СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

Труды
8-й Международной конференции

Тбилиси, Грузия, 6–10 октября 2025 г.

Ответственные редакторы
С.С. Черноморец, Г.В. Гавардашвили, К.С. Висхаджиева

ООО «Геомаркетинг»
Москва
2025

DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

Proceedings
of the 8th International Conference

Tbilisi, Georgia, 6–10 October 2025

Edited by
S.S. Chernomorets, G.V. Gavardashvili, K.S. Viskhadzhieva

Geomarketing LLC
Moscow
2025

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა

მე–8 საერთაშორისო კონფერენციის
მასალები

თბილისი, საქართველო, 6–10 ოქტომბერი, 2025

რედაქტორები
ს. ს. ჩერნომორეც, გ. ვ. გავარდაშვილი, კ.ს. ვისხაჯიევა

შპს „გეომარკეტინგი“
მოსკოვი
2025

УДК 551.311.8
ББК 26.823
С29

Селевые потоки: катастрофы, риск, прогноз, защита. Труды 8-й Международной конференции (Тбилиси, Грузия). – Отв. ред. С.С. Черноморец, Г.В. Гавардашвили, К.С. Висхаджиева. – Москва: ООО «Геомаркетинг», 2025. 496 с.

Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 8th International Conference (Tbilisi, Georgia). – Ed. by S.S. Chernomorets, G.V. Gavardashvili, K.S. Viskhadzhieva. – Moscow: Geomarketing LLC, 2025. 496 p.

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა. მე–8 საერთაშორისო კონფერენციის მასალები. თბილისი, საქართველო. – პასუხისმგებელი რედაქტორები ს.ს. ჩერნომორეც, გ.ვ. გავარდაშვილი, კ.ს. ვისხაჯიევა. – მოსკოვი: შპს „გეომარკეტინგი“, 2025. 496 с.

Ответственные редакторы: С.С. Черноморец (МГУ имени М.В. Ломоносова),
Г.В. Гавардашвили (Институт водного хозяйства имени Цотне Мирцхулава Грузинского технического университета), К.С. Висхаджиева (МГУ имени М.В. Ломоносова).

Edited by S.S. Chernomorets (M.V. Lomonosov Moscow State University), G.V. Gavardashvili (Tsotne Mirtskhulava Institute of Water Management, Georgian Technical University),
K.S. Viskhadzhieva (M.V. Lomonosov Moscow State University).

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).

ISBN 978-5-6053539-4-2

Mathematical support for forecasting slush flows and avalanches with the help of fuzzy analysis

M.I. Zimin[1], A.Kh. Adzhiev[2], O.A. Kumukova[2], T.V. Gavrilenko[3], N.V. Kondratyeva[2], O.M. Kulikova[4], S.A. Zimina[1]

[1]*Ontario Ltd., Toronto, Canada, zimin7@yandex.ru, zimin82@yandex.ru*

[2]*High-Mountain Geophysical Institute, Nalchik, Russia, adessa1@yandex.ru, kumukova@rambler.ru, kondratyeva_nat@mail.ru*

[3]*Surgut State University, Surgut, Russia, taras.gavrilenko@gmail.com*

[4]*Siberian State Automobile and Highway University, Omsk, Russia, , ya.aaaaa11@yandex.ru*

Abstract. Mathematical support for forecasting slush flows and avalanches with the help of fuzzy analysis is considered. All types of them can be foreseen. Prediction formulae are based on mathematical modeling of physical and mechanical processes in snow. They can be used at any region. Effectiveness of this mathematical support is confirmed by experimental data.

Key words: *slush flow, avalanches, mathematical support, forecast, snow, fuzzy analysis*

Cite of this article: Zimin M.I., Adzhiev A.Kh., Kumukova O.A., Gavrilenko T.V., Kondratyeva N.V., Kulikova O.M., Zimina S.A. Mathematical support for forecasting slush flows and avalanches with the help of fuzzy analysis. In: Chernomorets S.S., Gavardashvili G.V., Viskhadzhieva K.S. (eds.) Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 8th International Conference (Tbilisi, Georgia). Moscow: Geomarketing LLC, 2025, p. 469–472.

Математическое обеспечение для прогнозирования водоснежных потоков и лавин с помощью нечёткого анализа

М.И. Зимин[1], А.Х. Аджиев[2], О.А. Кумукова[2], Т.В. Гавриленко[3], Н.В. Кондратьева[2], О.М. Куликова[4], С.А. Зимина[1]

[1]*Ontario Ltd., Торонто, Канада, zimin7@yandex.ru, zimin82@yandex.ru*

[2]*Высокогорный геофизический институт, Нальчик, Россия, adessa1@yandex.ru, kumukova@rambler.ru, kondratyeva_nat@mail.ru*

[3]*Сургутский государственный университет, Сургут, Россия, taras.gavrilenko@gmail.com*

[4]*Сибирский государственный автомобильно-дорожный университет, Омск, Россия, ya.aaaaa11@yandex.ru*

Аннотация. Рассматривается математическое обеспечение для прогнозирования водоснежных потоков и снежных лавин. Все их типы могут быть предсказаны. Прогностические зависимости базируются на результатах математического моделирования физико-механических процессов в снеге. Они пригодны для использования в любом регионе. Эффективность этого математического обеспечения подтверждается экспериментальными данными.

Ключевые слова: *водоснежный поток, лавина, математическое обеспечение, прогноз, снег, нечёткий анализ*

Ссылка для цитирования: Зимин М.И., Аджиев А.Х., Кумукова О.А., Гавриленко Т.В., Кондратьева Н.В., Куликова О.М., Зимина С.А. Математическое обеспечение для прогнозирования водоснежных потоков и лавин с помощью нечёткого анализа. В сб.: Селевые потоки: катастрофы, риск, прогноз, защита. Труды 8-й Международной конференции (Тбилиси, Грузия). – Отв. ред. С.С. Черноморец, Г.В. Гавардашвили, К.С. Висхаджиева. – М.: ООО «Геомаркетинг», 2025, с. 469–472.

Introduction

Planners, designers, and managers of public and industrial roads in avalanche areas often need to decide whether or not their safety procedure with respect to avalanches is adequate, and to choose an appropriate level of avalanche control [*Schaerer, 1989*]. The same problem occurs on sites exposed slush flows. Therefore, further improvement of slush flows and avalanche forecasting methodologies present some features of interest.

Predicting avalanches with the help of using fuzzy sets and results of mathematical modeling of physical and mechanical processes in snow is described in [*Zimin et al. 2020*]. Suggested technique simulates activity of a group of experts; so, prediction formulae knowingly have maximized semantic charge, and their efficient combination may be considered as optimized theory of prognosis of this slope process by a collective of professionals.

Such approach permits to foresee all types of avalanches. But, forecast of slush flows is not addressed, although they may occur in the same places. In addition, influence of situation in origin zone on dynamic parameters of slope processes is not researched too.

This study uses the same approach for developing mathematical support for prognosis of slush flows, determination of type of slope process (it may be avalanche or slush flow), and calculating its dynamic parameters. Prediction formulae for avalanche risk forecast are worked out before [*Zimin et al. 2020*].

Prediction formulae

Analysis of slope process risk with the help of fuzzy analysis according to [*Zimin et al. 2020*] results in one of the following reports.

1. No slope process risk.
2. Snow is in instable state, slope processes having volume of up to 10% of amount of snow in the site are possible during the next 24 h.
3. Snow is in instable state, slope processes having volume of 10–50% of amount of snow in the site are possible during the next 24 h. Slope processes having volume of up to 10% of amount of snow in the site are possible during the next second day.
4. Slope processes having volume of 10–50% of amount of snow in the site are expected during the next 24 h. Slope processes having volume of 10–50% of amount of snow in the site are possible during the next second day. Slope processes having volume of up to 10 % of amount of snow in the site are possible during the next third day.
5. Slope processes having volume of more than 50% of amount of snow in the site are expected during the next 24 h. Slope processes having volume of 10–50% of amount of snow in the site are possible during the next second and the third days.

Therefore, such analytical prediction permits not only to estimate danger, but also to determine volume of a slush flow or an avalanche in rough way. It is important for computing parameters of this slope processes.

Descent of the slush flow or the avalanche is considered as motion of material point. The slope is approximated by the angled line. Frictional coefficient depends on snow properties, slope process parameters, and angle of gradient. It is computed by formula:

$$k = 0.28 k_\alpha k_V k_\rho k_m k_{w_0}, \tag{1}$$

where **k** is the frictional coefficient at a segment of the angle line, $\mathbf{k_\alpha}$ is parameter taking into account influence of angle of slope over frictional coefficient, $\mathbf{k_V}$ is parameter making allowance for influence of avalanche volume, $\mathbf{k_\rho}$ is parameter adverting of density of snow in avalanche site, $\mathbf{k_m}$ is parameter considering influence of moisture of snow, $\mathbf{k_{w0}}$ is parameter having respect to velocity starting at the first point of the segment.

Parameters $\mathbf{k_\alpha}$ and $\mathbf{k_{w0}}$ are calculated in such a manner. Firstly, factors of $\mathbf{k_{\alpha0}}$ and $\mathbf{k_{w00}}$ are figured out:

$$k_{\alpha o} = 1 - \frac{1.12}{\pi} arctan(0.02\alpha), \quad (2)$$

where $\boldsymbol{\alpha}$ is slope inclination, degrees,

$$k_{woo} = 1 - \frac{0.73}{\pi} arctan(0.6w_o), \quad (3)$$

where $\mathbf{w_0}$ is velocity starting at the first point of the segment, m/s.

Then, $\mathbf{k_\alpha}$ and $\mathbf{k_{w0}}$ are computed as

$$k_\alpha = k_{\alpha 0}^{1+0.076\, arctan\left(\frac{1.14}{k_{voo}}\right)}, \quad (4)$$

$$k_{wo} = k_{woo}^{1+0.069\, arctan\left(\frac{1.12}{k_{\alpha o}}\right)}. \quad (5)$$

Other parameters are calculated like that

$$k_v = 1 - \frac{0,64}{\pi} arctan(0.00044V - 4.2), \quad (6)$$

where $\mathbf{V}$ is slope process volume,

$$k_\rho = 1 + \frac{0.68}{\pi} arctan(0.012\rho - 3), \quad (7)$$

where $\boldsymbol{\rho}$ is density of snow,

$$k_m = 1 + \frac{1.82}{\pi} arctan[0.0144m(16.2 - m)], \quad (8)$$

where $\mathbf{m}$ is moisture of snow in mass percentage.

In some cases, computing the frictional coefficient permits to fine-tune the forecast. Simulation physical and mechanical processes in the snow shows that slope process risk under $\boldsymbol{\alpha} < 15^o$ or avalanche origin zone length less than 11 m or thickness of the snow mantle less than 0.26 m is roughly the same as such danger under increasing α to 15^o (if $\boldsymbol{\alpha} < 15^o$), increasing avalanche origin zone length to 11 m (if avalanche origin zone length is less than 11 m), increasing thickness of the snow mantle to 0.26 m (if thickness of the snow mantle is less than 0.26 m), as long as under these changes risk of avalanches or slush flows occurs and the frictional coefficient is suitable to start moving. In addition, $\mathbf{k_V}$ is computed under $\mathbf{V}$ being volume of all snow in the avalanche origin zone.

If $\mathbf{k_\rho} > \mathbf{k_m}$ and $\mathbf{m} > 27$, the slope process is considered as a slush flow. Otherwise, it is meant to be an avalanche.

Slope process speed decreasing in crossing area having barriers is figured out be formula

$$\Delta w = \sqrt{2gh_b}\frac{S_b}{S_t}, \quad (9)$$

where $\Delta\mathbf{w}$ is slope process speed changing, $\mathbf{g}$ is free-fall acceleration, $\mathbf{S_b}$ is area of barriers, $\mathbf{S_t}$ is value of total area, $\mathbf{h_b}$ is mean height of barriers.

If slope process speed decreases on a segment, its volume lessening is estimated as

$$\Delta V = \frac{\Delta w}{w_0} V, \tag{10}$$

where $\Delta \mathbf{V}$ is slope process volume decreasing.

If slope process speed increases on a segment, its volume may greaten in the presence of friable fragmental material consisting of particles with volume less than estimated change of volume of the avalanche or the slush flow. It is computed in the following way:

$$\Delta V_0 = \begin{cases} \frac{\Delta w}{w_0} \cdot \frac{\rho_a}{\rho_w} V if \rho_a < \rho_w \\ \frac{\Delta w}{w_0} \cdot V \cdot \left\{1 + \left[tanh\left(\frac{\rho_a - \rho_w}{\rho_w}\right)\right]^{0.71}\right\} if \rho_a \geq \rho_w \end{cases}, \tag{11}$$

where $\boldsymbol{\rho_a}$ is density of avalanche material, $\boldsymbol{\rho_w}$ is density of friable fragmental material, $\Delta \mathbf{V_0}$ is enlargement of slope process volume.

Discussion

Calculations performed with the help of described approach show that slush flows may occur if inclination of the origin zone is about at least 5º. It is in good agreement with data of [*McClung et al., 2022*]. Analysis also demonstrates possibility of some avalanches to have abnormally long runout distance. It confirms by experimental data too. On multiple occasions, such slope processes traveled unusually far [*Kazakov, 2006*]. For example, runout distance of an avalanche on Sakhalin Island in April 1993 was 1300 m [*Kazakov, 2006*]. In addition, this avalanche passed about 600 m, whereat inclination was 3–5º [*Kazakov, 2006*]. According to calculation with the help of technique described at [*Kozik, 1962*] such avalanche could cover 1100 m [*Kazakov, 2006*].

Conclusions

Developed mathematical support permits to improve accuracy of slush flows and avalanche. Its adequateness is confirmed by experimental data. Also, prediction formulae enable to determine slope process type.

References

Казаков Н.А. Лавинный фронт как уединённая волна – солитон // Материалы гляциологических исследований. 2006. Вып. 100. С. 22–25.

Козик С.М. Расчёт движения снежных лавин. Л.: Гидрометеоиздат, 1962. 74 с.

Schaerer P. The avalanche-hazard index // Annals of Glaciology. 1989. Vol. 13. P. 241–247.

Zimin M.I., Kumukova O.A., Zimin M.M. Mathematical model and software for avalanche forecasting // Russian Journal of Cybernetics. 2020. Vol. 1, No. 1. P. 63–80.

McClung D., Schaerer P. The avalanche handbook. Seattle: Mountaineers Book, 2022. 366 p.