I-90 Snoqualmie Pass East Project

Avalanche Mitigation Report
Avalanche Analyses

December 2007

Washington State Department of Transportation

U. S. Department of Transportation
Federal Highway Administration

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Acknowledgements

I-90 Snoqualmie Pass East

Agreement No. 9764
Task Order BR

Avalanche Mitigation Report

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November 21, 2007

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Avalanche Mitigation Report
I-90 Snoqualmie Pass East
Hyak to Keechelus Dam, Washington
URS Job Number 33758612
WSDOT Agreement Number Y-9764

Dear Mr. Giles:

URS Corporation and Arthur I. Mears P.E. & Associates are pleased to submit six copies of our Avalanche Mitigation Report for the I-90 Snoqualmie Pass East Project between Hyak and Keechelus Dam. This work was conducted in general accordance with WSDOT Agreement Number Y-9764, Task Order BR, and Amendment 1, dated March 1, 2006.

The analyses, conclusions and recommendations described in this Report reflect review comments received from WSDOT on a draft report that was submitted on September 10, 2007, and additional review by URS.

Sincerely,

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ACRONYMS

	I
I-90	Interstate 90
	M
MP	Milepost
	S
Sta.	Station
SI	International System of Units
	U
URS	URS Corporation
	W
WB	Westbound
WBS	Work Breakdown Structure
WSDOT	Washington State Department of Transportation

UNITS OF MEASURE

ft	feet (length)
ft/sec	feet per second (speed)
kg/m^3	kilogram per cubic meter (density)
Km	kilometer (distance)
kN/m	kilo Newton per meter (force per unit length)
kPa	kilo Pascal (pressure)
lb/ft^3	pound per cubic foot (density)
m	meter (length)
m/s	meter per second (speed)

m^2	square meter (area)
m^3	cubic meter (volume)
Pa	Pascal (pressure)
psf	pound per square foot (pressure)
tons/ft	ton per foot (force per unit length)
yd^2	square yard (area)
yd^3	cubic yard (volume)

EXECUTIVE SUMMARY

The Washington State Department of Transportation (WSDOT) has identified that the part of Interstate 90 (I-90) on the east side of Snoqualmie Pass between Hyak and Easton needs improvement. WSDOT selected the Hyak to Keechelus Dam (MP 55.1 to 59.9) segment as the first phase of the project.

A critical component of the project is to evaluate methods of snow avalanche mitigation. As a result, URS Corporation and Arthur I. Mears, P.E., Inc., along with Wilbur Engineering, Inc. undertook an avalanche mitigation study. The feasibility of three types of snow avalanche mitigation structures was evaluated:

- **Snowsheds** - Snowsheds are structures with most of the outer side open, and that cover the roadway so that avalanche snow passes over the top of the structure without impacting the roadway.
- **Ditch and Wall Systems** - Ditch and wall systems are built on slopes above the roadway to block the movement of avalanche snow and prevent it from reaching the roadway.
- **Snow Nets** - Snow nets are specialized fences that are installed across slopes to hold the snow in the starting zones and prevent it from moving down the slopes in unstable conditions.

Snow avalanches are episodic and catastrophic events. Their occurrence, severity, and loads on impacted structures are difficult to predict. The estimated loads, conclusions and recommendations in this report are based on professional judgment supported by engineering analyses using available analysis tools and commonly used assumptions. Therefore, adequate safety factors must be used in all structural designs.

The I-90 avalanche study area consists of mountainous terrain where snow avalanches occur. The steep slopes support moderately forested terrain except in the Slide Curve area. It was assumed that the terrain will remain forested in the same manner as it is at present. The following avalanche terminology is used in this report from the topographic high to the topographic low (vertically from top to bottom).

- **East Sheds** - East Sheds are geographic areas higher up on the slopes where snow avalanches have historically originated and are expected to continue originating.
- **Avalanche Paths** - Avalanche paths are the route that snow takes as it travels down a slope. The term "chute" has historically been used to define this route, but "path" is more appropriate.

Five East Sheds (1, 2, 3, 4 and 5) were identified in the project area from west to east. All are located in areas above the general vicinity of the existing snowshed, where snow avalanches have historically originated. East Shed 5 has two segments that are designated as 5 West and 5 East. East Sheds 2, 3, 4 and 5 have the potential to generate significant avalanches. East Shed 1 has the potential to generate relatively small and infrequent avalanches. There is also a potential for snow avalanches in the Slide Curve area.

Six avalanche paths were identified below East Sheds 2, 3, 4 and 5: one each for East Sheds 2, 3, and 4; and three for East Shed 5 that are designated as 5 West (1), 5 West (2) and 5 East. These paths have the potential to convey significant avalanches. The avalanche path for East Shed 1 is located west of the paths for East Sheds 2 to 5, but has the potential to convey relatively small and infrequent snow avalanches.

Based on preliminary feasibility analyses, one continuous snowshed was considered to be the preferred option to mitigate against snow avalanches originating in East Sheds 2 to 5. The snowshed would extend from approximately WB Sta. 1352+50 to 1363+50 for a length of about 1,100 feet. A snowshed is not considered necessary to mitigate snow avalanches that could occur from East Shed 1 and Slide Curve.

Two shorter snowsheds would also mitigate against snow avalanches from East Sheds 2 to 5. The two snowsheds would extend from approximately WB Sta. 1352+50 to 1358+50 for East Sheds 2, 3 and 4, and WB Sta. 1360+00 to 1363+50 for East Shed 5. The snowsheds would be about 600 and 350 feet long, respectively, for a total covered length of 950 feet. This would leave a 150-foot gap below an area that is between the edges of the avalanche paths of East Sheds 4 and 5, but does not experience avalanches.

The decision on whether to construct the one longer proposed snowshed, or two shorter snowsheds will depend on construction, operation and maintenance considerations and costs. The proposed snowshed will have two portals but could require more ventilation, lighting and fire suppression. Two shorter snowsheds will require four portals, but may not require as much ventilation, lighting and fire suppression.

Snow avalanche-related design loads for snowsheds include both static and dynamic loads. These two types of loads would not be expected to occur simultaneously. However, the designer must consider each type separately, and use the more conservative of the two. Additional loads due to normal snow deposits on roofs, earthquakes, wind, soils, landslides, and rock falls must also be considered separately.

The estimated static snow avalanche loads on the proposed snowshed roof would have a triangular distribution over a total roof width which is understood at present to be 141.25 feet. The maximum stress would occur along the mountain-side edge. The least stress would occur along the lake-side edge. The proposed snowshed roof is assumed to have a slope of approximately five percent down towards the lake.

The estimated maximum normal static loads due to snow avalanche deposits on the proposed snowshed roof varies from 1,450 pounds per square feet (psf) for East Sheds 4 and 5 East, to 1,000 psf for East Sheds 5 West (1) and 5 West (2), as tabulated below.

East Shed Number	Project Station	Maximum Normal Static Snow Load (psf)	Maximum Normal Impact Snow Load (psf)
East Shed 2	1353+50	1,250	400
East Shed 3	1355+00	1,350	450
East Shed 4	1358+00	1,450	1,000
East Shed 5 West (1)	1360+00	1,000	1,450
East Shed 5 West (2)	1362+00	1,000	1,100
East Shed 5 East	1363+00	1,450	300

Snow avalanche impact loads would apply to smaller widths of the snowshed roof, and would have a short duration where the maximum value could be reached within one second. The estimated maximum normal impact loads on the snowshed roof due to snow avalanches from the six avalanche paths ranges from 1,450 psf for East Shed 5 West (1) to 300 psf for East Shed 5 East, as tabulated above.

Portal protection walls are recommended at both ends of the snowshed(s). The portal protection walls would be required to slope from a height of approximately 20 feet above the snowshed roof at the mountain-side edge to approximately 10 feet above the snowshed roof at the lake-side edge.

To provide protection against snow avalanches at the Slide Curve area, snow net structures were found to be preferable to snowsheds because of the relatively small starting zone area and because no rights-of-way or easements would need to be aquired.

The potential for closure and damage to the I-90 roadway due to relatively small and infrequent avalanches from East Shed 1 and from other rock cut areas such as Jenkin's Knob could be minimized through construction of a ditch and wall system.

INTRODUCTION

1.1 GENERAL

The Washington State Department of Transportation (WSDOT) has identified that the part of Interstate 90 (I-90) on the east side of Snoqualmie Pass between Hyak and Easton (Milepost (MP) 55.1 to 70.3), needs improvement. The 2005 legislature provided $525 million for the first phase. WSDOT selected the Hyak to Keechelus Dam (MP 55.1 to 59.9) segment as the first phase of the project.

The objective of the project is to improve the roadway by widening and re-aligning the existing highway, and constructing or replacing structural elements that do not meet current Federal and WSDOT highway standards. The purpose of the improvements is to eliminate or reduce snow avalanche closures, increase capacity, stabilize slopes, enhance freight mobility, replace pavement, improve mobility, and address environmental stewardship.

WSDOT South Central Region contracted URS Corporation of Seattle as General Engineering Consultant for the project, under WSDOT Agreement No. Y-9764, dated February 14, 2006. A critical part of the project is to evaluate the feasibility of constructing snow avalanche mitigation structures for the purpose of eliminating or reducing highway closures caused by snow avalanches. The main avalanche mitigation would be a new 6-lane EB and WB snowshed that would replace the existing 2-lane WB snowshed.

URS and a natural hazards consultant, Arthur I. Mears, P.E., Inc., of Gunnison, Colorado, undertook an avalanche mitigation study as Task Order BR, work breakdown structure (WBS) PC-23-502 dated May 1, 2007. Another natural hazards consultant, Wilbur Engineering, Inc., of Durango, Colorado, was retained to assist with the study. Both consultants worked under sub-contracts to URS. White Shield, Inc. of Pasco, Washington, provided survey support as part of Task Order BU under sub-contract to URS.

1.2 PROJECT DESCRIPTION

The project is located east of Snoqualmie Pass in Kittitas County, Washington, along the five-mile section of the existing I-90 between Hyak (MP 55.1) and Keechelus Dam (MP 59.9) as shown in Figure 1-1. The existing roadway is the most heavily traveled east-west highway in Washington, and contains four lanes of traffic: two EB lanes and two WB lanes. This part of the highway is surrounded by the following:

- South or west facing slopes between MP 57.64 and 59.08 along the north or east side of I-90.
- Keechelus Lake along the south or west side of the I-90 roadway.
- Keechelus Lake Dam at the southeast end of the lake near MP 61.0.
- National Forest Route 4832 which is parallel to the existing I-90 on the north or east from MP 55.1 up to approximately MP 57.1, and then diverges east from I-90.

Figure 1-1 also shows the locations of the existing WB lane snowshed which is in an area that experiences severe snow avalanches and the Jenkins Knob and Slide Curve locations which are planned to undergo rock cuts for the roadway widening and could experience snow avalanches. A view of the highway looking north, with the existing snowshed centrally located, is shown on Figure 1-2.

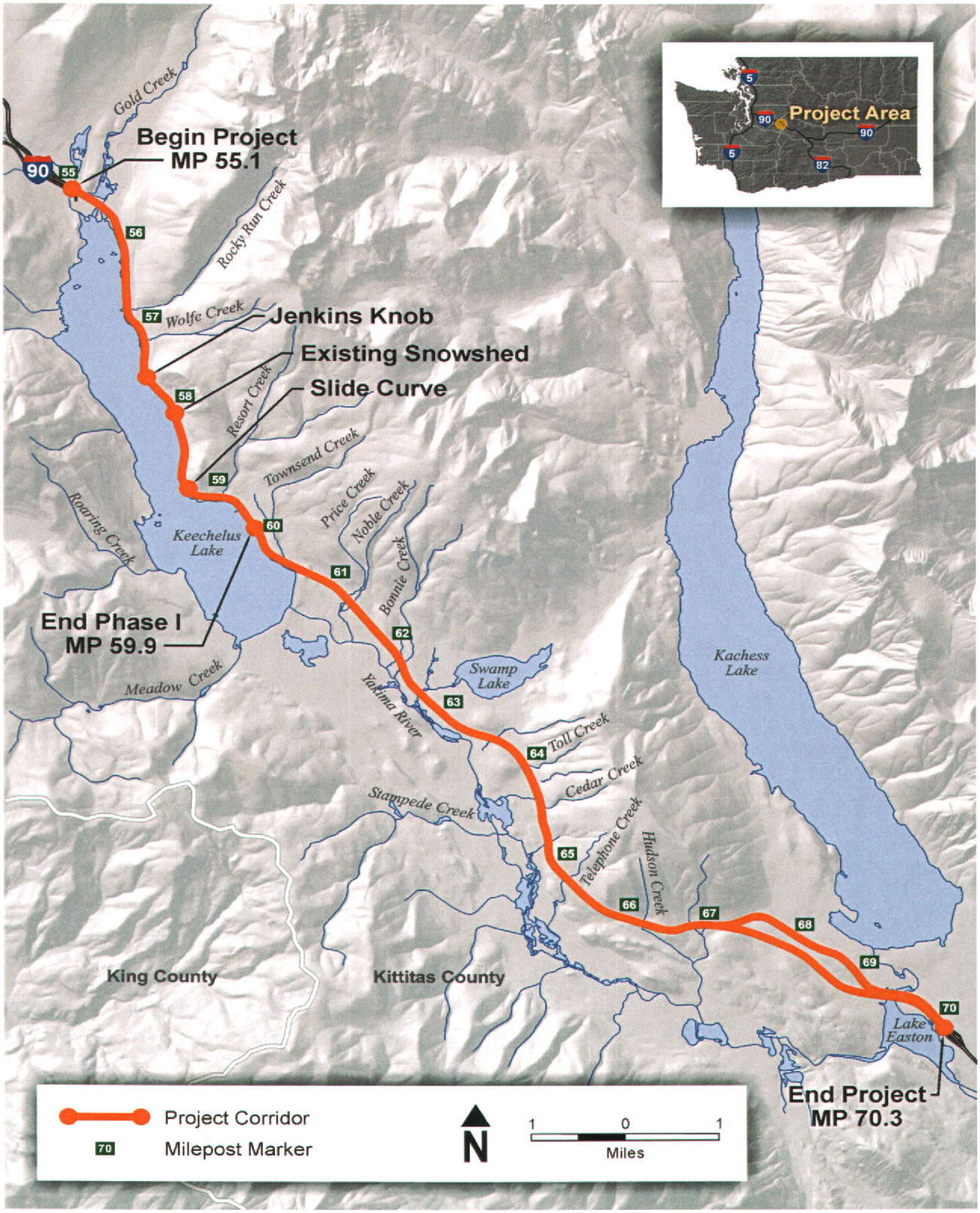

Figure 1-1: Project Location

Figure 1-2: Highway with Existing Snowshed Looking North

The roadway history, surface features, and subsurface soil and rock conditions within the project area are described in the 2006 geotechnical investigation reports (URS, 2007; and URS and Wyllie & Norrish, 2007). The following paragraphs are extracted from these reports because they have relevance to the avalanche mitigation study.

The general topography of the Project area is that of a rugged mountainous region. The ground surfaces ranges between elevations of 2,450 feet (El. 2,450) and El. 2,716. The existing EB road grade ranges from El. 2,505 to 2,551. The proposed road grade will range from El. 2,525 to about El. 2,600 in the Slide Curve area, where the WB lane will be approximately 50 feet higher than the EB lane, and the two lanes will be separated by a grade control structure.

The minimum proposed road grade of El. 2,525 is approximately 7 feet above the full lake level of El. 2,517.8 which is the level of the spillway crest in the dam. The 1981 to 2004 lake water level data shows that the lake level ranges from an average minimum of El. 2,430.8 to an average maximum of El. 2,517.8, with an annual average of El. 2,480.1.

The project is in the Pacific Coastal Eco-region which has a climate characterized by moist cold winters, dry warm summers, and highly variable precipitation over time and geographic area. To demonstrate the geographic variability of precipitation within the vicinity of the project area, data from the following two weather stations that are approximately eight miles apart and encompass the project area were reviewed.

- Snoqualmie Pass Weather Station (Latitude 47° 25' and Longitude 121° 25'), located less than three miles northeast of the north end of Keechelus Lake.

- Keechelus Lake Weather Station (Latitude 47° 19' and Longitude 121° 20'), located less than one mile southeast of the south end of Keechelus Lake.

Climate records from the two stations were reviewed on the Western Regional Climate Center (WRCC) website which has two sets of data: official National Climatic Data Center (NCDC) data; and unofficial data. The difference between the two data sets is that analysis on the official data has been completed and is adjusted for missing data and observation time, while only preliminary analysis has been performed on the unofficial data and it has not been adjusted for missing data and observation time.

The latest official NCDC annual precipitation at the two weather stations ranges from approximately 68 inches at Keechelus Lake to 105 inches at Snoqualmie Pass during the observation period of 1931 to 1977. The most recent unofficial data for Keechelus Lake is from 1961 to 1990 and 1971 to 2000, and shows annual precipitation of 67 and 73 inches, respectively, which is comparable to the official data.

The most recent Snoqualmie Pass unofficial data is from 1961 to 1990, and shows an annual average precipitation of 99 inches. In general, December and January are the months with the most precipitation and July is the month with the least precipitation. The annual average snowfall was found to range from 217.2 inches (18.1 feet) at Keechelus Lake to 440.4 inches (36.7 feet) at Snoqualmie Pass during the period between 1931 and 1977.

The temperature data between the two weather stations does not show much variability. The annual average temperature for both stations is approximately 33 °F, with the monthly average ranging from 20 °F in January to 47.7 °F in July for the observation period from 1931 to 1977.

1.3 PURPOSE AND SCOPE

The purpose of the avalanche mitigation study described in this report is as follows:

- Complete avalanche analyses and evaluate the impacts of potential avalanches along the project corridor on the roadway

- Provide recommendations for the design of a snowshed as a primary mitigation measure to protect the part of the roadway that will experience the most significant snow avalanches.

- Provide recommendations for avalanche mitigation structures that might be needed at starting zones, paths, rock cut slopes and other locations along the project corridor.

In order to achieve the purpose of the study, the following scope of work was performed:

- Completion of field reconnaissance, inspections and measurements to evaluate the potential for snow avalanches and identify associated snow avalanche paths along the project roadway.
- Evaluation of whether one continuous or several separate snowsheds or any other alternative snow avalanche mitigation measure would be preferable for a particular avalanche path.
- Analysis of the dynamics of plausible snow avalanches in each path and estimate of the potential snow avalanche loads/stresses on the roofs of the snowsheds.
- Development of design recommendations for supplemental structures to the snowsheds such as portal protection walls.
- Evaluation of the feasibility of alternative and additional snow avalanche mitigation measures for specific snow avalanche paths such as ditch and wall systems and snow net structures.
- Estimation of the design loads/stresses and preliminary construction, operation and maintenance costs for the snow net structures.
- Development of a typical designs for the ditch and wall systems.

This avalanche mitigation study field work was preceded by a technical memorandum entitled "Avalanche and Avalanche Deposit Loads on Proposed Shed (Stations 1352+00 to 1362+00) I-90, Snoqualmie Pass", dated April 2007," that was prepared under Task Order BR by Arthur I. Mears, P.E. and reviewed by URS. The memorandum addressed static and impact loads for the new snowshed using a conceptual design provided by WSDOT and snow data and storm return intervals based on previous work by (Arthur I. Mears 2006).

The field work was completed during June 15 to 20, 2007 by Arthur I. Mears of Arthur I. Mears, P.E., Inc. and Chris Wilbur P.E. of Wilbur Engineering, Inc. This work was completed in accordance with a Job Specific Safety Plan developed by Arthur I. Mears for the avalanche mitigation work, and a URS Site Specific Safety Plan that was developed for several 2007 field engineering activities including the avalanche analysis. Both safety plans were completed in compliance with WSDOT safety requirements.

Following the field work, Mears and Wilbur presented their findings and preliminary recommendations at a meeting with WSDOT and URS on June 21, 2007 at the I-90 Project Office in Yakima. At this meeting they also responded to review comments that were generated by Dr. Anand Prakash, Ph.D., P.E. of URS and by WSDOT on a draft submittal of the "Avalanche and Avalanche Deposit Loads on Proposed Snowshed" technical memorandum.

WSDOT provided URS and Arthur I. Mears with terrain image maps of the snowshed avalanche study area from the lake to the ridge line at a scale of 1:2000, and of the Slide Curve area from the lake to the top of the exposed slope at a scale of 1:1000. Cross sections of these areas were also provided. The additional detail 1:1000 map was required where snow support structures would need to be laid out. The provided materials were in hard copy and compact disk.

White Shield provided survey support under another task by surveying the end points of lines of snow net structures that are proposed to be located across Slide Curve for purposes of snow avalanche control. The survey data was submitted to Arthur I. Mears for use in laying out the proposed lines of snow nets so that the lines follow contours and are spaced down the slope as required by the results of the analyses.

URS and Arthur I. Mears submitted a draft avalanche mitigation report to WSDOT on September 11, 2007, and received WSDOT comments on September 24, 2007. Meanwhile, Dr. Anand Prakash completed an independent review of the report with emphasis on analyses, conclusions and recommendations, and communicated with Mr. Mears to resolve questions. This final avalanche mitigation report reflects the WSDOT review comments and the additional input from Dr. Prakash.

1.4 REPORT ORGANIZATION

Following Section 1.0 - Introduction, this report is organized into three major sections as follows:

- **Section 2.0 – Potential Snow Loads on Proposed Snowshed Roof.** This section defines the terms East Shed, avalanche path and snowshed, and recommends snowshed lengths and static and impact loads to protect the roadway from avalanches by evaluating the following options:
    - One snowshed to protect the roadway from the avalanche paths of East Sheds 3 and 4, in conjunction with snow net support structures as described below.
    - One snowshed to protect the roadway from the avalanche paths of East Sheds 2, 3, 4 and 5, in conjunction with snow net support structures as described below.
    - Two snowsheds with a gap between the avalanche paths of East Sheds 4 and 5 so that the roadway is protected by one snowshed from the avalanche paths of East Sheds 2, 3 and 4, and the other snowshed from the avalanche path of East Shed 5
    - Portal protection wall heights and design loads for the snowshed options described above.
- **Section 3.0 – Snow Net Structures at Slide Curve Avalanche Area.** This section provides:
    - Recommendations on the types, lengths, heights and locations of snow net structures in the Slide Curve area.
    - Preliminary cost estimates of the installation and annual maintenance of these snow net structures.
- **Section 4.0 – Additional Avalanche Control Options including Jenkin's Knob.** This section provides:
    - Recommendations on the feasibility of snow net structures in the Sheds 3 and 4 areas, in conjunction with the snowshed options described above.
    - Recommendations on the feasibility of wall and ditch systems for protection of the roadway from the avalanche paths below East Shed 1 and from potential

avalanche paths that would be created by cut slopes at Slide Curve, Jenkin's Knob, and other locations.

Reference materials are listed in Section 5.0, References.

1.5 STUDY LIMITATIONS

The evaluations, interpretations, findings and recommendations in this study and report were developed in accordance with current Engineering Best Practices and Professional Standards. The nature of this type of analyses does not always permit working under absolute certainty. The complex phenomena of avalanches cannot be perfectly evaluated and predicted. Methods used to predict avalanche behavior change periodically as new research becomes available.

This report reflects the best professional judgment of URS and Arthur I. Mears given the current understanding in this field. This report is site-specific and is only valid for the cross-sections and proposed slope cut data available and presented herein. The following additional limitations apply to the report and its findings and recommendations:

- Changes to the roadway profile and alignment, or size and steepness of the proposed cuts into existing slopes will require a re-evaluation of the findings and recommendations.
- Destruction of, or changes to the forest cover insitu after June 2007 by any natural or human-caused effects will require a re-evaluation of the findings and recommendations.
- No analyses were performed related to the design of the Proposed Snowshed structure or the strength of the soil or bedrock insitu at East Sheds 2 to 5 and the Slide Curve area.
- No factors of safety were applied to static or impact loads developed in this report. All loads were calculated based solely on evaluations related to avalanche surface area, snow volumes entrained into avalanches, new and compressed snow density, design snow depth, density and glide factors, and modeled avalanche dynamics characteristics (velocity, flow thickness, and flow density).
- No analyses were performed related to external loads developed from natural hazard phenomena such as earthquakes, landslides, rock falls, and wind.

2.0 POTENTIAL SNOW LOADS ON PROPOSED SNOWSHED ROOF

2.1 AREA DESCRIPTION

The segment of the I-90 roadway within the project area that has undergone the most significant snow avalanche occurrences and is prone to the most significant future snow avalanches is in the vicinity of the existing snowshed as shown on Figure 1-1. This segment of the roadway is alongside mountainous terrain as shown in Figure 1-2.

The steep slopes of this area support moderately forested terrain. Under severe snow conditions, avalanches have historically occurred, and are expected to continue to occur. The following snow avalanche terminology is used in this report from the topographic high to the topographic low (vertically from top to bottom):

- **East Shed** - East Sheds are geographic areas higher up on the slopes where snow avalanches have historically originated and are expected to continue originating.

- **Avalanche Path** - Avalanche paths are the route that snow takes as it travels down a slope. The term "chute" has historically been used to define this route, but "path" is more appropriate.

- **Snowshed** - Snowsheds are structures with most of the outer side open, and that cover the roadway so that avalanche snow passes over the top of the structure without impacting the roadway.

2.1.1 East Sheds

Five East Sheds (1, 2, 3, 4 and 5) were identified in this avalanche area from west to east. East Sheds 2, 3, 4 and 5 are shown on Figure 2-1. East Shed 1 is west of East Shed 2 and is not shown in this figure.

All five East Sheds are located above the general vicinity of the existing snowshed, where snow avalanches have historically originated and are expected to continue originating.

East Shed 5 has two segments that are designated as 5 West and 5 East. The potential of these East Sheds for generating avalanches is as follows:

- East Sheds 2, 3, 4 and 5 have the potential to generate significant avalanches.

- East Shed 1 has the potential to generate relatively small and infrequent avalanches.

The stationing of the East Sheds are listed in Table 2-1.

Table 2-1: Project Station Locations for East Sheds

East Shed Description	East Shed Location
East Shed 1	WB Sta. 1349+00
East Shed 2	WB Sta. 1353+50
East Shed 3	WB Sta. 1355+00
East Shed 4	WB Sta. 1358+50
East Shed 5 West 1	WB Sta. 1360+00
East Shed 5 West 2	WB Sta. 1362+00
East Shed 5 East	WB Sta. 1363+00

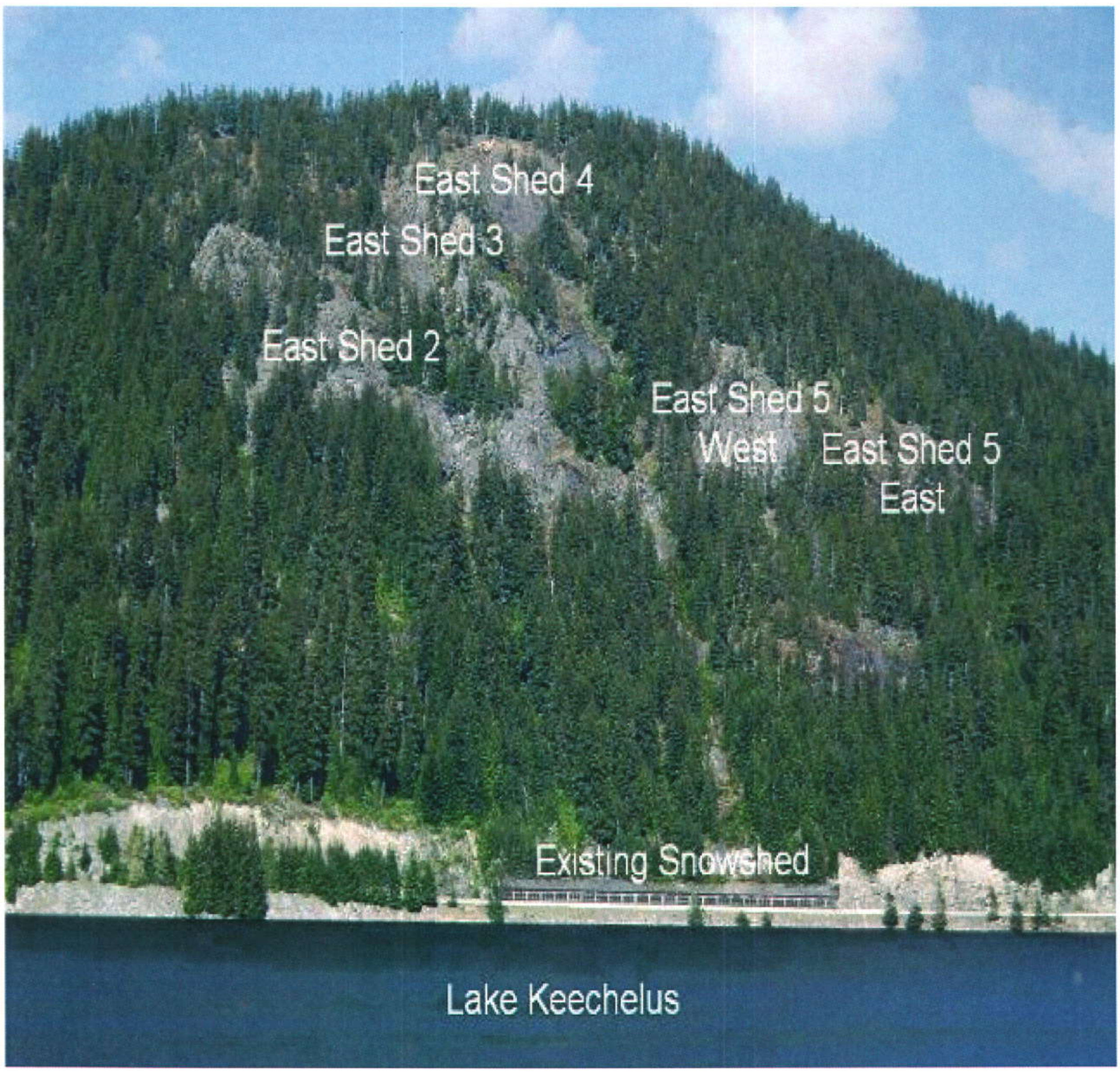

Figure 2-1: Locations of East Sheds 2 to 5

2.1.2 Avalanche Paths

Avalanche paths develop when snow from several avalanches travels down the slope along the same route over the course of time. The avalanche paths developed from avalanches originating in East Sheds 1 to 5 are shown in Figure 2-2.

Six avalanche paths were identified below East Sheds 2, 3, 4 and 5. There is one avalanche path each for East Sheds 2, 3, and 4. There are three avalanche paths for East Shed 5 that are designated as 5 West (1), 5 West (2) and 5 East. These paths are shown on Figure 2-2, and have the potential to convey significant avalanches of the magnitude as shown in Figure 2-3. This study concludes that a snowshed means of avalanche control is required for these six avalanche paths.

The avalanche path for East Shed 1 is located west of the paths for East Sheds 2 to 5, but has the potential to convey relatively small and infrequent snow avalanches. Avalanches originating in East Shed 1 have not impacted highway operations since the 1970s. This study concludes that the snow avalanche risk is low in East Shed 1 and can continue to be controlled effectively with current avalanche control procedures along with walls and ditches.

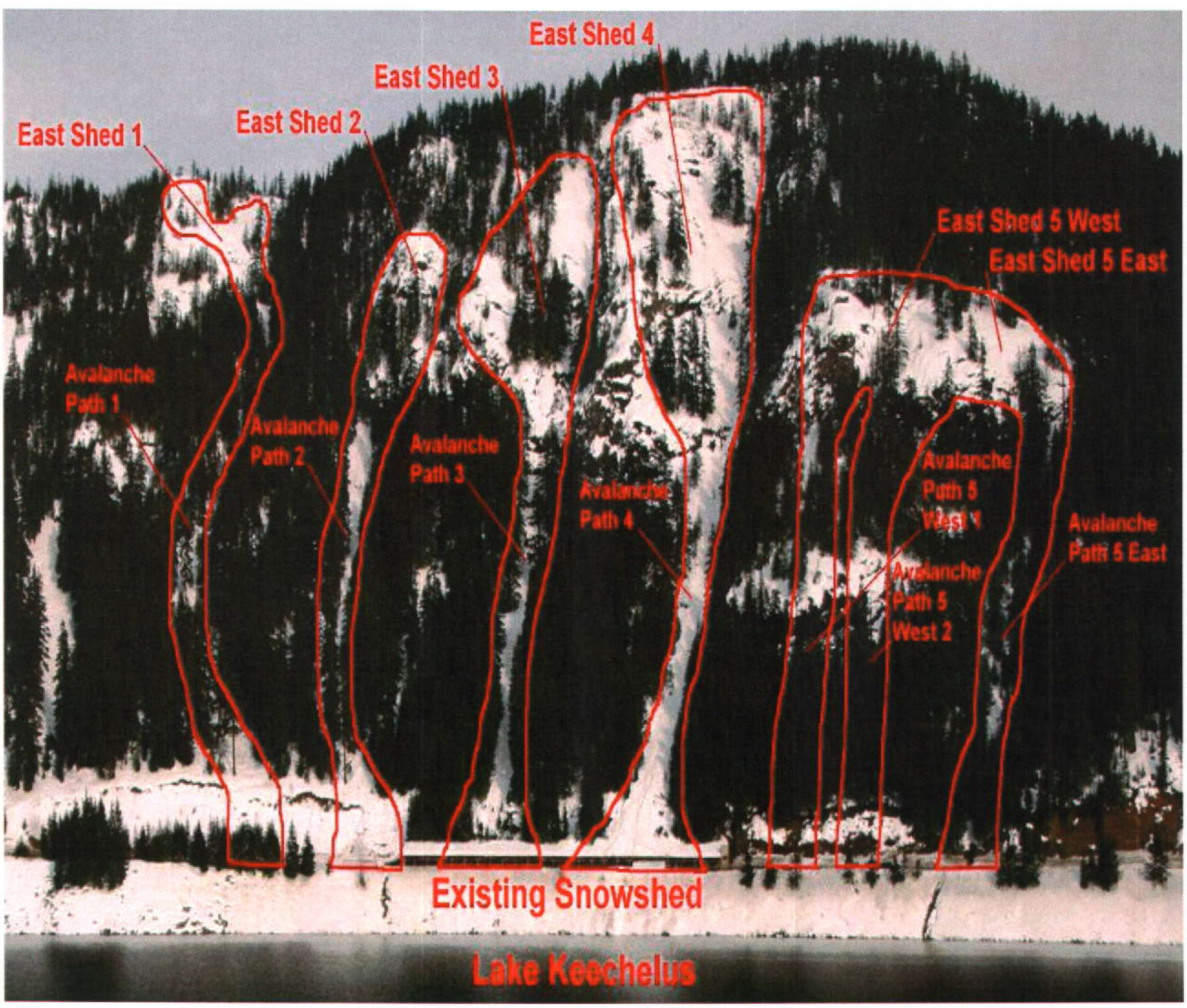

Figure 2-2: Avalanche Paths from East Sheds 1 to 5

2.1.3 Snowshed Options

Snow avalanches block the I-90 highway nearly every year and on the average cause more than 120 hours of roadway closure with 65 hours related to avalanche risk control within the project limits. A typical roadway closure caused by a snow avalanche at the existing snowshed is shown in Figure 2-3. This figure show the existing snowshed can protect the WB lanes, but not protect the EB lanes.

This avalanche mitigation study concludes that the existing two-lane WB snowshed needs to be replaced with a longer six-lane WB and EB snowshed. Several snowshed options are discussed in Section 2.8. The recommended option is Option 2, which is a single 1,100-foot-long snowshed that will protect the entire width of highway from East Sheds 2 to 5. This option is referred to as the "Proposed Snowshed" in this report. A snowshed to protect the roadway from snow avalanches from East Shed 1 is not considered necessary.

It should be noted that the Proposed Snowshed recommendation was made on the basis of the avalanche mitigation study, and did not consider snowshed system components such as fire suppression, ventilation and lighting. Consideration of the construction, operation and maintenance costs of these components may lead to a multi-snowshed option instead of a single snowshed option.

Figure 2-3: Existing Snowshed beneath Avalanche

2.2 TYPES OF LOADS

The roof of the Proposed Snowshed will be subject to static loads developed from snowfall and avalanche deposits, as well as from deflected avalanche impact loads. The deflected avalanche impact loads are based on 100-year avalanche flow data and could influence the design of the Proposed Snowshed roof independently, or in combination with the existing previously accumulated static avalanche deposits.

The results of this avalanche mitigation study indicate that loading conditions of the static avalanche deposits would place a greater force on the Proposed Snowshed roof than would the deflected avalanche impact loads. The calculated static and impact loads associated with snow avalanches are not assumed to occur simultaneously.

However, the locations on the Proposed Snowshed where the maximum loads for each type would occur are different. Therefore, the designer must evaluate maximum structural stresses (e.g., shears and moments) due to each type of load separately and use the more conservative stresses as shown on Figures 2-7 to 2-12 and Figures 2-15 to 2-20.

Avalanches of lesser magnitude could also place loads on the roof of the Proposed Snowshed and could also act in combination with any existing previous static snow deposits.

2.3 STATIC LOADS

2.3.1 Definition and Deposit Description

Static loads are developed from accumulated avalanche debris. The avalanche debris typically accumulates over the entire winter during years with snowfalls. During a high-snowfall winter, snow generally begins to fall in early November, and can continue to fall until late May.

Snow avalanche debris forms a wedge-shaped deposit that is typically much deeper at the upper (mountain-side) end of the deposit than at the lower (lake-side) end. During a severe winter, such as one that may occur approximately every 100 years, several large magnitude, and moderately fast-moving avalanches would be expected to occur.

Under severe winter conditions, the snow deposit would have a relatively shallow surface slope of approximately 20 degrees. This relatively shallow surface slope is assumed because moderately fast-moving avalanches of speeds greater than 50 ft/sec (15 m/s) tend to spread the deposit over a greater surface area. Under normal winter conditions, the surface slope of the deposit could be much greater than 20 degrees.

The approximated surface slope of 20 degrees is based on observations of avalanche deposits formed from numerous dry-snow avalanches. This surface slope is nearly equal to the angle of internal friction or angle of repose of the avalanche deposit. During the course of a severe winter, some avalanche debris is expected to flow over the Proposed Snowshed and fall into the lake.

In addition, under severe winter conditions, deep and dense snow will accumulate on the steep terrain above the Proposed Snowshed. This dense snow will tend to creep toward and over the Proposed Snowshed, and produce shear loading on the snowshed roof. Based on standard practices used in Switzerland, the shear forces are typically estimated to be 0.4 times the total magnitude of the vertical static overburden load on the roof.

The shear forces due to snow creep are generally much larger than the gravitationally-induced shear[1] force due to the static avalanche deposits. Both the snow creep and the gravitationally-induced components of the shear forces of the total snow load on the roof of the Proposed Snowshed are included in the 0.4 factor.

The snow creep friction coefficient is dependent on the granular properties of the snow and the roughness of the snow surface on the Proposed Snowshed roof. The snow creep friction coefficient (approximately 0.35) is similar to the values reported for cohesion less silts (Perloff and Baron, 1976).

The sections below describe the assumptions that were made and the methods that were used to determine the following parameters for the snow load analyses:

- Maximum total snowfall
- Average density of new uncompressed snow
- Density of snow in avalanche deposits
- Volume of snow removed by avalanches
- Typical avalanche path boundaries
- Design Static Loads

These parameters, dimensions and loads are described below. Values are provided in standard format with metric format in parentheses because most of the engineering formulas for snow avalanche analyses are in metric dimensions.

2.3.1.1 Maximum Total Snowfall

The maximum total snowfall during the winter (November through May) is estimated to be H_{max} = 69 feet (21.03 meters). This is the maximum winter season snow depth recorded at Snoqualmie Pass (El. 3,020) during the past 58 years (1949 to 2007), and represents the total amount of uncompressed new snow that was measured each day during the winter of 1955 to 1956.

Observations in similar coastal climates and the orographic effects on the east side of Snoqualmie Pass indicate that the snow depth generally reduces with elevation (See Table 3-1). However, the snow depth in the project area generally reduces from west to east. Therefore, in view of this, and in the absence of more detailed site-specific information, it is assumed that the snow depths during the winter in the project area are as follows:

- H_{max} = 69 feet (21.03 meters) above El. 3,100 (945 meters) at the avalanche paths
- 0.8 H_{max} = 55 feet (16.81 meters) below El. 3,100 (945 meters).

---

[1] Shear due to gravity, $S = P_V \sin \theta$, where P_V is the overburden load and θ is the roof vertical angle; when θ = 2.9 degrees as on the planned roof slope, and $S = P_V$ (0.05) and is included in the shear stress resulting from creep.

2.3.1.2 Average Density of New Uncompressed Snow

The average density of the new uncompressed snow is estimated to be 7.49 lb/ft^3 (120 kg/m^3), which is typical of new snow density in maritime climates. However, this value is likely to vary considerably from one storm to the next. The selected value is considered to be reasonably conservative because the reported average density of fresh snow is approximately 6.24 lb/ft^3 (100 kg/m^3) (USACE, 1956).

2.3.1.3 Density of Snow in Avalanche Deposits

The density of the snow in the avalanche deposit directly above and on the Proposed Snowshed roof will consist of snow compressed to an estimated average density of 31.21 lb/ft^3 (500 kg/m^3) due to the kinetic energy of the avalanche motion. Reported densities of compressed snow vary from 24.97 to 31.21 lb/ft^3 (400 to 500 kg/m^3) (USBR, 1966, Chow, 1964). Therefore, the selected value of 31.21 lb/ft^3 (500 kg/m^3) is considered to be reasonably conservative.

2.3.1.4 Volume of Snow Removed by Avalanches

The volume of snow removed by all avalanches during a 100-year winter is assumed to be approximately 50% of the total snow in open areas. This assumption is based on experience and observations in open areas that are subject to avalanches. The volume of snow removed by avalanches in the relatively heavily forested project area is assumed to be reduced to approximately 20% of the total snow in open areas.

2.3.1.5 Avalanche Path Boundaries and Snow Volumes

Typical avalanche path boundaries assumed for East Shed 5 are illustrated in Figure 2-4. Several transects were taken by Art I. Mears and Chris Wilbur across the avalanche paths to determine their widths across the slope, lengths down the slope, surface areas, and snow volume capacity. The 20% and 50% entrainment ratios were then applied to these areas, and the snow volumes were determined as follows:

- Horizontally projected avalanche path areas were calculated as $A_n = (W_n + W_{n+1}) / 2L$, where:
  - A_n is the area
  - W is the width
  - L is the horizontal length between W_n and $W_{n+1.}$
- The snow volume, K_u, (uncompressed) was calculated from $K_u = H_{max}$ (An).
- K_u was multiplied by the entrainment factor 0.2 or 0.5 (20% or 50%) depending on the forest cover.
- The volume of compressed snow, K_c, at and directly above the Proposed Snowshed roof within each East Shed avalanche path, was calculated from K_c = Ku (120/500).

- The compressed volume, K_c, was forced to fit in the available avalanche path width at the roof of the Proposed Snowshed roof as designated on the WSDOT section sheets, assuming a snow surface slope of 20 degrees.

- The snow widths for East Sheds 2 to 5 are presented in Tables 2-2 to 2-6 and were used to calculate the shed sectional areas in each case.

2.3.1.6 Design Static Loads

Design static loads were determined as follows:

- The maximum vertical static load, P_v, at the back of the Proposed Snowshed was calculated at selected stations as $P_v = H_d (\rho_c)$, where:
    - H_d is the vertical depth of deposit
    - ρ_c is the compressed density of debris.

- H_d for the static avalanche debris (see Figures 2-7 to 2-12), was estimated as a best graphical fit of the calculated compressed volumes with a 20 degree slope of the deposit laid over the terrain on the WSDOT section sheets.

The design static loads will vary along the length of the roof of the Proposed Snowshed primarily because of the differences in terrain and forest cover intrinsic to the avalanche paths above the snowshed. The design static loads will also vary due to the proposed changes to the geometry of the cut slope behind the snowshed.

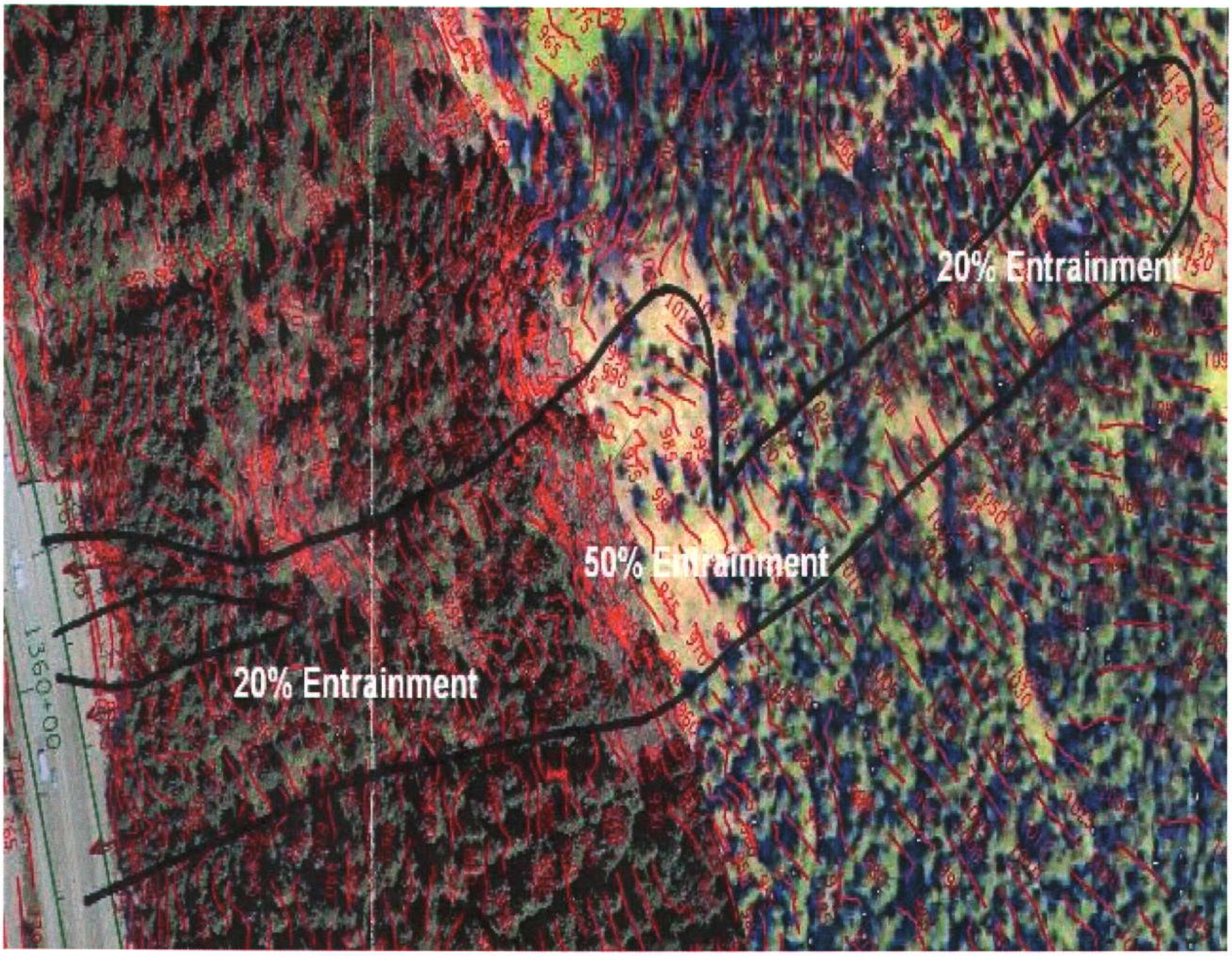

Figure 2-4: East Shed 5 Avalanche Path and Snow Entrainment Factors

The terrain of the avalanche starting zones in East Sheds 4 and 5 are shown on Figures 2-5 and 2-6, respectively. It can be seen that The East Shed 4 ground surface is more vegetated than the East Shed 5 ground surface.

Figure 2-5: East Shed 4 Starting Zone

Figure 2-6: East Shed 5 Starting Zone

2.3.2 Compressed Snow Volumes

Compressed snow volume calculations were performed for East Sheds 2, 3, 4, 5 West, and 5 East in accordance with the procedures described in Section 2.3.1. The results are summarized in Tables 2-2 to 2-6, respectively. These tables duplicate the spreadsheets that were used for the calculations.

Static Loading Diagrams were developed from the avalanche data that were derived for East Sheds 2, 3, 4, 5 West and 5 East, and are shown in Figures 2-7 to 2-12, respectively.

Table 2-2: Avalanche Path Data for East Shed 2

East Sheds Static Snow Load Calculation Parameters

Path	ES 2
E Ratio	0.50
C-Ratio	0.24
Aval W (m)	20

The value used for maximum snowfall depth (S ht) below Elevation 3116 feet (950 m) is 0.8*(S ht). See Section 2.3.1; assumptions and methods used.

X	Y	W	L	Mean W	Average Area	S ht	E Ratio	Entrained
0	1,130	40	------	------	------	------	------	------
22	1,075	32	22	36	792	21.03	0.50	10.52
48	1,030	39	26	36	923	21.03	0.50	10.52
73	1,010	42	25	41	1,013	21.03	0.50	10.52
91	990	34	18	38	684	21.03	0.50	10.52
108	980	38	17	36	612	21.03	0.50	10.52
127	950	40	19	39	741	16.81	0.50	8.42
187	905	26	60	33	1,980	16.81	0.50	8.42
285	835	25	28	26	714	16.81	0.50	8.42
342	795	20	29	23	653	16.81	0.50	8.42
359	780	20	30	20	600	16.81	0.50	8.42

E Vol	C-Ratio	C Vol
8,332	0.24	2,000
9,710	0.24	2,330
10,652	0.24	2,556
7,196	0.24	1,727
6,438	0.24	1,545
6,236	0.24	1,497
16,662	0.24	3,999
6,008	0.24	1,442
5,491	0.24	1,318
5,049	0.24	1,212

Definitions of Symbols	
X	x-coordinate (m)
Y	y-coordinate (m)
W	Width (m)
L	Horizontal Length (m)
Mean W	Average Width (m)
Average Area	Horizontal Area (m^2)
S ht	Maximum Snowfall (m)
E Ratio	Entrainment Factor
Entrained	Entrained Amount (m)
E Vol	Entrained Volume (m^3)
C-Ratio	Compression Factor
C Vol	Compressed Volume (m^3)
Aval W	Avalanche Flow Width at Snowshed Bridge (m)

Summary of Critical Values		
Total Compressed Volume (yd^3) [m^3]	Avalanche Flow Width at Snowshed Bridge (ft) [m[	Avalanche Flow Area at Snowshed Bridge (yd^2) [m^2]
(25,655) [19,626]	(66) [20]	(1,173) [981]

Table 2-3: Avalanche Path Data for East Shed 3

East Sheds Static Snow Load Calculation Parameters

Path	ES 3
E Ratio	0.50
C-Ratio	0.24
Aval W (m)	29

The value used for maximum snowfall depth (S ht) below Elevation 3116 feet (950 m) is 0.8*(S ht). See Section 2.3.1; assumptions and methods used.

X	Y	W	L	Mean W	Average Area	S ht	E Ratio	Entrained
0	1,130	40	------	------	------	------	------	------
55	1,090	42	55	41	2,255	21.03	0.50	10.52
133	1,010	46	78	44	3,432	21.03	0.50	10.52
163	985	36	30	41	1,230	21.03	0.50	10.52
184	965	36	21	36	756	21.03	0.50	10.52
208	930	38	24	37	888	16.81	0.50	8.42
261	885	40	53	39	2,067	16.81	0.50	8.42
379	805	34	118	37	4,366	16.81	0.50	8.42
407	785	29	28	32	882	16.81	0.50	8.42

E Vol	C-Ratio	C Vol
23,723	0.24	5,693
36,105	0.24	8,665
12,940	0.24	3,106
7,953	0.24	1,909
7,473	0.24	1,793
17,394	0.24	4,175
36,740	0.24	8,818
7,422	0.24	1,781

Definitions of Symbols	
X	x-coordinate (m)
Y	y-coordinate (m)
W	Width (m)
L	Horizontal Length (m)
Mean W	Average Width (m)
Average Area	Horizontal Area (m^2)
S ht	Maximum Snowfall (m)
E Ratio	Entrainment Factor
Entrained	Entrained Amount (m)
E Vol	Entrained Volume (m^3)
C-Ratio	Compression Factor
C Vol	Compressed Volume (m^3)
Aval W	Avalanche Flow Width at Snowshed Bridge (m)

Summary of Critical Values		
Total Compressed Volume (yd^3) [m^3]	Avalanche Flow Width at Snowshed Bridge (ft) [m[	Avalanche Flow Area at Snowshed Bridge (yd^2) [m^2]
(46,970) [35,940]	(95) [29]	(1,481) [1,239]

Table 2-4: Avalanche Path Data for East Shed 4

East Sheds Static Snow Load Calculation Parameters

Path	ES 4
E Ratio	0.50
C-Ratio	0.24
Aval W (m)	50

The value used for maximum snowfall depth (S ht) below Elevation 3116 feet (950 m) is 0.8*(S ht). See Section 2.3.1; assumptions and methods used.

X	Y	W	L	Mean W	Average Area	S ht	E Ratio	Entrained
0	1,145	0	------	------	------	------	------	------
32	1,120	88	32	44	1,408	21.03	0.50	10.52
71	1,075	76	39	82	3,198	21.03	0.50	10.52
152	1,005	45	81	61	4,901	21.03	0.50	10.52
208	965	42	56	44	2,436	21.03	0.50	10.52
224	950	48	16	45	720	16.81	0.50	8.42
268	910	52	44	50	2,200	16.81	0.50	8.42
348	855	51	80	52	4,120	16.81	0.50	8.42
410	810	49	62	50	3,100	16.81	0.50	8.42
438	785	50	28	50	1,386	16.81	0.50	8.42

E Vol	C-Ratio	C Vol
14,812	0.24	3,553
33,643	0.24	8,070
51,553	0.24	12,367
25,627	0.24	6,147
6,059	0.24	1,452
18,513	0.24	4,438
34,670	0.24	8,311
26,087	0.24	6,253
11,663	0.24	2,796

Definitions of Symbols	
X	x-coordinate (m)
Y	y-coordinate (m)
W	Width (m)
L	Horizontal Length (m)
Mean W	Average Width (m)
Average Area	Horizontal Area (m^2)
S ht	Maximum Snowfall (m)
E Ratio	Entrainment Factor
Entrained	Entrained Amount (m)
E Vol	Entrained Volume (m^3)
C-Ratio	Compression Factor
C Vol	Compressed Volume (m^3)
Aval W	Avalanche Flow Width at Snowshed Bridge (m)

Summary of Critical Values		
Total Compressed Volume (yd^3) [m^3]	**Avalanche Flow Width at Snowshed Bridge (ft) [m[**	**Avalanche Flow Area at Snowshed Bridge (yd^2) [m^2]**
(69,829) [53,430]	(164) [50]	(1,277) [1,069]

Table 2-5: Avalanche Path Data for East Shed 5 West

East Sheds Static Snow Load Calculation Parameters

Path	ES 5 West
E Ratio	0.20 to 0.50
C-Ratio	0.24
Aval W (m)	38

The value used for maximum snowfall depth (S ht) below Elevation 3116 feet (950 m) is 0.8*(S ht). See Section 2.3.1; assumptions and methods used.

X	Y	W	L	Mean W	Average Area	S ht	E Ratio	Entrained
0	1,100	54	------	------	------	------	------	------
32	975	50	32	52	1,664	21.03	0.50	10.52
62	930	39	30	45	1,335	16.81	0.50	8.42
132	875	50	70	45	3,115	16.81	0.20	3.37
184	825	60	52	55	2,860	16.81	0.20	3.37
244	775	60	60	60	3,600	16.81	0.20	3.37

E Vol	C-Ratio	C Vol
17,505	0.24	4,201
11,234	0.24	2,696
10,485	0.24	2,516
9,627	0.24	2,310
12,118	0.24	2,908

Definitions of Symbols	
X	x-coordinate (m)
Y	y-coordinate (m)
W	Width (m)
L	Horizontal Length (m)
Mean W	Average Width (m)
Average Area	Horizontal Area (m^2)
S ht	Maximum Snowfall (m)
E Ratio	Entrainment Factor
Entrained	Entrained Amount (m)
E Vol	Entrained Volume (m^3)
C-Ratio	Compression Factor
C Vol	Compressed Volume (m^3)
Aval W	Avalanche Flow Width at Snowshed Bridge (m)

Summary of Critical Values		
Total Compressed Volume (yd^3) [m^3]	Avalanche Flow Width at Snowshed Bridge (ft) [m[	Avalanche Flow Area at Snowshed Bridge (yd^2) [m^2]
(19,120) [14,633]	(125) [38]	(460) [385]

Table 2-6: Avalanche Path Data for East Shed 5 East

East Sheds Static Snow Load Calculation Parameters

Path	ES 5 East
E Ratio	0.20 to 0.50
C-Ratio	0.24
Aval W (m)	22

The value used for maximum snowfall depth (S ht) below Elevation 3116 feet (950 m) is 0.8*(S ht). See Section 2.3.1; assumptions and methods used.

X	Y	W	L	Mean W	Average Area	S ht	E Ratio	Entrained
0	1,145	40	------	------	------	------	------	------
20	1,130	50	20	45	900	21.03	0.50	10.52
64	1,100	37	44	44	1,914	21.03	0.50	10.52
158	1,035	36	94	37	3,431	21.03	0.20	4.21
213	1,000	32	55	34	1,870	21.03	0.50	10.52
270	960	35	57	34	1,910	21.03	0.50	10.52
286	930	35	16	35	560	16.81	0.50	8.42
341	885	30	55	33	1,788	16.81	0.20	3.37
406	840	30	65	30	1,950	16.81	0.20	3.37
456	805	28	50	29	1,450	16.81	0.20	3.37
491	775	22	35	25	875	16.81	0.20	3.37

E Vol	C-Ratio	C Vol
9,468	0.24	2,272
20,135	0.24	4,832
14,438	0.24	3,465
19,672	0.24	4,721
20,088	0.24	4,821
4,712	0.24	1,131
6,017	0.24	1,444
6,564	0.24	1,575
4,881	0.24	1,171
2,945	0.24	707

Definitions of Symbols	
X	x-coordinate (m)
Y	y-coordinate (m)
W	Width (m)
L	Horizontal Length (m)
Mean W	Average Width (m)
Average Area	Horizontal Area (m^2)
S ht	Maximum Snowfall (m)
E Ratio	Entrainment Factor
Entrained	Entrained Amount (m)
E Vol	Entrained Volume (m^3)
C-Ratio	Compression Factor
C Vol	Compressed Volume (m^3)
Aval W	Avalanche Flow Width at Snowshed Bridge (m)

Summary of Critical Values		
Total Compressed Volume (yd^3) [m^3]	Avalanche Flow Width at Snowshed Bridge (ft) [m[	Avalanche Flow Area at Snowshed Bridge (yd^2) [m^2]
(34,169) [26,141]	(72) [22]	(1,420) [1,188]

2.3.3 Static-Loading Diagrams

Static loads will develop as a result of the accumulation of snow avalanche debris. The calculated static loads for the 100-year avalanche debris from East Sheds 2, 3, 4, 5 West (1), 5 West (2) and 5 East are provided at selected stations shown on Figures 2-7 to 2-12, respectively. These stations correspond to avalanche paths that were identified from avalanches that would originate in the East Sheds.

The indicated loads are site and design specific, and only apply to the wide and relatively flat roof of the Proposed Snowshed. If a substantially modified design is used, the load calculations will need to be revised. The H_d values used to estimate the indicated loads are based on experience and judgment. A relatively conservative factor of safety should be used in designs based on these loads.

As shown in Figures 2-7 to 2-12 and Figures 2-15 to 2-20, the configuration of the mountain slope at its toe along the edge of the roof of the Proposed Snowshed is different at the location of each avalanche path. Depending on the slope configuration, a nearly flat bench, of different width, is provided between the toe of the slope and the edge of the snowshed roof at each location. Where required, the bench may be filled with well-compacted rock or soil to form a firm base to withstand the impact of the avalanche snow.

During winter, these benches may be covered with snow. The snow covered benches may absorb some of the kinetic energy of the avalanche snow before it hits the roof of the Proposed Snowshed. Also, the deposition of winter snow on these benches may form a pad where the avalanche snow may impact the snowshed roof at deflection angles nearly similar to those considered in the snow avalanche analyses.

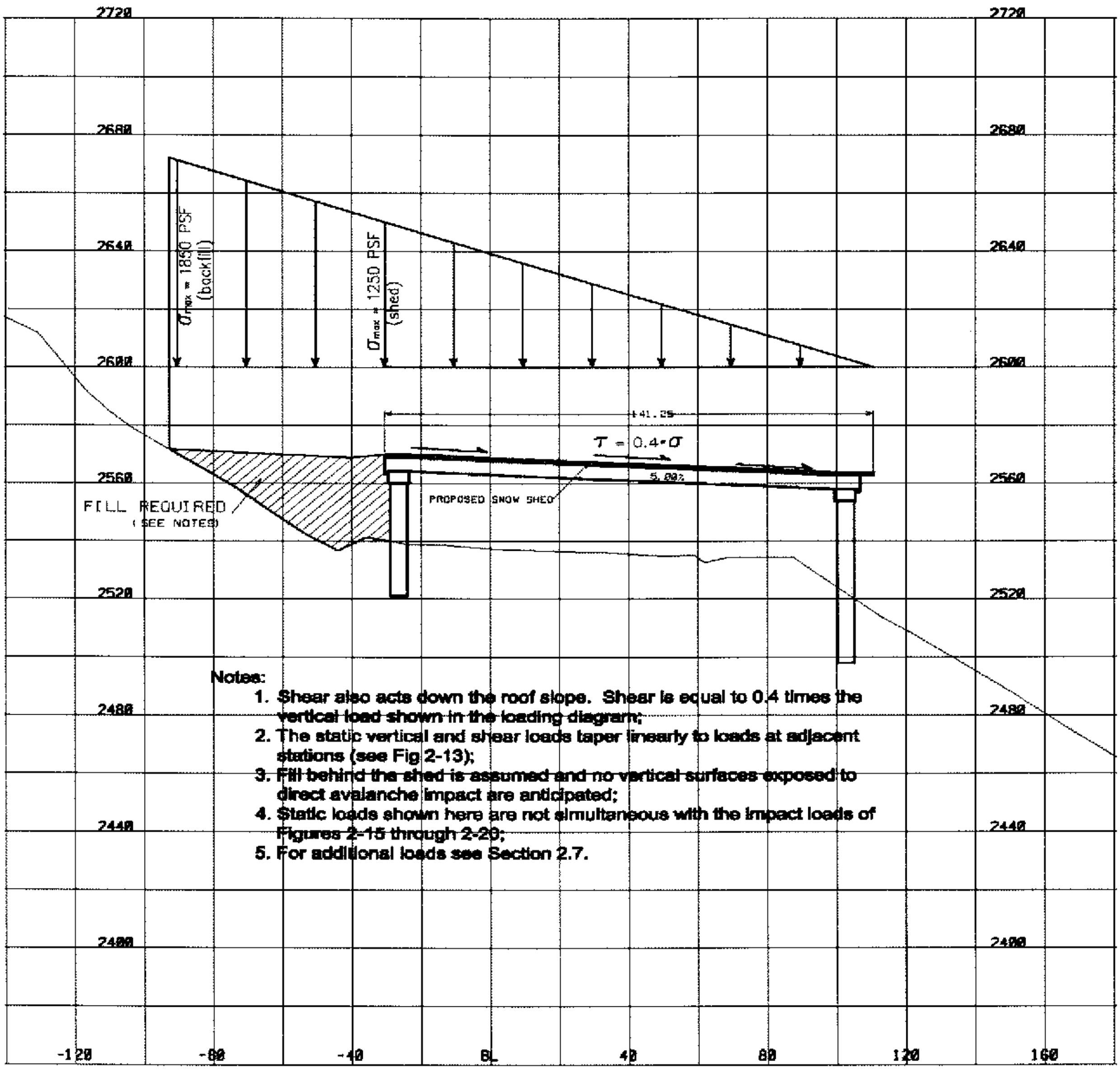

Figure 2-7: East Shed 2 100-Year Avalanche Debris Static Loading

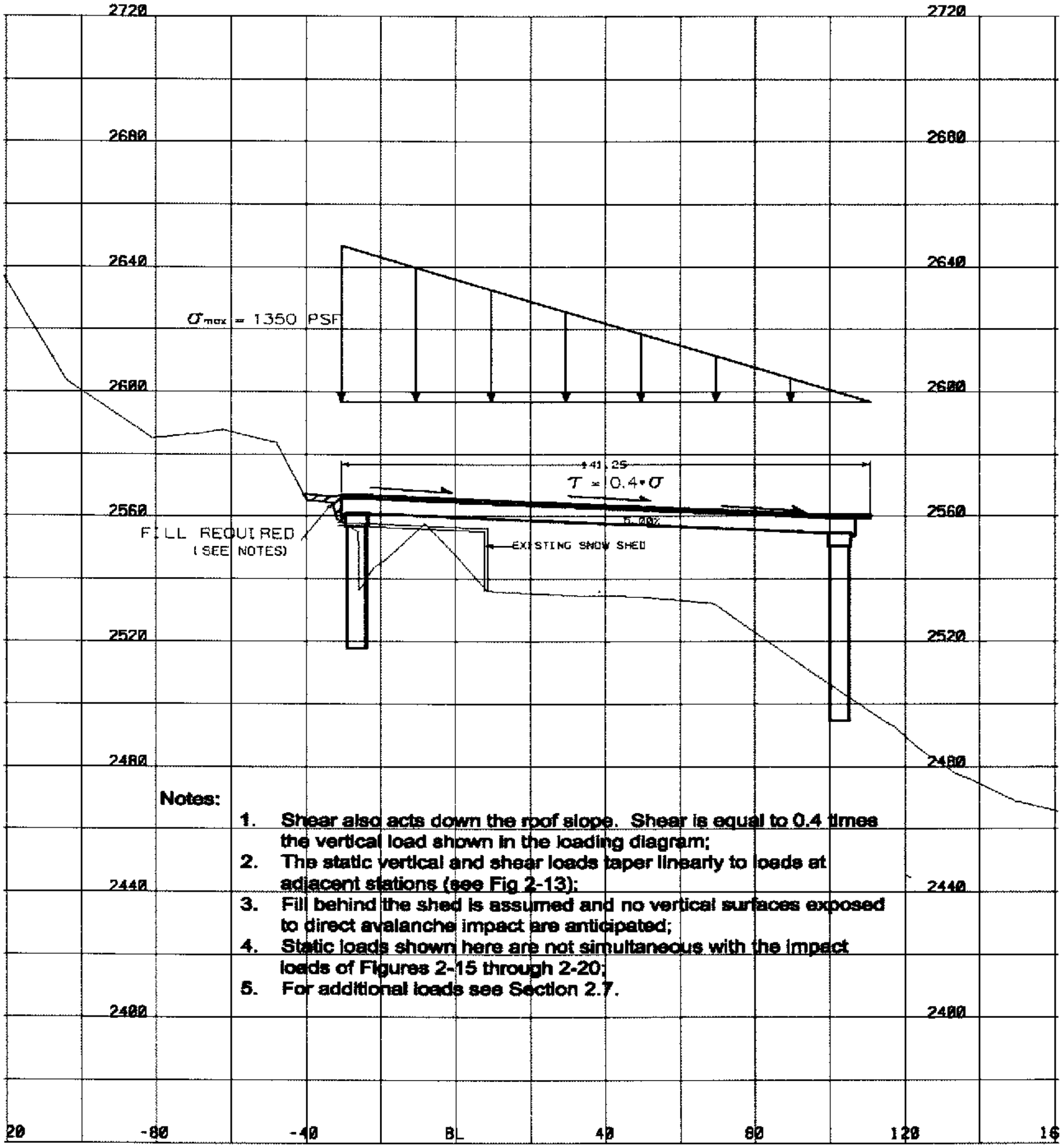

Figure 2-8: East Shed 3 100-Year Avalanche Debris Static Loading

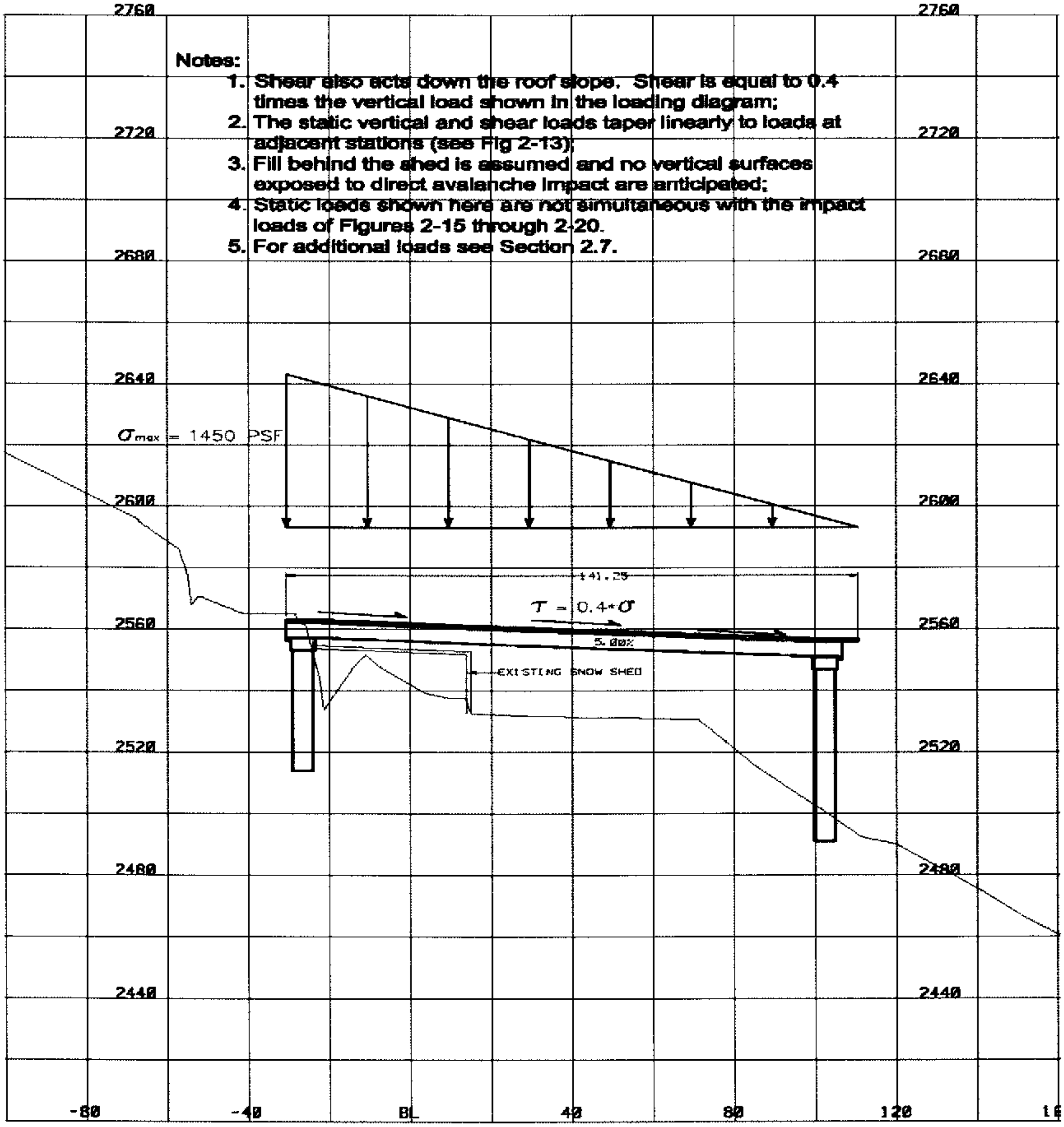

Figure 2-9: East Shed 4 100-Year Avalanche Debris Static Loading

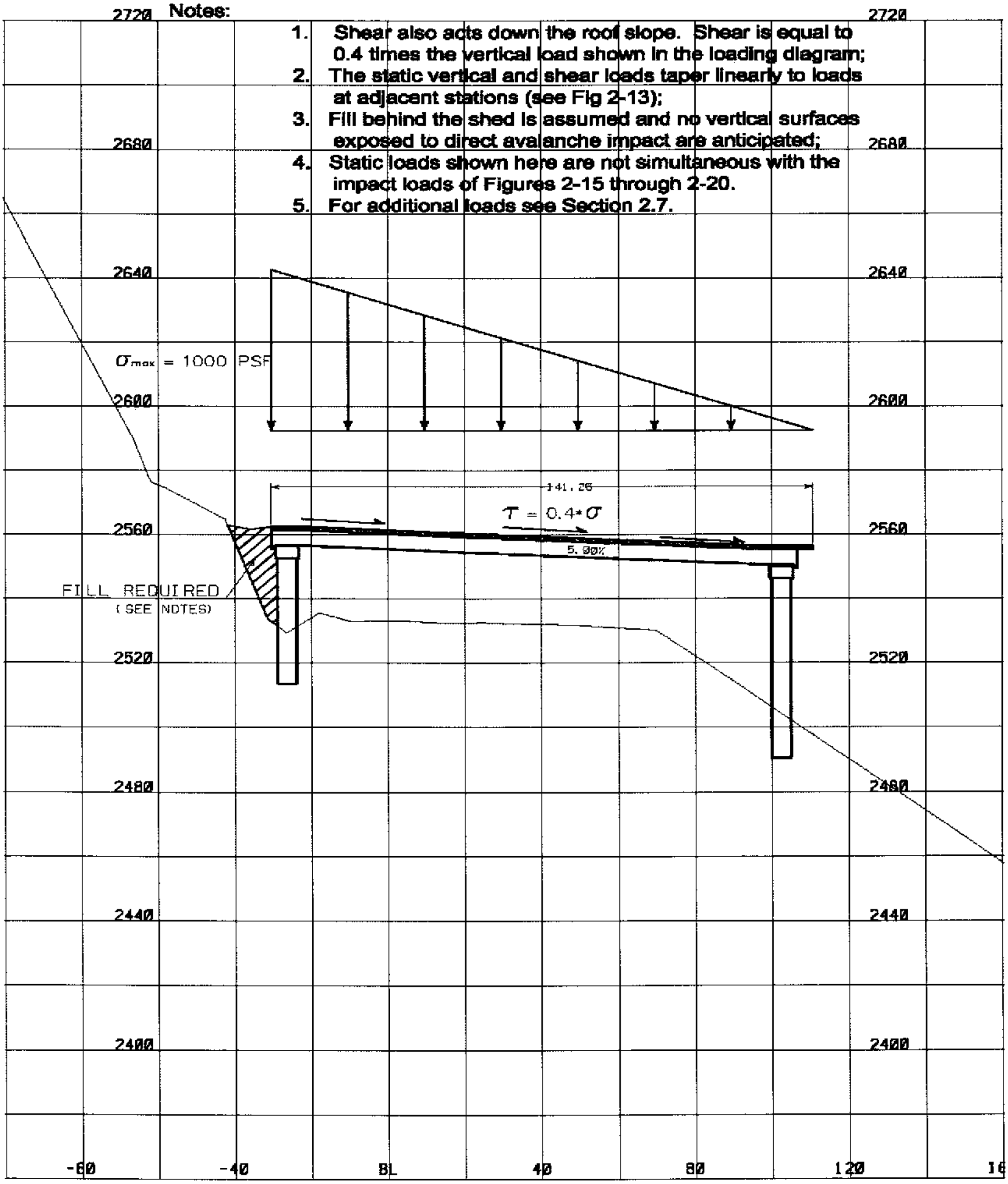

Figure 2-10: East Shed 5 West (1) 100-Year Avalanche Debris Static Loading

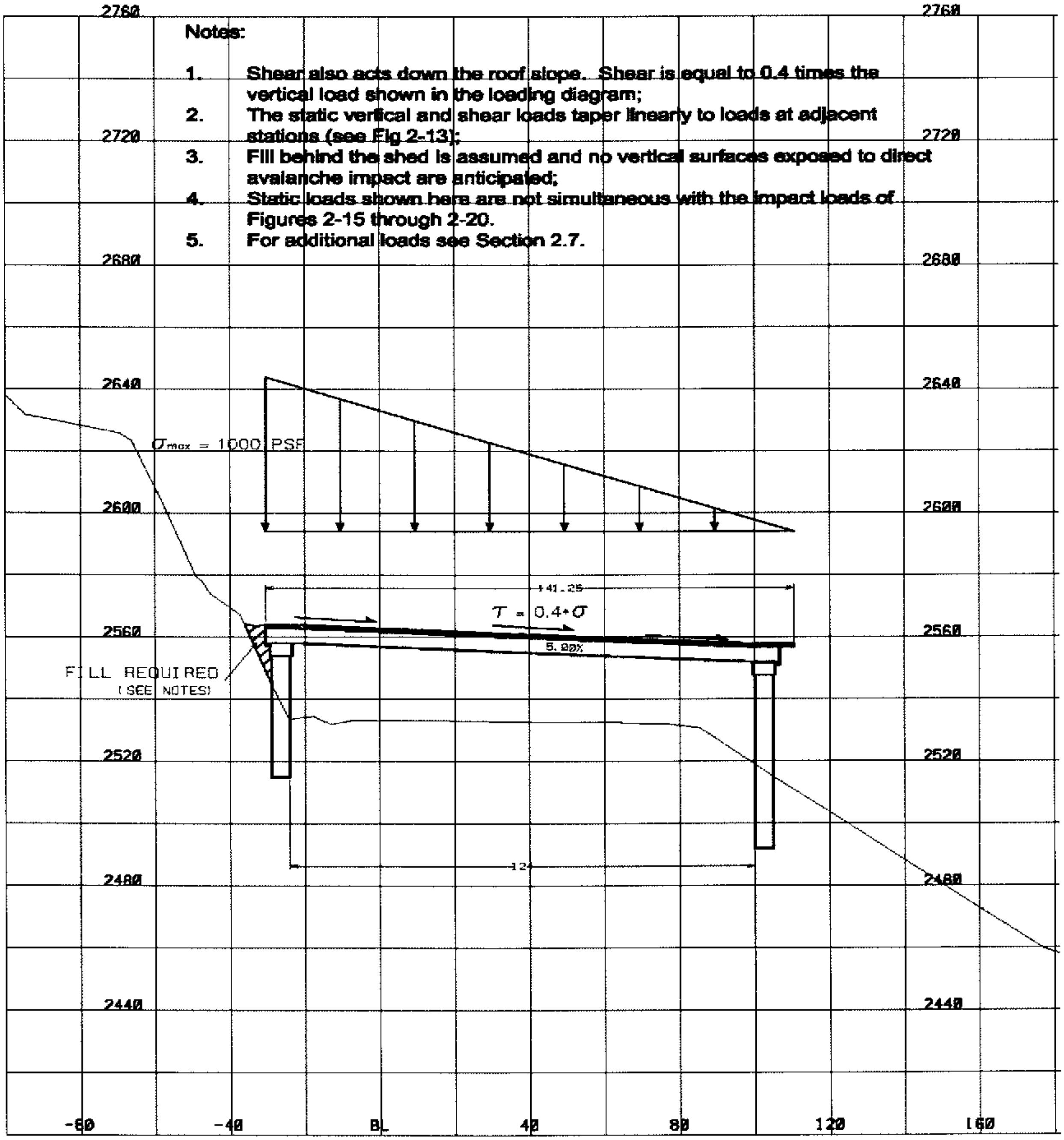

Figure 2-11: East Shed 5 West (2) 100-Year Avalanche Debris Static Loading

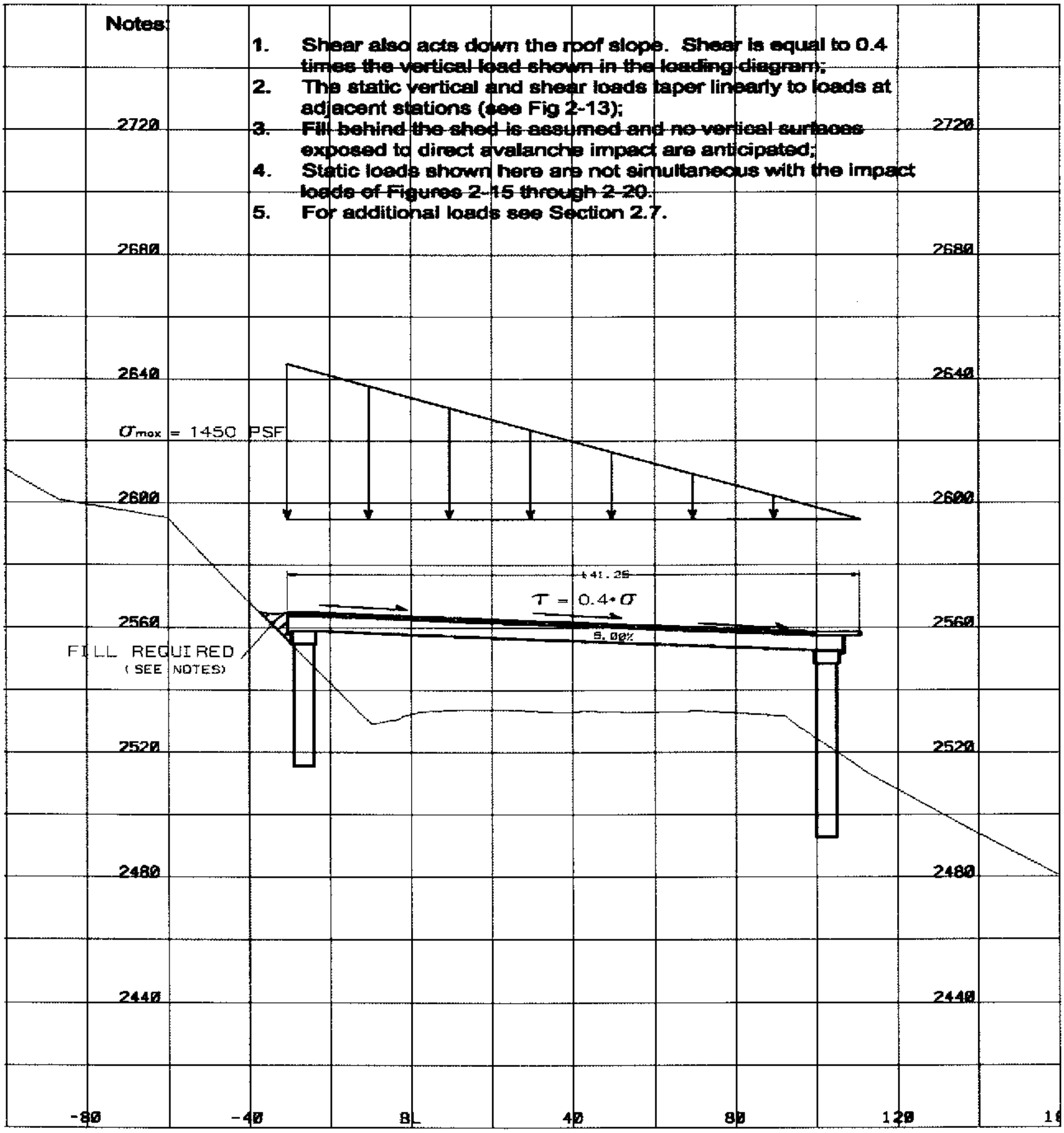

Figure 2-12: East Shed 5 East 100-Year Avalanche Debris Static Loading

2.4 MAXIMUM STATIC AND SHEAR LOADS

The maximum calculated static normal and shear loads for snow avalanches originating in East Sheds 2, 3, 4, 5 West (1), 5 West (2) and 5 East are summarized in Table 2-7. The shear loads are assumed to be 0.4 times the normal loads.

Table 2-7: Avalanche Static Normal and Shear Loads on Proposed Snowshed Roof

Shed Number	Project Station	Static Normal Load (psf)	Static Shear Load (psf)
East Shed 2	1353+50	1,250	500
East Shed 3	1355+00	1,350	540
East Shed 4	1358+00	1,450	580
East Shed 5 West (1)	1360+00	1,000	400
East Shed 5 West (2)	1362+00	1,000	400
East Shed 5 East	1363+00	1,450	580

Figure 2-13 shows the maximum calculated static loads along the entire Proposed Snowshed length of 1,100 feet which is planned to span from WB Sta. 1352+50 to WB Sta. 1363+50. These maximum loads will occur as shown in Figures 2-7 to 2-12.

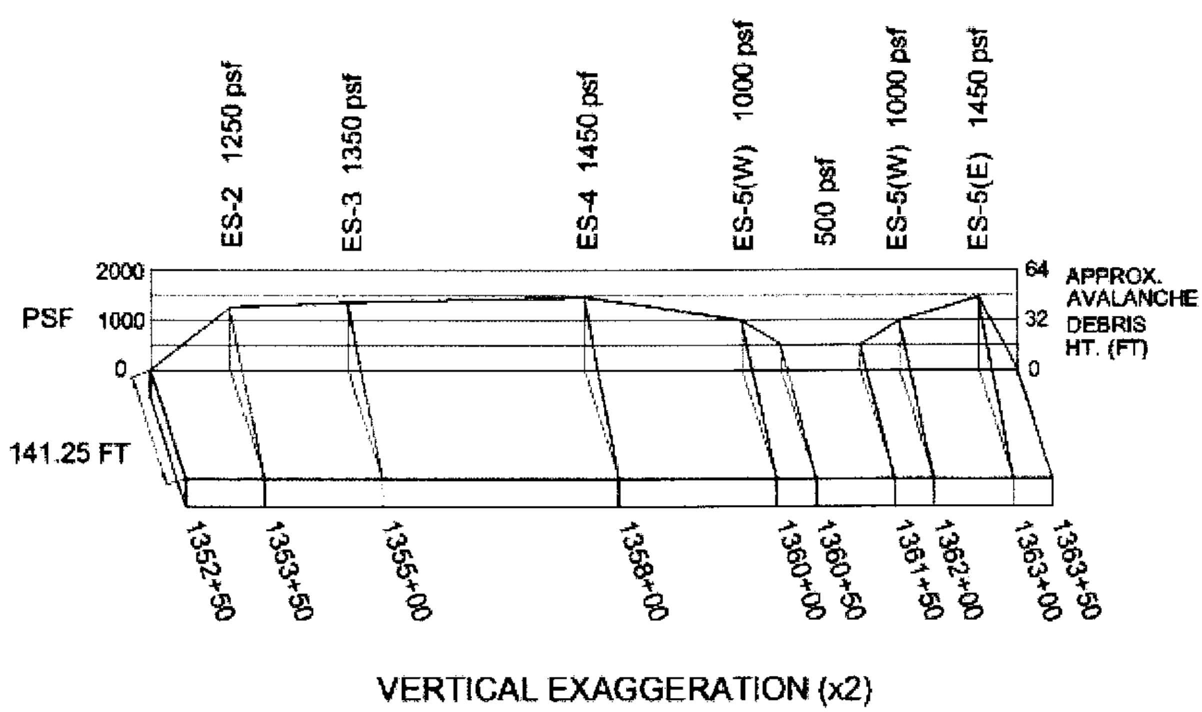

Figure 2-13: East Sheds Static Load Magnitudes and Locations

The maximum calculated static loads shown in Figure 2-13 do not include avalanche impact loads or other loads independent of snow avalanches such as those described in Section 2.7. Additional loads may need to be considered separately at each East Shed location.

2.5 MAXIMUM DEFLECTED AVALANCHE IMPACT LOADS

2.5.1 Description

As stated in Section 2.2, deflected avalanche impact loads and static and shear loads may not occur simultaneously. In addition, deflected avalanche impact loads will occur over relatively smaller length segments of roof of the Proposed Snowshed roof. In some cases, the calculated deflected avalanche impact loads at specific locations, are greater than the static and shear loads at the same locations, as illustrated by Figures 2-9 and 2-17, Figures 2-10 and 2-18, and Figures 2-11 and 2-19.

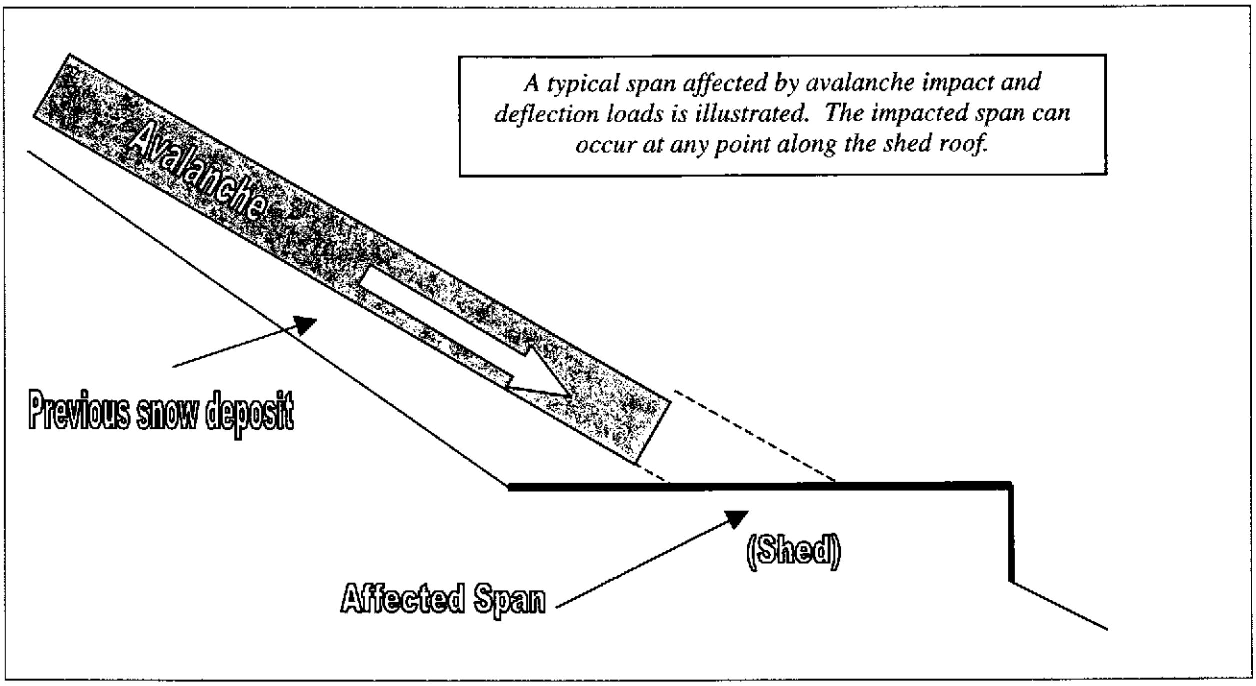

Figure 2-14: Deflected Impact Load Diagram

Impact deflection loads occur when a moving avalanche is deflected through a vertical angle as shown on Figure 2-14. In the vicinity of East Sheds 2 to 5, the snow slope formed from previous snow avalanche deposits on the Proposed Snowshed roof will always exceed the 2.9-degree roof angle of the snowshed. Changes in momentum will cause deflection forces with magnitudes depending on the following:

- Avalanche velocity
- Avalanche density
- Avalanche flow thickness
- Deflection angle
- Length of the affected span in the direction of the avalanche

Avalanche velocity, density, and flow thickness were calculated using the Swiss Avalanche Analysis program AVAL-1D, version 1.3. The deflection angle and the length of the affected span in the direction of the avalanche were determined from section views of East Sheds 2 to 5 provided by WSDOT.

The AVAL-1D model was developed by the Swiss Federal Institute for Snow and Avalanche Research. It includes two computational modules:

- FL-1D (dense flow avalanches)
- SL-1D (powder snow avalanches).

The FL-1D module was used because only dense flow avalanches occur in the project area. The SL-1D module was not used because it simulates erosion and deposition of snow during a powder snow avalanche which does not occur in the project area. The dense flow avalanche conditions were simulated by FL-1D, which predicts flow height, velocity, and pressure along a selected avalanche track.

The predictions are based on the assumption that avalanche snow moves as a fluid continuum of mean constant flow density with specified flow width and top surface slope. The flow height of the snow is assumed to be the same along the flow width at a cross section so that the flow height is level over the flow width. The vertical pressure distribution is assumed to be hydrostatic. The equations of mass and energy conservation are essentially the same as the dynamic equations for turbulent flow of water.

Input parameters for the model were selected on the basis of experience and judgment as follows:

- The initial snow height was determined to be 6.2 feet (1.9 meters).
- Friction coefficients were selected to produce an avalanche that traveled 200 to 300 feet (60 to 90 meters) on a frozen lake beyond the Proposed Snowshed.
- The avalanche track widths indicated in Note 3 of Figures 2-15 to 2-20 are based on flow widths at the snowshed calculated in Tables 2-2 to 2-6, with adjustments for track width variations and sideway deflection of avalanche snow.
- The predicted terminal velocity and flow depth at the snowshed were used to estimate deflected impact loads on the snowshed roof.

The calculated deflected avalanche impact loads are summarized in Table 2-8, which duplicates the spreadsheet used for the calculations.

The impact lengths in Table 2-8 are included in the Figure 2-15 to 2-20 notes. However, a uniform impact length of 16 feet (4.9 meters) is shown on these figures for conservatism and design convenience.

Table 2-8: Deflected Avalanche Impact Load Input Parameters and Calculated Total Loading

Avalanche Path Originating from	WB Sta.	L (m)	ρ (kg/m^3)	d (m)	$\theta_1 - \theta_2$ (degrees)	θ (radians)
East Shed 2	1353+50	4.96	300	1.9	22.5	0.393
East Shed 3	1355+00	3.96	300	1.8	27.0	0.471
East Shed 4	1358+00	4.25	300	2.0	28.1	0.490

East Shed 5 West (1)	1360+00	2.05	300	1.1	35.8	0.624
East Shed 5 West (2)	1362+00	2.79	300	1.1	33.0	0.577
East Shed 5 East	1363+00	4.98	300	2.0	23.7	0.413

Avalanche Path Originating from	$\mathrm{Sin}(\theta_1\text{-}\theta_2)$	V (m/s)	P_{Def} (psf)	P_{Def} (kPa)	$P_{Def} + P_{Aval}$ (psf)	$P_{Def} + P_{Aval}$ (kPa)
East Shed 2	0.383	17.8	290.93	13.93	407.68	19.52
East Shed 3	0.454	16.4	348.16	16.67	457.81	21.92
East Shed 4	0.470	25.2	880.95	42.18	1003.34	48.04
East Shed 5 West (1)	0.584	26.2	1370.92	65.64	1439.22	68.91
East Shed 5 West (2)	0.545	27.2	1015.03	48.60	1083.54	51.88
East Shed 5 East	0.401	13.4	181.08	8.67	304.09	14.56

Where:

L = Length of Proposed Snowshed roof on which avalanche snow would impact
$L \approx d / \sin(\theta1\text{-}\theta2)$
ρ = Avalanche flow density
d = Avalanche flow depth
$\theta1$ = Angle of assumed snow deposit on Proposed Snowshed roof = 20 degrees
$\theta2$ = Angle of slope of Proposed Snowshed roof = 2.9 degrees
$\theta = \theta1\text{-}\theta2$ (degrees) converted to radians
V = Avalanche flow terminal velocity
P_{Def} = Deflected avalanche impact load per unit length of Proposed Snowshed roof
$= (d/L)\, \rho V^2 \sin(\theta1 - \theta2)$
P_{Aval} = Component of weight of avalanche snow normal to the Proposed Snowshed roof
$\approx \rho\, d\, g \cos(\theta2)$
g = acceleration due to gravity = 9.81 m/s^2
$P_{Def} + P_{Aval}$ = Deflected avalanche impact load + component of weight of avalanche snow normal to the Proposed Snowshed roof

Figures 2-15 to 2-20 show the impact loading diagrams and the corresponding impact loading magnitudes summarized in Table 2-8 for East Sheds 2, 3 4, 5 West (1), 5 West (2), and 5 East, respectively. Deflected avalanche impact loads from these East Sheds could occur simultaneously, although unlikely. During a severe winter (100-year) when it would be possible for avalanches from all the East Sheds to occur simultaneously, only 800 feet of the total 1,100 feet of the Proposed Snowshed would be affected.

It is expected that many medium to large avalanche deposits may merge over the course of a severe winter season (100-year) and could cover the entire 1,100-foot length of the Proposed Snowshed.

The locations of the calculated maximum static and impact loads on the Proposed Snowshed are different as shown on Figures 2-7 to 2-12 and Figures 2-15 to 2-20. In particular, the deflected avalanche impact loads for East Sheds 4, 5 West (1), and 5 West (2) at the indicated locations on the Proposed Snowshed Figures 2-17, 2-18 and 2-19 are greater than the interpolated static loads at those locations.

The designer may have to compute structural stresses for both types of loads and use the more conservative values.

2.5.2 Deflected Impact Loading Diagrams

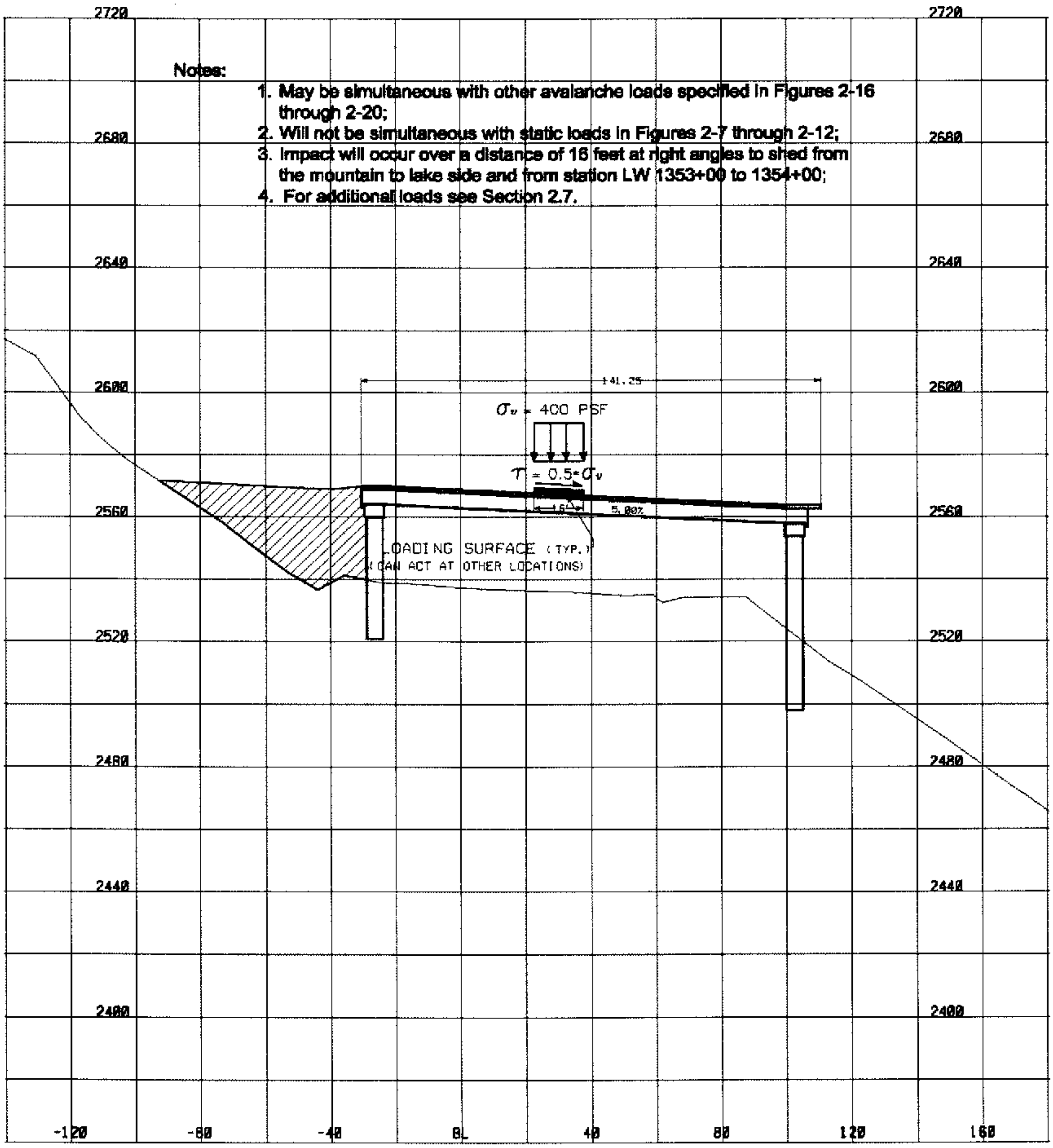

Figure 2-15: East Shed 2 100-Year Deflected Avalanche Impact Loading

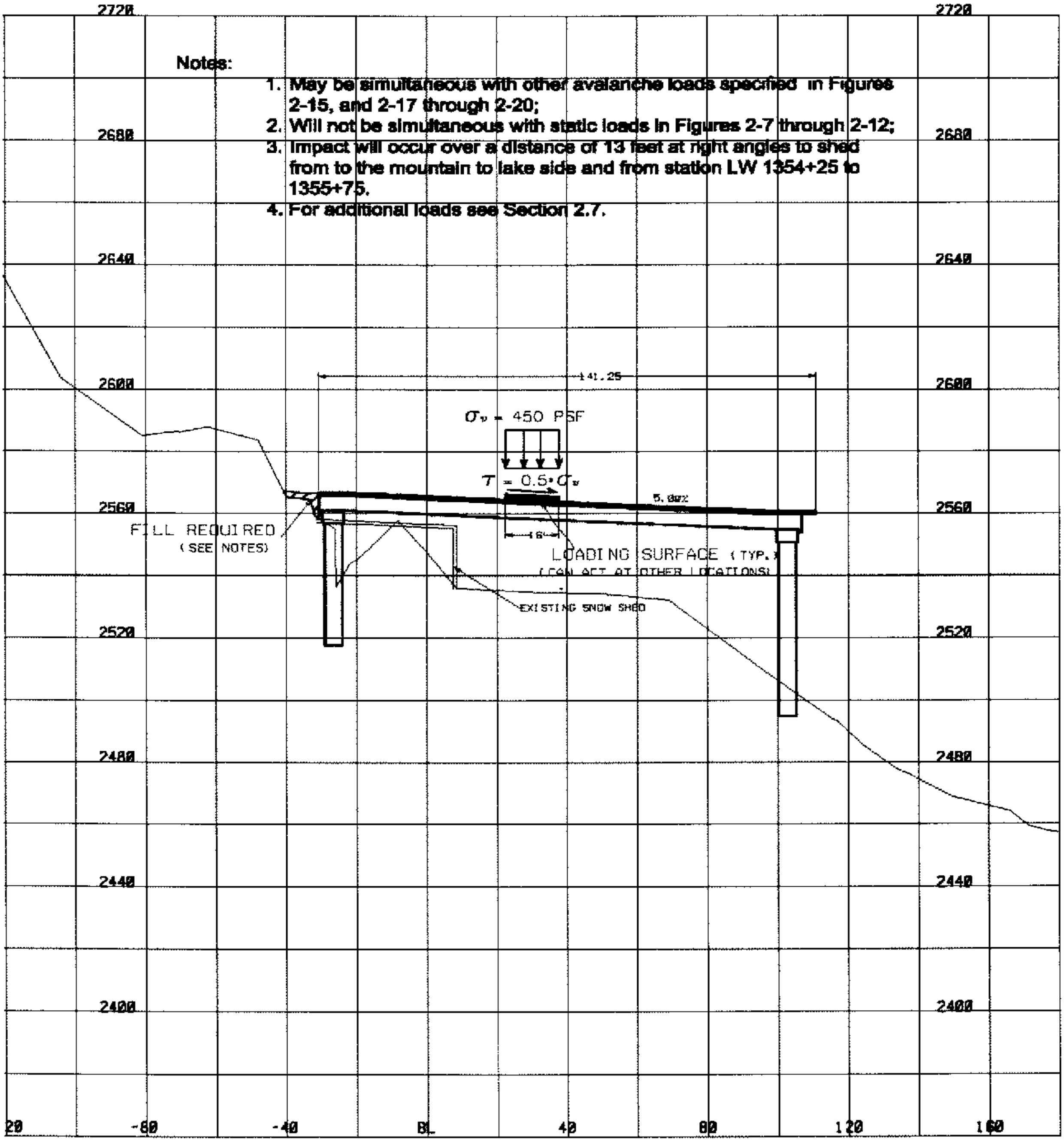

Figure 2-16: East Shed 3 100-Year Deflected Avalanche Impact Loading

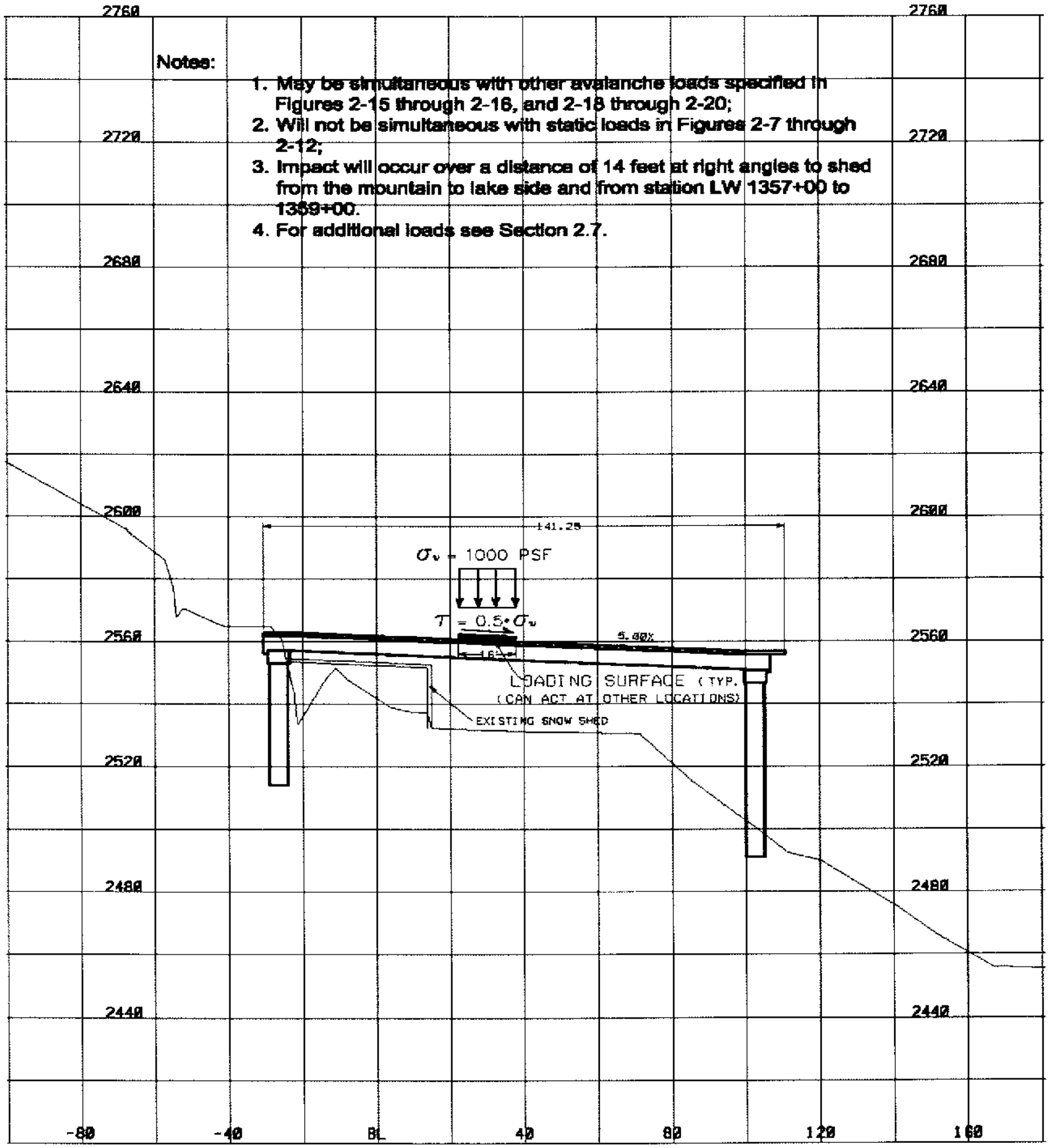

Figure 2-17: East Shed 4 100-Year Deflected Avalanche Impact Loading

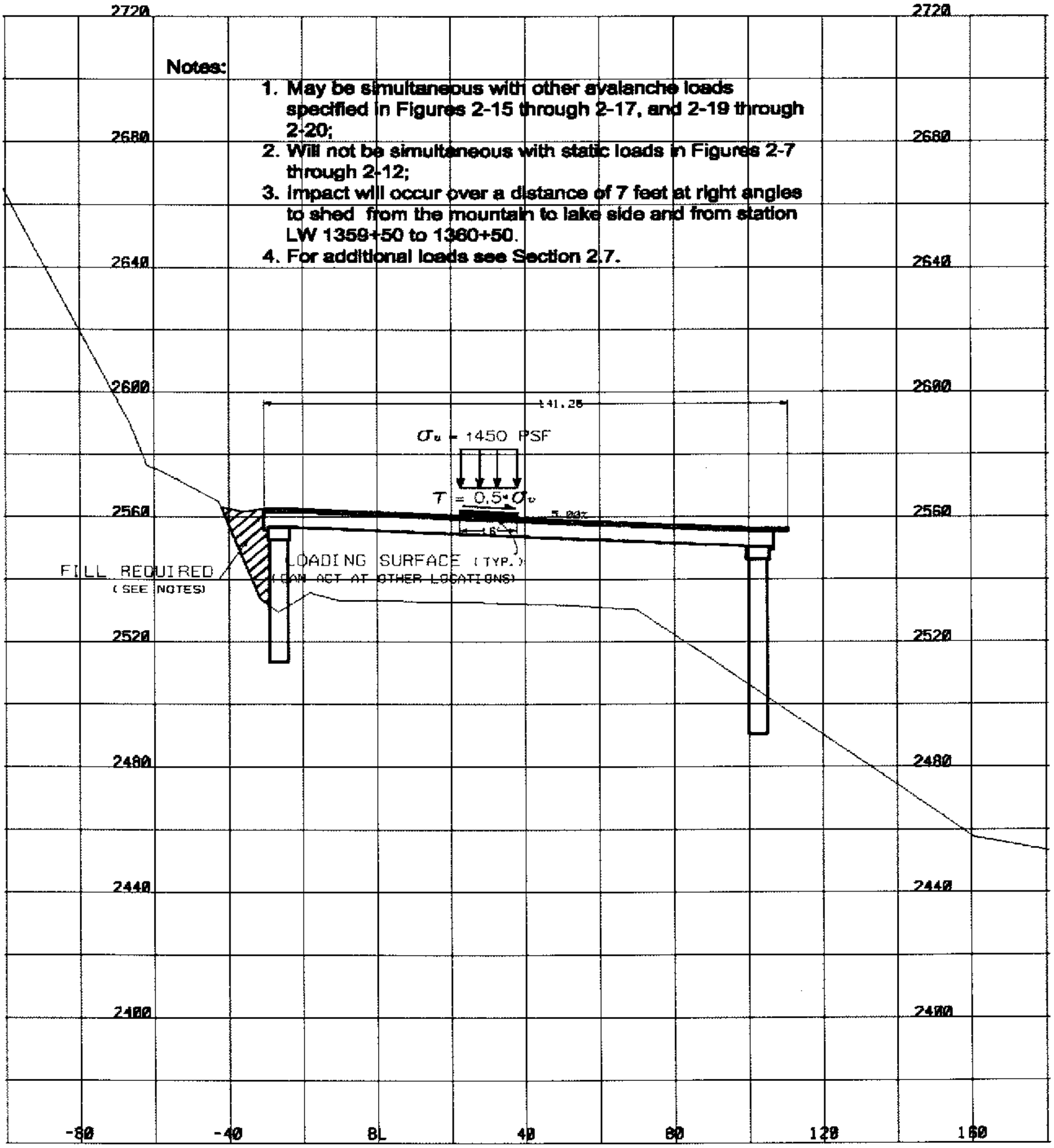

Figure 2-18: East Shed 5 West (1) 100-Year Deflected Avalanche Impact Loading

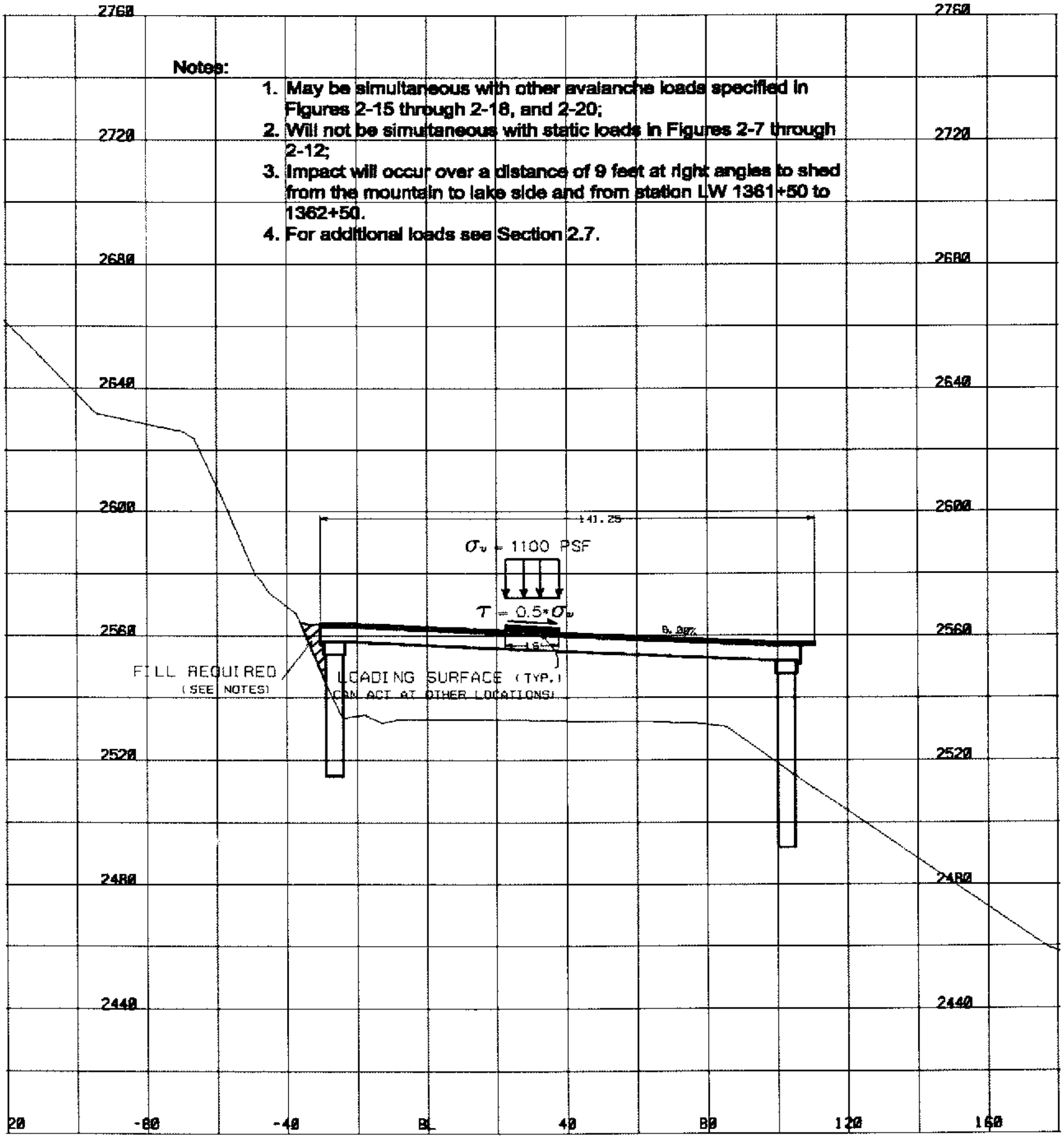

Figure 2-19: East Shed 5 West (2) 100-Year Deflected Avalanche Impact Loading

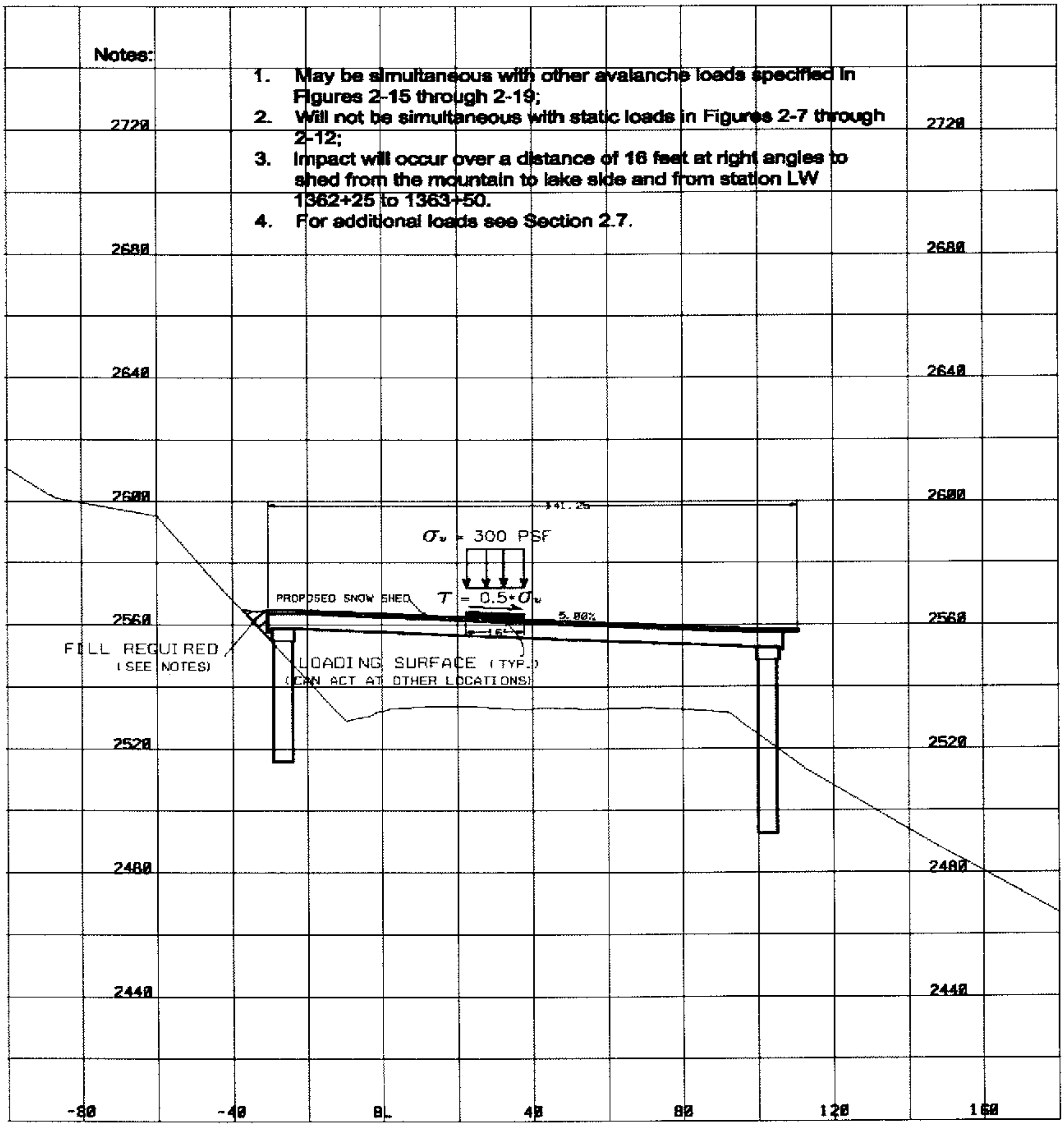

Figure 2-20: East Shed 5 East 100-Year Deflected Avalanche Impact Loading

The maximum calculated normal and shear loads resulting from snow avalanche impacts originating in East Sheds 2, 3, 4, 5 West (1), 5 West (2), and 5 East are summarized in Table 2-9. Shear loads are assumed to be 0.5 times the normal loads.

Table 2-9: Deflected Avalanche Impact Normal and Shear Loads on Proposed Snowshed Roof

Shed Number	Project Station	Deflected Impact Normal Load (psf)	Deflected Impact Shear Load (psf)
East Shed 2	1353+50	400	200
East Shed 3	1355+00	450	225
East Shed 4	1358+00	1,000	500
East Shed 5 West (1)	1360+00	1,450	725
East Shed 5 West (2)	1362+00	1,100	550
East Shed 5 East	1363+00	300	150

2.6 PROPOSED SNOWSHED PORTAL PROTECTION WALLS

Vertical portal protection walls will be needed above the Proposed Snowshed portals at WB Sta. 1352+50 and 1363+50. The portal walls should be designed for a uniform horizontal avalanche impact pressure of 1,400 psf (67.03 kPa) as shown on Figure 2-21.

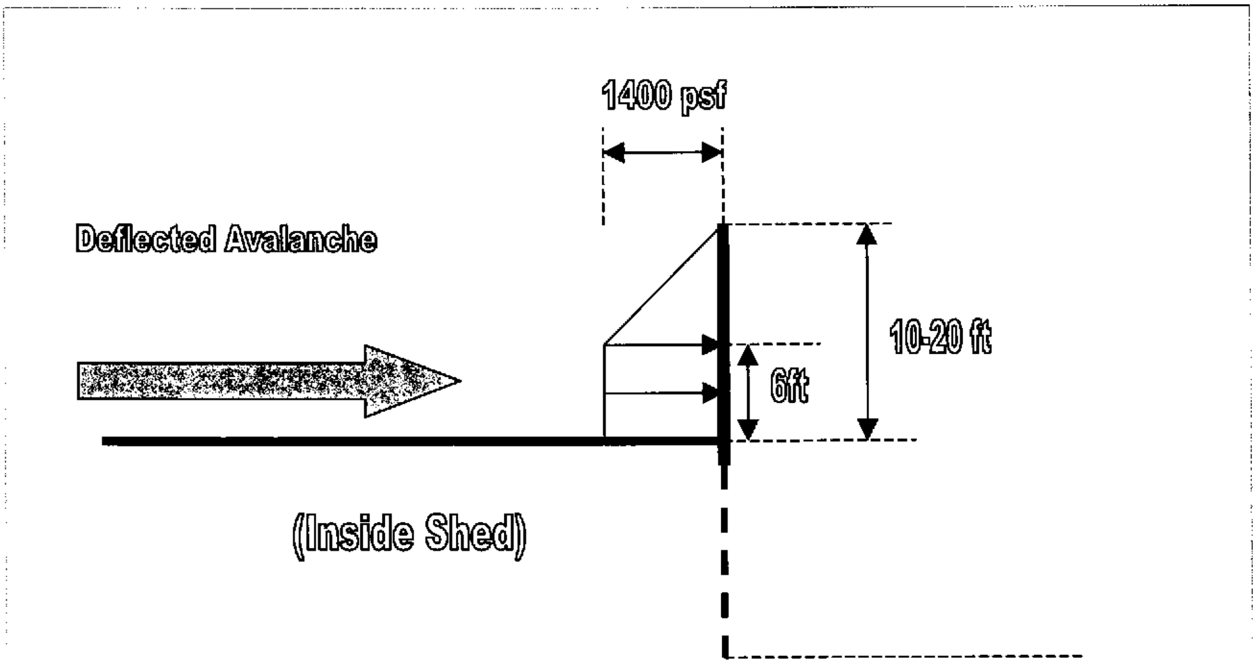

Figure 2-21: Portal Protection Wall Impact Pressures

Impact pressures normal to the portal protection walls will result from avalanche snow deflected laterally by existing avalanche snow deposits. The impact velocities and densities of deflected avalanche snow may be smaller than the values along the avalanche paths shown on Tables 2-8 and 2-9.

Based on field observations, the component of avalanche velocities (V) normal to the portal protection wall (See Table 2-9) is assumed to be 49 ft/sec (15 m/s). With an assumed density (ρ) of 18.7 lbs/ft^3 (300 kgs/m^3) for deflected avalanche snow, the impact pressure on the proposed portal protection wall due to momentum exchange (ρV^2) is estimated to be 1,400 psf (67.03 kPa).

The terminal depth of avalanche snow is approximately 6 feet as shown in Table 2-8. Therefore, the portal protection walls should be designed to withstand a uniform horizontal avalanche impact pressure of 1,400 psf (67.03 kPa) up to a height of 6 feet, as shown in Figure 2-21.

During momentum exchanges on impact, some avalanche snow may rise above the calculated terminal depth of 6 feet. Also, during severe snow storms, some snow may accumulate on the Proposed Snowshed roof near the portal protection walls above a height of 6 feet. To minimize the potential for such snow falling onto the roadway, the height of the portal protection wall should be at least 20 feet at the mountain-side, and should taper down to no less than 10 feet high at the lake-side edge of the snowshed.

During its climb above a height of 6 feet, avalanche snow may experience some energy loss. Therefore, a linear reduction in pressure is assumed above a height of 6 feet as shown in Figure 2-21. The indicated pressures will be greater than the static pressures that are likely to occur if snow piles up to the heights of 10 or 20 feet behind the proposed portal protection walls.

The portal walls should extend into the upper slope. The portal extensions into the slope must be designed for different loadings depending on the soil and snow loads on either side of the extensions. Some of the slope may have to be excavated for insertion of the portal wall into the slope. The loads associated with snow avalanches are shown in Figure 2-21.

The avalanche snow may be deflected toward the portals by previous avalanche deposits on the roof of the Proposed Snowshed. Therefore, a uniform deflected avalanche impact load is assumed over the entire wall height and length. Portal protection walls of height and length described above will prevent avalanche debris from falling onto the roadway and will prevent the formation of cornices from wind-drifted snow.

The portal protection wall characteristics outlined above only apply to the Proposed Snowshed portals planned to be located at WB Sta. 1352+50 and 1363+50.

2.7 ADDITIONAL LOADS ON PROPOSED SNOWSHED

In addition to the static avalanche debris loads and deflected avalanche impact loads discussed above and shown on Figures 2-7 to 2-12 and 2-15 to 2-20, the following additional loads will need to be considered:

- Static Snow Loads from Storms
- Dynamic Seismic and Wind Loads
- Soil and Rock Fall Loads behind Snowshed

2.7.1 Static Snow Loads from Storms

Static snow loads will develop as a result of accumulated seasonal snowfall from storms during the winter and are independent of static avalanche debris loads and deflected avalanche impact loads. These static snow loads must be added to the indicated design-basis loads. The static snow load from storms during a severe winter (100-year) would be uniform over the full roof length of the Proposed Snowshed.

Recommendations for ground snow loads in Kittitas County include 320 psf (15.32 kPa) for Lake Keechelus at El. 2,517; 227 psf (10.87 kPa) for Lake Kachees at El. 2,260; and 433 psf (20.73 kPa) at Stampede Pass at El. 3,000. To compute static snow loads on roofs of structures, the recommended snow loads are multiplied by a basic roof snow load coefficient of 0.8 or a lower coefficient of 0.6 if the roof is exposed to winds of sufficient intensity and there are no parapet walls.

Given that Lake Keechelus is near the Proposed Snowshed, a constant snow load of 200 psf (9,576 Pa) is judged to be reasonable for the roof of the Proposed Snowshed (Washington Association of Building Officials, 2000; National Bureau of Standrds, 1972).

2.7.2 Dynamic Seismic and Wind Loads

Dynamic seismic and wind loads could occur simultaneously with snow avalanche loads, but these combinations of events are typically not considered in design.

The magnitudes, directions and durations of potential seismic loads and of potential wind loads not associated with snow avalanches are beyond the scope of this avalanche mitigation study.

2.7.3 Soil and Rock Loads Behind Snowshed

At locations where engineered fill will be required behind the Proposed Snowshed, a vertical overburden load from snow deposits will develop on the soil as shown on Figures 2-7 to 2-12. All other soil loads that may result from fill placement are beyond the scope of this avalanche mitigation analyses.

The magnitude, direction and duration of landslide and rock fall loads, including debris flows, debris slides, rock and soil avalanches and/or other mass-wasting processes are beyond the scope of these avalanche mitigation analyses.

2.8 SNOWSHED OPTIONS

The following six-lane-wide single and multi snowshed options were considered as avalanche mitigations along the East Shed area of significant avalanche potential:

- Option 1 – Single Snowshed for East Sheds 3 and 4
- Option 2 – Single Snowshed for East Sheds 2 to 5
- Option 3 - Two Snowsheds: One for East Sheds 2 to 4; One for East Shed 5
- Option 4 - Snowshed for East Shed 1

2.8.1 Option 1 - Single Snowshed for East Sheds 3 and 4

Option 1 was considered as a single six-lane-wide snowshed to protect the roadway from the avalanche paths of only East Sheds 3 and 4. This is the extent of the existing snowshed along the current two WB lanes as shown on Figure 2-2 and 2-3.

Significant snow avalanches have occurred, are also likely to continue to occur, along the avalanche paths from East Sheds 2 and 5, as well as from the avalanche paths of East Sheds 3 and 4. Avalanches originating from East Shed 2 have occurred in the past, and are expected to block the highway on the average of once in three years[2]. The return period for avalanches originating in East Shed 5 is expected to be would be similar to the return period stated for East Shed 2.

A heavily traveled highway such as I-90[3] should be protected from avalanches that have return periods of between 3 and 10 years. Therefore, Option 1 was considered to be not feasible.

2.8.2 Option 2 - Single Snowshed for East Sheds 2 to 5

Option 2 was considered as a single six-lane-wide snowshed to protect the roadway from the avalanche paths of East Sheds 2, 3, 4 and 5. This is well beyond the extent of the existing snowshed. The Proposed Snowshed would extend continuously between WB Sta. 1352+50 and 1363+50 for a total length of approximately 1,100 feet.

Severe winters with large storms and heavy snowfall have caused, and will continue to cause moderate-to-large avalanches originating in East Sheds 2, 3 4 and 5. This option will reduce roadway closure delays that have occurred and would continue to occur due to avalanche control using explosives.

Roadway closure delays due to avalanche control using explosives would be reduced under Option 1 to less than 5 percent of what they are currently without mitigation. Therefore this option is recommended.

2.8.3 Option 3 – Two Snowsheds: One for East Sheds 2 to 4; One for East Shed 5

Option 3 was considered as two six-lane-wide snowsheds. One would protect the roadway from the avalanche paths of East Sheds 2, 3, 4. The other would protect the highway from the avalanche path of East Shed 5.

The two snowsheds would extend from approximately WB Sta. 1352+50 to 1358+50 for East Sheds 2 to 4 and WB Sta. 1360+00 to 1363+50 for East Shed 5. The lengths of these snowsheds would be about 600 and 350 feet, respectively, for a total snowshed length of 950 feet. This would leave a gap of 150 feet along a non-avalanche area between the edges of the avalanche paths of East Sheds 4 and 5.

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2 This is a nearest "half order of magnitude" estimate of the return period. The number "3" is approximated by $10^{0.5}$ and is the best estimate of the real return period based on the experience of Art Mears P.E.; this may lie between $10^{0.0}$ (or "1") and $10^{1.0}$ (or "10") years. A better estimate is not possible given the variable effectiveness of active (explosive) avalanche control and annual variability in weather and storm conditions.

3 Average Daily Traffic (ADT) for year 2006 on I-90 in the vicinity of the project was approximately 28,000 vehicles on weekdays, and was as high as 58,000 vehicles during a major holiday. Commercial traffic accounts for approximately 20% of these totals. Sources: *Project Draft EIS*, *WSDOT 2006 Annual Traffic Report.*

Option 3 would result in the 150-foot long section between the snowsheds being susceptible to avalanche flows if sufficiently high portal protection walls were not built. Although this option may be technically feasible, it is not recommended on the basis of this avalanche mitigation study because of uncertainties in specifying avalanche path boundaries in the existing forested terrain, constructability, and the importance of avoiding roadway closures.

However, there are other considerations that may make Option 3 more competitive with Option 2. The decision on whether to construct the Option 2 longer snowshed, or the Option 3 two shorter snowsheds will depend on construction, operation and maintenance considerations and costs. The proposed snowshed will have two portals with portal protection walls, but could require more ventilation, lighting and fire suppression. Two shorter snowsheds will require four portals with higher portal protection walls, but may not require as much ventilation, lighting and fire suppression.

2.8.4 Option 4 - Single Snowshed for East Shed 1

Option 4 was considered as a single six-lane-wide snowshed to protect the roadway from the avalanche paths of East Shed 1, in addition to Options 1, 2 and 3 described above.

Option 4 was considered to be not necessary because avalanches originating in East Shed 1 have not affected the highway since the 1970s, and it is the opinion of WSDOT that it can continue to be controlled effectively through the use of explosives and ditches at the toe of the slope.

3.0 SNOW NET STRUCTURES AT SLIDE CURVE AVALANCHE AREA

3.1 PREVIOUS STUDIES

The existing slope of Slide Curve is steep and sparsely vegetated as shown on Figure 3-1. Parts of the slope have no vegetation. The slope experienced structurally controlled rock slope instability when its adversely dipping bedrock structure was undercut during roadway widening construction in October 1957, and resulted in a rock slide. The feasibility of cutting into this slope was evaluated by (URS and Wyllie & Norrish 2007) and is being further evaluated for cut design purposes.

A previous snow avalanche study of the Slide Curve area was conducted by (Peter Shaerer and Chris Stethem & Associates Ltd. 2000). The study resulted in the recommendation that snow net structures be constructed in the starting zone of the Slide Curve avalanche area as the most appropriate means of snow avalanche control for the area.

Snow nets are specialized fences that are installed along multiple parallel lines along elevation contours in avalanche starting zones. The fences hold the snow in the starting zones and prevent it from moving down the slope in unstable conditions. Snow fences are common in the European Alps, and have proven to be an effective, safe and excellent snow avalanche mitigation alternative. Switzerland and other European countries have extensive experience constructing snow net fences in difficult environments.

Snow net structures limit the movement of snow by transferring stresses within the snow pack to the ground. The initiation of avalanches is usually prevented where snow net structures are used and the need for explosives as a means of snow avalanche control is therefore substantially reduced. Snow net structures do create visual impacts from the roadway. However, they also improve conditions for forest re-growth because the movement of snow down the slopes is more controlled.

The use of snow net structures for snow avalanche mitigation has been very limited in North America, especially along transportation corridors. These types of structures can be relatively expensive when used over large areas. Snow net structures typically require the acquisition of right-of-way or easements, and they tend to raise aesthetic and environmental concerns.

It is considered that the ground conditions in the starting zone at the Slide Curve snow avalanche area are favorable for the use of snow net structures for snow avalanche control. The favorable conditions are that the starting zone area is relatively small, and no rights-of-way are required.

It is estimated that roadway closure delays in the Slide Curve area due to snow avalanche control using explosives would be reduced with the installation of snow net structures to less than 5 percent of what they are currently without mitigation. The use of snow net structures would also improve conditions for forest re-growth.

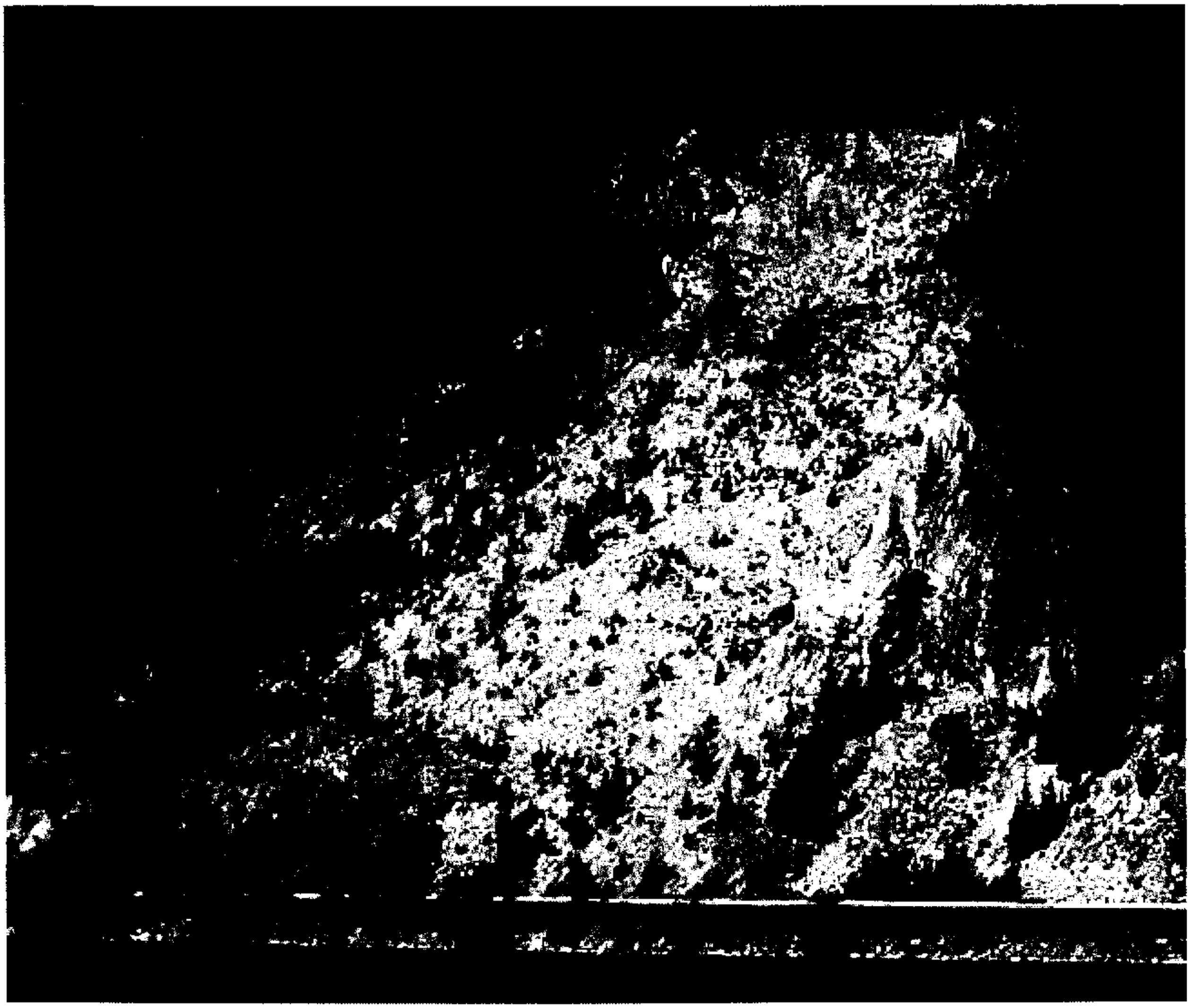

Figure 3-1: Slide Curve Avalanche Area

3.2 ANALYSIS METHODOLOGY

The layouts and heights for snow net structures in snow avalanche starting zones of the Slide Curve slope were based on updated 2006 Swiss Guidelines (Margreth, 2007). These guidelines dictate the nomenclature use in this study and the use of the metric International System of Units (SI). The guidelines have also been adapted for maritime climates in Iceland (Johannesson and Margreth, 1999 and 2003). These adaptations were considered and applied to Slide Curve where deemed appropriate.

Field observations and measurements were made by Art I. Mears and Chris Wilbur during snow-free conditions on June 18, 19 and 20, 2007. Mr. Steve Mumma of Geobrugg North America of Lake Oswego, Oregon, visited the site On June 20, 2007, and provided advice relating to the suitability, constructability, and cost of snow net structures. Mr. Robert Thommen of Rotec International of Santa Fe, New Mexico, also provided information on the technical aspects of snow net structures.

3.3 EXTREME SNOW DEPTH

The key variable in the design of snow net structures to be used in snow avalanche starting zones is the depth of the snow measured normal to the ground surface denoted as D_k. The thickness is a function of the vertically measured snow depth denoted as H, and slope angle denoted as ψ. The calculation for D_k is:

$$D_{k\,(ext)} = H \cos(\psi)$$

Snowfall data are being collected at various sites in the vicinity of the project study area. Extreme snow depth measurements were collected at each of these sites and the associated data is in Table 3-1. These extreme snow depths represent the maximum depth of snow measured on the ground at any time during the period of record. The measurements reflect any consolidation of the snow mass and settlement of the snow surface that may have occurred prior to the measurement.

The source of the data in Table 3-1 is the Western Regional Climatic Center (WRCC), www.wrcc.dri.edu, of Reno, Nevada. WRCC compiles data from the National Climate Data Center, National Weather Service (NWS), Natural Resources Conservation Service (NRCS), Bureau of Land Management, and U.S. Forest Service. The sites reported in this study are operated by the NWS, and the NRCS.

Table 3-1: Snow Depth Data Collection Sites

Data Collection Sites	Elevation (ft)[m]	Extreme Snow Depth (ft)[m]	Distance to Slide Curve (miles)[Km]	Direction from Slide Curve Avalanche Area	Period of Record
Snoqualmie Pass (457781)	(3,018)[920]	(18.7)[5.7]	(8.7)[14]	N-NW	1-1-1931 to 2-27-1972
Stampede Pass (458009)	(3,960)[1,207]	(19.7)[6.0]	(6.2)[10]	S-SE	1-1-1944 to 12-31-2006
Lake Keechelus (454414)	(2,480[756]	(11.8)[3.6]	(3.1)[5]	E-SE	1-1-1931 to 8-31-1977
Lake Kachess (454406)	(2,270)[692]	(9.5)[2.9]	(13.7)[22]	E-SE	1-1-1931 to 8-31-1977
Slide Curve	(2,560 to (3,018) [780 to 920]	(11.5 to 14.8) [3.5 to 4.5]	(NA)[NA]	NA	Interpreted

The weather data collection sites near the Slide Curve snow avalanche area are shown in Figure 3-2. The snow depth data for each site are listed in Appendix A.

Based on elevations, geographic position, historic weather data, and descriptions of local variations in snow depths provided by WSDOT Senior Avalanche Control Specialist, Craig Wilbour, the maximum vertical snow depths, $H_{ext,}$ were estimated, where H_{ext} is the extreme snow depth measured vertically. H_{ext} values were assigned to the Slide Curve avalanche area as follows:

H_{ext} = 14.8 feet (4.5 meters) above El. 2,789 feet (850 meters)
H_{ext} = 11.5 feet (3.5 meters) below El. 2,789 feet (850 meters)

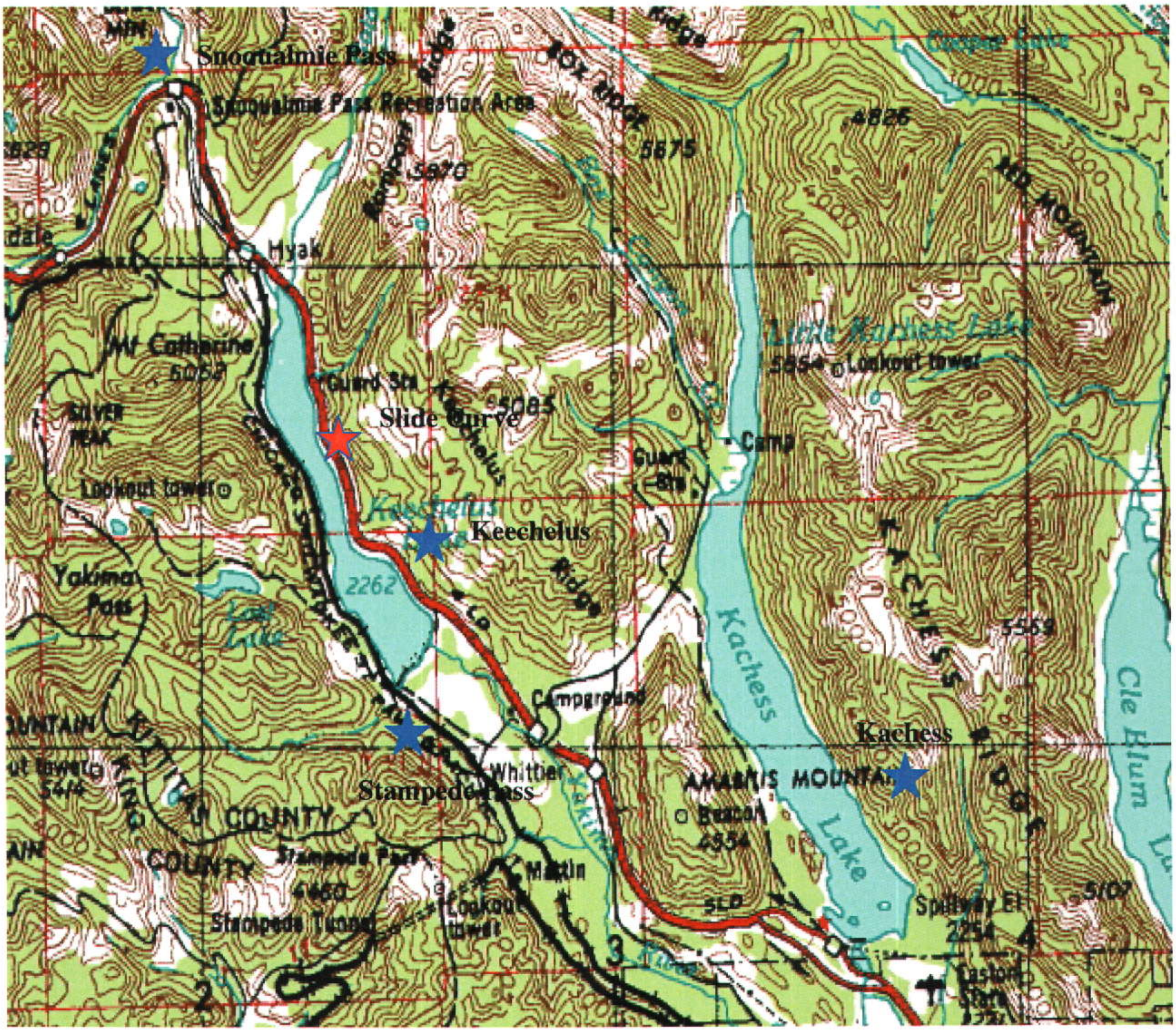

Figure 3-2: Weather Data Collection Sites Near the Slide Curve Avalanche Area

Based on discussions with Craig Wilbour, it is estimated that the estimated extreme snow depth values H_{ext} represent the maximum total snow depth accumulation during an extreme snowfall season with an anticipated 100-year return period.

Using Slide Curve slope angles that were measured in the field to be $\psi = 42^\circ$ above El. 2,789 and $\psi = 35^\circ$ below El. 2,789, the extreme snow depths, $D_{k\,(ext)}$ were calculated, where is $D_{k\,(ext)}$ is the extreme snow depth measured normal to the slope. The following $D_{k\,(ext)}$ values were calculated:

$D_{k\,(ext)}$ = 10.8 feet (3.3 meters) above El. 2,789 feet (850 meters)
$D_{k\,(ext)}$ = 9.5 feet (2.9 meters) below El. 2,789 feet (850 meters)

The heights of the snow net structure must be greater than the calculated extreme snow depth. However, snow net structures are only manufactured in 1.64-foot (0.5-meter) increments. Therefore, the recommended snow net structure heights, $H_{snow\ net}$, reflect the nearest 1.64-foot (0.5-meter) increment above the calculated extreme snow thickness. $H_{snow\ net}$ is the effective snow net structure height measured normal to the slope. Recommended snow net structure heights are listed below.

$H_{snow\ net}$ = 11.5 feet (3.5 meters) above El. 2,789 feet (850 meters)
$H_{snow\ net}$ = 9.8 feet (3.0 meters) below El. 2,789 feet (850 meters)

3.4 GLIDE FACTOR

Glide factor is an empirical value that is used to estimate snow pressures on snow net structures. It depends on the solar aspect, smoothness, and vegetation cover of the surface which snow must glide over before it arrives at the snow net structure.

Figure 3-3: Ground Conditions Representing Class 2 and 3 Glide Factors

Glide factors were estimated for the Slide Curve snow avalanche are by using the updated 2006 Swiss Guidelines for snow net structures. The estimates were based on field observations of ground vegetation, ground roughness and solar aspect characteristics of the Slide Curve slope in conjunction with published tables such as Table 4-5 in (Margreth 2007). This Table 4-5 is included in Appendix C.

The glide factor for most of the Slide Curve snow avalanche area can be described as either Class 2 or Class 3. The smooth bedrock slope is devoid of vegetation above El. 2,887 feet and can be described as Class 4 (See Table 4-5) included in Appendix C. Figures 3-3 and 3-4 show ground conditions for glide factor classification.

Figure 3-4: Ground Conditions Representing a Class 4 Glide Factor

Using the information found in Table 4-5 of (Margreth 2007), the following values for Glide Factors (N) were adopted for the Slide Curve snow avalanche area:

N = 2.0 below El. 2,789 feet (850 meters)
N = 3.0 above El. 2,789 feet (850 meters)

3.5 LAYOUT

The distance between the snow net structures measured horizontally (L'), and the true distance measured along the slope (L), are functions of the snow net structure height ($H_{snow\ net}$), slope angle (ψ), glide factor (N), and ground friction (tan Φ).

Glide factors and ground friction coefficients were estimated for the Slide Curve snow avalanche area by using the updated 2006 Swiss Guidelines for snow net structures (Margreth, 2007). Relevant tables (2.1, 2.2, 3.1, and 3.2 from (Margreth 2007) that were used to develop the estimates are in Appendix C.

Snow net structure spacing parameters for the starting zone of the Slide Curve snow avalanche area were estimated and are presented in Table 3-2.

Table 3-2: Snow Net Structure Spacing Parameters

Elevation (ft) [m]	$H_{snow\ net}$ (ft) [m]	ψ (deg)	tan Φ	Glide Factor (N)	L' (ft) [m]	L (ft) [m]
Above (2,789) Above [850]	(11.5) [3.5]	45	0.53	3.0	(49.2) [15]	(72.2) [22]
Above (2,789) Above 850	(11.5) [3.5]	35	0.53	3.0	(94.1) [29]	(114.8) [35]
Below (2,789) Below [850]	(9.8) [3.0]	35	0.53	2.0	(80.6) [25]	(98.4) [30]

Based on the calculations described above and the snow net structure spacings in Table 3-2, it was determined that ten lines (Lines 1 to 10) of snow net structures would be necessary in the starting zone of the Slide Curve snow avalanche area to protect the roadway from snow avalanches. A recommended Preliminary Layout of the Lines 1 to 10, from top to bottom, is shown Figure 3-5. It is recommended that each line follow a contour.

Table 3-3 is a summary of the Line 1 to 10 snow net structures details. Preliminary coordinates for the snow net structures, including the elevations, end points, number of bends, and number of breaks, and line lengths are presented in Appendix B. Surveys of the end points were completed by White Shield. The total length of snow net that would be required for the ten lines is 3,862 feet (1,177 meters).

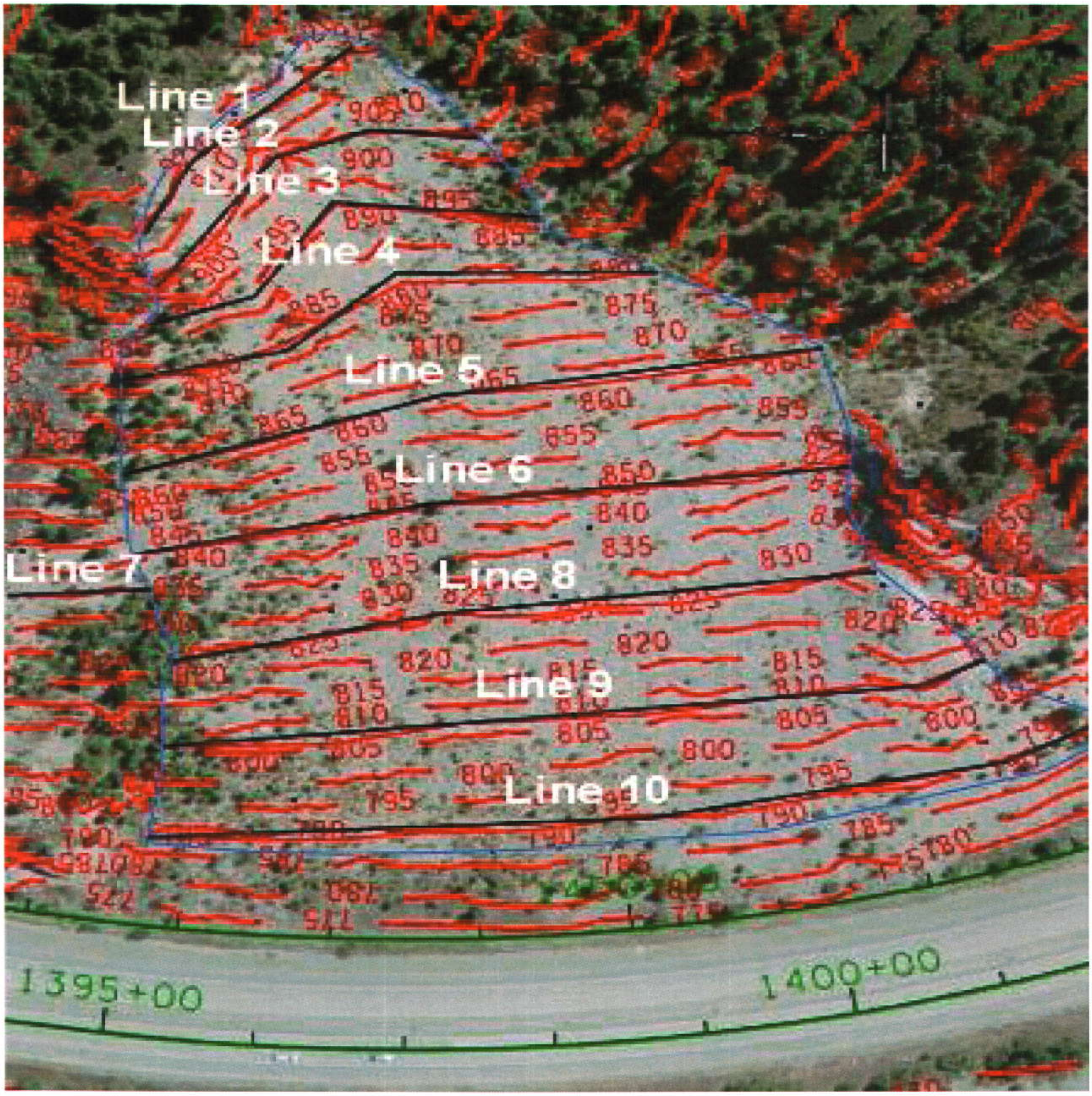

Figure 3-5: Preliminary Layout for Snow Net Structures at Slide Curve Avalanche Area

Table 3-3: Snow Net Structures Description Summary

Line ID	$H_{snow\ net}$ (ft) [m]	Elevation (ft) [m]	No. of Bends	No. of Breaks	Line Length (ft) [m]
1	(11.5) [3.5]	(3,005) [916]	1	1	(207) [63]
2	(11.5) [3.5]	(2,967) [904]	2	2	(269) [82]
3	(11.5) [3.5]	(2,927) [892	2	2	(302) [92]
4	(11.5) [3.5]	(2,887) [880]	2	2	(381) [116]
5	(11.5) [3.5]	(2,835) [864]	1	0	(476) [145]
6	(9.8) [3.0]	(2,769) [844]	1	0	(476) [145]
7	(9.8) [3.0]	(2,743) [836]	0	0	(102) [31]
8	(9.8) [3.0]	(2,707) [825]	1	0	(466) [142]
9	(9.8) [3.0]	(2,644) [806]	1	1	(551) [168]
10	(9.8) [3.0]	(2,592) [790]	2	1	(633) [193]
		Totals	**13**	**9**	**(3,862) [1,177]**

3.6 SNOW LOADS APPLIED TO THE SNOW NET STRUCTURES

The accumulated snow will apply loads both parallel to (S_n) and perpendicular to the slope (S_q). The component of creep and glide pressure in the line of the slope, or, parallel to the slope, on a rigid surface lying normal to the slope, is denoted as S_n. The force component normal to the line of the slope (S_q) occurs when the settling movement of the snow at the surface is prevented by adhesion and surface roughness.

Assuming that the snow net structures is a rigid surface, the snow forces parallel to the slope (S_n), on a unit length of the snow net structure, and perpendicular to the slope (S_q), were calculated using the following equations.

$$S_n = \rho\, g\, (H^2 / 2)\, K\, N$$
$$S_q = S_n\, a / (N \tan \psi)$$
$$= S_n \tan \varepsilon$$

Where:

ρ = Density of well-packed snow and melt mixture; assumed to be 600 kg/m^3
g = Acceleration due to gravity; 9.81 m/sec^2
H = Vertical snow depth in meters estimated as H_{ext} in Section 3.3
K = Creep coefficient dependent on slope angle ψ and snow density (Margreth 2007). Table 6 from (Margreth 2007) that was used to estimate the value for K, is in Appendix C.
N = Glide Factor; See Section 3.4.

a = Coefficient dependent on snow type, varies from 0.2 to 0.5; a conservative value of 0.5 was used.
ψ = Slope angle
ε = Angle between the resultant snow pressure arising from vectorial addition of S_n and S_q and the line of slope.

The calculated snow forces parallel to the slope (S_n) and perpendicular to the slope (S_q) are presented in Table 3-4. Glide factors were applied as discussed in Section 3.4.

Table 3-4: Design Forces on Snow Net Structures at the Slide Curve Avalanche Area

Line Number	Glide Factor (N)	Creep Factor (K)	Slope Angle ψ (deg)	Snow Depth (ft) [m]	Design Forces SI Units		Design Forces English Units	
					S_n kN/m	S_q kN/m	S_n tons/ft	S_q tons/ft
1	3.0	1.05	45	(14.8) [4.5]	188	31	6.4	1.1
2	3.0	1.05	45	(14.8) [4.5]	188	31	6.4	1.1
3	3.0	1.05	35	(14.8) [4.5]	188	45	6.4	1.5
4	3.0	0.99	35	(14.8) [4.5]	177	42	6.1	1.4
5	2.0	0.99	35	(14.8) [4.5]	118	42	4.0	1.4
6	2.0	0.99	35	(11.5) [3.5]	71	25	2.4	0.9
7	2.0	0.99	35	(11.5) [3.5]	71	25	2.4	0.9
8	2.0	0.99	35	(11.5) [3.5]	71	25	2.4	0.9
9	2.0	0.99	35	(11.5) [3.5]	71	25	2.4	0.9
10	2.0	0.99	35	(11.5) [3.5]	71	25	2.4	0.9

It should be noted in Table 3-4 that the snow forces S_n and S_q are calculated per unit length along a given line of snow net structure, either per unit meter, or per unit foot.. Also, the English Unit conversion of 1 ton = 2,000 lbs was used.

3.7 PERFORMANCE STANDARDS

3.7.1 Materials

Snow net structures are primarily manufactured by the two companies listed below, and have been tested and approved by the Swiss Government for use in Switzerland. More than 310 miles of permanent snow net structures have been installed in Switzerland.

- Geobrugg North America, LLC
  333 South State St., Suite V, #311
  Lake Oswego, OR 97034
  Steve Mumma, Regional Manager
  (503) 543-9020
  www.geobrugg.com
  Isofer, AG

- Rotec International, LLC
  P.O. Box 31536
  Santa Fe, NM 87594
  Robert Thommen, President
  (505) 989-3353
  www.rotecinternational-usa.com

3.7.2 Installation

The preliminary layout shown in Figure 3-5 is intended to be used as a guide for the final design of the permanent snow net structures proposed to be installed in the starting zone of the Slide Curve snow avalanche area.

Field staking of the coordinates determined by surveyors and listed in Appendix B is necessary prior to final design. End points, angle points and breaks should be determined based on field observations after staking the coordinates. Following the completion of the preliminary layout in the field, it is recommended that prospective snow net structure suppliers and installers visit the site and provide input and guidance for the final design.

Snow net structures allow for some flexibility and adjustment to specific site conditions during their installation. In general, the lines should follow contours. Experience suggests that the bends should be limited to a maximum of 5 degrees. Where greater deflection angles must be used, a break in the line is required. The minimum length for lines to be installed in the starting zone of the Slide Curve avalanche area should be 53 feet (16 meters), (Margreth, 2007, page 41). The maximum length of line should be 197 feet (60 meters). Lines longer than 197 feet (60 meters) would not allow for easy access to the site.

It is recommended that WSDOT, URS, and the Contractor, and the URS sub-consultants Arthur I. Mears and Wylie & Norrish, all be involved during the construction process. The construction process will be expedited by providing access to the Slide Curve snow avalanche area along the private road that was used for the 2007 Slide Curve avalanche area fissure excavations by URS and Wyllie & Norrish.

The snow net structures will apply forces to the anchors that hold the structures in place. Inspections of the selected anchor locations will need to be made by the Wyllie & Norrish prior to the final design. However, based on discussions with the snow net structure suppliers listed in Section 3.7.1, for preliminary design purposes, the maximum anchor forces on 3-meter high snow net structures are expected to be approximately:

- 35 tons for Lines 1 to 4

- 25 tons for Lines 5 to 10.

An anchor testing program will be required. Section 5.9 of the Swiss Guidelines (Margreth 2007) recommends that pull-out tests be performed on approximately 5 percent of all anchors or 3 tests for each type of ground having comparable geotechnical properties.

The Swiss Guidelines recommend testing the pull-out strength for each anchor up to 1.35 times the maximum expected load. The extent of the testing program should be based on these guidelines adjusted for variability of ground conditions and the geotechnical engineer's confidence in characterizing those conditions.

The failure of a single anchor may result in forces on adjacent anchors, posts, and connections in excess of their design strength. Therefore, a high degree of confidence in ground anchors is desirable due to the anticipated high costs of mobilizing to replace failed anchors, and the need to do this in the summer immediately following the failure so that the snow net is fully intact for the following winter.

Snow net structures may accumulate significant amounts of snow behind them during the winter. Under these conditions, if a snow net structure or a part of the structure gives way due to lack of maintenance, non-repaired damaged sections, or failure of an anchor, it may exacerbate a snow avalanche or similar event, which may be categorized as a man-made catastrophe.

3.7.3 Maintenance

The snow net structures constructed in the starting zone of the Slide Curve snow avalanche area should be inspected annually during snow-free conditions. Detailed inspections should be performed every 3 to 5 years, and after winters with significantly above-average snowfalls.

It is recommended that the construction contract be structured so that the contractor is responsible for the first post-winter inspection and for making all adjustments to the snow net structures that are required as a result of that inspection.

It is also recommended that the contraction contract include a line item for the contractor to conduct formal training of WSDOT personnel for subsequent inspection and maintenance.

3.8 OTHER MITIGATION METHODS

3.8.1 Reforestation

Reforestation is a compatible and complementary side benefit to the use of snow net structures for avalanche control. Ground conditions at the Slide Curve snow avalanche area are such that effective reforestation that would help in the control of snow avalanches, without the aid of snow net structures, could take several decades.

During the reforestation process, the snow net structures will help to control avalanches, prevent roadway closures, and enhance tree growth by stopping the movement of large quantities of snow that will accumulate in the starting zone.

Snow net structures manufactured in accordance with the specifications in the Swiss Technical Guidelines are expected to have a service life of approximately 80 years when regular inspections and maintenance are performed.

3.9 PRELIMINARY COST ESTIMATE

3.9.1 Preliminary Construction Costs

Preliminary construction labor and material costs for the snow net structures proposed for the Slide Curve snow avalanche area were estimated based on similar projects and related costs for snow net structures installed in the United States. Representatives of the manufacturers of snow net structures provided information relating to site specific issues and access conditions.

The preliminary cost estimate was based on costs obtained for the following snow net structure projects, with snow net heights in feet and meters:

- Alpental at Snoqualmie Pass - 14.8 feet (4.5 meters)
- Mt. Crested Butte, Colorado - 9.8 feet (3.0 meters)
- Teton Science School, Wyoming - 8.2 feet (2.5 meters)

Table 3-5 presents the estimated preliminary costs for the snow net structures proposed for the Slide Curve snow avalanche area.

Table 3-5: Preliminary Cost Estimate for Proposed Snow Net Structures

Height (ft) [m]	Total Length (ft) [m]	Unit Cost per (ft) per [meter]	Total Cost
(11.5) [3.5]	(1,634) [498]	($2,440) [$8,000]	$4.0 million
(9.8) [3.0]	(2,228) [679]	($2,010) [$6,600]	$4.5 million
		Estimate Total:	**$8.5 million**

Installation costs can vary substantially and therefore make it relatively difficult to estimating the costs. The installation cost of snow net structures depends heavily upon ground conditions and access to the site. Anchor installation costs can vary substantially depending on the soil and rock conditions and the depth of anchoring that is needed. Therefore, a geotechnical investigation of the anchor locations is necessary.

Helicopters are often used to deliver the snow net structures to the site, and will be required for delivery of the snow net structures materials to the Slide Curve avalanche area. Helicopters were also used during the 2007 Slide Curve geotechnical explorations. Rolling slowdowns of traffic will be required while helicopters are used for delivering the snow net structures, and during some of the installation work.

3.9.2 Preliminary Maintenance Costs

Maintenance costs for snow net structures can vary from site to site and are dependent upon the snow loads applied to the structures as well as other factors. Annual maintenance costs are expected to be approximately 1.0 to 1.5 percent of the installation costs (Margreth 2004). Therefore, the annual maintenance costs could range from $85,000 to $127,000.

4.0 ADDITIONAL AVALANCHE CONTROL OPTIONS

4.1 INTRODUCTION

Snow avalanche mitigation measures were discussed in Section 2.0 for the Proposed Snowshed below East Sheds 2 to 5, and in Section 3.0 for proposed snow net structures at the Slide Curve avalanche area. However, the implementation of these two recommended mitigation measures will not completely eliminate the risk of roadway closures because of other potential avalanche areas in the project study area.

It is expected that unforeseen conditions may result in an average of 1 to 4 hours of roadway closure per year, compared to a total of 120 hours of roadway closures without the recommended mitigation. Thus, the risk and delays associated with snow related avalanches in the project study area may be reduced to less than 5 percent of the level that would occur without mitigation.

Additional snow avalanche control options are necessary to reduce the snow avalanche risk and potential number and duration of roadway closures on I-90 along the project study area. Additional snow avalanche control options were considered for protection of the roadway in three specific areas as follows:

- Snow net structures below East Sheds 3 and 4 to reduce loads on the Proposed Snowshed roof
- Wall and ditch system below East Shed 1 where a snowshed was considered not necessary
- Cut Slopes such as at Jenkin's Knob and along other sections of the roadway.

4.2 SNOW NET STRUCTURES IN EAST SHEDS 3 AND 4

Snow net structures were considered for East Sheds 3 and 4 to supplement the Proposed Snowshed. The line lengths of these snow net structures would be approximately 500 feet (150 meters) for East Shed 3 and 1,000 feet (300 meters) for East Sheds 4. The heights of these snow nets for both East Sheds 3 and 4 would be approximately 15 feet (4.5 meters).

Snow net structures in East Sheds 3 and 4 would be located between El. 3,450 feet (1,050 meters) and 3,710 feet (1,130 meters). These structures would reduce the magnitude of severe winter snow avalanches and reduce the magnitude of the avalanche debris accumulated over the course of a severe winter. Also, the static and shear loads developed from avalanche deposits and the deflected avalanche impact loads that would be applied to the Proposed Snowshed roof structure would be reduced to approximately 70 percent of the total load that would be applied without the snow net structures.

It should be noted that it is difficult to predict the exact reduction in design loads. The approximate 70 percent reduction is based on the judgment and experience. The expected reduction in design loads due to snow net structures may be considered only as an additional factor of safety rather than a factor to reduce the calculated design loads for the Proposed Snowshed.

The moderately forested terrain in certain areas of the starting zones for East Sheds 3 and 4 contain old growth trees that under severe conditions could fall on and damage the snow net structures. The steep slopes of greater than 45 degree inclines in the starting zones for East Sheds 3 and 4 would make construction difficult. Deep drilling and long anchors would be required to hold the snow net structures in place on the steep slopes.

Access to the starting zones for East Sheds 3 and 4 would be relatively easy although permission and or permits may be required to use the forest service roads leading to the top of the ridge. The construction process would be expedited should access be made available to the top of the ridge along existing forest service roads.

The heights of the snow net structures in East Sheds 3 and 4 would be approximately 1.3 times higher than the height for the snow net structures at the Slide Curve avalanche area. The increased height, longer line lengths, more extensive drilling and longer anchors would significantly increase the total cost. The estimated cost per unit length would be approximately 1.3 times the unit cost for the snow net structures proposed for the Slide Curve avalanche area.

The total estimated preliminary cost for snow net structures at East Sheds 3 and 4 would be approximately $3,200 per foot of structure length for a total cost of $4.8 million.

Snow net structures in East Sheds 3 and 4 would reduce the avalanche risk between WB Sta. 1354+50 and 1359+00, although the Proposed Snowshed would still be required between these stations. Construction of the snow net structures would be feasible but difficult.

Based on experience and judgment, the cost reduction for the Proposed Snowshed construction is not likely to offset the total cost for the snow net structures in East Sheds 3, and 4. Therefore, snow net structures for the starting zones in East Sheds 3 and 4 are not recommended.

4.3 WALL AND DITCH SYSTEM BELOW EAST SHED 1

The avalanche path for East Shed 1 is located west of the westbound project station limits for the Proposed Snowshed. The approximate limits for the avalanche path of East Shed 1 are between WB Sta. 1348+00 and 1350+00. The terrain in East Shed 1 is moderately forested and the terrain configuration is not conducive to the origination of large magnitude avalanches.

Avalanches originating in East Shed 1 historically have had minimal impact to the I-90 roadway below East Shed 1. Historically, the avalanche flows originating in East Shed 1 have been smaller, move slower, and are less dense than snow avalanches originating in East Sheds 2 through 5.

Avalanches originating in East Shed 1 have not impacted highway operations since the 1970s as per the Mr. Craig Wilbour, the WSDOT Chief Avalanche Control Technician, and as stated by Schaerer and Stethem (2000). Explosives are currently used to test the stability of the snow pack and initiate avalanches when necessary.

The rare avalanches that might originate in East Shed 1 during a severe winter could be prevented from impacting roadway operations by constructing a wall and ditch system between WB Sta. 1348+00 and 1350+00. The wall would be 10 feet high and the ditch behind the wall would be 20 feet wide as shown in Figure 4-1.

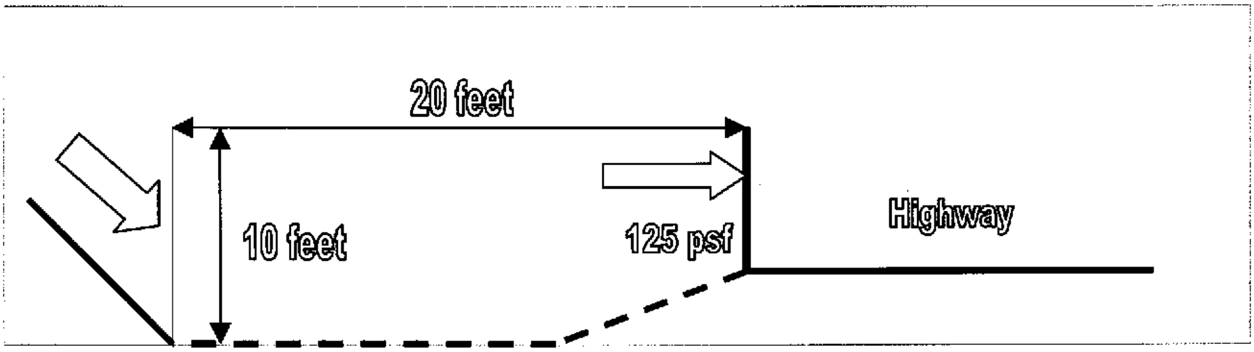

Figure 4-1: Wall and Ditch System Design Diagram

The wall/ditch system would provide adequate storage for snow avalanche flows originating in East Shed 1 that reach the toe of the slope and would provide sufficient space for snow removal equipment. Based on experience and judgment, the wall should be designed for a direct avalanche impact velocity of 10 mph (4.5 m/sec) and a snow density of 18.7 lbs/ft^3 (300 kg/m^3), which would result in a uniform horizontal impact pressure of 125 psf (6 kPa).

The wall should be tested to withstand pressures due to snow accumulation behind it during anticipated intervals between snow removals. The depth of the ditch below the roadway surface may be determined depending on the amount of snow expected to accumulate between two successive snow removals.

4.4 WALL AND DITCH SYSTEM UNDER CUT SLOPES INCLUDING JENKIN'S KNOB

The widening of the roadway will require steep cuts into the mountainside with slopes less than one horizontal to two vertical (1H:2V), or approximately 63 degrees. Such cuts could induce both loose-snow and slab avalanches in the maritime climate typical to the project study area.

The stability of the rock and the proposed cuts into the rock are currently under investigation by URS and Wyllie & Norrish. Wall and ditch systems similar to that shown in Figure 4-1 would keep small bank slides that might originate on the steep cut slopes from impacting the roadway.

5.0 REFERENCES

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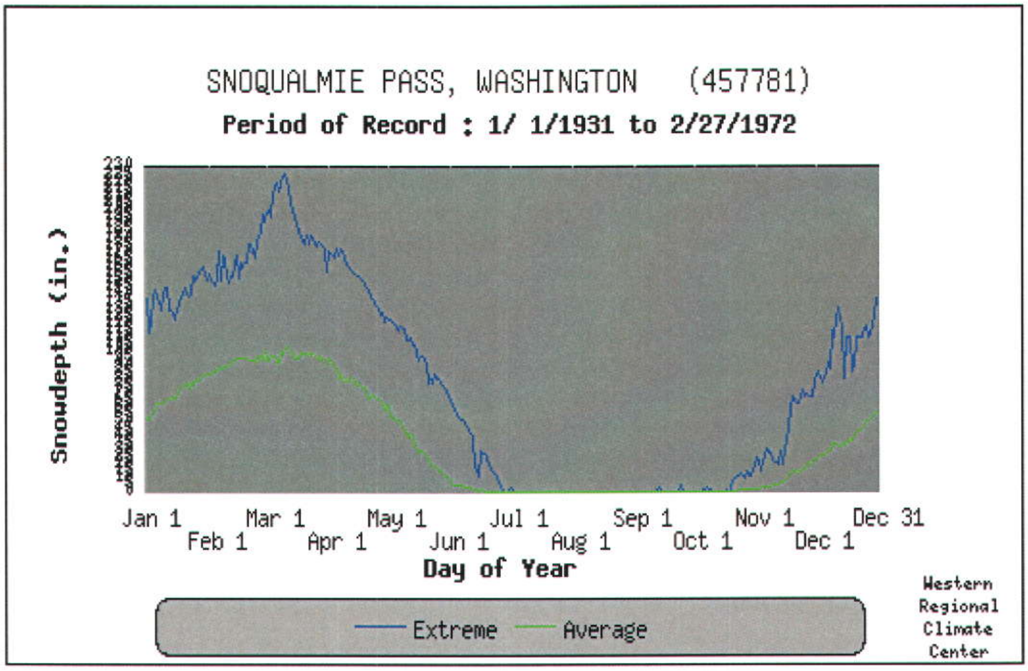
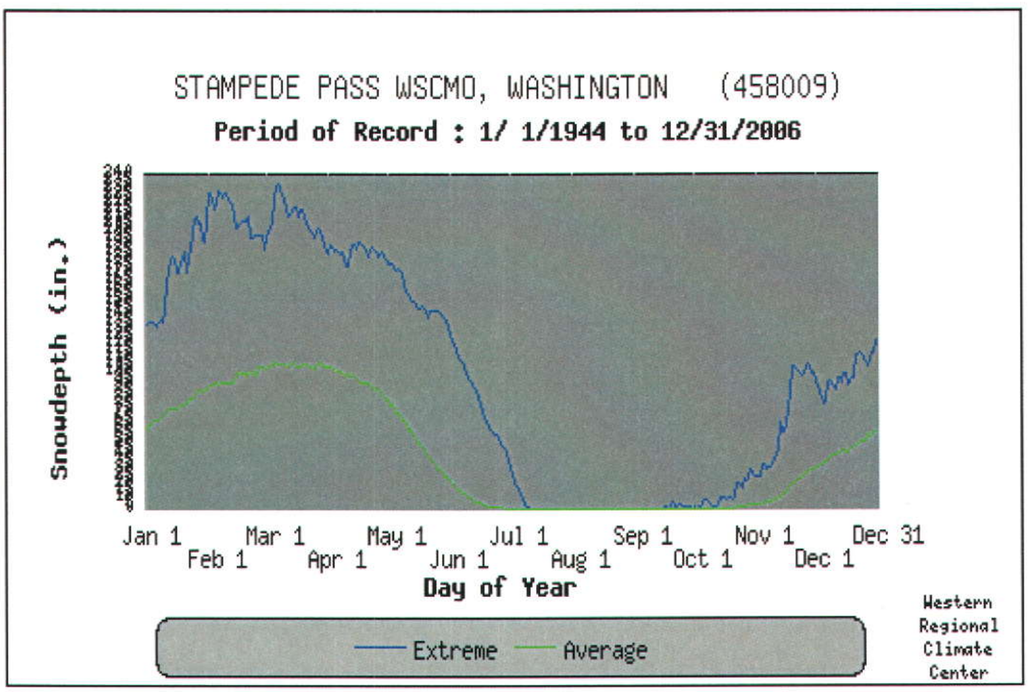
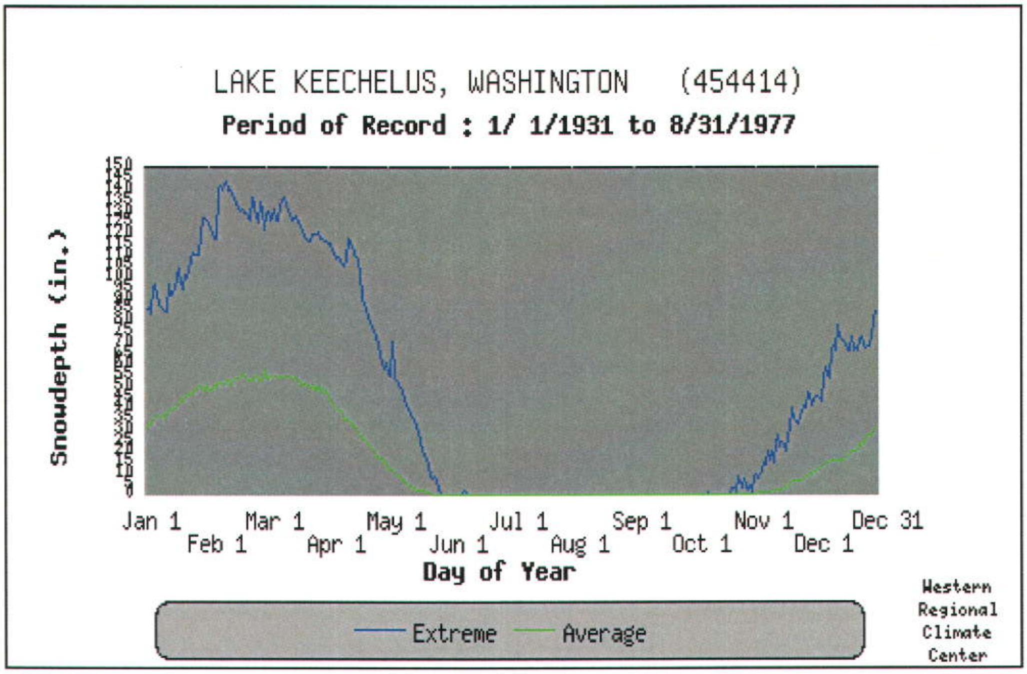
A-1


SNOQUALMIE PASS, WASHINGTON (457781)
Period of Record : 1/ 1/1931 to 2/27/1972
Snowdepth (in.)
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Dec 31
Day of Year
Extreme
Average
Western Regional Climate Center

A-2

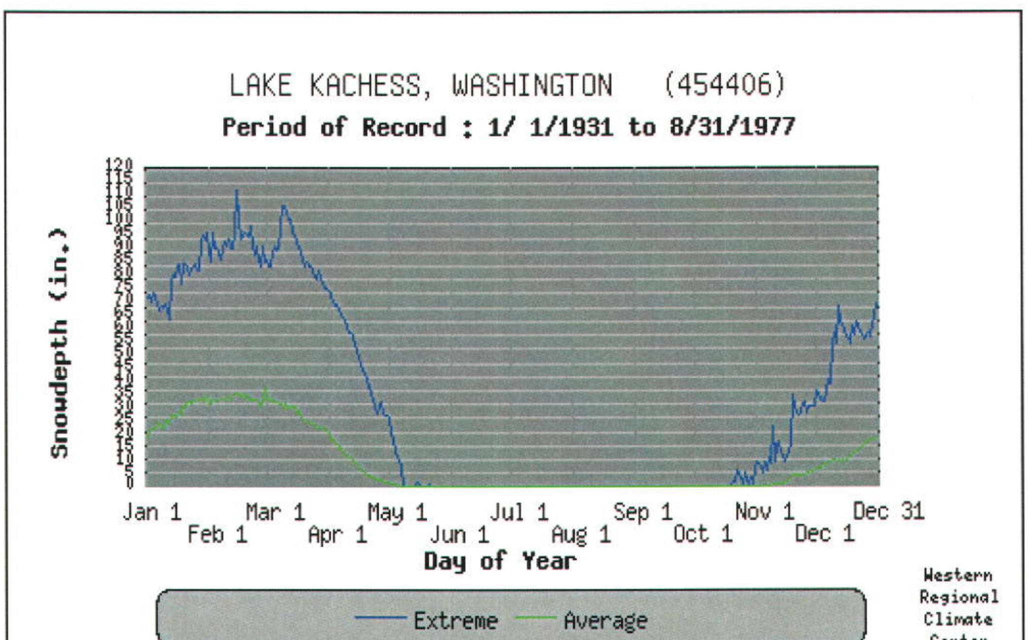

STAMPEDE PASS WSCMO, WASHINGTON (458009)
Period of Record : 1/ 1/1944 to 12/31/2006
Snowdepth (in.)
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Dec 31
Day of Year
Extreme
Average
Western Regional Climate Center

A-3



LAKE KEECHELUS, WASHINGTON (454414)
Period of Record : 1/ 1/1931 to 8/31/1977
Snowdepth (in.)
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Dec 31
Day of Year
Extreme
Average
Western Regional Climate Center

A-4



LAKE KACHESS, WASHINGTON (454406)
Period of Record : 1/ 1/1931 to 8/31/1977
Snowdepth (in.)
Jan 1
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Dec 31
Day of Year
Extreme
Average
Western Regional Climate Center

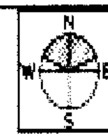
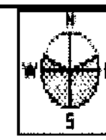
B-1
Preliminary Data for Snow Net Structures at the Slide Curve Avalanche Area

$H_{snow\ net}$ (m)	Line ID	Slope Angle (deg)	Coordinates[a]		Segment Length (m)	Total Line Length (m)	Snow Net Units Required[b]	
			Northing	Easting				
3.5	1		323,999.9	534,923.7				
3.5	1	21	323,990.6	534,941.3	19.9		5.7	
3.5	1		323,958.4	534,969.8	43.0	62.9	12.3	18.0
3.5	2		323,997.5	534,910.3				
3.5	2	34	323,974.0	534,942.4	39.8		11.4	
3.5	2	25	323,954.6	534,949.5	20.7		5.9	
3.5	2		323,933.1	534,947.6	21.6	82.0	6.2	23.4
3.5	3		323,998.6	534,901.1				
3.5	3	-37	323,977.9	534,908.2	21.9		6.3	
3.5	3	61	323,962.2	534,931.5	28.1		8.0	
3.5	3		323,920.9	534,928.0	41.4	91.4	11.8	26.1
3.5	4		324,004.8	534,887.2				
3.5	4	-28	323,971.3	534,894.8	34.4		9.8	
3.5	4	41	323,949.4	534,914.1	29.2		8.3	
3.5	4		323,897.2	534,914.3	52.2	115.7	14.9	33.1
3.5	5		324,004.6	534,863.8				
3.5	5	8	323,940.6	534,883.7	67.0		19.1	
3.5	5		323,863.9	534,895.4	77.6	144.6	22.2	41.3
3.0	6		324,002.0	534,844.0				
3.0	6	6	323,943.0	534,856.7	60.4		15.1	
3.0	6		323,858.6	534,866.0	84.9	145.3	21.2	36.3
3.0	7		323,999.1	534,835.3				
3.0	7		324,029.3	534,831.2	30.5	30.5	7.6	7.6
3.0	8		323,994.5	534,817.7				
3.0	8	5	323,939.2	534,829.8	56.6		14.2	
3.0	8		323,855.3	534,839.7	84.5	141.1	21.1	35.3
3.0	9		323,996.3	534,796.6				
3.0	9	-21	323,843.9	534,811.6	153.1		38.3	
3.0	9		323,831.3	534,818.1	14.2	167.3	3.5	41.8
3.0	10		323,999.5	534,774.1				
3.0	10	-8	323,898.3	534,779.1	101.3		25.3	
3.0	10	-16	323,827.3	534,792.6	72.3		18.1	
3.0	10		323,810.4	534,801.4	19.1	192.6	4.8	48.2
				TOTALS	**1173.5**		**311.1**	

Notes:

1. The Slope Angle is measured from the horizontal, and parallel to the slope. The positive values indicate humps, and the negative values indicate depressions along a given Line ID.
2. [a] Project Coordinate System as per URS Corporation consultant (Julie Drinkwater).
3. [b] Based on snow net structure unit sizes of 3.5 m by 3.5 m and 3.0 m by 4.0 m.

Tab. 5 > Ground classes and glide factors.

Ground classes	Glide factor	
	 Exposure WNW-N-ENE	 Exposure ENE-S-WNW
Class 1		
• Coarse scree (d* ≥ 30 cm) • Terrain heavily populated with smaller and larger boulders	1.2	1.3
Class 2		
• Areas covered with larger alder bushes or dwarf pine at least 1 m in height • Prominent mounds covered with grass and low bushes (height of mounds over 50 cm) • Prominent cow trails • Coarse scree (d* ca. 10–30 cm)	1.6	1.8
Class 3		
• Short grass interspersed with low bushes (heather, rhododendron, bilberry, alder bushes and dwarf pine below approx. 1 m in height) • Fine scree (d* ≤ 10 cm) alternating with grass and low bushes • Smallish mounds of up to 50 cm in height covered with grass and low bushes, and also those alternating with smooth grass and low bushes • Grass with shallow cow trails	2.0	2.4
Class 4		
• Smooth, long-bladed, compact grass cover • Smooth outcropping rock plates with stratification planes parallel to the slope • Smooth scree mixed with earth • Swampy depressions	2.6	3.2

d* is the boulder diameter characteristic of the roughness of the ground surface.

Tab. 2.1 > Distance between structures in the line of slope L [m] according to Fig. 13.

Inclination of slope	Dx [m]	Hx [m]	L [m]					
			N = 1.2			N ≥ 1.3		
			tan φ =			tan φ =		
			0.60	0.55	**0.50**	**0.60**	0.55	**0.50**
60 % (31°)	1.5	1.75		15.3			18.4	
	2.0	2.33		20.3			24.6	
	2.5	2.92		25.4			30.7	
	3.0	3.50		30.5			36.9	
	3.5	4.08		35.6			43.1	
	4.0	4.66		40.7			49.2	
	4.5	5.25		45.8			49.1	
	5.0	5.83		43.3			43.3	
70 % (35°)	1.5	1.83		13.6	**12.8**		16.4	**12.8**
	2.0	2.44		18.1	**17.1**		21.8	**17.1**
	2.5	3.05		22.7	**21.4**		27.3	**21.4**
	3.0	3.66		27.2	**25.6**		32.7	**25.6**
	3.5	4.27		31.8	**29.9**		38.2	**29.9**
	4.0	4.88		36.3	**34.2**		43.6	**34.2**
	4.5	5.49		35.9			35.9	
	5.0	6.10		32.5			32.5	
80 % (38.7°)	1.5	1.92	**13.1**	12.3	**10.2**	**15.4**	12.3	**10.2**
	2.0	2.56	**17.4**	16.4	**13.7**	**20.5**	16.4	**13.7**
	2.5	3.20	**21.8**	20.5	**17.1**	**25.6**	20.5	**17.1**
	3.0	3.84	**26.2**	24.6	**20.5**	**30.7**	24.6	**20.5**
	3.5	4.48	**30.5**	28.7	**23.9**	**35.9**	28.7	**23.9**
	4.0	5.12		32.1	**27.3**		32.1	**27.3**
	4.5	5.76		28.6			28.6	
	5.0	6.40		26.4			26.4	

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Tab. 2.2 > Distance between structures in the line of slope L [m] according to Fig. 13.

Inclination of slope	Dк [m]	Hк [m]	L [m] N ≥ 1.2 tan φ = 0.60	0.55	0.50
90 % (42°)	1.5	2.02	12.1	10.4	9.1
	2.0	2.69	16.1	13.8	12.1
	2.5	3.36	20.2	17.3	15.1
	3.0	4.04	24.2	20.8	18.2
	3.5	4.71	28.2	24.2	21.2
	4.0	5.38		26.5	24.2
	4.5	6.05		24.1	
	5.0	6.73		22.4	
100 % (45°)	1.5	2.12	10.6	9.4	8.5
	2.0	2.83	14.1	12.6	11.3
	2.5	3.54	17.7	15.7	14.1
	3.0	4.24	21.2	18.9	17.0
	3.5	4.95	24.7	22.0	19.8
	4.0	5.66		22.8	22.6
	4.5	6.36		21.0	
	5.0	7.07		19.7	
110 % (47.7°)	1.5	2.23	9.8	8.9	8.2
	2.0	2.97	13.1	11.9	10.9
	2.5	3.72	16.3	14.9	13.6
	3.0	4.46	19.6	17.8	16.3
	3.5	5.20	22.5	20.8	19.1
	4.0	5.95		20.2	
	4.5	6.69		18.8	
	5.0	7.43		17.7	
120 % (50.2°)	1.5	2.34	9.4	8.6	8.0
	2.0	3.12	12.5	11.5	10.7
	2.5	3.91	15.6	14.4	13.4
	3.0	4.69	18.7	17.3	16.1
	3.5	5.47		20.1	18.7
	4.0	6.25		18.3	
	4.5	7.03		17.1	
	5.0	7.81		16.2	
130 % (52.4°)	1.5	2.46	9.1	8.5	8.0
	2.0	3.28	12.2	11.4	10.7
	2.5	4.10	15.2	14.2	13.3
	3.0	4.92	18.3	17.1	16.0
	3.5	5.74		18.3	
	4.0	6.56		16.8	
	4.5	7.38		15.8	
	5.0	8.20		15.1	

Tab. 3.1 > Distance between structures L' [m] in plan view according to Fig. 13.

Inclination of slope	Dκ [m]	Hκ [m]	L' = L · cos ψ [m]					
			N = 1.2			N ≥ 1.3		
			tan φ =			tan φ =		
			0.60	0.55	0.50	0.60	0.55	0.50
60 % (31°)	1.5	1.75		13.1			15.8	
	2.0	2.33		17.4			21.1	
	2.5	2.92		21.8			26.4	
	3.0	3.50		26.2			31.6	
	3.5	4.08		30.5			36.9	
	4.0	4.66		34.9			42.2	
	4.5	5.25		39.3			42.1	
	5.0	5.83		37.1			37.1	
70 % (35°)	1.5	1.83		11.1	10.5		13.4	10.5
	2.0	2.44		14.9	14.0		17.9	14.0
	2.5	3.05		18.6	17.5		22.3	17.5
	3.0	3.66		22.3	21.0		26.8	21.0
	3.5	4.27		26.0	24.5		31.3	24.5
	4.0	4.88		29.7	28.0		35.7	28.0
	4.5	5.49		29.4			29.4	
	5.0	6.10		26.6			26.6	
80 % (38.7°)	1.5	1.92	10.2	9.6	8.0	12.0	9.6	8.0
	2.0	2.56	13.6	12.8	10.7	16.0	12.8	10.7
	2.5	3.20	17.0	16.0	13.3	20.0	16.0	13.3
	3.0	3.84	20.4	19.2	16.0	24.0	19.2	16.0
	3.5	4.48	23.8	22.4	18.7	28.0	22.4	18.7
	4.0	5.12		25.1	21.3		25.1	21.3
	4.5	5.76		22.4			22.4	
	5.0	6.40		20.6			20.6	

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Tab. 3.2 > Distance between structures L' [m] in plan view according to Fig. 13.

Inclination of slope	D_K [m]	H_K [m]	$L' = L \cdot \cos \psi$ [m]		
			$N \geq 1.2$		
			$\tan \varphi =$		
			0.60	0.55	0.50
90 % (42°)	1.5	2.02	9.0	7.7	6.7
	2.0	2.69	12.0	10.3	9.0
	2.5	3.36	15.0	12.9	11.2
	3.0	4.04	18.0	15.4	13.5
	3.5	4.71	21.0	18.0	15.7
	4.0	5.38		19.7	18.0
	4.5	6.05		17.9	
	5.0	6.73		16.7	
100 % (45°)	1.5	2.12	7.5	6.7	6.0
	2.0	2.83	10.0	8.9	8.0
	2.5	3.54	12.5	11.1	10.0
	3.0	4.24	15.0	13.3	12.0
	3.5	4.95	17.5	15.6	14.0
	4.0	5.66		16.1	16.0
	4.5	6.36		14.8	
	5.0	7.07		13.9	
110 % (47.7°)	1.5	2.23	6.6	6.0	5.5
	2.0	2.97	8.8	8.0	7.3
	2.5	3.72	11.0	10.0	9.2
	3.0	4.46	13.2	12.0	11.0
	3.5	5.20	15.1	14.0	12.8
	4.0	5.95		13.6	
	4.5	6.69		12.6	
	5.0	7.43		11.9	
120 % (50.2°)	1.5	2.34	6.0	5.5	5.1
	2.0	3.12	8.0	7.4	6.9
	2.5	3.91	10.0	9.2	8.6
	3.0	4.69	12.0	11.1	10.3
	3.5	5.47		12.8	12.0
	4.0	6.25		11.7	
	4.5	7.03		10.9	
	5.0	7.81		10.4	
130 % (52.4°)	1.5	2.46	5.6	5.2	4.9
	2.0	3.28	7.4	6.9	6.5
	2.5	4.10	9.3	8.7	8.1
	3.0	4.92	11.1	10.4	9.7
	3.5	5.74		11.1	
	4.0	6.56		10.2	
	4.5	7.38		9.6	
	5.0	8.20		9.2	

Table 6 (Reference 2)
Creep factor K as a function of average snow density (ρ) and slope inclination (ψ)

Average Snow Density (ρ)		$K/(\sin 2\psi)$
Ton/m^3	Kg/ m^3	
0.20	200	0.70
0.30	300	0.76
0.40	400	0.83
0.50	500	0.92
0.60	600	1.05