GEOGRAPHY

Avalanche Hazard Assessment in Low Mountains, Based on the Example of the January 2021 Norilsk Avalanche Disaster

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Abstract—This paper presents the reconstruction results of catastrophic avalanche characteristics. The avalanche occurred on the slope of the Gora Otdelnaya ski resort on January 9, 2021 (Norilsk). It had a peak pressure of 0.266 MPa and led to the destruction of a suburban settlement, covering an area of about 0.9 ha. Six people got caught in the avalanche, of whom three were killed. The virtual and calculated boundaries of the maximum avalanche run-out distance are given. The causes of the catastrophe are also under investigation. An avalanche hazard assessment methodology for the Russian Arctic region and other poorly studied areas with no long-term avalanche observations is suggested.

Keywords: avalanche zone boundaries, avalanche, avalanche hazard, maximal avalanche run-out distance

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INTRODUCTION

The disasters caused by activation of exogenous geodynamic processes include snow avalanches; in recent years, such disasters have become more frequent, even hitting human settlements. This is caused primarily by intensive (and often uncontrolled) building and development within residential areas. Broad development of avalanche processes in the Russian Arctic region is one of the factors that should be taken into consideration under expansion of the operated territory. Today, the regular impact of avalanches on human economic activity can be seen, for example, in the most developed arctic part of the Kola Peninsula, where controlled avalanches are triggered (it is also performed within residential areas), but nonetheless catastrophes occur [1].

Despite the fact that avalanche hazard assessment is an obligatory part of engineering survey works during development of an area, as well as when erecting and reconstructing capital construction facilities, we think that the degree of this hazard is underestimated. This is seen particularly in how novel areas are developed: since such areas are in fact poorly studied, there are no factual data on avalanche characteristics for them; hence, the expected effect cannot be estimated. A particular example of this is Sakhalin oblast,

where the largest number of avalanche-related catastrophes occurred precisely in the first decades of intensive development of this region [2].

METHODS

The majority of modern methods of assessment of avalanche hazards and determination of avalanche zone boundaries is based on empirical parameters that are obtained from the data on avalanches sliding down within a certain area [3]. We emphasize that snowslide models developed for alpine regions by Swiss and Austrian specialists are inapplicable when there is an absence or a lack of factual observations [4, 5], because modeling implies introduction of coefficients that are calculated from data on avalanches set off within the avalanche catchment for which the modeling is performed. Selection of analogous avalanche catchments is limited due to geomorphic and meteorological factors of avalanche formation, which are unique to each mountain region.

Lacking factual data on avalanches, we can use the method that was tested for the territory of Sakhalin oblast [6]: this is a compilation of formulas proposed by various researchers (S.M. Kozik, S.S. Grigoryan, A.N. Bozhinskii, and K.S. Losev), and each of these formulas enable us to obtain the dynamic characteristic of avalanches and an algorithm of avalanche hazard assessment. Resulting from the assessment, avalanche catchments can be classified in terms of the expected avalanche impact on objects and facilities. The main

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Table 1. Categories of avalanche hazard in terms of the expected effect of an avalanche on constructions of various classes

Hazard categories	Pressure on an object, MPa	Expected effect
I	>0.98	<ul style="list-style-type: none"> • damage in or destruction of KS-3 objects; • destruction of KS-1 and KS-2 objects; • destruction of motor vehicles; • threat to human life and health
II	>0.245	<ul style="list-style-type: none"> • damage in elements of KS-3 objects; • damage in or destruction of KS-2 objects; • destruction of KS-1 objects; • destruction of motor vehicles; • threat to human life and health
III	>0.029	<ul style="list-style-type: none"> • damage in elements of KS-2 objects; • damage in or destruction of KS-1 objects; • destruction of motor vehicles; • threat to human life and health
IV	>0.0196	<ul style="list-style-type: none"> • damage of motor vehicles; • threat to life and health of people beyond buildings
V	—	Area of potential hazard: presently, there are no avalanches or they are of no hazard; small-volume avalanches may occur passing through a forest; avalanche activity is expected to be launched due to the anthropogenic effect on landscapes (erection of buildings and facilities, removal of vegetation cover, etc.).

criterion is pressure, because it will determine the destructive effect of an avalanche. There are five categories of hazard; these categories are unified to assess the expected avalanche effect on objects during engineering survey works (Table 1). The avalanche pressure calculated is correlated with classes of buildings and facilities according to the State Standard (GOST 27751-2014). The KS-1 class includes greenhouses, relocatable (dismountable and container-like) buildings, and warehouses where no permanent presence of people is intended. The KS-3 class corresponds to hazardous and technically complex facilities, critical infrastructures for settlements, high-rise structures, tunnels, and other structures. The KS-2 class covers structures and facilities that cannot be referred to either the KS-1 class or the KS-3 class.

In our opinion, such an approach to avalanche effect assessment is illustrative enough to characterize the hazard for an area under study and enables us to either select appropriate objects to be constructed within an area prone to avalanches or to design engineering protection in advance.

The maximal avalanche run-out distance is estimated using the graphoanalytical method by S.M. Kozik [7]. This method is based on determination of the point where the slope profile intercepts with a tilted line drawn from the point of the most likely fracture line of an avalanche at an angle that is critical for the given avalanche catchment. It should be noted that graphoanalytical method of determination of the maximal avalanche run-out distance does not take into account the presence of any objects impeding

avalanche motion (for example, buildings, constructions, trees, terraces, and other things).

In this work we reconstruct the parameters of the avalanche disaster that occurred near Norilsk in 2021, using the aforementioned method.

STUDY AREA

The avalanche occurred in the night from January 8 to 9, 2021, on the slope of the Gora Otdelnaya ski resort. It caused three deaths and the destruction of a dacha settlement within an area of ≈ 0.9 ha. The ski resort is located 25 km from the center of Norilsk, Krasnoyarsk krai, in Talnakh district, at the base of Mount Otdelnaya, which is a western spur of the Putorana Plateau.

No cases of people caught by avalanches in the study area are mentioned in the *Cadastr of Avalanches in the USSR* for the period from 1961 to 1991 [8]. According to other sources [1, 9, 10], there have been such cases in the area of Talnakh. One of the most recent ones occurred at the Talnakh ore-dressing plant on January 29, 2018, when an avalanche hit a car (with a driver inside) parked near the industrial building [10].

The mountain ranges around the city of Norilsk are referred to areas of low and very low avalanche hazard [11]; however, the Administration for Civil Defense and Emergency Situations of the city of Norilsk reported [12] that avalanches form annually within small- and moderate-scale avalanche catchments on the slopes of the northwestern spurs of the Putorana

Fig. 1. Schematic map of the Gora Otdelnaya ski resort, showing the avalanche catchment where the catastrophic avalanche formed and the residential area within its zone of effect.

Plateau (Lokotoiskii Kamen' Range (Central) and Khaerlakh Range (Talnakh)). The volume of an avalanche is usually no more than 1000–3000 m³, although the conditions of the area are favorable for avalanches of more than 50000 m³ in volume to form [8]. The period of avalanche hazard is as long as seven months [8, 9].

CALCULATION OF AVALANCHE CHARACTERISTICS

The dynamic characteristics of the catastrophic avalanche of January 9, 2021, were calculated on the basis of information from the mass media, descriptions of eyewitnesses, and also the data obtained by the specialists of the Far East Geological Institute (Far East Branch, Russian Academy of Sciences) when assessing the avalanche hazard for the northeastern slope of the Lokotoiskii Kamen' Range in 2020. Assessment of the geomorphic factors of avalanche formation was based on the Arctic DEM digital elevation model having a resolution of 2 m [13]. For further calculations, a 3D model of the slope, with colored angles, was constructed in the QGIS program. The model also included the position of current residential buildings (Fig. 1) that appeared to be within the zone affected by the avalanche.

The avalanche formed within a trough-type avalanche catchment located on the western slope of the mountain. This avalanche catchment is an erosional

cut with a height difference of 280 m. The average angle of this slope is 27°, while the maximum one, in the zone of avalanche fracture line, is 34°; however, images and videos from the place of the disaster suggest that the avalanche occurred over a snow surface, not soil. This indicates that the slope angles in the avalanche catchment at the moment of avalanche fracture were smaller. The avalanche occurred during a snow storm. The fracture line of the avalanche was located at 360–380 m a.s.l.

The meteorological conditions of the avalanche occurrence and the snow cover thickness within the avalanche catchment suggest that it was a displaced snow avalanche. The maximal snow cover thickness in January for the period of 1966–2018, according to the in-field snow course survey made by a specialist of the Norilsk Hydrometeorological Station, is 178 cm [14]. The average snow cover thickness in the zone of the avalanche origin can be estimated, taking dispersion into account, at 194 cm, and the height of the avalanche fracture line is ≈110 cm.

Redistribution of snow within the avalanche catchment during the blizzard that lasted from January 5 to 8, 2021 [15], had led to the growth of a snow ledge formed earlier, the collapse of which triggered the avalanche itself. The formation of snow ledges at the slope edges is characteristic of all areas of the Putorana Plateau [9], and this can also be deciphered from GoogleEarth images. The thicknesses of snow ledges

Fig. 2. Second house (with people inside) hit and moved by the avalanche (image from <https://24.mchs.gov.ru/deyatelnost/press-centr/operativnaya-informaciya/4354328>).

Fig. 3. Snow drifts of over 5 m high in the area of search and rescue operations; the mentioned height is clearly seen from the character of avalanche deposits in comparison with the nearby buildings (image from <https://news.myseldon.com/ru/news/index/243574139>).

exceed the snow cover thickness of the zones of the avalanche origin.

Figure 1 indicates the virtual and calculated maximal avalanche run-out distances. The boundary of the avalanche catchment and the maximal run-out fan, taken together, outline the hazardous zone, without the existing buildings being taken into consideration (Fig. 1, inset 2).

RESULTS AND DISCUSSION

There were several houses involved in the avalanche. The first house in the path of the avalanche was located within the run-out fan, in the normal shock zone. The building was made of profiled log, 200×200 cm in section (the remaining houses in the area were made of another material); its construction site was elevated. The avalanche speed at the moment of impact, as reconstructed from the character of the destruction, was 18 m/s, and this was supported by the calculations [6].

At an avalanche speed of 18 m/s, the calculated peak avalanche pressure on the object was 0.266 MPa. Note that the peak avalanche pressure is short-term, but causes the maximal damage. The avalanche crushed the house walls and tore off and removed its roof, so the height of the avalanche front can be estimated at ≈ 10 m, while the calculated value was 9 m. A metallic container (store house) of 20 feet long was moved 80 m by the avalanche; remarkably, the roof of the house was located at approximately the same distance (Fig. 1, inset 1).

After the first impact, the avalanche pressure began to decrease (the calculated pressure dropped to 0.192 MPa), marking the second stage of avalanche interaction with objects in its path (Fig. 1, inset 1).

The second house in the path of the avalanche, with people inside, was assembled of metallic containers and had no basement, therefore it was not crushed, but moved with the avalanche flow. People inside felt a series of shocks [16] (by that moment, the avalanche had already slowed near the obstacles and reached that house as a series of waves) and then rotation of the house, until it toppled and ceased to move (Fig. 2). The total number of people involved in the avalanche increased to six.

The calculated volume of the avalanche is 22000 m^3 , and the area of avalanche deposits within the residential area is ≈ 0.9 ha. The average height of snow drifts near the objects was 3 m, while the maximum height was 5–7 m (Fig. 3). The calculated volume was justified by the real observed parameters of the snow drifts.

Regarding the avalanche under consideration, in terms of the criteria from Table 1, it can be referred to a second II category of hazard, which includes avalanches characterized by avalanches with calculated peak pressure exceeding 0.245 MPa. At such a pressure, objects of class KS-1 are destroyed; we emphasize that objects of this class were in the zone of the avalanche effect (Figs. 2, 3).

The characteristics of the avalanche considered are supported by the observed destruction in the dacha settlement. The occurrence of the avalanche caused the destruction of six houses and damage of various degrees to eight houses.

CAUSES OF THE DISASTER

The avalanche disaster near Norilsk occurred as a result of a combination of a number of factors: meteorological conditions (blizzard) at the moment of ava-

lanche fracture; the considerable thickness of snow cover within the avalanche catchment (at least 194 cm); and the absence of ski piste preparations at the ski resort (redistribution and compaction of snow on ski pistes).

Due to the complex epidemiological situation with respect to the COVID-19 pandemic, the administration of the Gora Otdelnaya ski resort decided not to open ski pistes in the current winter season, so snow compaction work has not been done. As a result of the absence of snow compaction on slopes, natural processes of snow redistribution within avalanche catchment prevailed; hence, the snow cover thickness within the avalanche catchment was not artificially reduced, and physical–mechanical characteristics of the snow cover developed without any technogenic influence; eventually, layers consisting of recrystallized snow formed within the snow cover. The higher load on these layers because of the increase in the snow cover thickness during the blizzard triggered avalanching with very high (near maximal) characteristics.

CONCLUSIONS

Based on the calculation results, the following avalanche parameters have been obtained:

- (1) the peak avalanche pressure on the object nearest to the slope was 0.266 MPa;
- (2) the avalanche volume was 22000 m³, and this calculation result is supported by the virtually observed snow drifts;
- (3) the speed near the first object hit was 18 m/s;
- (4) the factual avalanche run-out distance was 760 m, while the maximal calculated one was 980 m.

The method we proposed enables us to assess the expected effect of an avalanche on an object, depending of the class of the latter. Thus, the most vulnerable areas, safe operation of which requires engineering protection facilities to be built, can be identified at the earliest stages of area development.

The calculations for the avalanche disaster near Norilsk have shown good agreement with the factual data, suggesting that the method proposed is promising for assessing an avalanche impact in the absence of long-term observations.

RECOMMENDATIONS

The primary measure to prevent and reduce risks from avalanches within settlement areas is the development of so-called *Schemes of Land-Use Restrictions with Respect to Avalanche Hazard Zones*, which are supplementary materials to a settlement planning scheme (master plan). Preparation of such schemes should be performed at the stage of designing or correcting the master plans of urban areas and schemes of

territory planning. Scale of maps for the settlement areas should not be less than 1 : 10000.

The schemes mentioned, with avalanche hazard categories being indicated on them for every single avalanche catchment, allow specialists to elaborate measures to protect the population and various objects from avalanche hazards, and also to calculate possible losses from avalanches, including damage to buildings and facilities. The schemes are the basis for planning engineering protection facilities; in cases when such facilities cannot be built, they can be used to substantiate the reasonability of moving a certain object beyond the limits of a zone prone to avalanches or to introduce the limitations on the operation of such a facility, for example, when forecasting the avalanche hazard.

REFERENCES

1. A. S. Turchaninova, Yu. G. Seliverstov, S. A. Sokratov, et al., *GeoRisk* **13** (3), 60–68 (2019).
2. E. N. Kazakova and V. A. Lobkina, *Mater. Glyatsiol. Issled.*, No. 103, 185–190 (2007).
3. B. Yves, D. Rickenbach, A. Stoffel, et al., *Nat. Hazards Earth Syst. Sci.* **18** (12), 3235–3251 (2018).
4. A. S. Turchaninova, S. A. Sokratov, Yu. G. Seliverstov, et al., *GeoRisk* **14** (1), 38–47 (2020).
5. J.-T. Fischer, A. Kofler, A. Huber, et al., *Geosciences*, No. 10 (5), 191 (2020).
6. E. Kazakova, V. Lobkina, Y. Gensiorovskiy, et al., *Nat. Hazards*, No. 88, 237–251 (2017).
7. S. M. Kozik, *Calculation for Snow Avalanche Motion* (Gidrometizdat, Leningrad, 1962) [in Russian].
8. *Registry of the USSR Snow Avalanches*, Vol. 16: *Siberia and Far East* (Gidrometeoizdat, Leningrad, 1991) [in Russian].
9. *Avalanches Geography*, Ed. by S. M. Myagkov and L. A. Kanaev (MSU, Moscow, 1992) [in Russian].
10. “Zapolyarnaya Pravda” Newspaper. <https://gazetazp.ru/news/gorod/34139n-v-norilске-pod-snejnoy-lavinoy-postradal-chelovek.html>; <https://gazetazp.ru/news/gorod/14079n-v-tsentre-tal-naha-podrostok-popal-v-lavinu.html>.
11. Snow Avalanches. Russian National Atlas. <https://national'nyiatlas.rf/cd2/234-236/234-236.html>.
12. Official Website of Norilsk City. <https://norilsk-city.ru/>.
13. <http://www.pgc.umn.edu/data/arcticdem/>.
14. *Scientific and Applied Handbook of the USSR Climate*, Ser. 3: *Long-Term Data*, Parts 1–6, Iss. 21: *Krasnoyarsk Territory. Tuva Autonomous Soviet Socialist Republic* (Gidrometeoizdat, Leningrad, 1990), Books 1, 2 [in Russian].
15. Resource of Actual Meteorological Information on the Russian Territory. https://rp5.ru/Arkhiv_pogody_v_Noril'ske.
16. NGS24. <https://ngs24.ru/text/incidents/2021/01/10/69685551/>.

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