METHODS FOR EVALUATING AVALANCHE LOADS ON BRIDGES INTERNATIONAL SNOW SCIENCE WORKSHOP 2026, WHISTLER, CANADA

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ABSTRACT: Transportation corridors crossing mountainous terrain frequently intersect avalanche paths capable of producing destructive snow avalanches. Avalanche bridges can provide an alternative to snowsheds or operational avalanche control where terrain and highway geometry allow avalanche flows to pass beneath an elevated structure. Their designs are complex because loading may involve wet or dry dense flow and powder avalanches, entrained debris, deposition, and variable lateral, oblique, uplift, drag, and static loads acting on multiple bridge components. Historical failures demonstrate that avalanche actions cannot be represented by a single uniform impact pressure and that terrain, bridge geometry, flow direction, and construction phase exposure can strongly influence structural response.

This paper reviews the historical development of avalanche bridges and presents a practical framework for feasibility assessment and design. Key considerations include avalanche scenarios and return periods; flow depth, velocity, density, direction, and deposition; bridge clearance and geometry; component specific loading; vehicle safety; load factors; and independent review. Examples from Teton Pass, Goat Lick, Denny Creek, Snoqualmie Pass, and the Kicking Horse Canyon illustrate the evolution from early failures to designs that integrate avalanche avoidance, flow management, and structural resistance. The paper also discusses construction phase risk, long term operations, and future needs including reliability based load factors, improved methods for complex structures.

KEYWORDS: Avalanche loads, avalanche bridges, bridge design, transportation infrastructure, structural loading, avalanche mitigation.

1. INTRODUCTION

Snowsheds and tunnels have been widely used to reliably mitigate avalanches on transportation corridors where the risk of loss is high and/or closures are costly. Snowsheds and tunnels achieve a high degree of avalanche protection, but have very high construction costs, ongoing operations and maintenance costs, and introduce non-avalanche hazards and safety issues (Hendrikx, et.al, 2020). The tolerance for avalanche-related highway closures is largely governed by economic consequences and societal expectations for safe and reliable transportation. As consequences and expectations rise, typically due to increased traffic volume, transportation agencies may seek mitigation measures to reduce avalanche risk while limiting closure frequency and duration.

In situations where snowsheds or tunnels are not justified, avalanche mitigation in North America has relied on combinations of forecasting, temporary or seasonal closures, explosives, artillery and, less commonly, structures such as drift fences, mounds, and diversion/stopping dams. While these approaches are effective, they are often associated with high costs, maintenance requirements, or operational complexity. Two recent major highway projects in North America have used avalanche bridges that allow dense flow avalanches to pass beneath bridge structures rather than rely on explosive control programs or snowsheds. The Washington State Department of Transportation (WSDOT) opted for bridge structures to replace an existing snowshed on I-90, and the British Columbia Ministry of Transportation and Transit (BC MoTT) used bridges and viaducts rather than tunnels or snow sheds on the Trans-Canada Highway in Kicking Horse Canyon, British Columbia (Figure 1).

The objective of this paper is to review the historical development of avalanche bridges, summarize lessons learned from constructed projects, and present a practical engineering framework for evaluating feasibility, design and avalanche loads on highway bridges located in avalanche terrain. Several examples are used to illustrate key avalanche bridge design considerations.

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Figure 1. Avalanche Bridge Location Map

2. HISTORY OF AVALANCHE BRIDGES

Early bridge designs often reflected limited understanding of avalanche dynamics and were developed before numerical avalanche models or modern structural analysis techniques became available. Several historical failures have subsequently shaped current design philosophy.

One of the earliest avalanche bridges in North America was a suspension bridge near Teton Pass, Wyoming (Figure 2). The Crater Lake bridge spanned the Glory Bowl avalanche path on Wyoming State Highway 22. However, before completion in 1970, the bridge was severely damaged by a large avalanche. The bridge deck had not yet been installed, and the damaged bridge was removed. This event highlighted the importance of temporary construction loading and construction phase avalanche exposure for partially constructed structures. The bridge concept was ultimately abandoned at Glory Bowl, and avalanche mitigation evolved toward operational control supported by forecasting and explosive control programs (Jacobson, 2008; Yount and Gorsage, 2016).

Another incident involving a construction bridge occurred on Interstate 90 (I-90) over Snoqualmie Pass, Washington, where the highway is frequently affected by avalanches, and historic mitigation measures predate avalanche forecasting and control programs. These measures include snowsheds dating back to the 1930s and 1950s. WSDOT initiated a highway expansion project in the 1960s that proposed new westbound lanes to I-90 west of Snoqualmie Pass. These lanes cross under twenty avalanche paths, though the initial design accounted for mitigation in only seven paths, including a bridge, gabion retaining walls, and earthen attenuating mounds. A large avalanche struck and destroyed the temporary construction bridge at Franklin Falls in January of 1971 (Williams, 1975). This event, along with required environmental protections, led to a structural redesign to mitigate avalanches beneath Denny Mountain. The new design included a larger, more robust bridge across Franklin Falls

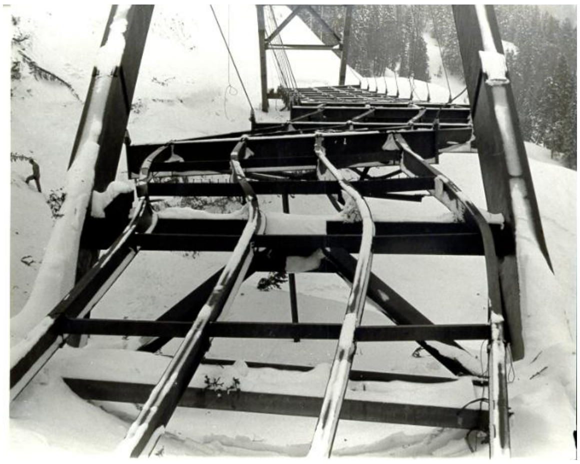

Figure 2. Damage to the unfinished Crater Lake bridge spanning the Glory Bowl avalanche path. (Wyoming Department of Transportation)

and an extended viaduct to replace the proposed gabion walls.

The Denny Creek Viaduct was built in the late 1970s and went into service in 1981. It is an early example of avalanche engineering being integrated directly into bridge design. Edward LaChapelle performed site assessments, and Peter Schaerer provided design loads (Vasishth, 1982). Approximately 305 m of the viaduct was identified as being exposed to frequent avalanches. Avalanche considerations influenced both structural loading and bridge geometry. The resulting design combined avalanche clearance, flow deflection, and structural resistance to reduce the potential for damaging interactions between avalanches and bridges. However, a deflection dam originally proposed to mitigate avalanche impacts to the Denny Creek Viaduct was not constructed, and the final design included avalanche control to protect the highway under certain circumstances. After construction, WSDOT received little information from the contractor regarding maintenance and operation of the viaduct, including avalanche impacts and debris accumulation beneath the structure.

The Goat Lick Bridge on U.S. Highway 2 in Montana represents another significant avalanche bridge milestone. A large wet avalanche destroyed the original bridge during the winter of 1979 by lifting it from its supports and carrying it downslope, demonstrating that conventional bridge design did not adequately account for avalanche loading (Martinelli, 1984). The replacement bridge was designed for increased superstructure clearances and loads. During a subsequent series of large wet avalanches in 1982, the replacement structure successfully resisted the imposed loads, demonstrating the importance of considering not only peak avalanche impact pressures, but also uplift, wet snow flow behavior, and the cumulative effects of multiple avalanche surges or successive events.

Perhaps the best documented structural collapse occurred at the Ri di Rialp Bridge on the Lukmanier Pass in Switzerland in April 1998. The bridge was constructed in 1972 and was designed for dead, traffic and snow loads, but avalanche loads were not considered. The 40 m long pre-stressed concrete bridge crossed a V-shaped gully with ground clearance ranging from approximately 3 to 16 m. A post failure investigation by Margreth and Ammann (2004) concluded that the governing load case was an inclined dense flow avalanche impact, with the highest loads concentrated near one abutment rather than uniformly distributed across the bridge span. Their failure analysis indicated an impact angle of approximately 40°, demonstrating the importance of local topography and bridge geometry.

Using the Ri di Rialp failure as a case study, Margreth and Ammann (2004) developed a practical framework for evaluating avalanche actions on bridges. They concluded that bridge loading is highly dependent on local topography, bridge geometry, avalanche flow direction, and flow characteristics, and that universal loading assumptions are therefore inappropriate. The authors proposed four principal hazard scenarios for bridge design: (1) horizontal dense flow impact, (2) inclined dense flow impact, (3) deposition on the bridge, and (4) powder avalanche impact. They also concluded that no available impact model could adequately predict avalanche actions on complex bridge structures and identified the need for further research into loads and avalanche flow density.

Figure 3. Snoqualmie Pass East Avalanche Bridges

The I-90 Snoqualmie Pass East program replaced an aging snowshed with a combination of elevated bridge structures (Figure 3) and operational improvements (Mears et al., 2007, Jones et al., 2014; Stimberis, 2023). The engineering studies evaluated dense flow avalanche behaviour, bridge clearances, powder avalanche exposure, bridge pier loading, and long-term operational considerations for snow removal and maintenance access, establishing comprehensive engineering, risk assessment and operational methodologies for modern avalanche bridges (Dynamic Avalanche Consulting Ltd., 2012).

Table 1. Avalanche Bridges and Key Characteristics.

Year	*Bridge*	*Lanes*	*WADT*	*Length*	*Vertical Clearance*	*Notes*
1970	Crater Lake, WY (Glory Bowl)	2	5,500	150 m	40 m	Destroyed during construction; Operational management with RACS
1972	Ri di Rialp, CH (Lukmanier Pass)	2	Winter Closure	40 m	3-16 m	Destroyed in 1998 by inclined dense-flow impact to superstructure.
1980	Goat Lick, MT	2	700	70 m	19 m	1930s bridge destroyed in 1979; 300 km detour for 1 mo. Replaced in 1980 post-tensioned structure designed for impact.
1981	Denny Cr. WA (Franklin Falls)	3	28,000	1103 m	40-60 m	Temporary construction bridge destroyed by avalanche. Tall piers on viaduct. 45 deg aval deflection on piers;
2019	East Shed, WA (Snoqualmie Pass)	6	28,000	730 m	15-21 m	Major terrain modification between piers. Large reduction in closures and operational measures. East and Westbound are different bridges.
2024	Kicking Horse Canyon, British Columbia	4	4200	2,300 m	2.5-40 m	Four Bridges and Nine Viaducts

Similarly, Phase 4 of the Kicking Horse Canyon Project (KHCP4) in British Columbia incorporated six avalanche bridges and several viaducts through complex, high frequency avalanche terrain (Figure 4). The risk to an existing rail corridor below the bridges presented an additional challenge. The bridge geometries were configured so that the design avalanche could pass beneath the superstructure, while exposed piers and abutments were designed to withstand calculated dynamic impact pressures based on local flow velocity, depth, density, and structural geometries. This approach treated avalanche loading as site specific rather than applying uniform loads to the bridges.

Figure 4. The KHCP4 Blackwall Bridge. (BC MoTT)

Temporary and industrial bridges have also experienced repeated avalanche damage. Documented examples include forestry road bridges in British Columbia, e.g., the Bull River Bridge that was destroyed by a large avalanche in 1997 (Weir, 2002), and an industrial access bridge in the Kemano area of British Columbia that was destroyed in 1989.

3. BRIDGE FEASIBILITY CRITERIA

The basic feasibility criteria for bridges in mountainous terrain are complex and include terrain conditions, structural practicality, economic viability, and regulatory compliance.

Bridge feasibility strongly depends on avalanche characteristics, terrain geometry, highway importance, environmental constraints, constructability, residual risk, and life cycle cost.

Site selection should begin with a detailed evaluation of whether a bridge is the most appropriate mitigation alternative compared with conventional snowsheds, tunnels, or operational avalanche control using temporary closures and explosives.

An avalanche site assessment forms the foundation of the feasibility assessment. Avalanche paths with large starting zones and large vertical relief to the bridge may not be suitable for bridges due to very high loads and uncertainties.

Engineers should identify scenarios for the design avalanche magnitude, expected flow regime, frequency, and runout characteristics. Dense flow avalanches generally govern structural loading due to their higher densities and impact pressures, whereas powder avalanches primarily affect vehicle safety, bridge deck exposure, and operational closures. Avalanche width relative to bridge span is particularly important because wide avalanches may load multiple piers and bridge elements simultaneously or produce concentrated loading near bridge abutments.

Terrain geometry also strongly influences bridge performance. Narrow, well confined avalanche tracks are generally more suitable because avalanche flow remains concentrated beneath the bridge opening. Wide debris fans, abrupt terrain transitions, or multiple converging avalanche paths introduce greater uncertainty in impact location and debris accumulation. The steepness of the terrain under and beyond the bridge affects deposition, and adequate storage beneath the bridge must be available for avalanche deposits, seasonal snowpack, and snow accumulations resulting from highway maintenance.

Bridge geometry should therefore be considered together with avalanche behavior rather than independently. Superstructure elevations must provide sufficient clearance above anticipated avalanche deposits and dense flows while maintaining economical span lengths and acceptable highway grades. Pier spacing, orientation relative to avalanche flow, and bridge skew should minimize exposure to avalanche movement and reduce localized impact forces.

Transportation corridors carrying high traffic volumes and those providing critical regional access generally justify the higher capital costs associated with avalanche bridges. Long-term operations may need to incorporate avalanche forecasting, remote avalanche control systems, detection technologies, routine inspections following avalanche events, and maintenance planning for debris removal beneath the bridge.

Finally, bridge feasibility should consider constructability. Temporary works, staged construction, and worker exposure often govern project risk during winter construction. Historical failures demonstrate that incomplete bridge structures may experience substantially different loading than completed bridges and therefore require independent evaluation. The I-90 Snoqualmie Pass project incorporated two independent, three lane bridges, allowing a staged construction approach that maintained multiple open lanes throughout construction.

4. BRIDGE DESIGN CONSIDERATIONS

Avalanche bridge design requires integration of several engineering disciplines and long-term operations. Unlike conventional highway bridges where gravity, traffic, wind, and seismic forces generally govern, avalanche bridges must resist transient, highly variable loads that may act simultaneously on piers, abutments, foundations, and the bridge deck. Consequently, design should follow a systematic process beginning with avalanche characterization before structural analysis is undertaken.

4.1 Design Avalanche Selection

The selection of the design avalanche will likely include avalanche frequency and magnitude in several scenarios to establish the basis for structural, civil, and geotechnical analyses. While a single large avalanche event typically governs design, the bridge design can be driven by several compounding avalanche events. For example, cold, dry, dense flows will usually produce the highest impact pressures, but slower wet flows may govern due to the higher flow density and deeper flow depth. The return period should reflect highway classification (e.g., inter-state, regional, local), acceptable closure frequency, redundancy within the transportation network, and consequences of structural failure.

The design avalanche should be estimated by the engineer, considering avalanche volume, snowpack height, flow depth, velocity, density, impact angle, entrainment potential, and deposition characteristics. Historic avalanche observations, aerial photographs, satellite imagery, dendro-geomorphic evidence, terrain analysis, numerical modelling, and operational records should all contribute to the development of representative design scenarios. Depending on forest conditions, the potential for partial or total loss of forest may need to be considered. This is particularly relevant in many areas of North America where recent large scale wildfires have altered the avalanche regime adjacent to major highways.

4.2 Avalanche Loads

Avalanche loads differ from many structural load cases because they are neither static nor uniformly distributed in time and space. In addition to the load cases suggested by Margreth and Amman, 2004, the principal structural load components should also include:

- **Flow regime:** wet, dry, powder, and mixed-flow avalanches.
- **Entrainment:** including snow, ice, rock, and woody debris.
- **Impacted elements:** piers, abutments, superstructure, and ancillary components such as signage, utilities, barriers, and lighting.
- **Impact direction:** lateral, drag, transverse, oblique, and uplift loading.
- **Static loads:** snow creep and glide loads on piers, and residual or deposited snow loads on the superstructure.
- **Load extents:** Width, depth, type of distribution (e.g. triangular, line, etc.), and duration of loading.

Avalanche Load Factors & Factors of Safety

Avalanche load factors are not defined in Load and Resistance Factor Design (LRFD) or Limit States Design (LSD) methods in North America. Project specific load factors should reflect both the uncertainty in avalanche loads and the probability of other load combinations. Within the LSD/LRFD frameworks, avalanche loads should be evaluated at applicable ultimate and serviceability limit states. At the Ultimate Limit State (ULS), avalanche loads should be factored to achieve an appropriate target reliability while providing sufficient strength and stability to prevent bridge collapse. For the Serviceability Limit State (SLS), avalanche loads should be evaluated where repeated or lower magnitude events could cause unacceptable deformation, cracking, displacement, or damage that requires repairs and impairs bridge function without causing structural failure.

Most North American projects have used project specific factors of safety for avalanche loads (Table 2). For the Denny Creek Viaduct, a factor of 1.5 was used for a 30-year return period event for the piers, and 1.0 was used for a 100-year return period event that could impact the bridge superstructure.

For the I-90 Snoqualmie Pass East project, a blanket factor of 1.5 was applied to avalanche loads associated with the 100-year return period event. In comparison, the Kicking Horse Canyon Phase 4 project applied a factor of 1.3 to avalanche loads associated with the 300-year return period event by treating avalanche loading as a special load case within the framework of the Canadian bridge design standard (CSA Group, 2025).

Margreth and Ammann (2004) suggest an avalanche return period of 30 years for the normal design situation (working loads) and a return period of 100-300 years for the accidental design situation – this is similar to the design for avalanche sheds (ASTRA and SBB, 1994). They also suggest a load factor of 1.5, as per the Swiss code SIA 160 (1989), as well as a 1.5 factor for clearance height under the bridge (i.e., the flow depth with the previously deposited snow).

Future development should move toward a reliability based framework compatible with LRFD and LSD structural design methods that considers avalanches alongside other design loads, such as dead, live, wind, and seismic loads, rather than applying a single factor of safety to all avalanche loads. This is important because conservatism can lead to unnecessarily large design requirements and significantly increased project costs, while insufficient factors can result in unacceptable structural performance.

Table 2. Bridge Specific Factors of Safety

	Design Event		
Bridge	***30-Year***	***100-Year***	***300-Year***
Denny Creek Viaduct	1.5	1.0	~
I-90 East	~	1.5	~
KCHP4	~	~	1.3

4.3 Bridge Geometry

Bridge geometry, including clearance and pier locations, plays a critical role in reducing avalanche loading.

Superstructure elevations must provide sufficient clearance for:

- Flowing avalanches and deposited avalanche debris,
- Seasonal snow accumulation including snowfall, rain and melting,
- Snow storage from plowing, which can significantly reduce available avalanche clearance or storage capacity,
- Uncertainty associated with multiple avalanche events.

Similarly, pier spacing should be optimized to minimize avalanche impacts while maintaining structural efficiency. Conversely, splitting structures may be required for piers that must be located in the central part of the avalanche flow.

Bridge skew also influences structural response. Historical failures have demonstrated that oblique avalanche impacts may concentrate loads near bridge abutments or individual piers rather than uniformly distribute forces across the structure.

4.4 Vehicle Safety

While structural loading often governs bridge design, vehicle safety remains an important design objective.

Powder avalanches may generate severe reductions in visibility while producing relatively small structural loads. Air blast pressures, suspended snow, and drifting snow may create hazardous driving conditions even where dense flow avalanches remain below bridge deck elevation.

In addition to the loss of visibility, there is a risk of vehicle overturning due to powder avalanches, particularly for large transport trucks with a high center of gravity. Traffic closures and artificial triggering should be considered when determining the design event for powder impacts on vehicles. The I-90 East project applied a minimum 30-year event for vehicle destabilization.

4.5 Independent External Reviews and Design Checks

Avalanche processes are complex with many uncertainties. Experience has demonstrated that unexpected events are possible, despite careful analysis. An effective process to address these issues entails independent reviews and design checks of assumptions, analysis methods, and design loads. The high costs and critical importance of bridge infrastructure justify the added design expense of independent third-party reviews and checks.

5. CONSTRUCTION ISSUES

Construction often represents the period of greatest project risk because incomplete structures may experience loading conditions substantially different from those assumed for the completed bridge.

Historical failures demonstrate that temporary bridge configurations may possess significantly reduced structural capacity while simultaneously increasing avalanche exposure for construction personnel. Construction planning should therefore integrate avalanche hazard management into all project phases. Recommended practices include:

- seasonal construction scheduling,
- temporary avalanche forecasting programs,

- active avalanche control,
- worker safety and evacuation procedures,
- temporary traffic restrictions,
- construction sequencing and strict snow and avalanche debris removal guidelines to minimize exposure and protect the structure.

Where possible, critical structural components should be completed before the onset of winter to reduce the duration of temporary loading conditions.

Large infrastructure projects, including the Snoqualmie Pass East Project and Kicking Horse Canyon Phase 4, demonstrated the value of integrating avalanche professionals directly into construction management teams. This approach allowed hazard assessments, avalanche control activities, and construction sequencing to evolve together throughout project delivery.

Additionally, temporary barriers or catchments may be required during construction for rockfall, debris flows, or small avalanches to reduce short-term hazards.

6. OPERATIONS AND MAINTENANCE

While avalanche bridges can significantly reduce avalanche risk, they may not eliminate the need for road closures, forecasting, or avalanche control. Instead, they should be considered one component of a broader transportation risk management system.

Project specific long term operational requirements may include:

- avalanche forecasting and control,
- access for snow removal of debris accumulation beneath bridges,
- routine structural inspections,
- bridge deck and pier inspections following major events.

Climate variability may further influence future operations. Changes in precipitation phase, rain-on-snow events, and altered avalanche frequency may require periodic reassessment of original design assumptions and operational requirements.

7. CONCLUSIONS

Avalanche bridges can provide an effective alternative to snowsheds and operational avalanche control where terrain and highway geometry allow avalanches to pass beneath an elevated structure. Historical failures and successful projects demonstrate the importance of integrating avalanche engineering early in project development so that bridge alignment, clearance, pier locations, and structural geometry can be used to avoid or minimize avalanche interaction.

Where avalanche interaction cannot be avoided, loads should be developed for credible site specific scenarios and individual structural components rather than represented by a single uniform lateral pressure. Flow regime, direction, depth, velocity, density, deposition, uplift, entrained debris, local terrain, and bridge geometry can produce substantially different loading conditions across a structure. Design must also consider construction phase exposure, vehicle safety, and the potential for multiple or successive avalanche events.

Successful avalanche bridge design therefore requires an integrated approach that combines avalanche avoidance and clearance, flow management, component specific structural resistance, and the management of residual risk. Avalanche bridges may substantially reduce risk and highway closures, but they do not necessarily eliminate the need for forecasting, avalanche control, inspection, maintenance, or temporary closures.

8. FUTURE RESEARCH

Future research needs include improving the translation of avalanche flow parameters into structural loads on bridges. Current methods can estimate velocity, flow depth, density, and direction reasonably well, but significant uncertainty remains in converting these parameters into loads and load distributions on complex structures. The effects of entrained ice, rock, and woody debris are also poorly quantified, creating the potential for either excessive conservatism or underestimation of design loads.

Another research priority is the development of a reliability based framework compatible with LRFD and LSD bridge design. Future work should define characteristic avalanche scenarios for different design situations, quantify uncertainty, and calibrate ULS load factors to appropriate target reliability levels. Load combinations should account for the probability of avalanche loading occurring concurrently with dead, traffic, snow, wind, seismic, and other actions, while SLS criteria should address more frequent events that may cause repairable damage or temporary loss of function.

Full scale measurements will also be important for reducing uncertainty. Instrumented test facilities in Europe provide valuable data on impact pressure, flow depth, velocity, density, and load distribution, but no comparable full scale avalanche impact facility currently exists in North America. A North American test site could provide regionally representative data to validate analytical and numerical models and improve avalanche load estimation on complex structures.

Additional research is needed on bridge clearance and deposition, including successive avalanches, seasonal snow accumulation, and snow storage from highway plowing. Design guidance should better define required clearance above predicted flow and deposition depths and how uncertainty should be incorporated.

Ultimately, these efforts should support practical engineering guidelines for avalanche bridges and other infrastructure, including design event selection, LRFD/LSD load factors and combinations, clearance criteria, and component-specific loading. The resulting knowledge would also apply to updated snowshed guidelines, towers, retaining and diversion structures, remote avalanche control systems, and other avalanche infrastructure.

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