QUANTITATIVE RISK ASSESSMENT FOR THE SNOQUALMIE PASS AVALANCHE BRIDGES

Alan Jones, P.Eng.[1]*, Greg Johnson, P.Eng.[2] and Kevin Dusenberry, S.E.[3]

[1]Dynamic Avalanche Consulting Ltd., Revelstoke, BC, Canada
[2]WSA Engineering, Castlegar, BC, Canada
[3]Jacobs Engineering, Bellevue, WA, USA

ABSTRACT: Interstate 90 is a primary transportation corridor that crosses the Cascade Mountains at Snoqualmie Pass, Washington, USA. The highway is currently undergoing improvements to replace aging infrastructure, increase ecological connectivity, add vehicle capacity, improve safety and reduce avalanche closures. On the east side of the Pass, avalanche risk from the seven East Shed avalanche paths will be mitigated by construction of two 365 m bridges that are designed to allow avalanches to pass underneath them. The bridges are designed to meet the project design criteria for dense flow impacts to the bridges and powder flow impacts to vehicles.

In order to help structural designers achieve the bridges' design criteria, Monte Carlo risk simulation methods were used to determine probabilistic avalanche impact loads, deposit geometries and risk to vehicles and the structures. This method allows designers to assign a range of model input parameters, which provides a range of model outputs. This allows for uncertainties to be better accounted for than deterministic analysis, increasing confidence in model results. This paper discusses how probabilistic avalanche risk analysis was applied, its advantages and limitations for the bridge design.

Verification of the probabilistic models followed traditional methods by comparing results to field observations, other models, and engineering judgment. Verification included creating 3D geometries using probabilistically determined volumes of snow, including seasonal sluffing below the bridges, snowfall, plowed snow, and avalanche deposits. Design work for these bridges is complete, and construction started in April 2014 as part of a USD $248 million highway improvement project.

KEYWORDS: Highway, bridges, quantitative risk assessment, probabilistic, Monte Carlo

1. INTRODUCTION

Interstate 90 (I-90) is a primary transportation corridor that crosses the Cascade Mountains at Snoqualmie Pass (921 m), Washington, USA (Figure 1). This corridor is a critical link connecting western Washington's large coastal population centres (Seattle and surrounding Puget Sound), businesses and ports with the rural communities, agricultural industries and recreational activities of central and eastern Washington as well as other regions within the USA. Due to the high volumes of commercial vehicles, traffic delays on I-90 have high direct costs and downstream economic consequences.

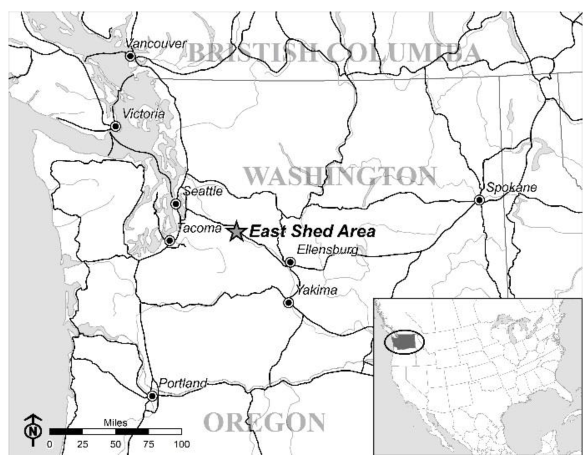

Fig. 1: Location map of East Shed Project area.

On average, 28,000 vehicles per day (vpd) pass over Snoqualmie Pass, often doubling to near 50,000 vpd on busy weekends and holidays. Annual Average Daily Traffic (AADT) volumes are projected to increase to over 41,000 vpd by 2030, which will produce additional pressures on the highway corridor (WSDOT, 2008). Winter Average

* *Corresponding author address:*
Alan Jones, Dynamic Avalanche Consulting Ltd., Box 2845, Revelstoke, BC, Canada, V0E 2S0;
tel: 250-837-1723; fax: 250-837-4464;
email: alan.jones@dynamicavalanche.com

Daily Traffic (WADT) values are estimated to be approximately 75% of the AADT volumes.

Highway safety and reliability improvements are currently being implemented within the I-90 Snoqualmie Pass East Project (Phase 1), which will improve 8 km of highway east of Snoqualmie Pass. Improvements will include reduction of highway closures due to avalanches, rockfall and landslides, and expansion of the highway from 4 to 6 lanes to reduce congestion. This project phase has an estimated capital cost of USD $551 million.

Within the larger Phase 1 project, Phase 1C includes improvements to 3 km of highway, including replacement of a snow shed with two bridges and upgrading bridge approaches. The planned completion date for this work is 2017, with an estimated capital cost of USD $248 million.

The project area discussed in this paper is referred to as the East Shed area, where the highway crosses through seven avalanche paths that frequently affect the highway (Figure 2). These paths affect the highway with return periods varying from once every 5-10 years to two paths that affect the highway multiple times per winter. Highway closures in this area average approximately 42 hours per year as a result of elevated avalanche hazard and explosive avalanche control.

A 152 m long concrete snowshed was constructed in 1951 to replace a wooden snowshed that was in service for many years prior to that. During the late 1950’s to early 1960’s, the highway was increased to four lanes and two additional lanes were built next to the snowshed. The snowshed protected the westbound lanes from the two largest avalanche paths, but no structure was added to protect the eastbound lanes or westbound lanes in the lower frequency avalanche paths.

This shed was removed in a 2-day period in April 2014, and will be replaced with two 365 m long, 3-lane bridges that are designed to allow avalanches to pass beneath them, as well as withstand potential avalanche impacts to the piers.

Figure 2: East Shed project area overview showing location of current highway, Keechelus Lake, seven East Shed avalanche paths, and proposed locations of bridges (green lines) and piers (pink dots).

The two bridges will treat avalanche risks. A combination of elevating the road surface and excavating material below the existing highway grade will provide clearance beneath the bridges to accommodate accumulations of snow from snowfall, plowing, and avalanches, with adequate freeboard (remaining distance between the top of the accumulated snow and the bridges) to protect motorists from additional avalanches. The excavated storage area beneath the bridges will act as a series of chutes that will direct avalanches, rockfall, and debris away from the bridge piers.

Avalanche impact loads, deposit geometries and risk to vehicles travelling on the bridges were determined probabilistically using Monte Carlo simulations. Probabilistic analysis provides designers with a better understanding of project uncertainties than deterministic analysis, increasing the confidence in model results.

Verification of the probabilistic models followed traditional methods by comparing results to field observations, deterministic model results, and engineering judgment. Verification also included creating 3D geometries of probabilistically determined avalanche deposit volumes, annual snowfall and plowed snow.

The objectives of this paper include:

1. Describe the I-90 avalanche bridges project, which is one of the largest and most challenging avalanche infrastructure projects in North America.
2. Discuss how Quantitative Risk Assessment (QRA) methods were applied to quantify avalanche risk.
3. Describe a practical application of Monte Carlo risk simulation methods for avalanche problems.
4. Discuss 3D modelling methods for estimating the snow volume and geometry of complicated avalanche deposits, using a combination of expert judgment and probabilistic methods.
5. Highlight methods that are routinely applied in other engineering fields, but less commonly for avalanche engineering problems.

2. BACKGROUND

2.1 Description of project area

The East Shed area is located between I-90 Milepost (MP) 57.7 and MP 58.5, approximately 90 km east of Seattle and 9 km southeast of Snoqualmie Pass within the Cascade Mountains of Washington State (Figure 1).

Snoqualmie Pass is located in a high precipitation Maritime snow climate, with an average annual snowfall at Snoqualmie Pass of 1106 cm, and observed maximum annual snowfall of 2103 cm. This corresponds to an average annual maximum height of snow of 310 cm, and an observed maximum of 572 cm.

The East Shed area is affected by 7 avalanche paths identified from west to east as: ES-1, ES-2, ES-3, ES-4, ES-5W1, ES-5W2 and ES-5E (Figure 2). The three larger paths (ES-3, ES-4 and ES-5E) produce larger avalanche deposits to the highway annually (Destructive Size D3 and potentially D4), while the other four paths (ES-1, ES-2, ES-5W2, and ES-5W2) typically produce smaller deposits to the highway (Size D2 typically but up to D3). Most highway closures are associated with avalanches in the larger ES-3 and ES-4 paths, which produce both dense flow and occasional powder flow effects to the highway (Figure 3).

Figure 3: Avalanche impacting eastbound lanes at path ES-4 (WSDOT photo).

The Washington State Department of Transportation (WSDOT) provides an extensive avalanche hazard evaluation and mitigation program in the East Shed area. The mitigation program and challenges with the current and future construction program are well described in Stimberis (2012).

2.2 *Design Criteria*

Avalanche design criteria for the bridges were determined by WSDOT in consultation with the construction contractor, Atkinson Construction, and Arthur I. Mears, P.E. Inc. These criteria consider guidelines from Canada and Switzerland that provide acceptable protection for vehicles travelling on the bridges and ensure structural integrity of the piers and superstructure. The CAA (2002) guidelines were used to establish acceptable risks to vehicles; the Swiss guidelines for snowsheds (ASTRA/SBB 2007) are applicable to snowsheds but, where appropriate, were also considered in the bridge design.

The bridges were designed to meet the following criteria:

- 100-year dense flow avalanches must pass underneath the bridges without impacting the superstructure;
- The bridges must provide sufficient clearance to accommodate the 100-year combined heights of snowfall accumulation, snow plowed from the bridge deck, prior avalanche deposits, 100-year dense flow and 30-year powder avalanche flow;
- The bridges must be sufficiently high so that vehicles are not impacted by powder avalanches more frequently than once in 30 years; and
- The bridge piers must be designed to withstand 100-year dense flowing avalanche impact loads. Structural designers factored these loads by 1.5 for the bridge piers. The dense flow and powder flow impacts to bridge columns were combined with other AASHTO Load and Resistance Factor Design (LRFD) load cases.
- Bridge columns were also designed for static loads due to accumulations of snow from snowfall, sluffing, plowed snow and avalanches. The Load Factor for static snow loads was 1.5. This load was added to the dynamic snow forces on the bridge.

The bridge design was constrained by many other highway engineering factors, including soil and rock stability, rock fall, foundation conditions, horizontal and vertical highway curves, seismic loading, environmental and aesthetic considerations, as well as cost.

Numerous iterations of the bridges' designs were required before all the avalanche design criteria were met. This included an iterative design refinement process for bridge heights, pier locations, and snow storage volumes for the excavated avalanche chutes. The design process included a robust, independent review by WSDOT and their avalanche consultants.

3. METHODS

3.1 *Quantitative risk assessment*

A Quantitative Risk Assessment (QRA) was completed to estimate avalanche risk to the bridges and vehicle traffic (Jacobs 2012). This QRA was a function of avalanche magnitude and frequency, structural and vehicle vulnerabilities and the potential for fatalities on the bridges from avalanches based on assumed traffic volumes.

The QRA considered six scenarios that have the potential to produce a loss, including structural damage to the bridge and resulting highway closure, or loss of life to the public travelling on the bridges. The following six scenarios were considered for each of the seven East Shed avalanche paths, and the risk from each path was summed to estimate total risk. These scenarios were:

1. Dense flow avalanche overloads the bridge substructure (i.e. pier failure);
2. Dense flow avalanche overloads the bridge superstructure (i.e. bridge deck);
3. Dense flow avalanche overtops the superstructure and impacts vehicle traffic;
4. Powder avalanche impacts vehicle traffic;
5. Powder avalanche creates visibility loss (i.e. whiteout);
6. Dense flow avalanches reach the highway at path ES-1 (risk in this path is mitigated by a sloping backfill and catchment, not the bridge).

Risk, R_i for each scenario was calculated using a standard risk function:

$$R_i = p_i E_i V_i$$

where p_i is the probability of an avalanche reaching a specified location (i.e. bridge pier or traffic lane), E_i is the temporal and spatial exposure of the element-at-risk, and V_i is the vulnerability of the element to the specific avalanche event.

Hazard probability, p_i, was estimated based on a combination of field observations, historical occurrence records and dynamic avalanche modeling.

Exposure, E_i, for vehicle traffic was a function of assumed traffic volume (30,000 vpd), average number of passengers per vehicles (1.6), width of avalanche paths (36-55 m), average speed of vehicles for winter conditions (65 km/hr), and distribution of vehicle type (standard height or over-height vehicles).

Vulnerability, V_i,for the bridges was specified by the project structural engineers for both the substructure (piers) and superstructure (deck) based on expert judgment.

Vulnerability for vehicles to powder avalanches was estimated by determining impact loads that could potentially destabilize a vehicle on a bridge, which was assumed to be 1.4 kPa for high profile vehicles (e.g. semi-trucks and Recreational Vehicles) and 2.4 kPa for standard profile vehicles (e.g. cars). These values were based on detailed analyses and Scmidlin et al. (2002). Subsequently, the death rate (vulnerability) values for passenger vehicles was applied based on Rheinberger (2009) (Table 1).

Table 1. Death rate (vulnerability) for passenger vehicles (Rheinberger et al., 2009).

Risk Case Scenario	Death rate per vehicle impacted
Low pressure powder avalanches (≤ 3 kPa)	0.05
High pressure powder avalanches (>3 kPa)	0.09
Dense flow avalanches	0.27
Where avalanches may push vehicles off a road and down a steep slope	0.3 to 0.4

Because very low pressure avalanches (i.e. < 1.4 kPa) were interpreted to only reduce visibility and not destabilize a vehicle, vulnerability was reduced from 0.05 to 0.02 for visibility effects only.

Once the quantitative avalanche risk was calculated by combining hazard probability, exposure, and vulnerability, this value was used to quantify the potential consequences of each scenario. For each scenario the consequences were presented as economic cost for structural repairs or replacement, the number of fatalities, and durations of highway closures.

3.2 *Monte Carlo Risk Simulation*

Monte Carlo risk simulation methods are commonly applied in many engineering and financial fields, but are only infrequently used for practical snow avalanche problems. This method was applied using the @Risk software package (www.palisade.com/risk) to assess avalanche risk to the bridges, including estimation of required clearance heights and impact loads to the bridge piers and superstructure.

Monte Carlo analysis involves quantification of risk by running multiple simulations to identify the range of possible outcomes. Individual input parameters are assigned a range values in the form of a probability distribution. Each simulation randomly selects a value from each input parameter's distribution. The output includes a range of values in a probability distribution function that may be analyzed to determine values associated with specific return periods. It can also be used to evaluate the potential range of outputs (i.e. assess uncertainty) and perform sensitivity analyses to determine the effect of inputs on the outcome(s).

A risk-based model using the Voellmy-Salm dynamic avalanche model was developed in which all of the input parameters were assigned probability distribution functions based on a combination of project data, information from published literature and expert judgment.

Output variables (e.g. impact pressure, dense flow clearance height) were provided by 500,000 model runs (simulations) in the form of probability distribution functions, from which values corresponding to a given return period (e.g. 30 years, 100 years) were obtained.

The model was calibrated using 100-year design values previously determined using deterministic avalanche modeling methods with a number of dynamic avalanche models, including the DANW (Hungr and McDougall, 2009) and AVAL-1D (Christen et al., 2002) frictional-turbulent (Voellmy-Salm based) models, and the PLK avalanche model (Perla et al., 1984).

The avalanche clearance heights and impact pressures obtained from the risk model were provided for each avalanche path for the appropriate design values: 100-year design dense flow and powder flow impact pressures for the bridges, and the 30-year flow height for powder avalanches. Figure 4 provides a typical loading diagram for the bridge, including static snow loads (e.g. deposits), dense flow and powder flow loads.

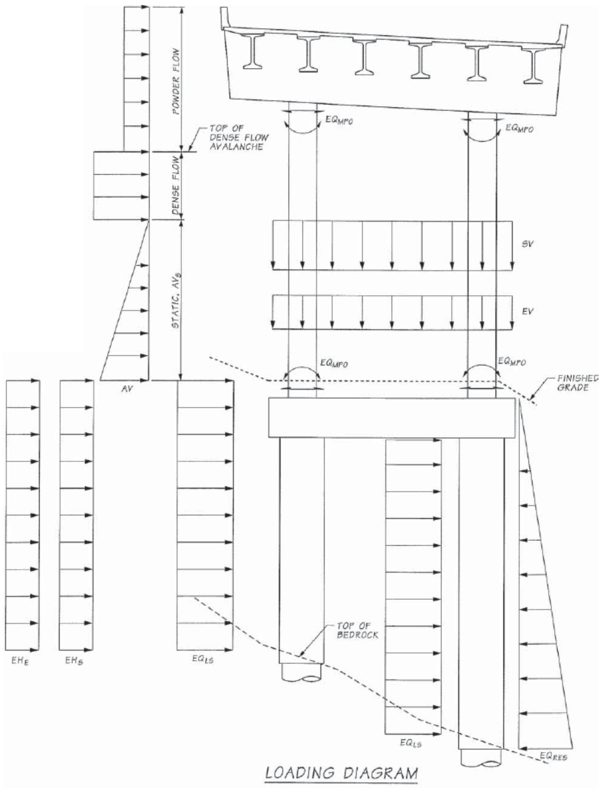

Figure 4: General bridge loading diagram showing loads on shafts, piers and superstructure.

Avalanche return periods in the range of 2 years to 1000 years were determined from the simulated probabilistic outputs. Values that exceed the project design return periods of 30 and 100 years were provided so that the project engineers could extrapolate risk beyond typical design return periods, which helps evaluate potential outlier events.

3.3 3D Modelling of Avalanche Deposits

There is limited space available for construction of the avalanche bridges between the steep East Shed avalanche paths and Keechelus Lake. The bridge design elevates the superstructure above the current highway grade, combined with excavation of distinct chutes in bedrock beneath the bridges. Bridge piers will be located on elevated rock areas between these chutes. Extensive rock excavations are required in 6 of the 7 avalanche paths (ES-1 is the exception).

Figure 5 illustrates the design excavation of the chutes and pier locations at the main avalanche chutes, ES-3 and ES-4.

Volume analyses were completed for all avalanche paths, however, because the potential snow volumes were close to the design capacity of the proposed excavation in path ES-5E, a more detailed assessment of snow volumes was completed for this path using Autodesk Civil 3D software.

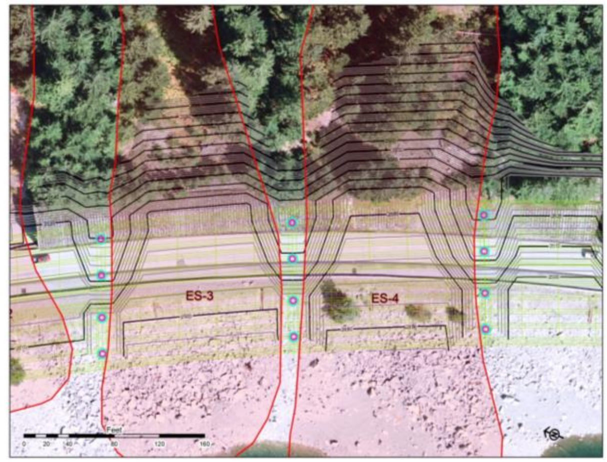

Figure 5: Avalanche paths ES-3 and ES-4. Black contour lines show the design topography, red outlines show approximate avalanche path boundaries. Green lines show roadway design, magenta/cyan circles show pier columns.

Snow storage capacity was determined by calculating the difference between the maximum volume of snow that could fit under the bridge and the proposed graded surface. This deposit was constrained to slope downhill at 25 degrees and allowed to fill to the bottom of the westbound bridge superstructure. Geometries constructed in Civil 3D and expert judgment-based analyses showed the maximum snow storage volume to be approximately 20,642 m^3, while the estimated 100-year snow and avalanche deposit volume was estimated to be 20,107 m^3.

After an independent review of the snow storage analysis, WSDOT requested that the storage volume and clearance analyses be refined. The refined analysis included characterizing the bulk volume as three individual deposits, determined by a combination of expert judgment, field observations and experience, and recommendations provided by WSDOT's avalanche consultants. The bulk deposit was split into three deposits because in a worst case scenario it was assumed snowfall, sluffing and plowed snow would build up under the bridges through the duration of a winter before a 100-year design avalanche occurs late in the winter and overruns other deposits. This situation represents a very complicated problem that is best conceptually modelled by using years of field experience observing many avalanche deposits.

Geometries of snow deposits were created with Civil 3D that represent the:

1) 100-year snowpack and eastbound lanes plowed snow deposit
2) 100-year sluffed snow and westbound plowed snow deposit; and
3) 100-year avalanche deposit.

The sluffed snow deposit was sloped downhill at 25 degrees and slightly skewed to one side of the path to reflect the natural terrain and planned rock excavation topography. The 100-year snowpack was distributed evenly, except over steep terrain, where sluffing would occur, or under the bridges. The 100-year plowed snow was applied evenly on one side of each bridge.

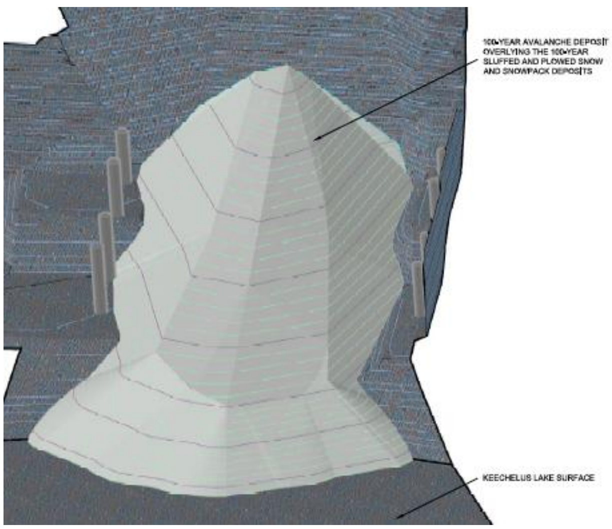

Figure 6: Isometric illustration of the 100-year return avalanche deposit conceptual model in Path ES-5E.

The 100-year avalanche deposit overlaid all other deposits (Fig. 6). It was assumed that the 100-year avalanche would be dry and runout with a relatively low angle of 12 degrees, with its terminus having steepness of 25 degrees. The deposit was also skewed to one side of the path to reflect the avalanche's probable trajectory.

In Civil 3D the geometry and total volume of all the deposits was confirmed to fit adequately under the bridges with an acceptable amount of freeboard to account for random variations that will occur with design avalanches.   .

4. DISCUSSION

Risk assessments and treatments for avalanche problems are complex and solutions are often found through an iterative process, which combines technical analysis and expert judgment. This project included both. The project team assessed the bridges design and confirmed that the structures meet the avalanche design criteria outlined in Section 2.3.

The QRA was used to estimate a combined annual fatality rate for all of the East Shed paths and 6 risk scenarios considered in Section 3.1. This number was estimated for the avalanche bridges at 0.49 fatalities per 100 million miles driven, which is lower than the National Highway Traffic Safety Administration target value of 1.1 fatalities per 100 million miles in the United States, or 0.8 in Washington State.

Risk assessment methods based on Diamantidis (2008) were used to evaluate the acceptability of residual risk for the bridges in terms of Negligible, Tolerable or Unacceptable risk. Estimation of residual risk for the 6 risk scenarios identified the following important results:

- Dense flow (Scenario 1) could overload the bridge piers in ES-4 with a return period greater than 500 years;
- Dense flow (Scenario 2) could overload the bridge superstructure in ES-4 with a return period greater than 300 years;
- Powder avalanche (Scenario 4): could destabilize vehicle traffic on the bridge with a return period greater than 160 years in ES-3 and greater than 100 years in ES-4;
- Powder avalanche (Scenario 5) could obscure visibility for vehicles in ES-3 and ES-4 with return periods of 50-70 years.

Each of these scenarios presents potential for loss in terms of fatalities, structural damage to the bridge and hours of highway closures. In terms of life safety (i.e. fatalities), methods outlined in Diamantadis (2008) showed that the bridges satisfy the life-safety risk acceptability consideration, but does not fully reach the acceptable level for which no further risk reduction should be considered.

WSDOT will address this residual risk with a long-term monitoring and maintenance plan. This plan includes the removal of debris from the catchments during summer, as well as monitoring snow accumulations under the bridge. Conservative clearance heights were provided that, if exceeded in a major snow winter, would require removal of snow from catchments under the bridges.

5. CONCLUSION

The I-90 avalanche bridges project located east of Snoqualmie Pass is one of the largest and most challenging avalanche infrastructure projects in North America (Figure 7). Quantitative Risk Assessment using the Monte Carlo simulation method was used to ensure avalanche risks to the bridges and vehicles met the design criteria, and that residual risks were well understood.

QRA is a versatile method used in many fields of engineering and finance because results can be easily compared to risk tolerance standards. However, this method has limited use to date in the avalanche engineering field. The authors encourage other practitioners to incorporate probabilistic methods in their work, which can help reduce uncertainty and provide a better understanding of project risks.

Figure 7: Conceptualization of completed avalanche bridges.

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