A SUCCESSFUL ATTEMPT TO INTRODUCE THE PROTECTIVE DAMS INTO SNOW AVALANCHES SIMULATIONS BY RAMMS IN THE KHIBINI MOUNTAINS, RUSSIA

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ABSTRACT: Snow avalanches are the most pronounced natural hazards in Khibini Mountains (Northwest of Russia, Arctic). In this study the back-calculations of well-documented avalanches in the original avalanche tracks (Mt. Ukspor site) using “historical” DEM and simulations with the present-day DEM with two avalanches protection dams incorporated were performed. In the latter case RAMMS was applied to simulate two artificially triggered powder avalanches that have unexpectedly overshot the two catching dams situated perpendicular to the flow on February 18, 2016. The event resulted in 3 victims. While it is not recommended to apply RAMMS for simulating avalanches over dams lying perpendicular to the flow, in this case the RAMMS reproduced the observed avalanches behavior and runout distance successfully. Moreover, the avalanche risk in the area taking the presence of catching dams into the account was assessed. Full social risk values were calculated separately for three different zones depending on the type of land use and characterized by different density of people as well as the duration a personal stay in an avalanche-prone zone during the day. The results demonstrate the necessity of reconstruction of the present avalanche protection system to prevent the loss of human lives and the damage of infrastructure in future.

KEYWORDS: avalanche protection, numerical modeling, RAMMS, avalanche risk, Arctic

1. INTRODUCTION

The Khibini Mountains are located behind the Polar circle in the Northwest of Russia and snow avalanches are widespread in there. The industrial development of the region was first carried out without avalanche hazard considered. However, after the avalanche disaster in the town of Kirovsk in December 1935 claimed 88 lives (Zuzin, 2006), the event and the area became a starting point for active avalanche science development in the former Soviet Union. Various mitigation measures were tested by the avalanche service of the mining industry, and several avalanches catching dams have been constructed as the least expensive measure for the region with plenty of refuse heap.

The avalanche dams’ construction experience in Khibini Mountains came from the experiments of Goff and Otten (1936). For now, the avalanche protection measures including the dams must be designed in Russia by standard engineering procedures (SP…, 2012). SP… (2016) shows the territories of Russia where results of the engineering surveys on snow avalanche danger are the must for approval of the construction of an infrastructure. However, the are no official regulations on the actual calculations of the characteristics of snow avalanches to be stopped by such dams, and the calculation are normally based on the simplest one-dimensional avalanche models scattered over years in various departmental documents. Also, there are no requirements of reevaluation of an effectiveness of existent mitigation measures possibly changing due to human or natural factors during the long-term operation period.

In this research, we apply the Swiss avalanche dynamics program RAMMS (Christen et al., 2010; Bartelt et al., 2017) to simulate snow avalanches in the Khibini Mountains. The idea was to test the capabilities of two-dimensional avalanche dynamics model RAMMS to simulate the interaction of avalanches with catching dams as well as to reproduce the avalanche flow behavior after transition through a dam. The test was done with the artificially triggered and well-documented avalanches (February 18, 2016) from the Mt. Ukspor, that unexpectedly overshot two lying perpendicular catching dams (3 fatalities). In addition, we assess the avalanche risk in the research area taking the recent state of mitigation structures into account.

2. KHIBINI MOUNTAINS

Khibini Mountains are the small mid-mountain massif (30×45 km). The highest point is 1200.6 m a.s.l. The relative altitude of the slopes rare exceeds 500–600 m; the altitudes of the plateau-like peaks vary within 900–1200 m.

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The climate of the region (located between 67–68° N) is characterized by a long winter with low air temperatures. The average precipitation amount is 1000–1500 mm (more than 50% fall during the winter seasons). The snow cover height can reach 1–2 m in the valleys and 2–3 m on the plateau (up to 5 m due to the wind redistribution). The average annual air temperature goes down from −0.2 °C in the town of Kirovsk (400 m a.s.l.) to −4,9 °C on the plateau Lovchorr (1091 m a.s.l.) (Zuzin, 2006). The average air temperature of the coldest month January is −13 – −15 ºC in the mountains. Avalanches of all types can occur in these climate conditions. About 80% of avalanches release during a blizzard or snowfall. Avalanche hazard period lasts 8 months and can be longer.

Snow avalanches are among the most significant natural hazards in the Khibini Mountains. Since 1935 to 2017 the snow avalanches took the lives of 170 victims (120 locals and 50 tourists). The constant growth of winter sports and tourism, and therefore the increased avalanche hazard and risk are taking place in the Khibini Mountains.

Since 1936 in the Khibini Mountains the wide range of avalanche protection measures is applied as well as the most accurate quantitative data on snow avalanches is collected. The avalanches catching dams together with the artificial triggering play a major role in avalanche protection in the region.

3. MT. UKSPOR SITE

Three avalanche tracks (№ 21–23, see Figure 1) are located on the northwest slope of the Mt. Ukspor. Every year, numerous dry and wet snow avalanches fall on the Mt. Ukspor 30–40º slopes belonging to the territory of the town of Kirovsk. Avalanche tracks are from the top of the Mt. Ukspor (846 m a.s.l.) to the valley bottom (300 m a.s.l.). While the № 21 avalanche track is an open slope, the № 22–23 are channeled. The runout zones of №21–23 tracks are partly forested (standing along firs). Avalanche formation is observed from November till May. The biggest avalanche disaster in the region with 88 fatalities in December 1935 took place in № 22 avalanche track. The volume of that avalanche was 57,000 m^3 (Zuzin, 2006). Regular avalanche observations have been started in the Mt. Ukspor site since the end of 1930th and are carried out up to now.

3.1. Avalanche protection

Artificial avalanche triggering was used since the end of 1930th to prevent large avalanches in the research site. Nearly half of all recorded avalanches were artificially triggered by the avalanche warning service (46%) or technical explosions on the neighbored mine (4%) over this period. In the end of 1980th a system of 2 catching dams has been developed to protect the mining railway, road as well as five-floor houses built below. The first dam had to reduce avalanche velocity. Then the avalanche had to fall to the avalanche catchment sink where lose the main mass and energy. The second higher dam was the third line of protection against extreme avalanches (Zuzin, 2006). The initial characteristics of dams are unknown. The avalanche protection system has been damaged during the long-term operation. Characteristics of catching dams in 2015 were: first dam – length 250 m, width 35 m, height 10 m; second dam – length 550 m, widths 55 m, height 17 m. Due to the damage of this avalanche protection system an artificial avalanche triggering has begun to be applied again above the dams.

Figure 1: Mt. Ukspor: avalanche tracks №21-23.

3.2. Testing of RAMMS

The avalanche dynamics program RAMMS (Christen et al., 2010; Bartelt et al., 2017) was used to back-calculate 5 well-documented artificial avalanches with volume from 26,000 up to 42,500 m^3 recorded in the № 22 avalanche track before the avalanche protection structures construction between 1974–1987. These avalanches have been chosen due to their medium volume (no evidences of large volume avalanches were found) and the existence of detailed descriptions. We used 5 m resolution DEM without avalanche protection system which was prepared by digitizing large-scale topographic map from 1970–1980th. As the input, we specified the observed release zones as well as fracture heights. Variable friction parameters (μ and ξ) were automatically calculated in RAMMS using GIS-based terrain analysis. The entire calculation domain was below 1000 m.a.s.l. We tried two different scenarios: (1) friction values (μ and ξ) as recommended for Switzerland (Bartelt et al., 2017); (2) friction values (μ and ξ) as we found to be more accurate in reproduction of the observed snow avalanches characteristics in Khibini Mountains (Turchaninova et al., 2015), corresponding to the upper altitude limit “above 1500 m a.s.l.” of the table for Switzerland (Bartelt et al., 2017). The avalanches runout distances were significantly underestimated (up to 100 m) when we used (1) scenario. Much better level of correspondence of the observed and the simulated avalanches was found when we used (2) scenario (see Figure 2). The runout distances of 3 avalanches were predicted well. The runout distances of 2 avalanches were overestimated (from 40 m up to 150 m). The maximum velocity (38 m/s) of an avalanche recorded in 1974 was reproduced well. The maximum observed avalanche deposition heights were from 1.6 up to 3 m while the modelled values were from 2.1 up to 2.7 m.

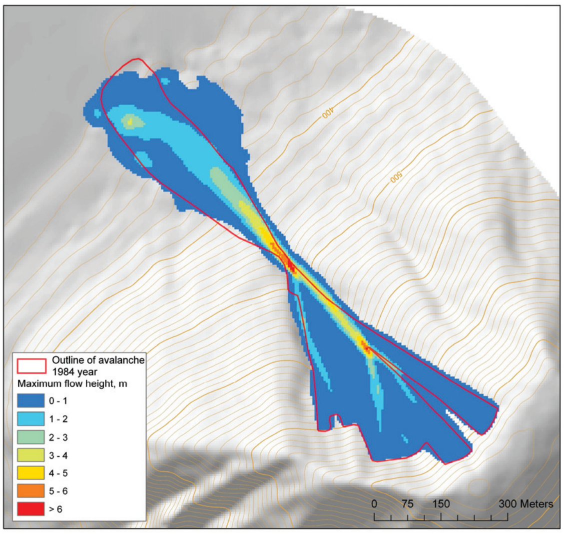

Figure 2: Calculated maximum flow height of an avalanche recorded in 1984 in the № 22 avalanche track.

4. CASE STUDY AVALANCHES BACK-CALCULATION USING RAMMS

On the evening of 18th of February 2016 two artificially triggered dry avalanches (see Figure 3-4) accompanied by a powder cloud overshot two catching dams, the railway line and the road. Avalanches were triggered after a snowfall which began on the 5th and continued till the 17th of February and deposited 158 mm of precipitation. The snowfall was followed by a blizzard finished on the 18th of February, which prevented the artificial triggering before that and caused significant snow redistribution increasing the snow height in the release zones. The artificial avalanche triggering has been done during the first possible day after the blizzard. While avalanches were triggered by detonating explosive charges in 2 release zones (№ 22–23), 3 zones (№ 22–23, № 21 in part) released together. The avalanches flowed down in two different arms and an open slope (see Figure 4). The west arm reached the five-floor houses. This allowed an exact positioning of the runout distance. The powder cloud caused damage to the houses – the windows were broken. The estimated release volume of avalanche from № 21–22 release zones was ~ 167,000 m^3. The railway line was barred by the avalanche deposits over 190 m. The estimated release volume of avalanche from № 23 release zone was ~ 40,000 m^3.

Figure 3: The powder cloud of the case study avalanches. Photo by Vachmistrov B., 2016.

4.1. Simulation set-up

We performed simulations with an accurate 5 m resolution DEM (terrestrial laser scanning, summer 2015) including recent-state of mitigation structures. As input we specified the observed release zones as well as fracture heights. The mean fracture heights of 0.8 m (release zones № 21–22) and 0.5 m (release zone № 23) were used for the back-calculation of avalanches, resulting in release volume: of ~ 167,000 m^3 in № 21–22 release zones; of ~ 40,000 m^3 in № 23 release zone. The influence of the forested terrain was not considered, since we assumed that the trees growing on the Ukspor site didn’t decelerate the avalanche. We set: the flowing avalanche density to ρ=300 kg/m^3; the calculation grid to 5 m. The avalanche return period was assumed as 100 years based on the avalanche data analysis in the test site since the end of 1930th.

We simulated avalanches with the automatically generated variable friction coefficients. There is no information about friction coefficients representing large avalanches (volume > 60,000 m^3) in the site. Therefore we computed two different scenarios similar as above: (1) scenario – friction values (μ and ξ) representing large avalanches with 100 years return period as recommended for Switzerland (Bartelt et al., 2017) – the automated procedure found values between 0.18≤μ≤0.31 and 1200≤ξ≤3000 m/s; (2) scenario – friction values (μ and ξ) representing large avalanches with 100 years return period as found by Turchaninova et al. (2015) for the Khibini Mountains – altitude limit “above 1500 m a.s.l.” (Bartelt et al., 2017) – the automated procedure found values between 0.17≤μ≤0.28 and 1500≤ξ≤3000 m/s.

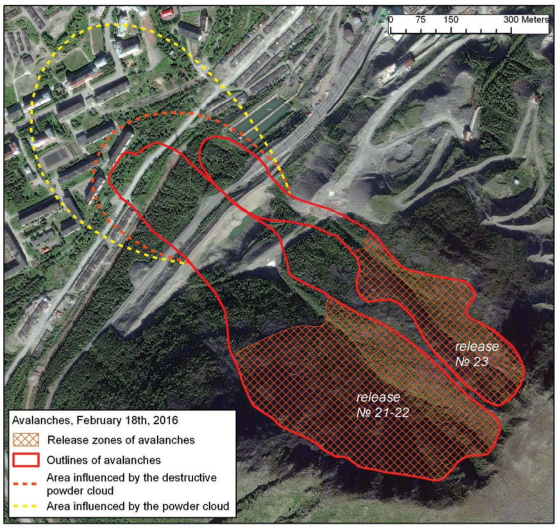

Figure 4: Case study avalanches.

4.2. Simulation results

Unlike to the previous experience of using RAMMS in the Khibini Mountains the model could reproduce in general the case-study avalanches only with the (1) scenario (see Figure 5). The runout distance of avalanches could be simulated with the 100 years return period with friction coefficients as recommended for Switzerland (Bartelt et al., 2017).

The maximum simulated avalanche characteristics are: flow velocity – 40 m/s; impact pressure – 474 kPa; flow height – 27 m; deposition height – 12 m. The simulated avalanche, as well as the real one, crossed the system of 2 catching dams, the railway and the road and stopped near the wall of the house. However, RAMMS predicted more lateral spreading of the avalanche flow. As it was observed the dams partially caught the avalanches and reduced their characteristics. Maximum calculated velocity of 40 m/s show good agreement with the value (38 m/s) measured in the № 22 avalanche track by V.A. Samoylov (1976).

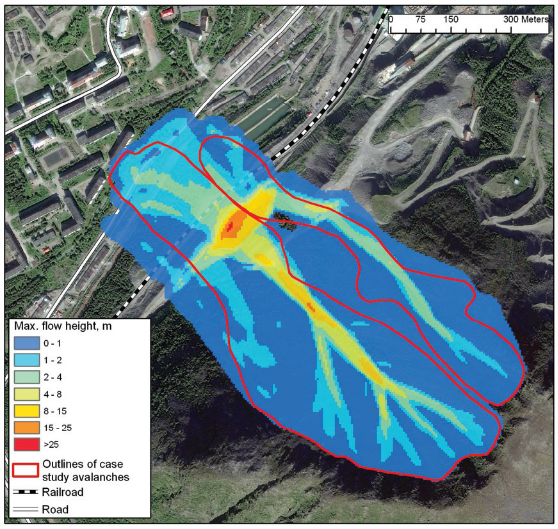

Figure 5: Maximum flow height of case study avalanches calculated in RAMMS using (1) scenario.

The avalanches flow behavior could not be simulated using the (2) scenario – with the 100 years return period and friction coefficients as we earlier recommended for Khibini Mountains. Runout distance was overestimated (over 180 m, see Figure 6). The maximum predicted avalanche characteristics are: flow velocity – 46 m/s; impact pressure – 644 kPa; flow height – 19 m; deposition height – 6 m.

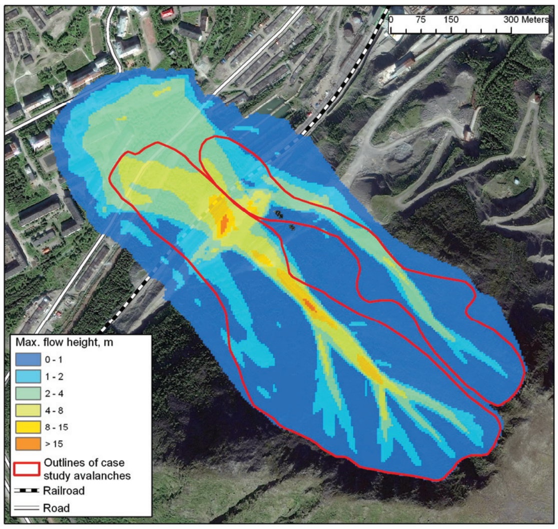

Figure 6: Maximum flow height of case study avalanches calculated in RAMMS using (2) scenario.

5. AVALANCHE RISK ASSESSMENT

Avalanche risk assessment in the Mt. Ukspor site was based on the approach developed by Komarov et al. (2016). Full social avalanche risk characterizes the expected average number of people killed in avalanches during the year within the study area. Individual risk represents the risk situation related to the probability of premature death of an individual in the study area.

Full social risk values were calculated separately for three different zones dedicated manually depending on the land use type (urban, industrial, forested) and characterized by different density of people as well as by the duration a person's stays in an avalanche-prone zone during the day. Then, the avalanche risk values were summarized. The area of avalanche-prone zones was obtained using RAMMS simulations of 30 years and 100 years return period avalanches ((1) friction values scenario) including recent state of mitigation structure. RAMMS simulations proved by field observations show that the avalanches with the 10 years return period and the more frequent ones are stopped by the avalanche catching dams and don't endanger the people and infrastructure below the dams.

The full social risk value equals 4.4 persons per year for the whole research area. We assumed that the number of people within the research area (Kirovsk town, 25th district) is about 9940 based on the Federal State Statistics Service data. The total individual risk value equals 4.5×10^{-4}.

6. CONCLUSIONS

While RAMMS was calibrated for large-scale avalanches in Switzerland it produced realistic results with modified friction values in completely different conditions in the Khibini Mountains.

We confirmed the obtained earlier conclusion (Turchaninova et al., 2015) that the better-fit friction values (μ and ξ) for RAMMS in this region, despite the actual altitude is less than 1200 m a.s.l., may be taken from the upper altitude limit "above 1500 m a.s.l." of the table recommended for Switzerland (Bartelt et al., 2017) without avalanche dams in Nature and in the corresponding DEM.

However, the run-out distance of the two artificially-triggered avalanches, which crossed the two catching dams, was overestimated more than 180 m with such friction values. However, it was reproduced using the friction values recommended for Switzerland. RAMMS also reproduced realistic results with smaller and more frequent (10 years return period) avalanches. As it is observed they were totally stopped by two catching dams.

While it is not recommended to apply RAMMS for simulating the effect of a dam lying perpendicular to the avalanche flow direction (Bartelt et al., 2017), in this case the RAMMS could reproduce the observed avalanches behavior and the runout distance. The question of valid friction values remains open.

No one expected that the presented case study avalanches can cross the catching dams. However they did, and RAMMS clearly demonstrated that as well. Avalanche risk assessment results show that the avalanche mitigation system reconstruction must be done as soon as possible to protect the population and the infrastructure in Kirovsk. Until then the temporary avalanche protection measures must be used with care to prevent the loss of human lives in the research area.

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