow movement given that the channel geometry and geological characteristics of the potential debris flow mass are known. In describing the model, the characteristics sought will be the distribution of velocities and heights of the debris flow at all moments of its movement. The mudflow motion is modelled by the flow of some hypothetical incompressible fluid subject to the action of gravity, internal friction forces, and Coulomb friction [15].

The occurrence of a mudflow is modelled as an instantaneous breakthrough of the lake's dam. For simplicity, the channel is approximated by a rectangular channel. Formulas 1-5 will form the motion equations for the debris flow. A specific expression for q can be obtained from the assumption that the intensity of mass entrainment in a given section is determined by the total load P transmitted by the moving flow to the underlying surface. As soon as this load exceeds a certain value P^* , which characterises the strength properties of the slope, the destruction of the underlying surface will begin. The conditions at the fracture front can be written in the following formulas 6-12. The task is to facilitate and ensure the safe transfer of the mudflow discharge through the mudflow culverts (Fig.2) [16].

The principle of operation of the mudflow facility is as follows: the mudflow is directed to irrigation canal 5. Certain measures are taken to prevent sediment retention in the canal and to direct debris flows into the debris chute 8 and then into the outlet channel 9. A narrowing section 4 is created in the irrigation channel 5 in front of the siltation tray 3, and a concrete spur 7 is installed in the irrigation channel 6 after the siltation tray 3 and outside the siltation section at an angle to the axis of the irrigation channel 5, with a height of $0.5 h$ (where h is the average depth in the channel).

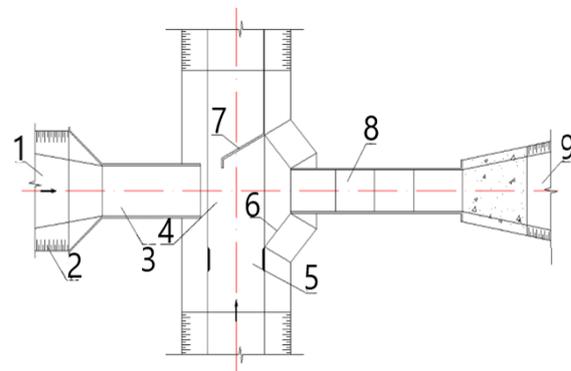


Fig. 2 Mudflat construction

Note: 1 – selenium river channel; 2 – dams; 3 – mudflow inlet; 4 – narrowed section; 5 – irrigation canal; 6 – selenium river channel in the irrigation canal; 7 – concrete spur; 8 – siltation; 9 – outlet channel.

Table 4. Engineering classification of mudflow control measures

Anti-mudslide measures	Genetic conditions of mudflow formation, peculiarities, and characteristics of mudflow basins and streams, as well as protected objects, determine the effectiveness and rationality of these anti-mudflow measures.
Preventive	
Slope afforestation, shrub planting, grass seeding	All mudflow hazardous basins, regardless of the genesis of mudflow formation and the peculiarities of their movement. Basins with slopes serving as focal points or trajectories for rock fracture products are particularly effective.
Channel forestry	Mudflow formation channels through all basins of erosion.
Slope terracing	Runoff regulation, soil restoration, and reforestation stimulation are necessary in the basins of erosion-slope mudflow formation.
Sealing of mudflow-forming foci (biological, hydrophobic coatings and other means)	Screens, sinkholes, floats, and the covering of buried ice by moraine coats are the primary causes of mudflow formation in certain areas.
Forced collapse of coastal massifs and marginal moraines before the mudflow period	Areas of coastal erosion and collapse of unstable rocks into the channel, marginal areas of moraine coats covering buried ice, as well as near-bank and channel gravity accumulations of loose debris – natural or caused by anthropogenic activities.
Regulating (lowering) the level of glacial lakes by channelling them at a given level or by other means (siphons, drainage)	Basins may form due to glacial lake outbursts reaching dangerous levels during periods of intense ablation (hot summer months).
Spreading out the seasonal snowmelt and managing it by artificially accelerating melting in certain areas (blackening the snow cover)	Intense spring snowmelt, frequently paired with warm rainfall, can lead to the formation of mudflows in basins, including snowmelt streams.
Slowing down ablation by shading glaciers (creating smoke screens that simulate cloud cover)	During periods of intense solar radiation (during the daytime hours of the mudflow hazard period), basins of glacial mudflow formation with a significant glacier area are formed.
Arrangement of snow fences to regulate snow accumulation before the start of spring snowmelt	Water flows form in basins where spring snowmelt mudflows originate.
Reducing the intensity and duration of heavy rainfall by influencing cloud cover (turning liquid precipitation into solid precipitation)	Storm and mixed mudflow basins form during mudflow hazard periods. These areas have heavy and long-lasting liquid precipitation (warm showers) in high-altitude areas, which are where mudflows start and get their solid material.
Grazing management on mountain slopes	The goal is to maintain and replenish the soil cover on slopes vulnerable to erosion and mudflow formation.
Agricultural activities (organisation of proper ploughing of mountain slopes)	Erosion mudflow formation basins occur when slopes are improperly ploughed vertically, leading to the creation of new erosion furrows, channels, and potential mudflow routes.
Measures of short-term warning of a moving mudflow by automatic means and devices with the use of radio signalling (emergency measure)	There are basins where the passage of mudflows poses a threat to human casualties or significant material damage, and where signals of a moving mudflow can be transmitted tens of minutes or more before the mudflow reaches the protected facilities.
Rational and safe placement of economic and recreational facilities in mudflow-prone basins	All mudflow-prone basins.
Engineering structures	
Debris dams	Basins with areas capable of retaining mudflow in the necessary volumes, along with geologically stable shafts, are ideal for the construction of mudflow retention dams above protected facilities.
Systems (cascades) of channel stabilisation and sediment retention dams	Basins with significant riverbed lengths (at least 200-300 m) enable the construction of a system of "supporting" dams to reduce the longitudinal slope of the riverbed in such a section, which is caused by the mudflows themselves.
Bridges with a capacity of up to 1000 people	If there are longitudinal slopes in the channel at the crossing site, mudflows can pass through linear facilities such as railways and roads.
Overpasses with a capacity of overpasses	If the width of the mudflow zone is significant (hundreds of meters or more) and it is impossible (irrational) to narrow it for mudflow passage by a bridge, then it is unavoidable for linear objects to cross the channels.
Sedimentation channels, chutes and artificial channels	To facilitate the transit of mudflows through settlements with a sufficient longitudinal slope, it is possible to give the channels the necessary cross-sections.
Upper mudslides	Basins where topographical conditions allow for the passage of mudflows over the roadway or a channel, with mudflows of low magnitude.
Guiding, fencing and diversion dams	To fix the movement of mudflows in the desired direction (mainly on the approaches to and exits from bridges) and divert them away from protected objects.
Semi-dams, spurs, retaining walls, girders, gabions and other reinforcement and debris flow structures	Strengthen banks, channels, and unstable slopes to divert mudflows from protected banks.

Source: compiled by the authors.

By narrowing Section 4, the water velocity in the channel increases, which means that the sediment transport rate also increases. Concrete spur 7 directs the mudflow into the mudflow 8 with a high slope. Thus, the entire flow rate of the mudflow is directed to the mudflow spillway 8 and then to the outlet

channel 9. Irrigation Canal 5 continues its journey, having lost a small flow rate while clearing its channel and passing the mudflow. Another application for an innovation patent was filed after analysing several studies in this area [15-19]. The technical result is achieved by using one-piece spurs

made of soil and lined with a working slope, installed in the bed of a siltstone river. The final section of the mudflow outlet is designed to ensure smooth flow and prevent the level in the channel from being supported by settled sediments [20]. The essence of the alleged invention, known as a mudflow conduit (Fig.3), is that the inlet port is a funnel 1 with a reinforced bottom and dam 2, as well as spurs 3 located across the mudflow channel tray.

Spurs 3 acts as a threshold, ensuring a smooth approach of the mudflow to the structure and preventing its breakthrough by passing the structure into channel 4. The outlet part is also reinforced and protected by dam 3. The teeth 5 crossing the mudflow channel tray 4 from the upper and lower sides prevent the tray from being washed away [20]. The tray is usually lined with a material that is resistant to abrasion. The axis of the structure is designed to be straight.

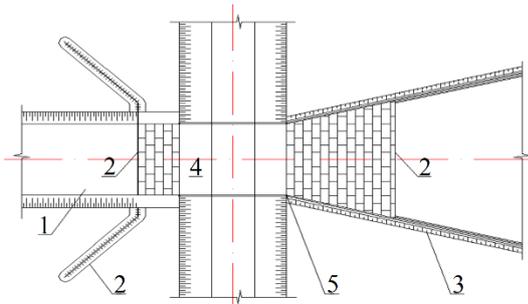


Fig. 3 Mudflow conduit

Note: 1 – funnel; 2 – reinforced bottom and dams; 3 – spurs located across the debris flow channel; 4 – debris flow channel; 5 – teeth.

Table 5. Mudflow Prevention Measures and Effectiveness

Mudflow Prevention Measure	Application Area	Effectiveness	Environmental Impact
Slope Afforestation	Erosion-prone slopes	High	Positive (promotes vegetation growth)
Channel Forestry	Erosion channel basins	Moderate to High	Positive (enhances forest cover)
Slope Terracing	Terraced slopes for erosion control	Moderate	Neutral to Positive
Sealing of Mudflow-forming Foci	Mudflow centres, sinkholes, moraine coats	Variable	Variable (depends on method used)
Preventive Lowering of Glacial Lake Levels	Glacial basins with lake outburst risk	High	Neutral (depends on implementation)

The mudflow tray is calculated on the assumption that no mudflows are deposited in it. The end section

of the mudflow diversion channel is made to ensure smooth flow and prevent sediment from backing up the level in the channel (Fig.5). After analysing other sources and scientific papers on the topic of research, a utility model application was filed, and a patent was obtained for the design of a passage structure with a threshold [21-22].

5. DISCUSSION

This study developed a mathematical model of mudflow movement, which made it possible to analyse and predict the parameters of mudflow events. The most recent study by Falconi, Moretti, Puglisi, and Righini focuses on the use of empirical and geometric methods for the analysis of debris flows, with a focus on simple geometric relationships between landslide parameters and the distance of displaced material exit [23]. For this study, the effectiveness of various geometric ratios for determining runout distances was compared at a test site in the Sicily region of Italy. When using these methods, the paper acknowledges the level of simplification in debris flow dynamics but highlights their value in providing useful information on the propagation of shallow and fast landslides. After analysing several events, a consistent set of data was collected and processed for the analysis. A broad analysis of events and classification of mudflow events is prioritised, while the study by the researchers addresses specific geometric methods for studying specific areas of a mudflow basin.

One of the works by da Paz and de Paula focused on extreme mud and debris flows that can flood alluvial plains [24]. The focus was on the study area in the Jacaray River Basin, Brazil, which was affected by mudslides in March 2011. The study's authors conducted deposit mapping using a geospatial database and collected samples for laboratory analysis. The sediment volume was estimated based on field samples whose thickness was measured and then interpolated into a geographic information system (GIS) environment. Different types of sediments, such as pelitic, psephitic, and psammitic sediments, were identified in the analysis results. The main results showed that psammite deposits exhibited two different behaviours depending on the flow and burial dynamics in the alluvial plain. The researchers' work focuses on analysing the sedimentology and volume of instantaneous sediments produced by mudslides, which play an important role in understanding the morphogenesis of alluvial plains. The work mentioned above aims to develop a general approach for classifying mudslide events, to apply practical measures for their prevention.

The latest study by Chaytor, Baldwin, Bentley, Damour, Jones, Maloney, Miner, Obelcz, and Xu was devoted to the study of debris flows at the front of the Mississippi River Delta and their impact on oil and

gas infrastructure in the Gulf of Mexico [25]. The authors pointed to high sedimentation rates, steep slopes, inadequate compaction, and biogenic gas production as factors that contribute to the seabed's preparation for failure. The study emphasized the cyclic loading of the seabed by waves, particularly during major hurricanes.

The catastrophic failures of production platforms and pipelines during hurricanes indicated that this factor was a major trigger for movement. Pierre and Claudia [26] focused on hyper-concentrated sediment flows. The writers found four kinds of tangential stresses that are connected to the rheology of a water-sediment mix. They also emphasised how yield strength and viscous stresses affect how fines stick to the mixture. This study proposes a classification of hyperconcentrations based on the mixture's rheological properties, distinguishing mudflows, debris flows, and mudflows with debris flows. The paper focused on the classification of hyperconcentrations concerning their rheological properties, while the study written above focused on the universal classification of debris flows and the evaluation of the effectiveness of debris control measures.

In their recent work, Gurgenzidze, Kipiani, and Obgadze [27] highlighted the insufficient scientific validity of mathematical models used to predict the origin, dynamics, and destructive power of mudflows. The study highlights several researchers' contributions to the study of mudflow hydrology. Particular attention is paid to the works of Voynich-Sianozhensky, Obgadze, Mikhailov, and Chernomoretz, as well as Herheulidze, who developed various mathematical models that accurately reflect the dynamics of mudflows. The article presents solutions and models proposed by the authors reviewed, including the development of the Geniev-Gogoladze mathematical models and the application of the Rvachev-Obgadze variational method. Comparing the researchers' study with the present study, it is possible to see that they differed in approach and emphasis. The researchers addressed the scientific validity of mathematical models used for debris flow analysis and highlighted the complexity of the process of studying debris flow dynamics.

6. CONCLUSIONS

This study developed an engineering classification of mudflow basins and analysed mudflow dynamics to propose effective protective measures. The research emphasizes that a universal classification of mudflows for all practical applications is not feasible due to the complexity and variability of these phenomena. Instead, the study focused on assessing the rationality and effectiveness of various anti-mudflow measures based on the

specific characteristics of the mudflow basins. A mathematical model was created to estimate the behaviour of debris flows, taking into account their unpredictable nature. The model enables the calculation of debris flow movement based on known parameters such as channel geometry and geological features, providing insight into mudflow velocity and height distributions.

The study provided technical solutions for improving mudflow facilities, including the development of mudflow diversion and sediment capture structures, which are effective in preventing mudflow damage. These solutions were validated through mathematical modelling, leading to the submission of several utility model applications. The research contributes to advancing mudflow control techniques, particularly for regions prone to such hazards, like the city of Almaty in Kazakhstan.

Further research in this area may focus on the following aspects: consideration of different geographical and climatic conditions to adapt the proposed technical solutions to different situations and regions; in-depth study of the impact of the proposed mudflow protection measures on ecosystems; and development and implementation of more effective methods to minimize negative environmental impacts.

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