THE KEMANO T2 PROJECT AVALANCHE RISK MANAGEMENT PROGRAM

Greg Johnson[1], Mark Vesely[1],

[1] *6 Point Engineering, Nelson, BC, Canada*

ABSTRACT: The Kemano T2 Project (2016-2022) included completing a 16 km long water supply tunnel bored through the central Coast Mountains in British Columbia, Canada, to serve a hydroelectric power generation station at Kemano. The primary project worksite operated in the runout of a large avalanche path and was accessed by an 11 km long industrial road that crossed numerous high-frequency and large-magnitude avalanche paths. This project is an important case history for managing severe avalanche risk for industrial work sites in Canada.

Avalanches were identified as a critical project risk during the initial planning stages. The avalanche risk assessment encompassed the development of passive and active protection strategies. The passive mitigation approach included a large defection berm and a stopping wall. The active mitigation approach incorporated 11 Gazex remote avalanche control systems and a forecasting and control program.

This paper summarizes the avalanche risk management program. Key experiences include performing a risk assessment; and designing and implementing passive and active controls. Despite several close calls throughout the five winters of project execution, we maintained a record without injuries due to avalanches while concurrently minimizing infrastructure damage and closures to the access road and worksites.

KEYWORDS: Risk Assessment, Mitigation Design, Avalanche Control.

1. INTRODUCTION

The Kemano T2 Project (T2 Project) is an important case history for managing severe avalanche risk for industrial work sites in Canada. Avalanche risk was assessed and managed to support the construction of a secondary tunnel securing the water supply to the Kemano hydroelectric facility.

The remote T2 Project site lies within the Kitimat Ranges of the Coast Mountains of British Columbia, Canada (Figure 1). Tunnel construction was situated within the steep coastal Horetzky Creek drainage.

Our work focused on planning and operational aspects of avalanche mitigation through T2 Project construction over five winter seasons. During this period, workers and project infrastructure were exposed to avalanche hazard along the 11 km long industrial Horetzky Road and at the project's primary worksite, Horetzky Landing.

2. PROJECT LOCATION AND REGIONAL WEATHER

Located within the unceded traditional territory of the Haisla Nation, Kemano's name origin refers to the 'people of the rock.' The name is associated with the river that leads into the Gardner Canal, a Pacific Ocean Inlet along the British Columbia coastline. The Kemano hydroelectric facility receives water from the Nechako reservoir and provides power to an aluminum smelter in Kitimat and neighbouring communities.

The Kemano site is approximately 53 degrees north, 127 degrees west, and is 130 km inland from the open waters of the Pacific Ocean. Inlets lead to within seven kilometers of the site.

Regionally, winter weather patterns are severe due to latitude, unmodified Pacific weather systems, and the amplifying effects of local topography. The mountains abruptly ascend from sea level to over 2000 m, which promotes rapid orographic lift and intense precipitation rates in avalanche start zone elevations.

Situated in a maritime snow climate, the region receives some of the heaviest snowfalls in North America, with settled snowpack depths ranging from four to eight meters. Tahtsa Lake snow pillow station (1300 m), located east of the Horetzky Valley, averages 1200 mm of snow water equivalent annually. The accumulation profile shows steady gains beginning in late October and lasting until early May. Typically, October through December are the wettest months of the year. A drying trend occurs from January to May.

The project site experiences precipitation as a mix of snow and rain with heavy rainfall at lower elevations. Strong to extreme winds commonly occur at upper elevations. Periodically, outflow events trigger the eastward movement of Arctic air, inducing significant reverse loading events.

* *Corresponding author address:*
Greg Johnson, 6 Point Engineering,
202c-330 Baker St., Nelson, BC V1L4H5, Canada
email: greg.johnson@6pointeng.com

Typical avalanche concerns include storm instabilities, wind slabs, cornices, and glide slabs of both wet and dry nature, with notable events linked to outflow conditions.

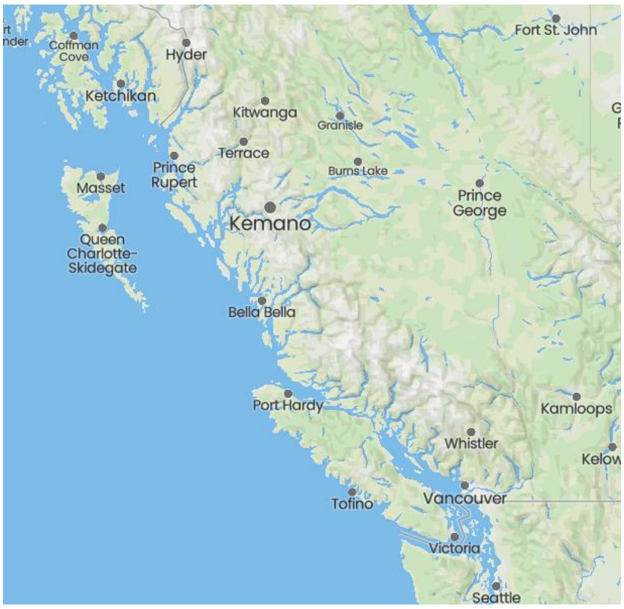

Figure 1: Locator Map.

3. KEMANO PROJECT HISTORY

The Horetzky Valley was named after a Canadian Pacific Railway surveyor who explored the valley in the late 1800s, searching for a railway route. Charles Horetzky writes of a terrifying valley continually echoing the sound of crashing snow.

After World War II, the Aluminum Corporation of Canada (Alcan) identified a location on Canada's west coast for aluminum production. Construction of an aluminum plant powered by a hydroelectric facility began in 1951. A water reservoir on the east side of the Coast Range, connected by a 16 km long tunnel, was built to supply water to the facility. An 80 km long transmission line was also constructed. During this time, the Horetzky Road and Landing were built to allow tunnel access at its midpoint.

Around 1951, Marcel de Quervain (SLF) was hired to perform avalanche consulting services. His work is documented for the transmission line tower locations but not for the Horetzky Road or Horetzky Landing. To our knowledge, an avalanche mitigation program was not implemented. In February 1954, an avalanche fatality occurred on the Horetzky Road.

The Kemano Completion Project (KCP) involved the addition of a second water supply tunnel. In 1988, work began in the Horetzky Valley. An avalanche risk assessment by Peter Schaerer produced mapping and recommendations for the project. A small catchment berm was created at the Horetzky Landing to help contain avalanches, and a three-person avalanche forecast and control team led by Alan Dennis was implemented. Their primary control methods were closures, deployment of explosives with a Bell 206 Jet Ranger helicopter, and a 105 mm recoilless rifle (Alcan, 1991). In 1991, halfway through the project, it was canceled. During that time, a tunnel boring machine advanced eight kilometres from Horetzky Landing towards Kemano that would be completed during the T2 Project (Figure 2).

Good record keeping during the KCP provided useful operational information for the T2 Project's risk assessment and mitigation design. KCP records noted 1219 avalanche events from two seasons of work, with 89 deposited on the Horetzky Road or Landing.

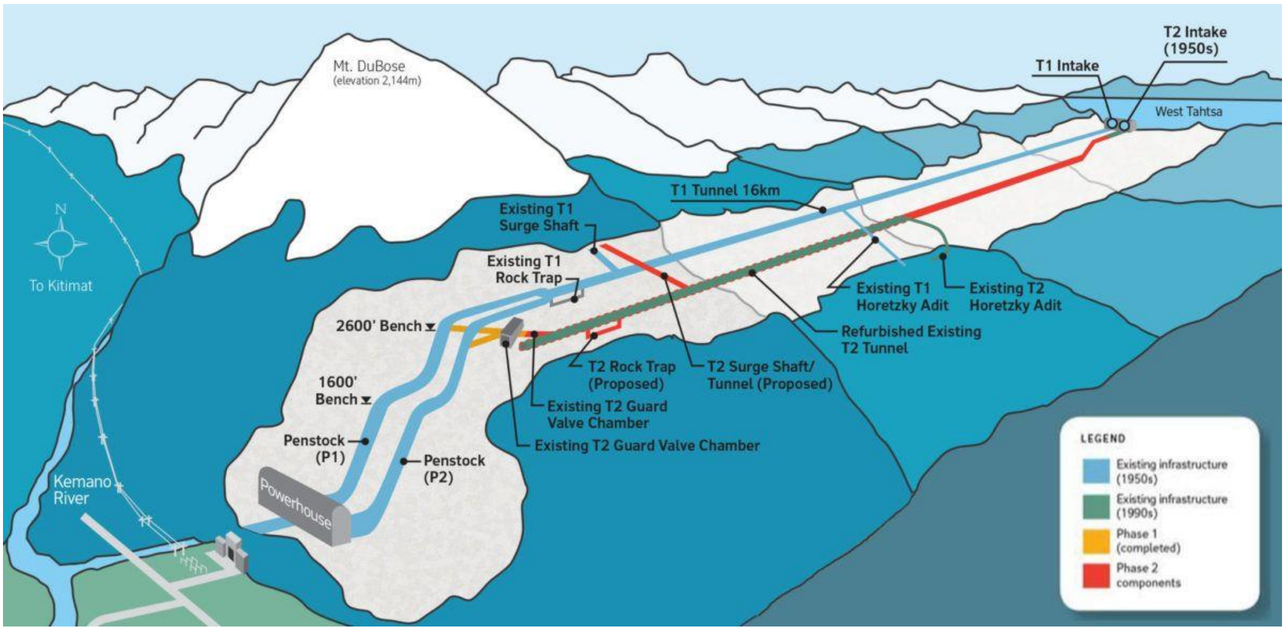

Figure 2: Graphical description of the T2 Project. Illustration by Rio Tinto Alcan.

4. AVALANCHE RISK ASSESSMENT

An avalanche risk assessment assessed worker, infrastructure, and schedule risks. The risk assessment was comprised of several scenarios that considered avalanche size and occurrence frequencies against the exposure and vulnerabilities of elements at risk, including the following:

- Horetzky Road – vehicle traffic and stream crossing infrastructure (bridges).
- Horetzky Landing – worksite; buildings and critical infrastructure; the T2 portal; and a large waste rock conveyor and disposal area.
- Project schedule – avalanche closure time.

The Technical Aspects of Snow Avalanche Risk Management (CAA, 2016) was used as a guideline to define risk thresholds. Specifically:

- For industrial roads safety provisions such as an avalanche forecast and control program if there is potential for Size 2 or greater avalanches with a 30-year return period or less.
- Occupied structures or critical infrastructure are typically located outside areas where avalanches have return periods 300 years or less and potential impact loads of 1 kPa or greater.
- For worksites, mitigation measures commensurate with the severity of risk (avalanche control, closure, evacuation plans, structural defenses, etc.).

4.1 Terrain Evaluation

Evaluation of avalanche terrain within the Horetzky Valley exhibited unique risk management challenges due to its large scale and severe character. Vegetation damage showed evidence of highly destructive avalanches affecting extensive project areas.

Our inventory of avalanche paths defined 42 hazardous paths to the project area, including 16 north-facing and 26 south-facing paths (6 Point Engineering, 2017b). The relief of these paths ranged from 400-1500 m with slope lengths between 500-3000 m.

Avalanche paths were generally steep, with sizeable alpine elevation start zones of four to thirty hectares. Tracks maintained steep or steepening inclines, leading to abrupt runout areas on the valley floor. A defining feature in the Horetzky Valley is a characteristic convex breakover at mid-elevation. This geologic feature supports lower elevation start zones and causes avalanches to accelerate.

Avalanche paths were grouped according to mountain features, including the southeast face of Mt. Dubose, the south-to-northwest aspects of Horetzky Peak (Figure 3), the east and west basins of the Jaws, and the northwest part of Third Jaw Mountain.

Figure 3: Southeast face of Horetzky Peak. Horetzky Road and Horetzky Landing are visible at the bottom right.

4.2 Horetzky Road

Destructive avalanches affect much of the Horetzky Valley. The Valley is deeply incised and has a west-to-east orientation. Over 40 large avalanche paths affect the Horetzky Road, including seven kilometers exposed to continuous avalanche terrain (Figure 4). The majority of paths impact the road annually with Size 3 or 4 avalanches. Approximately ten paths affect the road multiple times per winter. The road was aligned on the valley's north side, resulting in south-facing paths presenting the highest risk.

The terrain in the lower portion of the valley can be generally described as large smooth granite slabs; in the mid-valley, large open bowls and snowfields; and in the upper section of the valley, steep gullies. Each of these terrain features presented unique avalanche problems. For example, during the heavy snowfall winter of 2020-2021, large glide slab avalanches occurring on the granite slabs in the lower valley proved very difficult to forecast. In the upper valley, steep gullied terrain produced numerous avalanches with each storm system, often crossing the Horetzky Road.

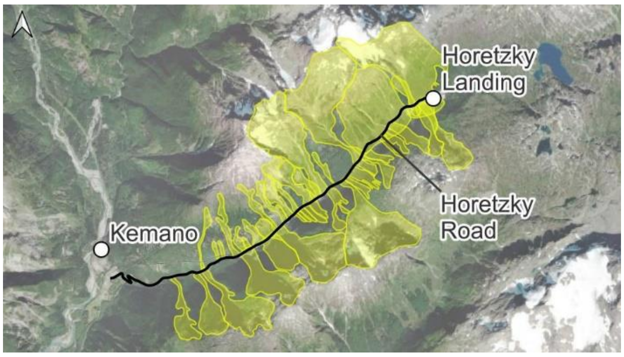

Figure 4: Avalanche paths affecting the Horetzky Road.

4.3 Horetzky Landing

The Horetzky Landing site supported the portal for tunnel construction with a 200-person workers' camp, offices, grout batch plant, tunnel boring machine maintenance shed, water treatment facility, two waste rock dumps, and multiple equipment laydown areas.

The Horetzky Landing is situated in the runout of a very large avalanche path (Figure 5). Field investigations and modeling indicated avalanches that exceed 50-year return periods cross the entire workspace and run up the other side of the valley.

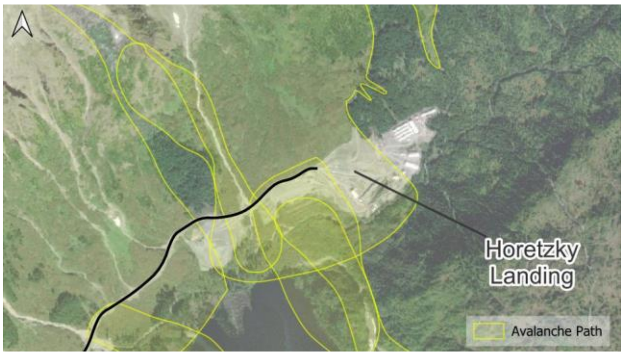

Figure 5: Avalanche paths affecting Horetzky Landing and the upper Horetzky Road.

5. MITIGATION DESIGN

The avalanche mitigation design balanced maximizing worker and infrastructure safety and minimizing road and worksite closures. Cumulative avalanche closure time can extend an overall project schedule, significantly increasing direct and indirect costs. Our avalanche mitigation approach included static defenses and an operational forecast and control program.

Static infrastructure at the Horetzky Landing was installed to divert or stop avalanches, reducing the likelihood and consequence of impact on infrastructure and people. Along Horetzky Road, previously installed bridges at stream crossings had been damaged or destroyed by avalanches since the KCP. Initial project planning included reinstallation using a modified tear-away bridge design to facilitate rapid bridge deck replacement. Ultimately, this stream crossing approach was rejected in favor of sizeable upstream catch basins in combination with multiple culverts to provide a more robust, lower risk design.

The operational forecast and control program supported construction to continue 24 hours per day, seven days a week. The control program included an 11-unit remote avalanche control system (RACS) and an extensive helicopter-deployed explosive program.

5.1 Deflection Berm and Stopping Wall

Two reinforced earth avalanche defense structures were designed and constructed to reduce risk to infrastructure and equipment at the Horetzky Landing (Figure 6). The structures consisted of a ten-meter tall, 150 m long deflection berm and an eight-meter tall 120 m long, reinforced gabion-faced stopping wall immediately above the portal (Ross and Johnson, 2019). The deflection berm was designed to divert the flow of a 10-year return period avalanche and the stopping wall to resist a 30-year return period avalanche.

During the project, the diversion berm was hit twice. The stopping wall was not impacted. Both structures were left in place after the project was finished.

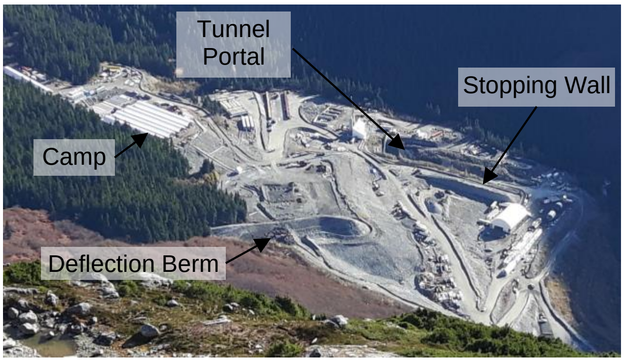

Figure 6: View of Horetzky Landing and static defense structures (looking southeast).

5.2 Remote Avalanche Control System

The remote avalanche control system (RACS) was installed to reduce the duration of closures by providing avalanche control capabilities during storms and at night. The RACS was located above the Horetzky Landing, two waste rock dumps, and about 800 m of the Horetzky Road.

An evaluation of available RACS was performed during the risk assessment. The Gazex system was selected due to the large shot capacity and the owner's preference to avoid flying primed explosives. The system was designed with a gas supply of 65 shots per winter per exploder. Eleven exploders, four 3.0 m^3 and seven 1.5 m^3 were installed.

Limited prior avalanche control experience in the Horetzky Valley required reliance on judgment for the selection of Gazex locations. Some of the sites were more effective than others. The less efficient Gazex locations reflect the potential value of an extensive explosive testing program during winters before construction.

On average, 30 Gazex missions were performed per season. A complete shoot with all 11 exploders took as little as 20 minutes and often could be timed during worker shift changes. As a result, closure times were significantly reduced at Horetzky Landing, proving effective.

The Gazex system was removed following project completion.

6. FORECAST AND CONTROL PROGRAM

We developed the avalanche forecast and control program (AC program) to protect workers, equipment, and infrastructure from avalanches while minimizing interruptions and closures to the worksites and access roads. Specific objectives included:

- Development and implementation of an Avalanche Safety Plan that satisfied local Occupational Health and Safety Regulations,
- Implementation and execution of an avalanche control program capable of 24-hour operations,
- Development and administration of avalanche safety training for T2 Project workers,
- Provision of 24-hour avalanche incident response.

The AC program had regular access to a helicopter for snow, weather, avalanche observations, and control work. Three remote weather stations were installed: one at Horetzky Landing, one at an 1100 m treeline location, and one in the lower alpine. In addition, each of the five Gazex control shelters contained temperature measurement telemetry.

Reliable alpine wind measurement was challenging at the site due to rime ice and severe wind. The lower alpine weather station had an ultrasonic anemometer, which was essentially non-functional. Weather conditions also destroyed an anemometer installed at a 2000 m elevation Gazex control shelter. Consequently, the program was commonly forced to operate without upper elevation wind observations, increasing forecaster uncertainty.

An explosive magazine was located below Kemano with a storage capacity of 14,000 kg. Placement of the magazine in the Horetzky Valley was not possible due to regulatory explosive quantity and standoff distance requirements with roads and infrastructure. Typically, 25 kg bags of ANFO were used for control.

Strategies used for control incorporated extensive 'carpet bombing' missions that included most key targets to reduce the immediate hazard and overall mass of snow in start zones. While this technique can be successful, it places less reliance on forecasting avalanche problems and is less effective in developing localized forecast skill.

6.1 Snow and Avalanche Summary

Over five operational seasons, the project experienced a range of snow and avalanche conditions. Variations in weather conditions, including precipitation and air temperature (Table 1), influenced the development of avalanche conditions each season.

The AC program started in March 2018. Spring snowpack depths were average. Temperatures remained well below average, keeping the snowpack cold until April 18. Warm spring temperatures and little precipitation were recorded through mid-May.

The winter of 2018-2019 was characterized by below average snowfall. Snowfall was not recorded at Horetzky Landing until December 10. From December to the end of January, periods of heavy snow were recorded. The weather pattern changed in late January and was dominated by strong outflow events and little precipitation. In March, the outflows stopped after one storm event, and a high-pressure system dominated, bringing very warm temperatures and very little precipitation for the duration of the season.

The winter of 2019-2020 was characterized as average. Winter started dry, with below normal precipitation in October and November. This caused a facet-crust instability to form near the base of the snowpack. Periods of snow were consistent through December, January, February, and March. Outflow events occurred in January, February, and late March. A blocking ridge of high-pressure setup in early April persisted through mid-month.

The winter of 2020-2021 received above average precipitation. The precipitation received was between a 10-year and 30-year winter, as indicated by the Kemano and Tahtsa Lake weather stations. A wet fall trend continued into winter with frequent storms, except for a two-week dry period in early February. In mid-April, the storm cycles stopped for the season, apart from a couple of late April and early May storms.

Winter 2021-2022 received slightly above average seasonal precipitation totals with below average spring temperatures. November through mid-December experienced consistent snowfall. Cold and dry conditions dominated until early January. Constant storms with above average temperatures delivered a mix of rain and snow through mid-January. Through the end of March, seasonal temperatures returned along with periodic snowfall. The spring was colder than average, with the Horetzky Landing seasonal maximum height of snow recorded on April 7.

Table 1: Observed winter season weather conditions at Horetzky Landing plot (810 m).

Season	*Days Observed*	*Precip. Days*	*Snowfall Days*	*Total Snowfall (cm)*	*Total Water Equivalent (mm)*	*Temp Air Max (Date)*	*Temp Air Min (Date)*	*Temp Air Average*
2018/19	124	65	58	596	749	+18°C (Mar 21)	-24°C (Feb 3)	-1.7°C
2019/20	151	102	86	872	1,434	+16°C (Apr 16)	-24°C (Jan 15)	-2.1°C
2020/21	176	123	121	1,258	1,615	+19°C (Apr 16)	-21°C (Feb 10)	-1.4°C
2021/22	146	65	56	800	1,450	+8°C (Mar 30)	-24°C (Dec 21)	-6.1°C

A summary of winter snowpack depth for the Horetzky Landing is shown in T, which includes two winters from the KCP project and five winters from the T2 Project. The Horetzky Landing is below treeline. Typically, in the upper alpine elevations above 1600 m, the average snowpack depth is at least twice as deep as the 800 m Horetzky Landing.

A summary of avalanche observations for the KCP and T2 Projects is shown in Table 3. The above average snowfalls in 2020-2021 resulted in above average observed avalanches and avalanche events crossing the road. The average size of these avalanches was Size 3. It was common to observe Size 4 avalanches. The project experienced one Size 5 avalanche while performing explosive control.

The total number of avalanches reaching the Horetzky Road or Horetzky Landing is summarized in Table 4. Approximately 40% of the avalanches affected the upper section of the Horetzky Road below Horetzky Landing.

Table 5 provides additional AC program statistics, including a breakdown of RACS and helicopter-deployed explosives and closure hours for the access road and Horetzky Landing.

Annual closure hours on the Horetzky Road were significant. During the below average 2018-2019 winter, the road was closed only 162 hours, with one closure over 24 hours. After the 2019-2020 winter, which included several near misses, the project decided to close the road at night unless the hazard was low. This is reflected in the closure hours during the 2020-2021 and 2021-2022 winters.

Closure hours for the Horetzky Landing ranged between 22 and 69 hours. During the initial winter of 2019-2020, the high closure hours are attributed to forecaster uncertainty. After the first winter, experience helped to lower the hours. The RACS also substantially contributed to keeping Horetzky Landing open with control capability anytime.

Table 2: Monthly maximum snow depth (cm) at Horetzky Landing 800 m ASL.

	KCP		*T2 Project*				
	1989-1990	*1990-1991*	*2017-2018*	*2018-2019*	*2019-2020*	*2020-2021*	*2021-2022*
October	~	~	~	0	0	~	~
November	32	230	~	0	24	122	104
December	92	302	~	99	89	161	175
January	257	263	~	130	173	243	195
February	280	292	260	157	230	365	214
March	237	293	280	180	284	384	243
April	168	~	265	90	232	395	252

Table 3: Observed avalanches, natural and controlled.

	1989-1990	*1990-1991*	*2018-2019*	*2019-2020*	*2020-2021*	*2021-2022*
Natural	304	319	543	388	486	491
Controlled	196	400	361	825	1,083	593
Total	500	719	904	1,213	1,569	1,084

Table 4 Observed avalanche crossing the Horetzky Road or entering the Horetzky Landing.

	1989-1990	*1990-1991*	*2018-2019*	*2019-2020*	*2020-2021*	*2021-2022*
Natural	28	33	4	25	39	19
Controlled	21	7	7	42	31	11
Total	49	40	10	67	70	30

Table 5: AC Program Summary Statistics.

	2018-2019	*2019-2020*	*2020-2021*	*2021-2022*
Helicopter Avalanche Control				
Control Days	22	41	48	32
Explosive Quantity	397	1,064	988	504
Explosive Weight (kg)	9,500	24,000	23,500	12,500
Gazex Avalanche Control				
Control Missions	18	44	40	18
Detonations	137	335	327	155
Horetzky Road Closures				
Total Closure Hours	162	605	996	624
Longest Closure (Hours)	28	107	102	64
Quantity of 24-Hour Closures	1	4	25	11
Horetzky Landing Closures				
Total Closure Hours	69	35	30	22

6.2 Notable Events

The AC program observed 4,770 avalanche events, an average of nearly 1,200 each season. Of these events, 177 crossed the project's roads or hit the Landing. An average of 40 events per season to the valley floor correlated with KCP's data set. These avalanche events were mainly managed within the project's accepted risk tolerance. This is reflected in the zero recorded injuries from avalanches over the project life. However, notable avalanche events also provided learning opportunities for the AC program.

Throughout the project, 22 avalanches were observed on open roads or worksites. Notably, four occurrences involved vehicles/equipment, workers, or structures. All worker and vehicle avalanche involvements were associated with significant 'dustings' from the terminal powder avalanche component and did not result in damage or burial. In the case of the structure, a snow deposit damaged an upslope wall of a large industrial storage shelter.

A tracking system was developed and implemented during the project to create a dataset for recording and analyzing notable events as they occurred. Each notable event was associated with unique circumstances arising from weather, specific avalanche problem types, and operational constraints.

This dataset proved to be a valuable medium for critical reflection and learning. Where observable patterns were identified, lessons from notable events were applied to future forecasting and control decisions. For example, thresholds for outflow events in particular paths were refined, and strategies for dealing with worksite pressures, such as worker exchanges during poor weather conditions, were developed.

7. LESSONS LEARNED

The T2 Project was a large-scale avalanche risk management program in a complex and hazardous environment. Numerous lessons were learned throughout the planning, construction, and operational phases. We hope consultants can use our experiences as a stepping stone for future work in the Horetzky Valley or other similar projects. Some of our key takeaways are shared below.

- Good record keeping is essential. The records from the KCP proved highly valuable for the T2 Project. Avalanche path summaries, notable patterns, and high-frequency paths offered preliminary perspectives and correlations with our records. Notes of being prepared for unexpected and consequential events highlighted the type of risk environment. Remember that your work may serve future projects.
- Have a process for critical reflection and adjustment. Learning about a regional climate, avalanche path characteristics, and optimal work practices takes time. Understanding and buy-in from the entire project team help facilitate these adjustments as experience is gained.
- RACS are challenging to place without years of location specific control experience. There is value in implementing an extensive explosive testing program before RACS site selection in unfamiliar terrain if project constraints allow.
- Project pressures are real and must be worked within. Demands on avalanche risk management programs in complex environments can be high. It is not always realistic to expect project schedules to accommodate uncertainties. Avalanche hazard should be monitored as accurately as possible to provide every

opportunity possible for project schedule progression. Small daily decisions can become impactful interruptions over cumulative hours.

- Recognize the role of luck. Learning to operate in severe avalanche risk management environments is demanding and requires a degree of exposure acceptance. As refined as our management systems may be, snow avalanches are a complex natural phenomenon that human decision making cannot always accurately predict.

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