DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

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

Risk assessment of debris flows in vulnerable areas

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Abstract. The study provides the first assessment of debris flow risk for locally detected debris flow basins within the confines of the study area. On the basis of the quantitative and qualitative data on debris flows and consequences of their descent, acquired while carrying out works in the territory of the Republic of Crimea near the village of Dachnoe, the initial data on debris flows are divided into three groups, for each group a stage-by-stage assessment with assignment of scores is carried out, and calculated indicators such as debris flow velocity and flow rate are determined. According to the results of the study, the third group belongs to second category debris flow risks, which is characterised by a high probability of significant damage. The first and the second groups belong to the third category debris flow risks. The conducted semi-quantitative assessment of debris flow risk allows to identify potentially dangerous areas, inform about the threat, and take timely measures to protect the lands. In order to protect lands from the destructive force of debris flows within third group basins, it is necessary to erect debris flow control structures, namely: agroforestry and erosion control structures, debris flow retention structures, debris flow check and prevention facilities, and other engineering protection facilities.

Key words: *debris flow, debris flow hazard, semi-quantitative assessment, debris flow risk, land conservation*

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Оценка риска селевых потоков на незащищенных территориях

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Аннотация. В работе впервые дана оценка селевого риска для локально выявленных селевых бассейнов в пределах исследуемой территории. На основе количественных и качественных данных о селях и последствиях их схода, полученных при проведении работ на территории Республики Крым в районе села Дачное, исходные данные о селях разделены на три группы, для каждой группы проведена поэтапная оценка с присвоением баллов, определены расчетные показатели, такие как скорость и расход селей. Согласно результатам исследования, третья группа относится ко второй категории селевых рисков, которая характеризуется высокой вероятностью значительного ущерба. Первая и вторая группы относятся к третьей категории селевых рисков. Проведенная полуколичественная оценка селевого риска позволяет выявить потенциально опасные участки, информировать об угрозе и своевременно принять меры по защите земель. Для защиты земель от разрушительной силы селей в пределах бассейнов третьей группы необходимо возведение противоселевых сооружений, а именно: агролесомелиоративных и противоэрозионных, селезадерживающих, селепропускных и противоселевых сооружений и других объектов инженерной защиты.

Ключевые слова: *сель, селевая опасность, полуколичественная оценка, селевой риск, охрана земель*

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Introduction

Debris flows cause colossal damage to the national economy, agriculture and certain local inhabitants by destroying not only settlements and industrial enterprises, but also transport infrastructure and adjacent infrastructure facilities (electric power lines, gas and water pipelines, communication lines, etc.). The territory of the Crimean Peninsula is actively affected by landslides, debris flows and other dangerous geological phenomena. The main factors of debris flow formation are lack of green cover on slopes, and land degradation (water and wind erosion) [*Gorbunov,2020, Popovych, 2021*]. During the works on the site, it was determined that the greatest danger was posed by debris flows near Dachnoe village. For further works, basins and channels formed by debris flows were studied, some of which were known to occur annually and cause catastrophic damage. The emergence of debris flows was caused by a sharp rise in the water level in the channel, active erosion processes, and significant slopes [*Ghetto, 2022*].

Brief overview of the issue

An area is considered as debris flow-prone if one or more debris flow basins are found there. Since there is no generally accepted methodology to rank land sites by the degree of debris flow danger, the use of semi-quantitative, quantitative, qualitative and other methods is possible for research purposes. It is possible to comprehensively assess the degree of debris flow danger if the method of field surveys is combined with the analysis of meteorological, geological and other data, which can be achieved by semi-quantitative assessment of debris flow risk [*Kiul, 2011*].

Reclamative afforestation is used to protect the terrain from the impact of debris flows and erosion processes. It includes: forestry practices aimed at improving the soil, hydrological and climatic conditions of the terrain (creation of field-protective forest belts, afforestation of gullies, steep slopes and sands) [*Maltseva, 2021*].

Therefore, the purpose of the present study was to determine the level of debris flow danger in the area, including determination of the category of debris flow risks based on the debris flow basins found in the area, and determination of the main causes of debris flow formation. If required for further stabilisation of the situation, the following debris flow control works should be carried out: erection of debris flow protection structures, and development of a system of reclamative afforestation activities.

The Crimean Peninsula belongs to the areas with moderate risks of fluviomorphological processes, where sediment-water debris flows (with predominantly large fractions) prevail (Fig. 1) [*Chalov, 2016*]. The solid part of such debris flows is formed due to the washout of friable fragmental material from bare slopes and erosion of river sediments. Low-density flows with solid material saturation up to 330 kg/m^3 are more often formed in small water catchments [*Kiul, 2011*].

Atmospheric precipitation is the only source of water inflow to the analysed area [*Gorbunov, 2021*]. Fissure-karst waters and precipitation falling in the area are infiltrated into the thickness of rockfall and landslide formations. The greatest amount of precipitation falls in Crimea during the passage of meteorological fronts of cyclones; this period falls on summer months (summer type of atmospheric circulation begins from the second half of May and lasts until the end of September) [*Yefimov, 2022*]. Due to these climatic conditions, the rainfall type of debris flow formation prevails, and combined with the lack of erosion control measures, the risk of debris flows increases significantly (Fig. 2).

a b c

Fig. 1. Debris flow channel: a – PK294, within the boundaries of the modern debris flow fan; b – PK299, near the bed of a temporary watercourse; c – PK289, within the boundaries of the ancient debris flow fan

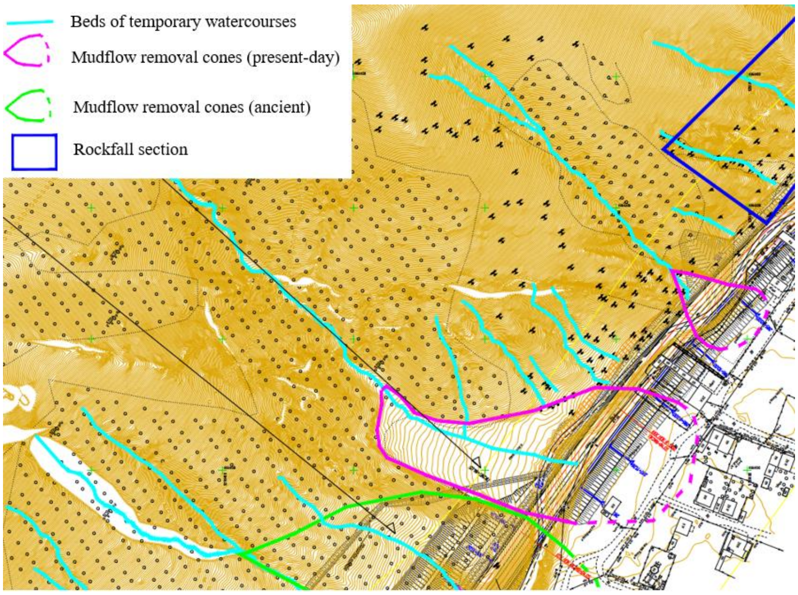

Fig. 2. Summary plan combined with the layout of debris flow channels

When debris flows are formed by climatic and geological factors, the debris flow-forming soils differ from friable fragmental material by conditions of bedding, genesis, particle-size material composition, and such debris flow-forming sources are referred to potential debris flow massifs [*Kiul, 2011*].

The collection and analysis of information on debris flows includes:

– identification of the areas subject to active debris flow processes for further observation, and of the main factors of debris flow formation (lack of vegetation on slopes, presence of prolonged heavy precipitation);
– study of the consequences of debris flows with respect to transport installations and the adjacent territory (partial or complete disruption of roadway integrity, reduction of performance of adjacent engineering utilities);
– determination of the priority of works, formulation of recommendations on protection of the areas exposed to debris flows.

For convenience and clarity, the debris flow basins were divided into three groups according to the maximum basin height.

The soils composing the debris flow channel were 5–10 cm thick in the upper part and 0.5–1.0 m thick in the lower part. The thickness of the soils composing the fans reached 5–7 m.

Materials and methods

The assessment results provide a basis for prioritising the reconstruction and construction of protection structures, including structures to protect agricultural lands from debris flows. Once the number of scores for a debris flow basin or a group of debris flow basins has been determined, a risk category is assigned, on the basis of which design decisions are made [*Matsiy, 2019*].

In order to conduct a semi-quantitative assessment of the debris flow risk of the area, the debris flow risk assessment factors were adjusted, with scores assigned for them taking into account the factors dominating in the territory of the site (Table 1) [*Matsiy, 2019*]. The assessment results provide a basis for prioritising the reconstruction and construction of protective structures, including ones to protect agricultural lands from debris flows. Once the number of scores for a debris flow basin or a group of debris flow basins has been determined, a risk category is assigned, on the basis of which design decisions are made [*Matsiy, 2019*].

In order to conduct a semi-quantitative assessment of the debris flow risk of the area, the debris flow risk assessment factors were adjusted, with scores assigned for them taking into account the factors dominating in the territory of the site (Table 1) [*Matsiy, 2019*].

Table 1. Semi-quantitative assessment of the debris flow risk

Reference	Score	Description of factor	Influence quantity
Group I			
H1	2	Average catchment slope steepness – 27°	0.2
H2	4	Catchment channel steepness – 24°	0.3
H3	2	limiting factor of water balance change – atmospheric precipitation	0.1
H4	2	active development of water erosion and deflation processes, lack of green cover on slopes.	0.3
H5	1	friable fragmental material involved in debris flow formation – up to 2,500 cubic metres per square kilometre	0.2
H6	2	channel is partially sodded (<1%)	0.3
H7	1	max basin height – 165 m	0.2
H8	4	frequently recurring debris flows (once in 2–3 years)	0.3
H9	0	absence of breakthrough lakes	0.3
H10	2	dispersed debris flow centres and/ or potholes	0.3
A	0.1	no debris flow control structures	–
D1	3	regional road	–
D2	4	section length over 100 m	–
D3	1	low degree of debris flow impact on transport infrastructure and adjacent infrastructure facilities	–
D4	2	presence of engineering communications in the vicinity of the motorway	–

Thus, quantitative and qualitative indicators of Table 1 serve as a basis for making design decisions on stabilisation of the situation, where in accordance with qualitative characteristics the following are determined: level of responsibility, additional coefficients for reliability calculation, etc., and quantitative ones are necessary for direct calculations of retention capacity of designed structures, calculation of loads on such structures, etc. [*Sidaravičute, 2023*]. If there are protective structures in the debris flow-prone area, decisions on their replacement, reconstruction or reinforcement are made depending on their wear and tear.

Coefficient D5 – the debris flow discharge is determined by the formula recommended for use by Industry Road Guidance Document 218.2.052-2015:

$$Q_c = V_c \cdot \omega, \tag{1}$$

where Q_c is the debris flow discharge, m^3/s; V_c is the debris flow velocity, m/s; ω is the debris flow cross-section area, m^2.

According to Industry Road Guidance Document 218.2.052-2015, debris flow speed is calculated by the following formula:

$$V_c = \frac{\sqrt{2g\Delta h}}{\alpha'}, \tag{2}$$

where V_c is the debris flow speed, m/s; g is the free-fall acceleration, m/s^2; Δh is the height difference between absolute elevations of level marks, m; α' is the coefficient depending upon the peculiarities of the debris flow mass (the average value α' = 0,65)^2.

Thus, for Group I of debris flow basins the maximum absolute elevation of level traces was 119.01 m, the minimum was 117.36 m, here Δh = 1.65 m, hence, the debris flow velocity V_c = 8.75 m/s (2), which corresponds to cohensionless debris flows [*Perov, 2012*]. The cross-section area was determined in field conditions, the average value for Group I being ω = 0.369 m^2. Thus, substituting the values into the formula, the debris flow discharge is obtained: Q_c = 3.23 m^3/s (1).

The value of potential damage directly depends on the significance of the motorway. The formula to calculate the value of damage is shown in [*Matsiy, 2019*]:

$$C_n = D_1 + D_2 + \ldots + D_n, \tag{3}$$

where $D_{1, 2, \ldots, n}$ is the partial damage coefficient.

For Group I, the value of damage is as follows: C_1 = 19.

$$P_n = H \cdot A, \tag{4}$$

where P_n is the probability of impact of a hazardous geological process (debris flow) on road infrastructure facilities; H is the total indicator of predisposition to the emergence of debris flow; A is a constant reflecting the state of protective structures (debris flow protection structures), depending on the level of wear; in the absence of such structures the highest significance coefficient of 0.1 is assigned [*Matsiy, 2021*].

The probability of debris flow impact on road infrastructure facilities is: P_1 = 0,52.

$$H = \sum H_n \cdot t, \tag{5}$$

where H the total indicator that reflects predisposition to the emergence of debris flow; H_n is debris flow formation factor; t is the significance coefficient of the debris flow formation factor [*Sidaravičute, 2023*].

Here for Group I the following was obtained: H = 5.2.

The risk category is determined by the formula [*Sidaravičute, 2023*]:

$$R_c = P_n \cdot C_n, \tag{6}$$

where R_c is the debris flow risk category; P_n is the probability of impact of a hazardous geological process (debris flow) on road infrastructure facilities; C is the indicator of potential damage value.

Results and discussion

Thus, RI = 9.88, hence, Group I of basins is included in R_3 risk category; debris flows of this group pose a low threat. To prevent catastrophic consequences, it is necessary to apply slope-greening measures.

A similar assessment was carried out for Groups II and III, and the results were as follows.

Group II – atmospheric precipitation is the limiting factor of debris flow formation; active development of erosion processes and lack of green cover on slopes; sodding of channels. In terms of distribution, debris flow-forming sources are dispersed, and there are no breakthrough lakes. In terms of quantitative parameters, the basins belonging to this group are characterized by an average catchment slope steepness of 29° and channel steepness of 23°, while the maximum height of the debris flow basins reaches 232 m on average in the Baltic Elevation System. Here, the friable fragmental material involved in debris flow formation do not exceed 2500 m^3/km^2, and the recurrence of debris flows of this group takes place once every two to three years. According to the debris flow discharge calculation, the average value is 11.00 m^3/s. The debris flow basins are located in close proximity to the regional motorway with adjacent engineering utilities. Here, the area affected by debris flows reaches 100 m. However, the debris flows' impact on objects of various purposes is assessed as low, bearing in mind the absence of debris flow control structures. The total weight of "*H*" indicators for Group II is 5.4.

For Group II of debris flow basins, the flow velocity was determined by formula (2), at Δh = 2.32 m; V_c = 10.3 m/s. The cross-sectional area was determined in field conditions: ω = 1.06 m^2. Consequently, the flow rate was determined by the formula (1): Q_c = 11.00 m^3/s. For Group II, the index of potential damage C_2 = 21, and the probability of the impact of a dangerous geological process (debris flow) on road infrastructure facilities P_2 = 0.54. The weight of "*H*" indicators is determined by formula (5): H_2 = 5.4. Thus, according to the formula (6); *RII* = 11.34, Group II of basins is included in *R3* risk category; debris flows of this group pose a low threat; without greening measures on slopes applied to prevent water and wind erosion, the situation will aggravate.

For Group III, atmospheric precipitation is the main factor of debris flow formation; active development of erosion processes of weathering, deflation and absence of greening on slopes, and significant sodding of channels (more than 48%) were identified for this group. By nature of distribution, debris flow centers are dispersed, and there are no breakthrough lakes. The quantitative parameters of the basins belonging to this group are: catchment slope steepness – 36°; channel steepness – 19°, and the maximum height of debris flow basins on average reaches 344 m in the Baltic Elevation System. In this group, the friable fragmental material involved in debris flow formation do not exceed 20,000 m^3/km^2, and debris flows of this group recur with a frequency of once every two to three years. Based on the calculations, the average debris flow discharge is 67.86 m^3/s. The debris flow basins are located in close proximity to the regional motorway with adjacent engineering utilities. The area affected by debris flows reaches 100 m. However, the impact of debris flows on objects of various purposes is assessed as low, in the absence of debris flow control structures. The total weight of "*H*" indicators for Group III is 6.6.

Calculations for Group III debris flow basins were carried out similarly, viz.: the flow velocity was determined by formula (2), at Δh = 3.44 m: Vc = 12.6 m/s. The cross-sectional area for Group III was determined in field conditions and was equal to: ω = 5.37 m^2. Consequently, the flow rate was determined by the formula (1): Q_c = 67.86 m^3/s. For Group III, the index of potential damage C_3 = 23, and the probability of the impact of a dangerous geological process (debris flow) on road infrastructure facilities P_3 = 0.66. The weight of "*H*" indicators is determined by formula (5): H_3 = 6.6. Thus, according to the formula (6); *RIII* = 15.18, Group III of basins is included in R_2 risk category, which implies a high probability of damage to engineering, transport and other structures.

Conclusions

The study is the first assessment of debris flow risk for debris flow basins found within the boundaries of the area studied. Based on the semi-quantitative assessment of debris flow risk for three groups, the following results were obtained: Group I belong to risk category R_3 (medium), Group II – to R_3 (medium), Group III – to R_2 (high). For Groups I and II it is recommended to arrange cascade anti-debris flow basins, and it is necessary to apply erosion control measures, such as slope greening, prohibition of cutting of existing plantations, and regular monitoring of the condition of the debris flow control structures. The R_2 section is subject to intensive accumulation of solid component, which in case of heavy rainfall will serve as material for debris flow formation. It is unsafe to use this road during prolonged rains. Along the Lgovskoe – Grushevka – Sudak motorway, it is necessary to immediately erect debris flow-preventing, debris flow-retaining, debris flow-stabilising, debris flow-discharge and other types of debris flow control structures, and to carry out reclamative afforestation to control wind and water erosion and strengthen the slopes.

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