I-90 SNOQUALMIE PASS: EVOLUTION OF AN INTERSTATE HIGHWAY AVALANCHE PROGRAM

Craig Wilbour*, John Stimberis*, Washington State Department of Transportation

ABSTRACT: Interstate 90 over Snoqualmie Pass, WA (921 m) is the major highway through the Cascade Mountains of Washington State. Snoqualmie Pass receives an average of 1100 cm of snowfall annually. I-90 is affected by 5 active avalanche areas containing nearly 40 individual paths. Increasing traffic volumes have exceeded the capacity of the 4 lane highway. Avalanche delays and closures have an economic impact that often exceeds several million dollars (USD), depending on the length of the closures. The current two-lane snow shed was built in 1950, and additional lanes were added in the 1960's. These lanes are unprotected from avalanches.

Avalanche control along I-90 over Snoqualmie Pass will be dramatically reduced by building passive defense structures. WSDOT has started a $595 million (USD) project to upgrade and expand an existing 8 km section of I-90. Plans include replacing the existing 2-lane 152 m snow shed with a 6-lane snow shed 335 m long. Approximately 1200 m of snow supporting structures will be installed in other avalanche starting zones. This will be one of the largest highway snow sheds and the most extensive fencing projects in North America.

KEYWORDS: snow sheds, avalanche fences, explosives tramways, highways

1. INTRODUCTION

Interstate highway 90 (I-90) is a critical transportation link across the Cascade Mountains of Washington State. The Washington State Department of Transportation (WSDOT) has begun construction on an 8km section of highway east of Snoqualmie Pass (Figure 1). This 8km section of highway will be widened from four to six lanes and is estimated to cost $595 million (USD). I-90 is six lanes west of the project area with an extra hill climbing lane where warranted. Increasing traffic volumes have exceeded the capacity of the four lane highway east of Hyak. Natural hazards such as rock fall and snow avalanches present a problem.

The I-90 Snoqualmie Pass East Project contains two of the most active and problematic avalanche areas affecting I-90 over Snoqualmie Pass. These are the East Shed avalanche paths, 10 km east of the summit along Lake Keechelus, and Slide Curve, 1.6 km further east (Figure 1). The existing 152 m East Snow Shed covers the two westbound lanes and protects these lanes from the two most active paths.

Avalanches fall directly onto the eastbound lanes from the existing show shed. This shed will be replaced by a clear span, six lane snow shed 335 m long. About 1200 m of snow supporting structures (fences) will be installed at Slide Curve and two smaller paths. When the new snow shed and fences are completed it will eliminate all but about three percent of the existing avalanche hazard in the project area. Up to 70 avalanches per year affecting highway operation have been recorded in the project area. Various versions of this project been proposed since 1970, with the current project beginning in 1996.

The objectives of our paper are to provide a historical overview of the development of the highway and evolution of both passive and active avalanche control methods for I-90 over Snoqualmie Pass. We also present future plans for the highway east of Snoqualmie summit that emphasizes the structural avalanche mitigation components.

1.1 *Geography*

I-90 crosses the northern portion of the United States of America from Seattle, in the Pacific Northwest, to Boston, in the Atlantic Northeast. This highway provides an important trade route

*Corresponding authors addresses: Craig Wilbour and John Stimberis, WSDOT, P.O. Box 1008, Snoqualmie Pass, WA 98068, 509-577-1909, wilbouc@wsdot.wa.gov , stimbej@wsdot.wa.gov

from the coastal ports to the interior regions. In the Pacific Northwest, I-90 provides a critical link between the large population, business centers, and ports of the Puget Sound region to the farmlands, diverse industries, and recreation of Eastern Washington. I-90 also provides access to four ski areas in the Snoqualmie Summit area, some 80 km east of Seattle. Although Snoqualmie Pass (Elev. 921 m) is located at a low elevation, the highway gains about 350 m over the last 8 km as it crosses the crest.

A rapid increase in elevation, coupled with a unique regional weather phenomenon, provides abundant precipitation at Snoqualmie Pass. The Cascade Mountains occur in a maritime snow climate, characterized by heavy precipitation and mild temperatures (McClung and Schaerer, 2006). The effects upon transportation are significant. Travel is delayed for many hours each winter due to snow-related concerns. Typically delays are due to loss of traction, vehicle collisions, and avalanche closures due to heavy precipitation and steep avalanche paths. The slopes above the highway rise sharply and contain nearly 40 avalanche paths that affect the highway on either side of the pass.

The Cascade Mountains are oriented north to south along the Pacific Northwest region of the USA, and southern British Columbia, Canada. The mountains divide Washington State; the area west of the mountains includes the large population centers and wet climate generally associated with Washington State. The area east of the mountains is much drier, and is dominated by agriculture and a more rural lifestyle. Several highways and railways cross the Cascade Mountains to link the west to the east. These transportation routes not only link Eastern Washington to Western Washington, they link the ports and industries of the Pacific NW to the northern third of the United States. I-90 is the only major highway across the Cascade Mountains of Washington, and is the most significant transportation route in terms of economic and recreational impacts.

I-90 has been maintained for winter use since the 1930's, originally as a two-lane highway. Improvements in the 1950's and 1970's increased the capacity of the highway by adding additional lanes and structures. Average daily traffic (ADT) volumes have steadily increased over the years, and so has the reliance on I-90 to provide a reliable transportation route. The ADT on I-90 has increased from approximately 5000 vehicles a day in the 1950's to 30,000 a day currently (Figure 2). Trucks account for nearly 20% of the weekday traffic volume (Figure 3). The ADT may exceed 50,000 vehicles during holidays and summer weekends.

1.2 *Weather*

Snoqualmie Pass typifies the maritime climate. The predominant storm track arrives from the Southwest, drawing moist sub-tropical air that provides the area with abundant precipitation. The average annual snowfall, recorded at the WSDOT Snoqualmie Pass study plot (921 m), is nearly 11 m. Annual precipitation is 2500 mm, and rain-on-snow events are common throughout the winter. In addition to the large Pacific storms, post-frontal westerly flow produces significant orographic precipitation. A localized phenomenon, known as the Puget Sound convergence zone, is capable of further enhancing precipitation in the Central Cascade Mountains including Snoqualmie Pass. Ample snowfall, fluctuating freezing levels, and steep mountainous terrain combine to produce avalanche conditions.

2. INTERSTATE 90 SNOQUALMIE PASS

The highway over Snoqualmie Pass has generally followed the same route used today, though the highway itself has evolved considerably over time. Avalanche concerns, particularly at the East Shed (Figure 1), were recognized long ago. Structures were placed in the most avalanche prone areas to mitigate the hazard. Improvements to the highway were often made utilizing the existing route. The one exception is the west side of the pass, where a new route was chosen in the 1970's. This new route added two additional areas of avalanche concern.

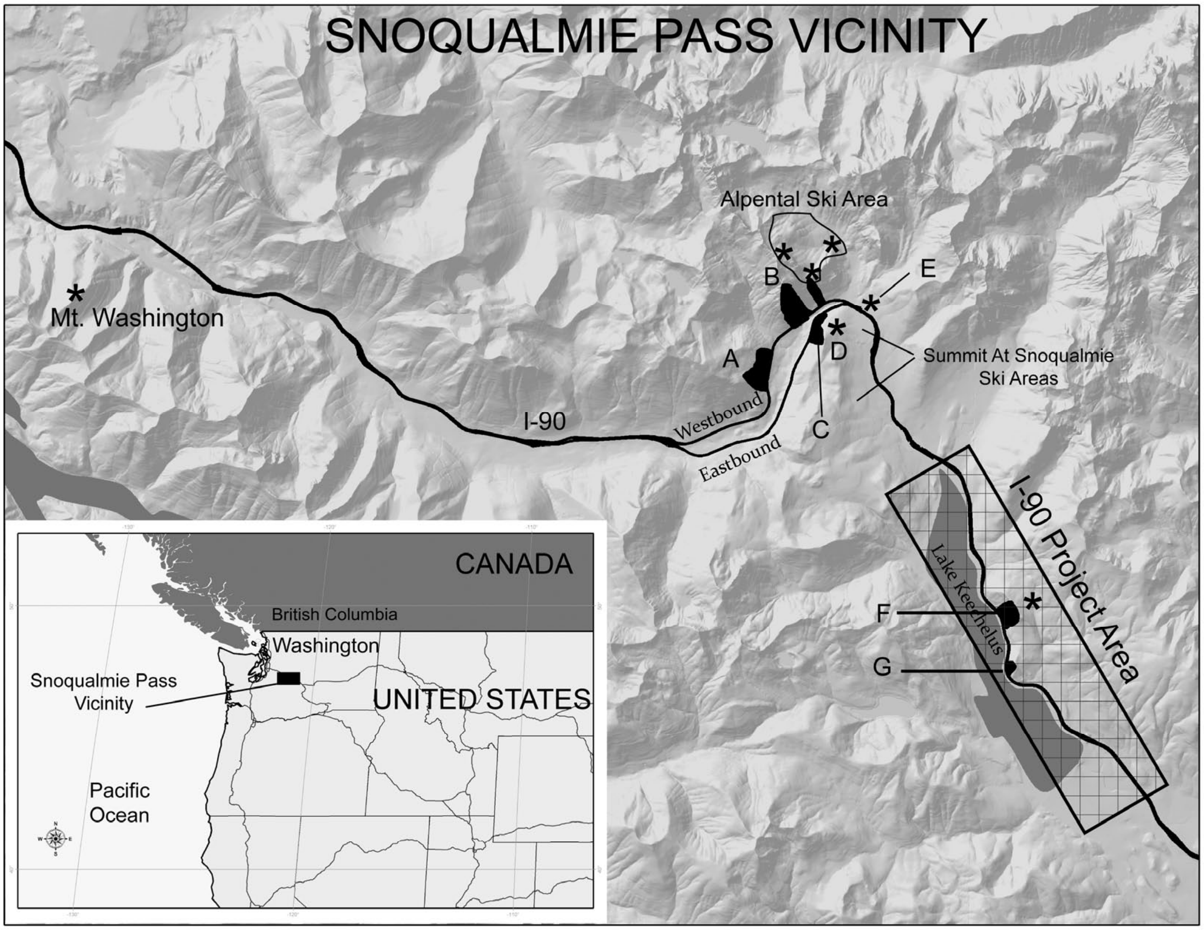

Figure 1.Snoqualmie Pass Vicinity: A- Granite Mtn., B- Denny Mtn., C- West Shed/Airplane Curve, D- Dodge Ridge, E- WSDOT study plot, F- East Shed, G- Slide Curve. Primary weather stations are shown with asterisks.

2.1 *Evolution of the Highway and Structural Avalanche Defenses*

Travel over Snoqualmie Pass predates European settlers (Prater, 1981). The route offers a low elevation passage through the mountains and improvements were made to the existing foot trail to accommodate increased traffic and commerce, including a rail road. By the early twentieth-century an improved gravel road crossed Snoqualmie Pass allowing travel during the summer months. Winter maintenance of the road began in 1931 and a wooden snow shed was constructed in what is known as the East Shed area. The wooden shed was replaced in 1950 with the current concrete design. At the time the highway was two lanes wide, thus a two lane shed was built.

The west side of Snoqualmie Pass contains a variety of avalanche terrain. The old highway followed the current eastbound alignment (Figure 1). A 400 m snow shed protected the area known as the West Shed. This snow shed was also constructed for two lanes, though at the same time two additional lanes were added to the highway, providing four lanes of travel. The concept at the West Shed was to run eastbound traffic through the shed, and switch to two-way traffic when avalanches blocked the unprotected westbound lanes. This same concept was brought to the East Shed when two additional lanes were added.

Although avalanches were recognized as a threat to the highway, the WSDOT continued to operate I-90 without a formal avalanche program, which was relatively common at the time. Highway expansion in the late 1950's added two more lanes around Lake Keechelus (Figure 1). The additional eastbound lanes were outside the existing snow shed. Traffic was detoured into the shed when avalanches blocked the unprotected lanes, though occasionally vehicles would be caught in avalanches in the unprotected lanes. The East Shed area, in particular, is notorious for having an avalanche block the highway and then having subsequent avalanches reach the road due to the multiple starting zones in the paths above the shed. Multiple starting zones complicated efforts to extract vehicles, or to simply clear the snow. Snow removal equipment was outfitted with supplemental oxygen as an early form of avalanche safety. Another consequence of the construction was a massive landslide at what is now known as Slide Curve (Figure 1). The landslide created another avalanche prone area for the expanding highway.

Traffic volumes continued to increase, as did the dependence on a reliable highway throughout the winter months. As a result, avalanche accidents occurred, particularly at the East Shed site (Figure 1). The East Shed site is especially dangerous due to the multiple starting zones. Although one avalanche may block the road, subsequent avalanching may continue. This is troublesome during snow removal and excavation of trapped vehicles. A fatality at the East Shed in 1971 was one of the catalysts for initiating the forecast and control program.

By the late 1960's plans were made to construct a new section of highway on the west side of Snoqualmie Pass. These three new lanes would carry westbound traffic, while the existing four lane alignment would be used for eastbound traffic. The new westbound alignment travels through two avalanche areas, Denny Mountain and Granite Mountain which are on the west side of the valley (Figure 1). Avalanche mitigation included a bridged section of highway through the Denny Mountain area, and construction of attenuating and diversion mounds above an avalanche dam in one of the Granite Mountain South paths. Both areas were known avalanche areas; the Granite Mountain South path had seen two cabins destroyed by avalanches in 1950's.

The Denny Mountain site (Figure 1) was recognized as an avalanche area as well, but the bridge design was modified during construction after a work bridge was heavily damaged by an avalanche. The addition of an avalanche program was included in the new westbound alignment. Artillery would be used to control the slopes above the highway on Granite and Denny Mountains. The roof of the West Shed was removed due to traffic collision concerns. The number of accidents caused by the detours and two-way traffic through both snow sheds increased to beyond what the avalanche accident rate would have been. The increase in collisions was a catalyst for an improved avalanche control program, and modifying structural avalanche defenses. The removal of the West Shed roof included a large excavation creating storage behind the slope side shed wall for avalanche catchment. The slope side wall was left in place creating an avalanche dam. Construction of the new section of highway, rerouting traffic, and removal of the West Shed was completed in the early 1980's.

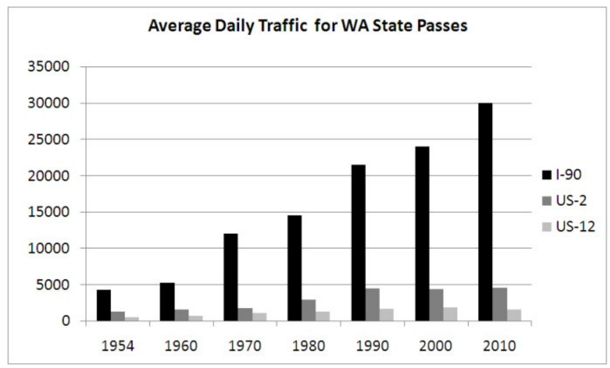

Figure 2. Washington State mountain pass traffic volumes.

2.2 <u>Evolution of the Avalanche Forecast and Control Crew</u>

The Avalanche Control program was started in 1973 and consisted of engineers who had little experience in the snow. The WSDOT bought the group skis, and provided ski lessons. A graduate student from Dr. Ed LaChapelle's program at the University of Washington was hired to teach them about avalanches. The initial crew size was reduced the following winter, but the remaining crew members had artillery experience from their military service.

The program evolved over the next few years. Conventional explosives were brought into the program, and the transition from engineers with little snow experience to those with ski resort avalanche control experience was under way. By the late 1970's proactive avalanche control was tried, though WSDOT management was skeptical about closing a highway before avalanches had occurred. The avalanche crew found it necessary to produce big results to prove the concept of preemptive control work. This often led to long delays while the avalanche debris was removed from the highway.

2.3 *Evolution of Avalanche Control Methods*

Local topography, logging roads, and ski resorts provide good snow cat and lift access to many of the highway starting zones. The ski areas also provide easy access to the high elevation snow pack. The avalanche program initially relied on artillery, a 105 mm recoilless rifle, to perform avalanche control west of the pass. A mobile Avalauncher was used in many of the other avalanche prone areas. Hand charges and ski cutting were also used. These methods evolved as access to the starting zones was improved. At the same time the concept of using larger explosives in the wet maritime snow was explored. Initially these larger shots consisted of hand placed case charges elevated on sticks. Soon, trams were constructed to deliver the increasingly larger charges and provide a greater effect to the snow (Redden, 1988). Avalauncher shots were replaced, or tree re-growth greatly reduced avalanching, and the Avalauncher was phased out. Trams also eliminated many hand-thrown shots and ski cuts. This evolution increased efficiency and improved safety for the program.

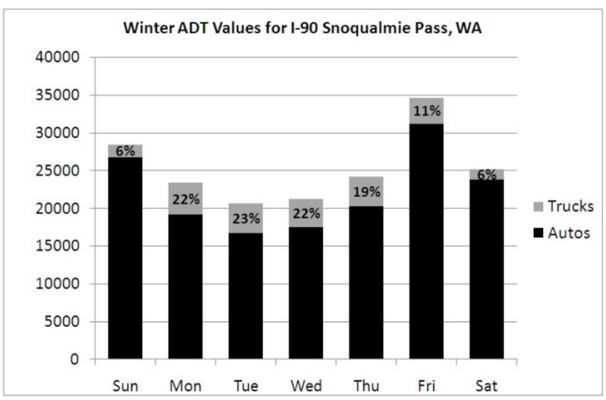

Figure 3. Winter traffic volume on Snoqualmie Pass, WA

Over the years the trams, now numbering 16, have replaced all but three hand charge locations and several artillery targets (Wilbour *et al*, 2008). In locations such as the East Shed and Slide Curve (Figure 1), the explosive charges are suspended from three trams and linked with detonating cord. This method provides simultaneous aerial detonation of 39 kg across multiple portions of a starting zone. The continued use of large, elevated explosives has proven to be necessary in the low elevation maritime snow climate. These control procedures have reduced post-control avalanches, particularly during rain-on-snow events. The use of large shots also maintains a relatively shallow snow pack, which provides a benefit of early melting and a reduction in the length of the avalanche control season. Frequent control with large elevated charges reduces the consequences of natural avalanches, and debris cleanup time following controlled avalanches, by keeping the avalanches smaller. Many paths have seen tree growth greatly reduce or eliminate the need for avalanche control. These areas have naturally regenerated, though it is possible that repeated long-term use of ANFO may produce a fertilizing effect upon the local slope. Improvements to snow catchment along the roadside have also reduced the need for avalanche control. Maintaining these catchments is critical to preserving their ability to perform throughout the winter.

Each improvement has reduced the time required to perform avalanche control. Firing the 105 mm recoilless rifle was a time consuming process. This weapon was recently replaced with an M60 tank. The M60 tank also delivers a 105 mm round, providing similar results in the avalanche starting zones. The increased efficiency is found in the time required to operate the weapon. The reduction in time required to perform control work provides less delay to travelers, and also to WSDOT maintenance crews. The results are improved traffic flow. In addition to control work, forecasting techniques have improved greatly over the years.

2.4 *Instrumentation and Weather Forecasting*

The WSDOT Avalanche Forecasting and Control program began in 1973 as an avalanche control program with forecasting duties only. Snow and weather observations were made for the first two years, then for the next three years avalanche control was only allowed after a natural avalanche had blocked the highway. Weather observation equipment started with analog instruments installed at the WSDOT study plot (921m) and near the 105 mm recoilless rifle mount on Dodge Ridge (Elev. 1160 m) (Figure 1). Additional stations have been added to the network, including a station adjacent to the starting zones above the East Shed (Elev. 1130 m), and a station 22 km west of Snoqualmie Pass on Mt. Washington (Elev. 1340 m) (Figure 1). The current program utilizes weather data from nearly 20 stations in the Snoqualmie Pass area. Improvements to instrumentation greatly benefited the forecasting program by providing more accurate meteorological information.

Weather forecasts are a critical component of avalanche forecasting in a maritime climate (Conway *et al*, 1988). The Northwest Weather and Avalanche Center (NWAC) started as a WSDOT research project about the same time that avalanche control started on I-90. The WSDOT has continued to fund the NWAC and the two agencies work closely, providing one another with beneficial information related to mountain weather and avalanche forecasting. NWAC continues to be the primary source for weather forecasts. The WSDOT also uses a private forecasting service and National Weather Service forecasts. Online forecast models and other weather-related information is integral to the forecasting program.

2.5 *Safety and Communication*

Daily weather and avalanche forecasts are compiled by WSDOT avalanche personnel and delivered to the WSDOT maintenance program both orally and electronically. Daily forecast meetings at the start of each highway maintenance shift provide a unique opportunity to present an overview of any avalanche or weather concerns. Site specific safety information is made available at that time as well. Improved communications between these programs has led to further efficiencies and safety in addressing avalanche hazards. These daily meetings have reduced uncertainties about when or where avalanche hazards exist.

3. RESULTS

The WSDOT I-90 Avalanche Forecasting and Control Program continues to evolve. Additional aerial trams have been installed and improved. A weather station network was created and expanded, and the concept of performing more frequent control work to reduce cleanup time was introduced and improved. The highway ADT continues to increase each year (Figure 2). Recently, an expansion of the avalanche program, with additional crew members and a night shift to perform control work during periods of decreased traffic volume has improved has reduced impacted to travelers. The program has evolved to the point that it is maximizing the available resources. Future avalanche mitigation options include additional control, more frequent control, or the construction of additional engineered defenses to reduce avalanche closures and risk.

3.1 *Snoqualmie Pass East Project*

Economic demands continue to grow, putting more pressure on the WSDOT to maintain an open highway. In 1996, the process to expand the highway, and protect against avalanches and other natural hazards, was initiated. Funding and design work continued into the next decade. Once the funding was secured, and the necessary environmental documentation was completed, the process was in place to increase traffic from four lanes to six lanes and build several large avalanche defense structures east of Snoqualmie Pass (Figure 1).

The Snoqualmie Pass East project specifically addresses two avalanche areas on Snoqualmie Pass, the East Shed and Slide Curve (WSDOT, 2008) (Figure 1). In addition, two minor avalanche prone areas are addressed as well, since the potential for additional avalanches affecting the highway will increase due to expansion of the roadway. Two solutions have been proposed: (1) construction of a larger snow shed at the existing East Shed site, and (2) extensive snow retention fencing at Slide Curve and two minor avalanche slopes (WSDOT, 2008). These mitigation features are still in the design phase and the contract is expected to be advertized for bid by February 2011. The following project description is based on the current design and anticipated construction schedule.

3.2 *East Snow Shed Project Description*

The East Shed location is currently the most active avalanche area on I-90 at Snoqualmie Pass (Figure 1). The area consists of five main avalanche paths with two paths accounting for the majority of the avalanche activity. The East Shed paths have a vertical drop of nearly 350 m. The paths have a southeast aspect, and maintain a 35-40° slope to the highway. Avalanche activity evolves spatially and temporally throughout the season, generally reaching a peak by mid-winter as the adjoining paths fill in. Activity increases as the tracks fill and the solar effects become more prevalent during the spring season. As the snow pack melts, the avalanche hazard decreases, returning to the two main tracks. This is a typical evolution experienced by many avalanche programs.

3.3 *Snow Shed Design*

The existing snow shed covers two lanes and protects these lanes from two of the five main avalanche paths. The dimensions of the current shed are 4.9 m inside height, 9.8 m width, and 152 m length. The proposed snow shed is a much larger structure with a 7 m inside height, a 36.7 m width, and a length of 335 m. The proposed shed will cover the majority of the controlled avalanche terrain. The shed is designed to accommodate six lanes without a center support. The support girders will be about 2.4 m high, and will almost touch each other for the length of the shed. Additional components include graduated lighting to transition from daylight, a ventilation system, and traffic monitoring and communication systems. The snow shed infrastructure will have a backup power generator.

The WSDOT is committed to providing four lanes of travel during the Snoqualmie Pass East construction project. Temporary structures will help reroute traffic across bridges during construction. The snow shed design, construction, and operations are challenging. The challenges include removing the existing snow shed, excavation and slope stabilization, and construction of the new shed. During the construction phase the WSDOT is committed to providing four lanes of travel.

At this point in the design phase, WSDOT engineers anticipate at least one winter without any snow shed protection for the highway. This will be the first time since the highway has been maintained for winter travel that the East Shed area has been unprotected. The demands on the avalanche forecasting and control program will be high.

3.4 *Snow Supporting Structures*

The expanded snow shed is one component of avalanche mitigation in the Snoqualmie Pass East project. In addition, approximately 1200 m of 3.0 and 3.5 m fencing are included in the project. The primary location for the fences is a large open slope known as Slide Curve (Figure 1). Two additional areas, Bald Knob and East Shed Minus-One, will receive several short rows of fences to provide additional protection. The total amount of fences and the overall height of the fences will make this the largest snow retention project protecting highways in North America. This project is also one of the largest in a maritime climate.

The Slide Curve area is a 135 m slope with a 30° average slope angle and a SE aspect. The slope formed as a result of a massive rockslide that failed during highway construction in the 1950's. The main slope consists of boulders and scree. Vegetation consists of smaller conifers to the east, increasing in height towards the west, in particular near the boundary between the western boulder field and the Slide Curve slope. It is possible that ANFO based avalanche control over that past 25 years may have contributed to increased vegetation growth.

Current design calls for eight rows of fencing across the slope (Mears *et al*, 2010). The lower portions of the slope will have 3.0 m high fences, while the upper portions of the slope will have 3.5 m high fences. Historic maximum snow depths for Slide Curve approach 365 cm. Fence row lengths range from 75 m to 166 m. Immediately west of the main Slide Curve slope is a boulder field that pre-dates the Slide Curve landslide. This slope has a history of avalanche activity and has been part of the active avalanche program since its inception. Similar to the Slide Curve slope, the boulder field is controlled by an aerial tram using ANFO based explosives. The boulder field has three rows of fences proposed for installation. These fences will include both the 3.0 m and 3.5 m high fences. The Boulder field will have a total of 95 m of fence. The main Slide Curve face will have 936 m of fence installed.

Additional fences are proposed for the Bald Knob and East Shed Minus-One sites. The Bald Knob site will have three rows of 3.5 m high fences, with a total of 101 m. This location has a limited history of avalanche activity, though it is capable of producing avalanches that cover the westbound lanes of travel. The redesigned highway will be somewhat closer to the base of this slope, thus the decision to install snow retention structures. The East Shed Minus-One site is a large open rock face at an elevation of 850 m. This slope has an aspect similar to the other slopes in this area, though it doesn't have a well documented avalanche history. The decision to include East Shed Minus-One is based on the terrain and the highway design. The highway will be much closer to the slope, thus increasing the likelihood for possible avalanche activity to reach the highway. Two rows of fences will be included on the slope, centered above an area of disturbed vegetation that was likely caused by avalanche activity. The fence height will be 3.5 m and a total of 57 m of fences are expected to be installed.

4. CONCLUSIONS

The WSDOT Avalanche Forecast and Control program on Snoqualmie Pass is about to embark on a major change to their program. The eventual addition of a larger six-lane snow shed will eliminate the vast majority of avalanche control required at the East Shed site (Figure 1). Currently the East Shed accounts for nearly 85% of all avalanche closures on I-90 Snoqualmie Pass. The addition of the snow shed will greatly reduce avalanche threats to the highway, vastly reducing the amount of control work required for this area. Occasional avalanche control will still take place under extreme conditions.

The Slide Curve site (Figure 1) is another area of repeated avalanche activity. Snow retention fences will be installed at the Slide Curve site, as well as two smaller locations. All told, these structures will dramatically reduce avalanche control in this area. The fences are designed for a 100-year snow pack maximum. Based on the proposed design, avalanche control should not be required in these areas because the fence design is not compatible with active avalanche control.

In addition to the structural improvements, the roadside ditches will be improved throughout the project area. These improvements increase the capacity for snow storage and lessen the likelihood that small sluffs will reach the highway. The Airplane Curve avalanche area (Figure 1), west of Snoqualmie Pass, is an example of improvements to the catchment providing an additional benefit of avalanche protection. Avalanche control has been reduced in the Airplane Curve area due to widened catchments. The improvements and structural defenses on the Snoqualmie Pass East project will provide a benefit to avalanche forecasting and control west of Snoqualmie Pass; the WSDOT Avalanche Program will be able to focus more effort on one area, rather than attempting to manage a number of areas at one time.

One of the outstanding challenges is operating the highway without the East Snow Shed for at least one winter. The WSDOT already has the tools and program in place to deal with the avalanche hazard. The biggest challenge will be performing more avalanche control then what is currently done, at times that are less convenient to highway operations. Furthermore, avalanche control will result in additional snow removal, thus longer delays to traffic are anticipated. The present two-lane shed often holds some of the snow in the track, on the roof of the shed. Avalanches run into the two eastbound lanes, with the excess spilling into Lake Keechelus (Figure 1). The removal of the snow shed will allow more snow to cover the highway, possibly backing up the 20 m cut bank. Snow removal from a much wider highway area will be required than just the present 2 lanes.

The avalanche program currently uses 20 mm snow water equivalent (SWE) as a rule of thumb for avalanche control. Snow structure and certain weak layers will alter the SWE estimates. Thus, the 20 mm SWE rule is based more on the amount of snow likely to reach the highway, and the amount of clean up time involved. The rule of thumb will need to be reduced based on path run out changes and increased cleanup time due to the removal of the snow shed.

ACKNOWLEDGEMENTS

We thank the many people who have contributed to the growth and development of the WSDOT Avalanche Forecasting and Control program on Snoqualmie Pass.

REFERENCES

Conway, H., Breyfogle, S., and Wilbour, C., 1988, Observations relating to wet snow stability, Proc. ISSW, Whistler, 211-222.

McClung, D.M. and P.A. Schaerer. 2006. *The Avalanche Handbook*. Seattle, WA, The Mountaineers, 22.

Mears, A., Urlich, C., Wilbur, C., Zeman, J., 2010. *Avalanche Mitigation Snow Net Optimization Report*. URS Corporation.

Prater, Y., 1981, Snoqualmie Pass -From Indian Trail to Interstate, The Mountaineers, 168p

Redden, L., 1988, Low cost delivery systems for avalanche control, Proc. ISSW, Whistler, 1988, 28-33.

Washington State Department of Transportation (WSDOT) 2008. *I-90 Snoqualmie Pass East Final Environmental impact Statement*

Wilbour C., Marston K., and Redden L., 2008, Tram improvements on Snoqualmie Pass, Proc. ISSW, Whistler, 875-880.