USING SNOW REMOTE SENSING AND AVALANCHE SIMULATIONS TO INFORM THE PLACEMENT OF REMOTE AVALANCHE CONTROL SYSTEMS

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ABSTRACT: Snow avalanches regularly damage infrastructure and block transportation corridors in mountainous regions in Alaska, impeding access to natural resources and critical public services. In response to imminent mandatory retirement of the avalanche mitigation artillery program, avalanche safety programs across the country are now challenged with finding new solutions to mitigate snow avalanche hazards. Remote Avalanche Control Systems (RACS) offer a slope-based alternative avalanche mitigation option, but system deployments are most successful when design and operational decision making is supported by local snow distribution data and accurate predictions of avalanche dynamics. In a collaborative project with Alaska Railroad Corporation (ARRC), we assessed the proposed placement of RACS towers in a prominent avalanche path ("Door 4") along the railroad west of Whittier, Alaska. The project consisted of near-peak snow height aerial lidar surveys for winters 2020/2021 and 2021/2022 and avalanche simulations using Rapid Mass Movement Simulations (RAMMS) to investigate the destructive potential of avalanches released at the proposed RACS locations, and to assess the potential damage (impact pressure of moving snow from above) at the proposed RACS tower sites. Results from the lidar campaigns show a consistent snow distribution pattern in the Door 4 avalanche release areas, with highly variable snow depths from 0 m to 10 m. Most of the initially proposed tower locations target the deeper pockets of snow, suggesting ideal placement. However, simulated avalanche impact pressures for both wet and dry avalanches, from empirically derived and modeled potential release areas, led to location changes for some of the proposed RACS tower sites. This study demonstrates the importance of identifying patterns in snow distribution and simulating avalanche dynamics to strategize RACS tower placements prior to installation to optimize mitigation efforts and minimize damage to towers.

KEYWORDS: Avalanche modeling, Remote Avalanche Control Systems, Remote Sensing, Lidar, Snow Mapping

1. INTRODUCTION

Snow avalanches are a significant cryosphere hazard in mountainous areas around the world. In Alaska, snow avalanches affect an estimated 30 percent of the state, significantly impacting the natural landscape and gaining the title of the deadliest natural hazard (Alaska Division of Homeland Security and Emergency Management, 2023). Avalanche activity in Alaska regularly damages or destroys infrastructure and blocks transportation corridors, impeding access to natural resources and critical public services.

In the Western United States there are currently 39 Howitzer weapons in use for avalanche mitigation by 16 avalanche safety programs (Figure 1). The U.S. Army has informed all 16 user organizations that the Howitzers will be retired, though the time frame is currently undetermined. There are several reasons behind the decommissioning of the Howitzer program: (1) the advanced age of

Figure 1: Howitzer in use at Door 4. Photo courtesy of Alaska Railroad Corporation.

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the weapon; (2) the lack of personnel to inspect and maintain weapon; (3) the limited availability of point-detonating fuses; (4) the artillery system that was set aside to replace the current Howitzers was sent to Ukraine; and (5) technological advances have led to the development of new mitigation methods.

Remote Avalanche Control Systems (RACS) are infrastructure installed in or near avalanche starting zones that operate remotely to deliver a blast to the snowpack using gas or high explosives to trigger an avalanche. Even though RACS do not offer the ability to hit as many targets or shoot as frequently as the Howitzers, they do offer some benefits—they have better effect and are quicker and easier to use in frequently producing or high-consequence release areas. However, improperly located RACS can lead to expensive and potentially disastrous outcomes, for instance,

- an O'bellx system was destroyed by a skier-triggered avalanche above the I-70 highway in Colorado;
- in Colorado, a Gazex system was placed in what appeared like an ideal trigger location in the summer, only to find out in the winter the system was inoperable as it was in an area of cornice development and buried under 10 m (30 ft) of snow; and
- in Utah, snow-buried Gazex exploders experienced ruptured explosion chambers when operation was attempted.

It is important that avalanche mitigation programs install the RACS in proper locations to target specific trigger points in the snowpack, optimize their use for various avalanche types and sizes, and limit avalanche mitigation system costs related to damage to the RACS or their required relocation. A proper assessment of snowpack distribution at the proposed site and an investigation of the potential avalanche threats to the proposed RACS is highly recommended *prior* to installation.

The Alaska Railroad Corporation (ARRC) has nine avalanche zones controlled by artillery with Howitzers. Like many places in Alaska, few baseline snowpack data exist in alpine areas along the railroad between Anchorage and Whittier. This knowledge gap impacts the understanding of avalanche dynamics and the placement of avalanche mitigation features and equipment. Twenty years ago, ARRC ceased artillery control at the 43 Mile avalanche path and installed two Doppelmayr Blaster Box towers. The next avalanche path in line for RACS installation is the "Door 4" avalanche path in the Portage Valley, west of Whittier (Figure 2). ARRC currently has 12 Howitzer targets that address the various release areas on the slope that all funnel into a large gully, which then crosses the railroad, Portage River and eventually the Portage Highway. Door 4 is a complicated and challenging avalanche path to understand due to its complex topography and variable snowpack. The frequently active release areas at Door 4 are located in the middle portion of the slope, and this area is targeted for RACS installation, leaving a lot of low angle terrain above the release areas where additional snow could accumulate.

In this study we assess the efficacy of the proposed RACS tower sites in the Door 4 avalanche path and evaluate threats to the system by considering the effect of snow distribution and the impacts of potential avalanches, sourced from above, on the planned tower locations.

To do this, we collected airborne lidar data for two winter seasons (2020/2021 and 2021/2022) to map snow depth distribution at Door 4. Then, we set up experimental avalanche scenarios using both empirically and geostatistically derived potential release areas (PRAs) and simulated these avalanche scenarios with varying snowpack depths and temperatures in the dynamical avalanche runout model Rapid Mass Movement Simulations (RAMMS) Extended (see Christen et al., 2010, for description). Based on our simulation results, we investigated the destructive potential of avalanches released at the proposed RACS locations, and we assessed the potential damage (avalanche impact pressure of moving snow from above) at the proposed RACS tower sites. Finally, we highlight some important take-away points from the modeling work and how the modeling results informed ARRC's decision-making for RACS sites.

Figure 2: A moving train crossing the Door 4 avalanche runout zone. Photo courtesy of Frank Keller.

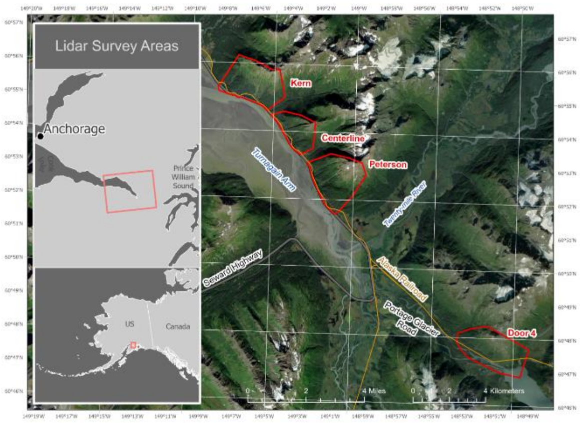

Figure 3: Location map of lidar survey areas within the Turnagain Arm–Portage study area.

1.1 *Snow depth distribution mapping*

While this paper is focused on the Door 4 avalanche path, we considered a broader region of avalanche paths for our snow mapping campaigns. Snow distribution was mapped in four areas within the Turnagain Arm–Portage study area (Figure 3) by collecting multiple epochs of aerial lidar data, building digital terrain models (DTMs), and differencing snow-on and snow-off DTMs. We conducted near-peak snow height aerial lidar surveys between Girdwood and Portage on 03/24/2021 and 03/15/2022. Bare-earth (snow-off) reference surfaces were developed from lidar data acquired on 10/16/2020 at the Kern–Centerline–Peterson areas, and we used lidar data provided by Water Science Institute (acquired in 2012) at Door 4.

We used a Riegl VUX1-LR laser scanner integrated with a global navigation satellite system (GNSS) and Northrop Grumman LN-200C inertial measurement unit (IMU) and operated the system from a Cessna 180 fixed-wing platform. The surveys were flown with a pulse refresh rate of 50,000 pulses per second in the alpine areas and 400,000 pulses per second over forested areas at a scan rate between 80 and 220 lines per second, and with an average elevation of 130 m above ground level and a ground speed of approximately 35 m/s. The scan angle was set from 80 to 280 degrees. The total area surveyed was approximately 25 km^2 (10 mi^2).

The lidar data were processed in SDCimport software for initial filtering and multiple-time-around (MTA) disambiguation. Inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) data were then processed in Inertial Explorer and integrated flightline information with the point cloud in Spatial Explorer software. Point data were calibrated at an incrementally precise

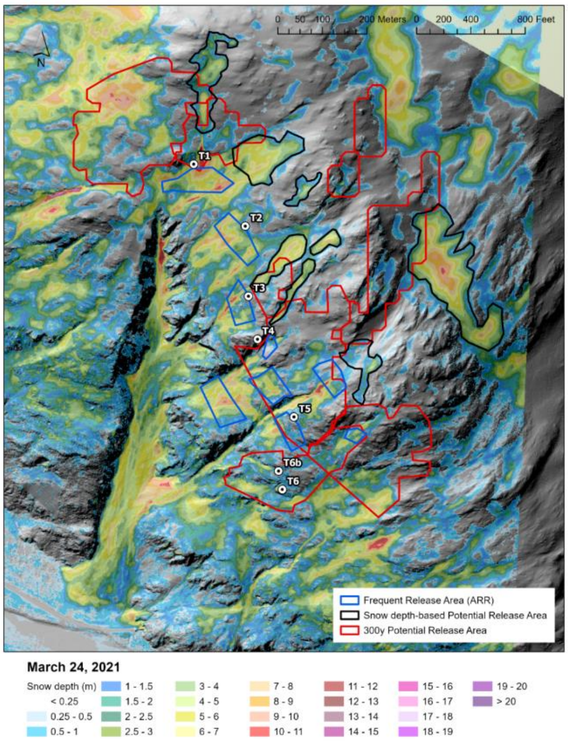

Figure 4: Frequent release areas, snow depth-derived PRAs, and geostatistically derived PRA polygons overlayed on March 24, 2021, snow depth at Door 4.

scale of sensor movement and behavior, incorporating sensor velocity, roll, pitch, and yaw fluctuations throughout the survey.

A total of 150 ground control points and check points were collected on paved surfaces along the Seward Highway and Portage Glacier Road on February 23 and October 16, 2020, to be used for calibration and assessment of the vertical accuracy of the lidar data. We derived 1 m raster products from the LAS point cloud using ArcGIS Pro and coregistered snow-on DTMs with the snow-off DTMs prior to differencing.

1.2 *Avalanche modeling in Door 4*

The RAMMS::EXTENDED model simulates both the avalanche core and the powder cloud, and includes snow entrainment and other processes such as temperature evolution. The model also includes impact pressure modules for both the avalanche core and powder cloud to better determine external avalanche loads on both wide (buildings) and slender (pylons) structures, such as RACS towers (see Christen et al., 2010). Avalanche simulations were addressed in two phases.

In Phase 1, we used the frequent release areas identified by ARRC avalanche specialists as input to investigate the destructive potential at the railroad from avalanches released at future RACS sites (Figure 4). We also increased the extent of the frequent release areas based on the 2021 lidar-derived snow depth data and ran the same set of scenarios with the larger release areas. We ran sensitivity tests for 0.5 m, 1 m, and 2 m release depths, and for cold (-5 °C), moderate (-3 °C), and warm (0 °C) snowpack temperatures. Testing the flow behavior for moderate snow temperatures allowed us to identify where terrain factors play a dominant role in enhancing avalanche flow (Vera Valero et al., 2015).

In Phase 2, we used two types of PRAs as input in RAMMS::EXTENDED: (1) geostatistically derived PRAs that represent release area extent of a 300-year extreme snowpack scenario (Bühler et al., 2018); and (2) empirically derived PRAs delineated over deep pockets of snow from the 2021 snow depth data collection (Figure 4). In this simulation phase, we also included ARRC's 'AG 21' and 'Tower 5' release areas since they are both located above other proposed RACS tower locations. We simulated fracture depths at 1 m, 3 m and 5 m at -5 °C and 0 °C snowpack temperatures in the release area.

For each avalanche scenario in RAMMS, we analyzed the output of maximum flow height and maximum core obstacle impact pressure in ArcGIS Pro using the Zonal Statistics tool for zones of interests. For Phase 1, the zone of interest was the railroad tracks (polygon feature), and for Phase 2 the zone of interest was the proposed tower locations (point features).

2. RESULTS

2.1 Snow depth distribution

For this paper we explore the snow depth distribution at the Door 4 avalanche path. Overall, the snowpack was deeper at mid-elevations in March 2021 compared to March 2022, but at higher elevations it was deeper in 2022. In 2021, the avalanche runouts were longer and showed a deeper debris pile, indicating transport of snow from release areas to deposition zones, supporting the observation of less snow in the higher elevation/release areas compared to 2022 (Figure 5). The two surveys show a consistent snow distribution pattern in the higher elevations of the avalanche path with highly variable snow depths from 0 m to 10 m (Figure 6).

2.2 Destructive potential from avalanches released from the frequent release areas

The results from Phase 1 avalanche modeling enabled us to discern which release areas can produce destructive avalanches. Shallow instabilities

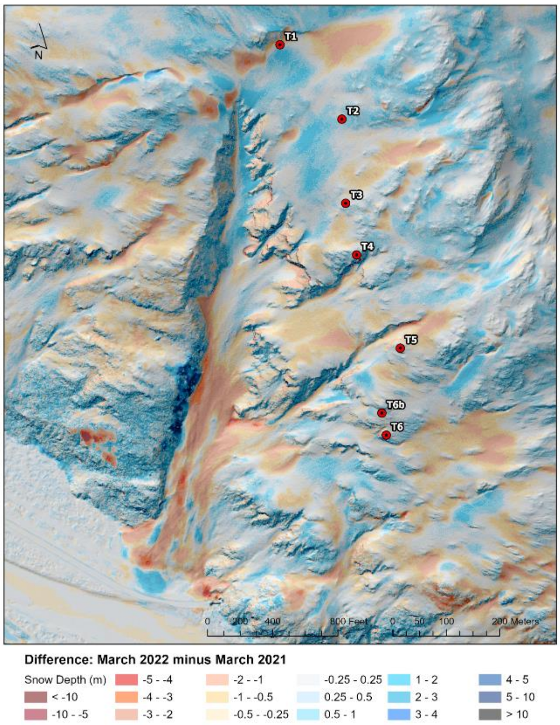

Figure 5: Difference in snow depth distribution between March 24, 2021, and March 15, 2022. T1-T6b are proposed RACS locations.

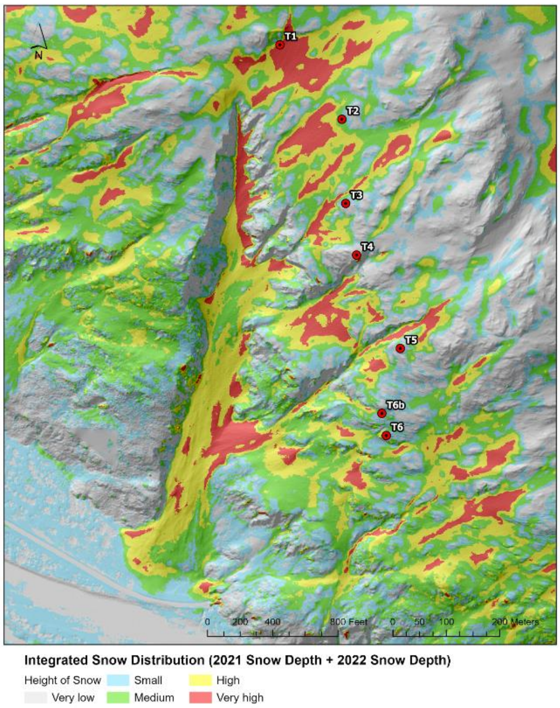

Figure 6: Integrated snow distribution at Door 4 avalanche path categorized by height of snow. Height of snow from 03/24/2021 was added to height of snow from 03/15/2022 to show an index for snow depth distribution over two winter seasons. < 0.5 m = very low, 0.5–2 m = small, 2–5 m= medium, 5–10 m = high, and 10–15 m = very high.

resulting in release depths of less than 1 m yield smaller release volumes, whereas larger release volumes are generated when deeper instabilities are prevalent that can produce far-running, destructive avalanches. All scenarios with a release depth of 2 m or greater produced avalanches that reached the railroad, with one exception: ‘AG 21 low’ stopped short of the railroad tracks when simulated with a release temperature of -3 °C. To determine destructive potential, we refer to the Swiss guidelines of maximum impact pressures, where 30 kPa is considered the maximum impact pressure that a building can withstand before it is damaged (BFF/SLF, 1984). Velocities > 25 m/s were also used to assess destructive avalanches and potential damage on RACS anchoring. We categorized our large dataset (n=423) into three classes: (1) did not reach the zone of interest; (2) reached the zone of interest but with impact pressure < 30 kPa; and (3) reached the zone of interest and with impact pressure > 30 kPa.

We highlight the following results:

- Cold (-5 °C) and warm (-1 to 0 °C) scenarios produced the longest runout distances and the largest values of flow height and impact pressure across the railroad tracks;
- Scenarios with release temperature -3 °C or -5 °C with dT 0.5 °C (stronger elevational temperature gradient) produced shorter runout and lower impact pressures across the railroad tracks;
- None of the scenarios from ‘Tower 6’ release area reached the railroad tracks;
- All scenarios with a release depth of 2 m produced avalanches that reached the railroad, except ‘Tower 6’ and ‘AG 21 low’ with a release temperature of -3 °C;
- For the scenarios with a release depth of 1 m, ‘Tower 1’, ‘Tower 2’, and ‘Tower 5’ reached the railroad tracks but only with warm release temperatures (-1 °C or 0 °C);
- ‘Tower 3’ was the only release area that with 1 m release depths could produce avalanches that reached the railroad regardless of release temperature and with impact pressures exceeding 30 kPa; and
- None of the scenarios with a release depth of 0.5 m reached the railroad tracks (release volumes < 10,000 m³).

2.3 Potential avalanche impact on proposed RACS tower sites

We summarized the results from Phase 2 (n=107) in a box and whisker plot to show avalanche scenarios that hit the proposed RACS towers with a maximum impact pressure exceeding 30 kPa (Figure 7). All other scenarios are excluded as they (1) did not hit the tower, or (2) hit the tower but with a maximum impact pressure less than 30 kPa. None of the 300-year modeled PRA scenarios with 1 m release depth resulted in impact pressure exceeding 30 kPa at the proposed RACS sites; impact pressures > 30 kPa were only generated by larger release volumes (release depth 3 m and 5 m). ‘Tower 2’ was the only site with no impact pressures exceeding 30 kPa (Figure 7). All the other sites received higher pressures and maximum flow velocities exceeding 25 m/s for most of the scenarios at impact. ‘Tower 3’ and ‘Tower 4’ only got impacted by > 30 kPa avalanches during warm (0 °C) snowpack conditions.

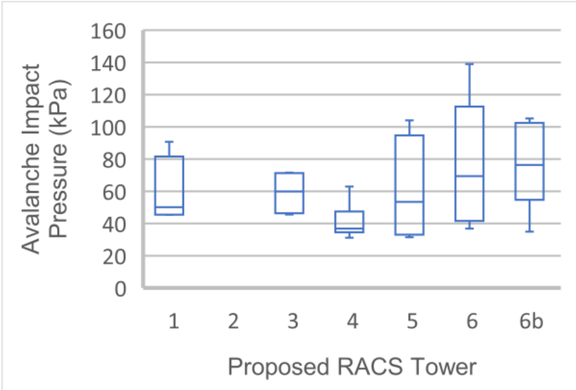

Figure 7: Box and whisker plot showing the distribution of avalanche impact pressures exceeding 30 kPa recorded at proposed RACS tower sites. The box shows the Q1–Q3 distribution, where the horizontal line is the median pressure and whiskers show the min/max values (kPa).

The 300-year modeled PRAs yield substantial release volumes; the smallest one has a release volume of ~61,400 m^3 with 3 m release depth, which is considered a large to very large avalanche, and not including entrained snow. Releases from two of the modeled 300-year PRAs impacted several tower sites within their reach. These extreme PRAs are possible to form given the largely terrain-specific parameters typical for avalanche release areas but are also restricted by snowpack availability.

Only a few of the snow depth-derived PRA scenarios impacted the tower sites and only with warm (0 °C) snow release conditions. In addition to simulating avalanches from the modeled 300-year PRAs and snow depth-derived PRAs, we simulated avalanches from the ‘AG 21’ and ‘Tower 6’ frequent release areas, located above proposed RACS Tower 5, 6, and 6b. All avalanches released from ‘AG 21’ hit Tower 5 but remained < 30 kPa for all releases with release depths of 3 m or less, and 38 kPa (26 m/s flow velocity) was recorded at Tower 5 from a wet flow avalanche of 5 m release depth. The frequent ‘Tower 6’ release area is within the extent of one of the modeled 300-year PRAs. Avalanches released from ‘Tower 6’ release area did not hit proposed Tower 5 or Tower 6b, but affected Tower 6, though with impact pressures < 10 kPa and flow velocities < 25 m/s.

2.4 *Avalanche impact on modified Tower 1, 4, 5, and 6 sites*

After reviewing photos of Tower 1 release area that resulted in a destructive avalanche in 2009 that crossed the railroad tracks, took out the powerline, and even covered the highway, ARRC proposed to move the proposed site for Tower 1 ~40 m downslope and ~30 m westward from the old site (Figure 8). We compared the maximum impact pressures for the old and the new site in our modeling scenarios. For the snow depth PRA scenarios, the avalanche impact results varied at the two sites, and we did not find a correlation between release volume or snow temperature and the avalanche impact pressure at the new vs. old tower site. The old site was worse impacted by scenarios released from one of the 300-year modeled PRAs, and the new site was worse impacted by a different 300-year PRA. While the number of worse impacts was equal for the two sites, for most of the scenarios where the old site was worse, the impact pressure was also much higher, which suggests more damage potential at the old site. In addition, 17% of the scenarios showed complete tower avoidance at the new site.

To lower the avalanche hazard exposure at Tower 5 from frequent release area ‘AG 21’, this site was moved ~50 m south (downslope) and ~5 m west (Figure 8), which puts it further away from the gully. We analyzed the percentage change in maximum impact pressure at the new vs. the old Tower 5 site and the results were variable: reduced by ~50% or more for avalanches released

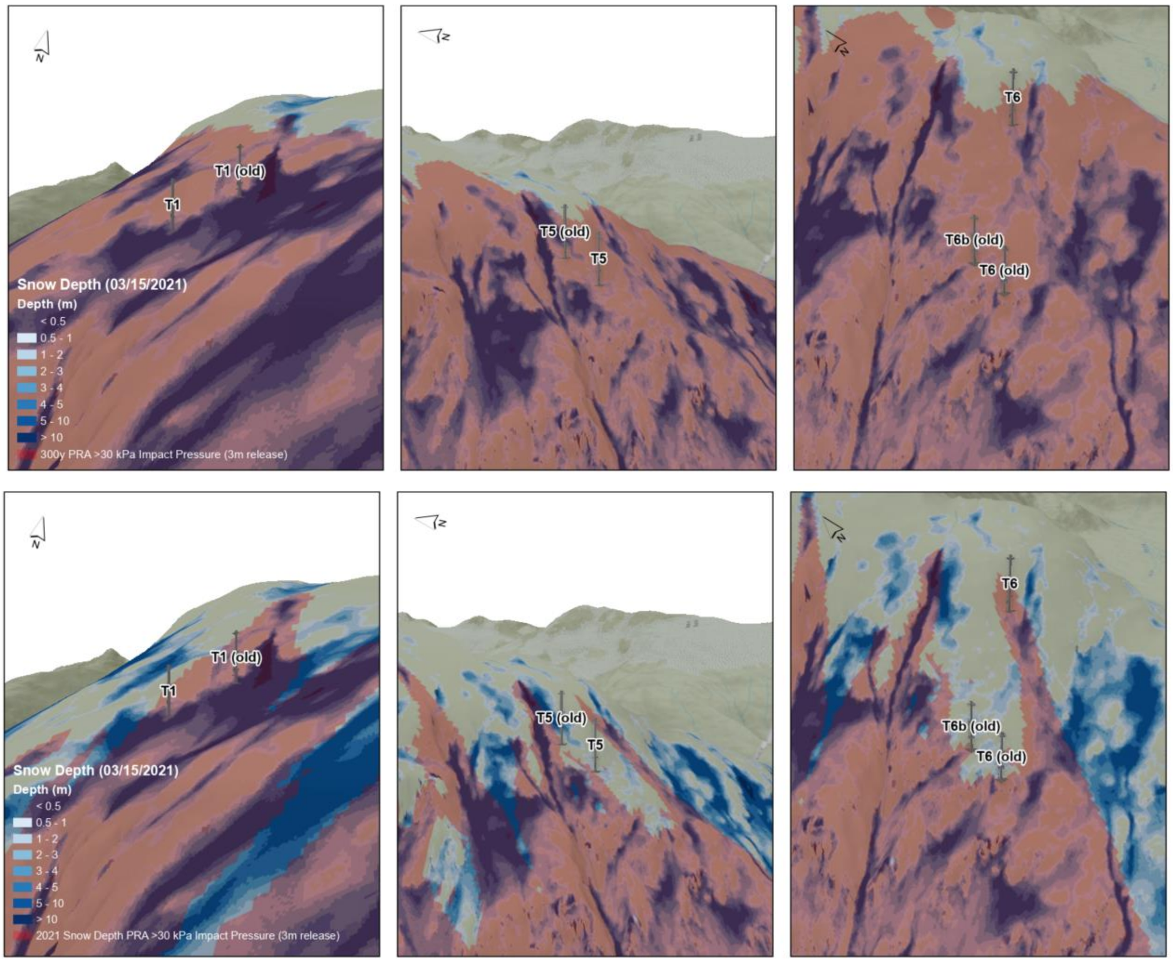

Figure 8: (Upper panels) Extent of avalanche runout with impact pressure > 30 kPa released from 300-year modeled PRAs and a 3 m release depth overlaying March 24, 2021, snow depth. (Lower panels) Extent of avalanche runout with impact pressure > 30 kPa released from 2021 snow-depth derived PRAs and a 3 m release depth overlaying March 24, 2021, snow depth.

in one of the modeled 300-year PRAs but increased for two of the other PRAs. For the snow depth PRA scenarios, the results were improved in some scenarios, but worsened in some of the others, and no relationship between snow volume and temperature was found.

Based on the Phase 2 modeling results, which suggested a concerning exposure to avalanches at the proposed Tower 6 and alternative 6b sites (Figure 7), these sites were eliminated from construction plans completely. The new Tower 6 site is located ~170 m upslope (north) and ~135 m east of the old Tower 6 site (Figure 8) and targets the deep pocket of snow that accumulates in the upper part of the gully (frequent release area Tower 6) that was obvious in the snow depth data from both seasons (Figure 6) and was also detected as a likely PRA by our 300-year geostatistical PRA algorithm (Figure 4).

In addition to the modified Tower 1, 5, and 6 sites, modifications were also made to Tower 4 after reconsidering the type of RACS design needed to address four separate release areas. The new Tower 4 is located on a rock outcrop ~45 m south and ~25 m east of the old Tower 4, optimized for the specific design of the new RACS tower. The change in location meant complete avoidance of the snow depth PRA located above the tower. For the 300-year modeled PRAs located above the old and new Tower 4, the results of the comparative analysis were variable; like the other tower modifications, the results significantly improved (lower impact pressures or completely avoided) for some scenarios but worsened (higher impact pressure) for others.

The results of the site modifications highlight the importance of researching each PRA and its likelihood of forming during different snowpack conditions.

3. DISCUSSION

3.1 *Snow depth distribution patterns*

The snow depth distribution maps at Door 4 show evidence of strong influence from wind, with patterns of wind scouring (close to zero snow depth) and wind deposition on the leeside of features (Figure 5-6). Apart from showing areas of avalanche deposition, the snow depth change maps also depict areas of released/unreleased snow in the alpine, which highlight the complexity and the critical role that avalanches play in redistributing snow in this complicated topographic setting. Results from both lidar survey years at Door 4 show a consistent snow distribution pattern in the higher elevations of the avalanche path with highly variable snow depths from 0 m to 10 m (Figure 6). The proposed tower locations target the deeper pockets of snow, suggesting ideal placement.

3.2 *Identifying extreme potential release areas in Door 4*

Some of the geostatistical 300-year PRAs are very extensive areas. With release depths of 3 m or 5 m, their release volumes (220,000 m^3 to 365,000 m^3) would be classified as beyond extremely large avalanches (> 100,000 m^3 or Size 5). The snow depth distributions from March 2021 and 2022 showed that major parts of these areas lacked snow cover entirely, as they were significantly wind-scoured. Because their extents differ from the 2020/2021 and 2021/2022 snow depth distributions, we believe that such extensive release areas are extremely unlikely to form at depths of 3–5 m. However, Door 4's topographic characteristics suggest that their formations are possible and should therefore be considered during extreme avalanche cycles (300-year) in years with abnormal and shifting wind patterns; further, possible future climate scenarios could produce more intense precipitation events (see e.g., Kotlarski et al., 2023 for anticipated future changes in winter precipitation and subsequent avalanche activity).

3.3 *Prioritization strategy for RACS tower placement and detonation*

With the installation of six permanent RACS structures at Door 4, avalanche specialists at ARRC still must strategize and prioritize when to detonate a charge. Though the installation cost for RACS structures is the major expense, detonating a load at every snowpack instability quickly becomes costly as well. An important objective of this project was to investigate if some of the frequent release areas targeted by these RACS structures deserve more attention than others because of their ability to produce destructive avalanches with small release depths.

In Phase 1 of this project, we tested for both cold (-5 °C), moderate (-3 °C), and warm (0 °C) snowpack temperatures to investigate if some avalanches tend to run far regardless of flow regime. Previous research studies have shown that avalanche releases with neither cold (~ -5 °C) nor warm (> -1 °C) average snow temperatures, i.e., around -3 °C, tend to not fully develop a fluidized or lubricated flow regime, but rather display a dampening behavior after entraining warmer snow in lower elevations and often stop shorter than beforementioned colder and warmer avalanche types (Vera Valero et al., 2015). Testing the flow behavior for this specific snow temperature (-3 °C) therefore allowed us to identify where terrain factors play a dominant role in enhancing avalanche flow at Door 4.

Based on our modeling results from Phase 1, Tower 3 deserves careful attention; a shallower weak layer (down 1 m in the snowpack) in the release area can cause an avalanche that would hit the railroad track and impact infrastructure or a moving train regardless of snowpack temperature. The modeling results for Tower 3 illustrated the delicate interplay of snow variables (such as snow volume and temperature) and terrain (slope steepness, curvature, etc.) in generating destructive avalanches during less obvious snow instability conditions. Based on the surprising but convincing results, the decision to add Tower 3 was cemented. We believe that the topographic features (rock band/cliff) right below the 'Tower 3' release area plays a critical role in the fast acceleration of avalanches sourced from this area. This means that even smaller release volumes could transition into fast, highly fluidized or lubricated avalanches, both of which result in long runout distances and high impact pressures at the railroad tracks.

3.4 Model limitations

The results of this project are based on modeled avalanches that represent general avalanche flow behavior in RAMMS::EXTENDED (2.7.95). The simulated avalanches were restricted by the limited data available to this project and by the physical constraints in the specific RAMMS code version. For example, in the current version of RAMMS::EXTENDED (2.8.25) the powder cloud module has improved in regards to turbulence formation. Also, the core vs. powder impact pressure on obstacles have been better constrained. It is known that when the avalanche core hits an obstacle (for example, a tower structure) the avalanche core height will expand so the pressure at a specific point along the tower is reduced as a function of the expanded core height. To accommodate this, we applied a simple correction equation (Bartelt, pers. comm.) to the tower impact pressure results in this project. These impact pressure values are believed to be too high, and the newer version of RAMMS::EXTENDED generate more realistic impact pressures that compare to values measured in the field.

4. CONCLUDING REMARKS

In this project, we adopted a combination of aerial remote sensing, geospatial, and geostatistical analyses, and dynamical avalanche modeling to map snow depth distribution and model a large range of avalanche scenarios in a key avalanche path that endangers an important infrastructure corridor in Southcentral Alaska. At the Door 4 avalanche path, the results of this project will help avalanche specialists at ARRC to strategize the placement of future RACS towers and to prioritize specific areas during snowpack instabilities due to their destructive avalanche potential at the railroad tracks.

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