# I-90 Snoqualmie Pass East Project

Snow Net Avalanche Mitigation
Final Design Recommendations

July 2010

Washington State Department of Transportation

U. S. Department of Transportation
Federal Highway Administration

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# I-90 Snoqualmie Pass East

Agreement No. 9764
Task Order DV

## Snow Net Avalanche Mitigation
## Final Design Recommendations

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I-90 Project Office

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## APPENDICES

## ACRONYMS

| | |
|---|---|
| I-90 | Interstate 90 |
| MP | Milepost |
| Sta. | Station |
| URS | URS Corporation |
| WB | Westbound |
| WSDOT | Washington State Department of Transportation |

## UNITS OF MEASURE

| | |
|---|---|
| ft | feet (length) |
| $ft^2$ | square feet (area) |
| $ft^3$ | cubic feet (volume) |
| ft/sec | feet per second (speed) |
| $kg/m^3$ | kilogram per cubic meter (density) |
| Km | kilometer (distance) |
| kJ | kilojoules |
| 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) |

## 1.0 PURPOSE

URS Corporation (URS) and Arthur I. Mears, P.E. Inc. completed an Avalanche Mitigation Report for the Interstate 90 (I-90) Snoqualmie Pass East Project in December 2007 (Ref. 1). Section 3 of the 2007 report described the design parameters and a preliminary layout for snow net starting zone structures at Slide Curve. The design alignment at Slide Curve has been revised since the submittal of this report and Washington State Department of Transportation (WSDOT) has identified additional locations within the project area where starting zone structures could provide an appropriate method of avalanche mitigation. The specific areas are shown in Figure 1.

This report updates the snow net layout at Slide Curve and provides design parameters and layouts for two additional avalanche areas at Bald Knob and East Shed Minus One. The revised Slide Curve layout includes the addition of snow nets to the boulder field adjacent to and north-northwest of Slide Curve. Design parameters and layouts are presented for the Bald Knob and East Shed Minus One paths shown in Figure 1. Small avalanche paths immediately south of Slide Curve, including avalanches with starting zones on the smooth rock slabs, can impact a planned rockfall control fence. Avalanche impact loads and energies are provided for the rockfall control fence.

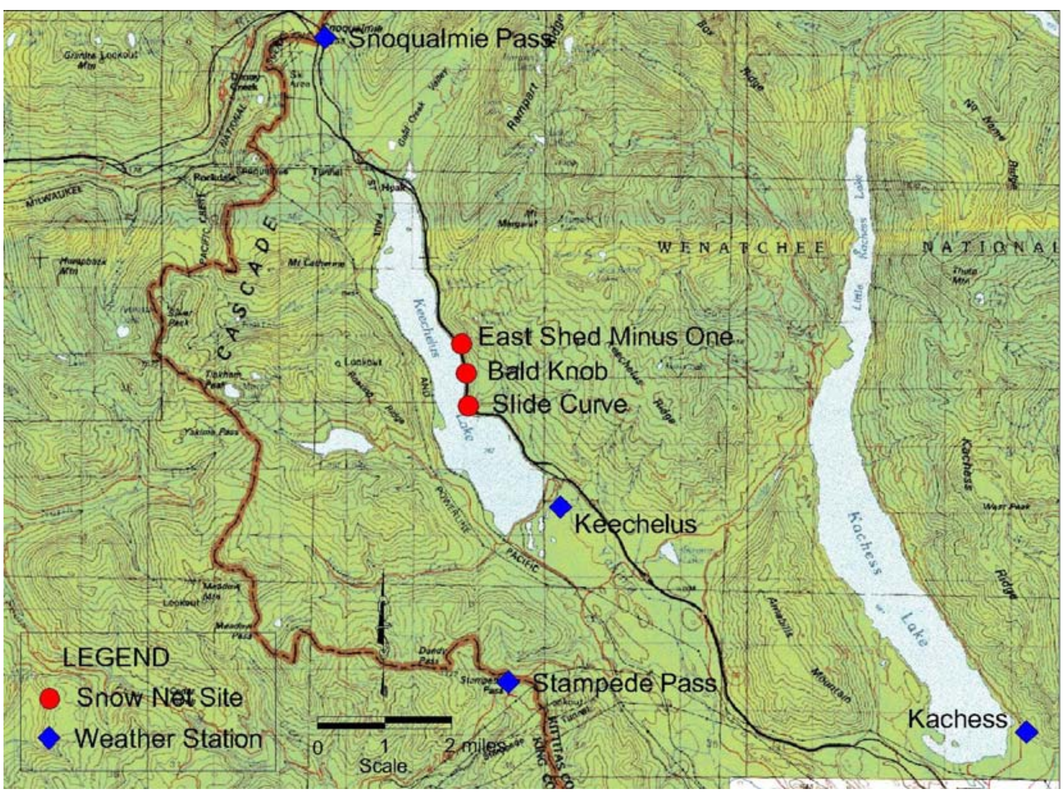


**Figure 1**: Site Location Map for Snow Nets and Nearest Weather Stations

The analysis methodology follows the 2006 Swiss Guidelines (Ref. 2) and is summarized in this report. Additional details and supporting data are provided in the 2007 Avalanche Mitigation Report (Ref. 1) and the Appendixes.

This report also presents an evaluation of an alternative starting zone structure system manufactured by VELA, an Italian company. This modular system requires fewer anchors than the Swiss designs previously recommended and, therefore, might offer cost and constructability advantages. Finally, this report presents information and recommendations related to snow net anchors and foundations.

This report is a supplement to the December 2007 Avalanche Mitigation Report and is intended to address the issues described above. It is based on more current information, additional data, and observations. Consequently, the snow net layouts and design parameters outlined in this report supersede those in the 2007 report (Ref. 1).

## 2.0 SLIDE CURVE SNOW NET OPTIMIZATION

### 2.1 BACKGROUND

The Slide Curve area consists of rocky, sparsely vegetated slopes between westbound (WB) Station Sta. 1396+00 and 1403+50. The Slide Curve Boulder Field is a separate avalanche path adjacent to the main Slide Curve path between WB Sta. 1394+70 and 1396+00. Both avalanche areas have been actively controlled with large elevated charges since about 1980.

Snow nets were recommended as a practical avalanche mitigation method at Slide Curve by Peter Shaerer and Chris Stethem in 2000 (Ref. 4). Section 3.0 in the 2007 Avalanche Mitigation Report by URS and Arthur I. Mears, P.E., Inc. (Ref. 1) presented a preliminary layout and design loads for the main avalanche path at Slide Curve, as shown in Figure 2. This layout was based on the 2006 “Swiss Guidelines” for structures in avalanche starting zones (Ref. 2).

The roadway design alignment (horizontal and vertical) has been revised at Slide Curve. The WB lanes will be raised approximately 50 vertical feet and placed on fill material, as shown in Figure 3. This revised alignment will eliminate the need for the lowest row of structures (Row No. 13), as shown in Figure 2.

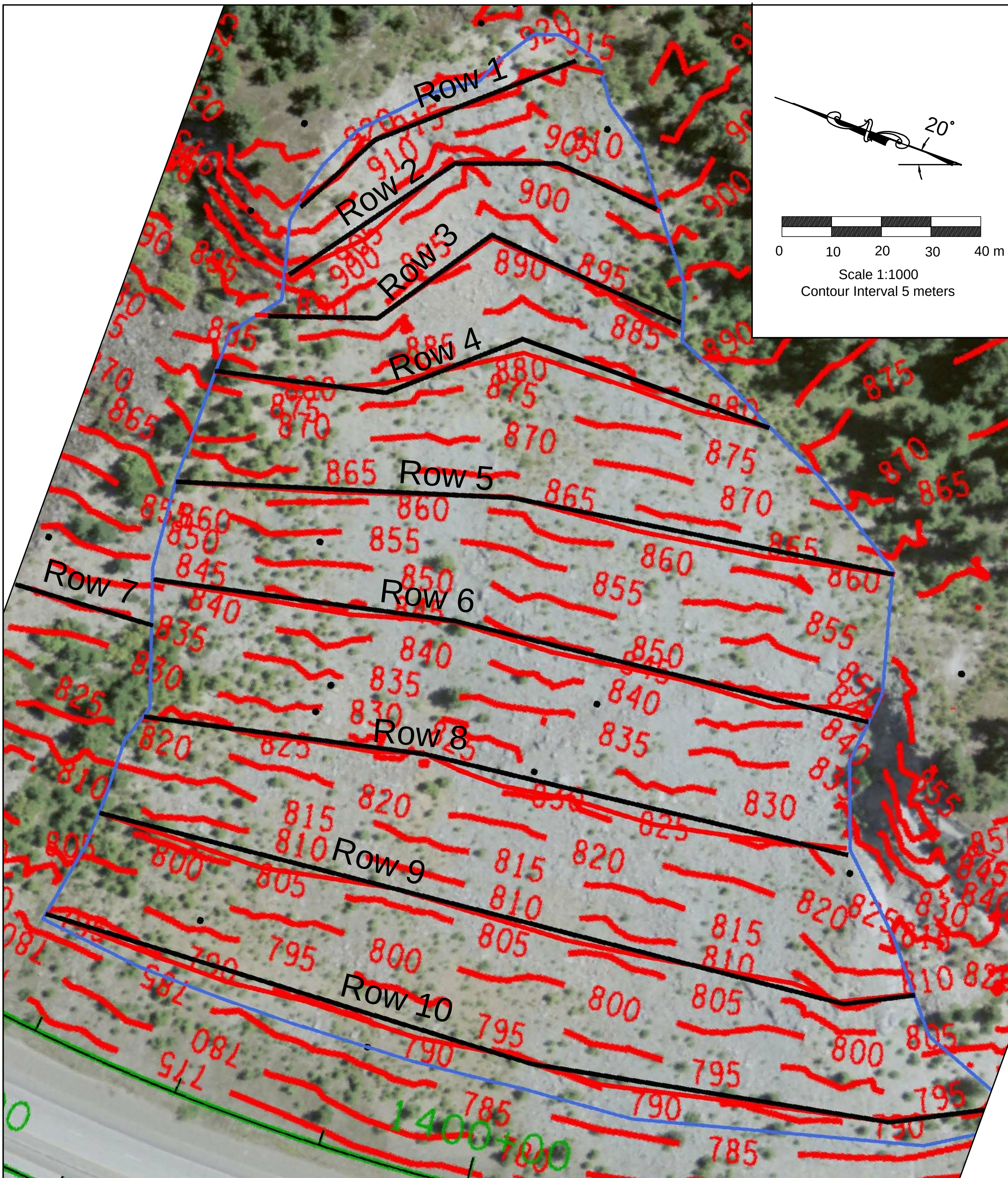


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Figure 2 - Preliminary (2007) Slide Curve Snow Net Layout

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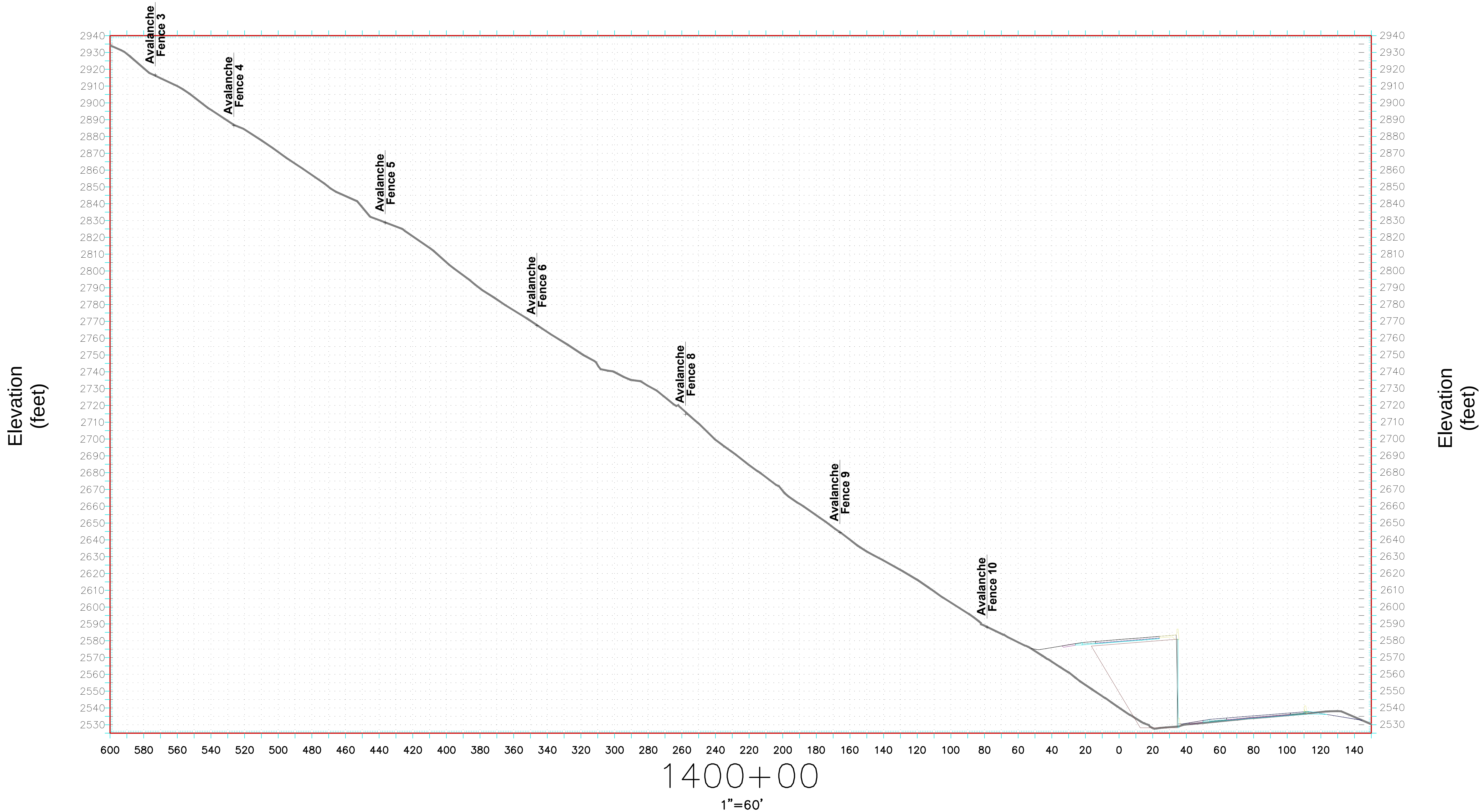


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Arthur I. Mears, P.E., Inc.

*Wilbur Engineering, Inc.*

Figure 3 - Slide Profile at Sta. 1400+00

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Site visits were conducted during winter conditions by Art Mears, Chris Wilbur, and avalanche specialists, Craig Wilbour and John Stimberis, both with WSDOT, on March 17, 2010. Figure 4 shows relatively little snow during the field visits due to a below average precipitation winter. A second site visit was conducted by Art Mears on April 28, 2010 and included an on-site meeting with Norm Norrish of Wyllie and Norrish Rock Engineers, Inc. to discuss ground conditions and anchoring. Based on observations and information obtained during the March and April 2010 site visits, and additional terrain analysis with LiDAR mapping, the following minor adjustments to the snow net layout at Slide Curve were made.

1. The snow net endpoints of rows 1, 2 and 3 were adjusted based on field observations and input from WSDOT avalanche control specialists.
2. The elevations of rows 1, 2 and 3 were adjusted. Row 1 was lowered based on slope angles and the spacing between rows 2 and 3 was reduced. The purpose of this adjustment was to account for the smooth rock and high glide potential in this area.
3. Two-meter wide breaks were added to rows which were longer than 50 m and where the bend angle exceeded 15 degrees.
4. Two additional lines were added in the Boulder Field. These lines are shown in Figure 5 and are described in more detail in Section 3.0 of this report.

Figure 5 shows the revised layout for Slide Curve starting zone structures. The row locations on Figure 5 represent the "root" line of the nets, which corresponds to the base of the net swivel posts. Minor adjustments will be required during construction to accommodate manufactured dimensions and field conditions. Tables 1 and 2 present a summary of the layout. The coordinates for the structures, including end points, angle points and row breaks, are presented in Appendix A.

**Figure 4**: Slide Curve on March 17, 2010

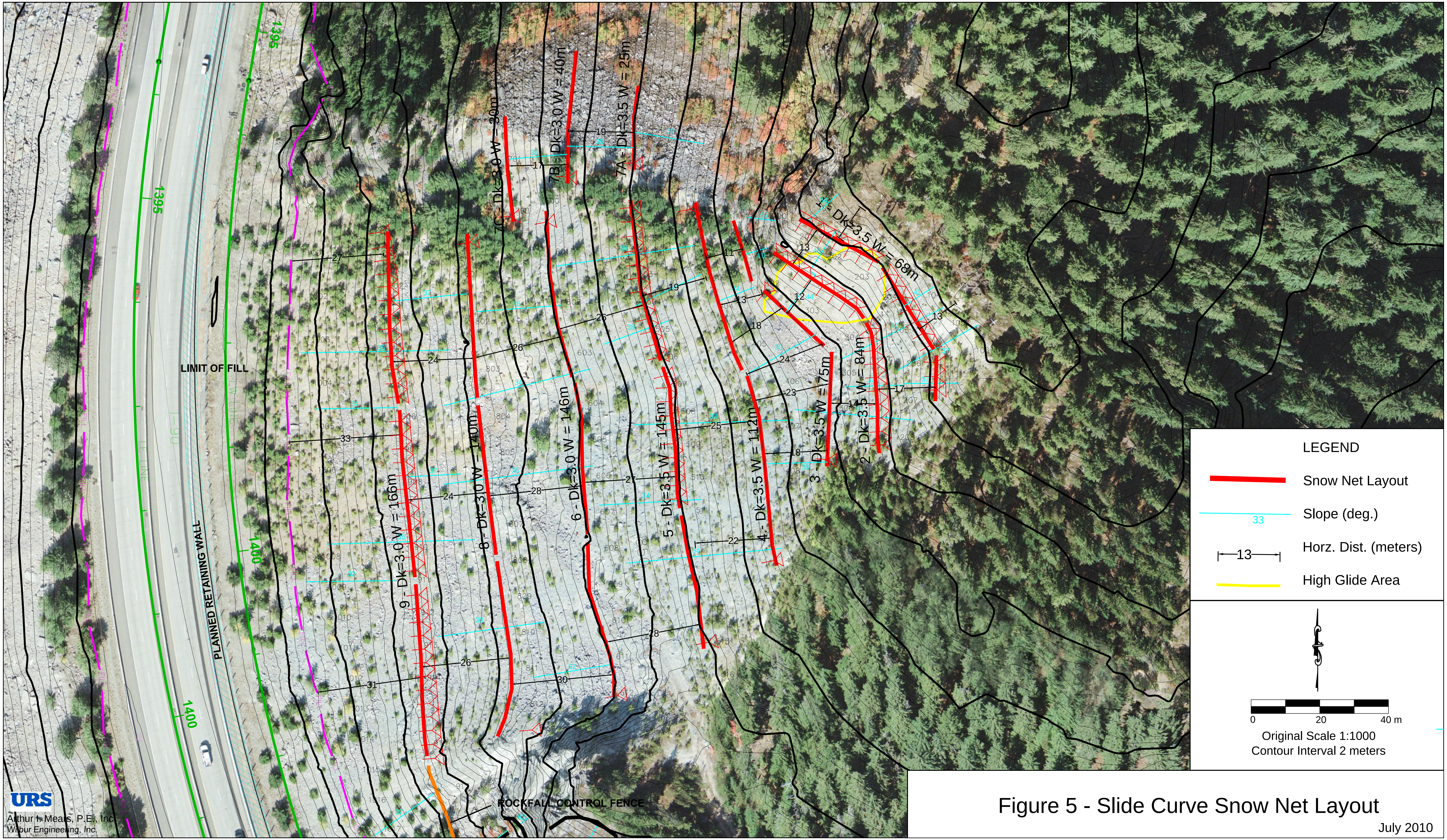


Figure 5 - Slide Curve Snow Net Layout

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**Table 1 [Metric]: Summary of Slide Curve Snow Net Layout**

| Line ID | $D_K$[1] (m) | Elevation (m) | No. of Breaks | Line Length (m) |
|---|---|---|---|---|
| 1 | 3.5 | 910 | 2 | 67 |
| 2 | 3.5 | 898 | 1 | 84 |
| 3 | 3.5 | 888 | 2 | 75 |
| 4 | 3.5 | 876 | 1 | 112 |
| 5 | 3.5 | 860 | 2 | 145 |
| 6 | 3.0 | 842 | 2 | 146 |
| 7A | 3.5 | 860 | 0 | 31 |
| 7B | 3.0 | 846 | 0 | 40 |
| 7C | 3.0 | 832 | 0 | 25 |
| 8 | 3.0 | 824 | 2 | 140 |
| 9 | 3.0 | 805 | 2 | 166 |
| | | **Totals** | **13** | **1,032** |

**Table 2 [English]: Summary of Slide Curve Snow Net Layout**

| Line ID | $D_K$[1] (ft) | Elevation (ft) | No. of Breaks | Line Length (ft) |
|---|---|---|---|---|
| 1 | 11.5 | 2,986 | 2 | 220 |
| 2 | 11.5 | 2,946 | 1 | 276 |
| 3 | 11.5 | 2,913 | 2 | 246 |
| 4 | 11.5 | 2,874 | 1 | 367 |
| 5 | 11.5 | 2,822 | 2 | 476 |
| 6 | 9.8 | 2,762 | 2 | 479 |
| 7A | 11.5 | 2,822 | 0 | 102 |
| 7B | 9.8 | 2,776 | 0 | 131 |
| 7C | 9.8 | 2,730 | 0 | 82 |
| 8 | 9.8 | 2,703 | 2 | 459 |
| 9 | 9.8 | 2,641 | 2 | 545 |
| | | **Totals** | **13** | **3,386** |

[1]Height of snow nets normal to slope.

## 3.0 SLIDE CURVE BOULDER FIELD

Figure 6 shows a photograph of the Slide Curve Boulder Field located between Sta. 1394+00 and 1396+00 taken during the March 17, 2010 site visit. According to WSDOT personnel, this area has produced avalanches that can reach the proposed WB lanes. The current method of road closures and artificial triggering with explosives is not compatible with the proposed snow nets for the main avalanche path at Slide Curve. It was previously thought that the large boulders would make installation of starting zone snow net structures impractical; however, discussions with rock engineering specialist, Norm Norrish, indicate that rockfall control fences will be installed in similar terrain and it should be feasible to install snow nets at this location. Given the potential avalanche hazard in this area, avalanche protection is recommended. Some extra expenses should be expected to create access and suitable surface conditions for the snow nets.

## 3.1 SNOW HEIGHT

Snowfall data, including extreme snowfall and snow depths, are available from the sites listed in Figure 1. The aspect and location of these sites are similar; therefore, the values of maximum vertical snow depth, $H_K$, from the previous report (Ref. 1) remain valid. These values represent the maximum snow depth for the design magnitude (100-year return period) snow conditions. Net heights normal to the slope, $D_K$, were calculated based on design vertical snow depth, $H_K$ and slope angle, $\Psi$, where

$$D_K = H_K \cos \Psi$$

**Figure 6**: Slide Curve Boulder Field

## 3.2 GLIDE FACTORS AND ROW SPACING

The Glide Factor and ground friction were determined based on field observations of vegetation, ground roughness and solar aspect in conjunction with Table 5 in Reference 2 (included in Appendix B). Glide Factor for most of the Slide Curve Boulder Field can be described as Class 1 for a west facing exposure. The ground friction (tan $\Phi$) was determined based on field observations.

**Table 3 [Metric]: Design Parameters for Slide Curve Boulder Field**

| Line | Elevation (m) | $H_K$ (m) | $D_K$ (m) | Ψ (deg.) | tan Φ (deg.) | Glide Factor, N | L' (m) | L (m) |
|---|---|---|---|---|---|---|---|---|
| 7A | 860 | 4.5 | 3.5 | 39 | 0.55 | 1.3 | 22.4 | 28.7 |
| 7B | 846 | 3.5 | 3.0 | 35 | 0.55 | 1.3 | 26.8 | 32.7 |
| 7C | 832 | 3.5 | 3.0 | 38 | 0.55 | 1.3 | 19.2 | 24.6 |

**Table 4 [English]: Design Parameters for Slide Curve Boulder Field**

| Line | Elevation (ft) | $H_K$ (ft) | $D_K$ (ft) | Ψ (deg.) | tan Φ (deg.) | Glide Factor, N | L' (ft) | L (ft) |
|---|---|---|---|---|---|---|---|---|
| 7A | 2,822 | 14.8 | 11.5 | 39 | 0.55 | 1.3 | 73.5 | 94.2 |
| 7B | 2,776 | 11.5 | 9.8 | 35 | 0.55 | 1.3 | 87.9 | 107.3 |
| 7C | 2,730 | 11.5 | 9.8 | 38 | 0.55 | 1.3 | 63.0 | 80.7 |

where: $H_K$ = Maximum vertical snow height
$D_K$ = Maximum snow height normal to the slope
Ψ = Slope angle
N = Glide Factor
tan Φ = Snow Creep Factor
L' = Horizontal distance between rows
L = Slope distance between rows

## 3.3 LAYOUT

The maximum horizontal distance between structures, L' and slope distance between structures, L, were determined based on net height ($D_K$), slope angle (ψ), glide factor (N), and ground friction (tan Φ). Tables 3.1 and 3.2 of the Swiss Guidelines (included in Appendix B) were used to determine spacing distance between rows of structures, with recommended distances presented in Table 3 and 4. Figure 5 shows the design layout for snow nets in the Slide Curve Boulder Field. The preliminary coordinates for the structures, including end points, angles and breaks are presented in Appendix A.

## 3.4 SNOW PRESSURES

Snow pressures parallel to the slope ($S'_N$) and perpendicular to the slope ($S'_Q$) are presented in Tables 6 and 6. A glide factor, N = 1.3 was assigned to all areas of the Boulder Field. An average snow density, ρ, of 0.5 metric tons per cubic meter was assumed based on the relatively dense snow conditions for this climate. The snow type coefficient, a, was assumed to be 0.6 based on the maximum value for Swiss Guidelines. Snow creep factor, K, was assumed to be 1.05, or approximately 20 percent higher than would be calculated with the Swiss Guidelines. This assumption is based on the potential for a high degree of snowpack saturation that could result from an extended rain-on-snow event. Snow pressure parallel to the slope, $S'_N$, and normal to the slope, $S'_Q$, are calculated according to the Swiss Guidelines:

$$S'_N = \rho g H^2 KN/2$$

$$S'_Q = S'_N\, a/(N \tan \Psi)$$

**Table 5 [Metric]: Snow Pressures for Slide Curve Boulder Field**

| Line No. | Glide Factor, N | Creep Factor, K | Slope Ψ (deg) | Snow Depth, H (m) | Design forces | |
|---|---|---|---|---|---|---|
| | | | | | $S'_N$ (kN/m) | $S'_Q$ (kN/m) |
| 7A | 1.3 | 1.05 | 39 | 3.5 | 42 | 20 |
| 7B | 1.3 | 1.05 | 35 | 3.5 | 42 | 23 |
| 7C | 1.3 | 1.05 | 38 | 3.5 | 42 | 20 |

**Table 6 [English]: Snow Pressures for Slide Curve Boulder Field**

| Line No. | Glide Factor, N | Creep Factor, K | Slope Ψ (deg) | Snow Depth, H (ft) | Design forces | |
|---|---|---|---|---|---|---|
| | | | | | $S'_N$ (ton/ft) | $S'_Q$ (ton/ft) |
| 7A | 1.3 | 1.05 | 39 | 11.5 | 1.4 | 0.69 |
| 7B | 1.3 | 1.05 | 35 | 11.5 | 1.4 | 0.79 |
| 7C | 1.3 | 1.05 | 38 | 11.5 | 1.4 | 0.69 |

## 4.0 BALD KNOB

Bald Knob is an area of smooth moss-covered rock approximately 30 to 70 m (100 to 230 ft) above the existing road surface between WB Sta. 1371+50 and Sta. 1373+00. Figure 7 shows ground and vegetation conditions at Bald Knob during the March 17, 2010 site visit. The steep smooth slopes and lack of vegetation combine to make favorable conditions for relatively frequent small avalanches that can reach the proposed WB lanes. As shown in Figure 7, a steep cut slope is planned immediately below this area.

**Figure 7**: Bald Knob Photo March 17, 2010

### 4.1 EXTREME SNOW HEIGHT

The maximum vertical snow depths at Bald Knob are the same as those at Slide Curve because of proximity and aspect. The proposed locations for snow nets at Bald Knob lie below elevation 850 m, so an extreme vertical snow depth of 3.5 m was used.

### 4.2 GLIDE FACTORS AND ROW SPACING

The Glide Factor was determined based on field observations of vegetation, ground roughness, and solar aspect in conjunction with Table 5, Reference 2. A Glide Factor, N=3.2 was assigned to the moss-covered bedrock slope devoid of vegetation at Bald Knob. This corresponds to Class 4 for a west facing exposure in Table 5 of the Swiss Guidelines. The ground friction (tan Φ) was determined based on field observations with consideration given to the maritime snow climate and glide measurements made on smooth rock face at Alpental (Ref. 5). Selected design parameters for snow nets at Bald Knob are shown in Tables 7 and 8.

**Table 7 [Metric]: Design Parameters for Bald Knob**

| Line No. | Elevation (m) | $D_K$ (m) | ψ (deg.) | Tan Φ (deg.) | Glide Factor, N | L' (m) | L (m) |
|---|---|---|---|---|---|---|---|
| 11 | 841 | 3.0 | 39 | 0.50 | 3.2 | 16.0 | 20.5 |
| 12 | 830 | 3.0 | 35 | 0.50 | 3.2 | 21.0 | 25.6 |
| 13 | 818 | 3.0 | 51 | 0.50 | 3.2 | 10.0 | 16.0 |

**Table 8 [English]: Design Parameters for Bald Knob**

| Line No. | Elevation (ft) | $D_K$ (ft) | ψ (deg.) | Tan Φ (deg.) | Glide Factor, N | L' (ft) | L (ft) |
|---|---|---|---|---|---|---|---|
| 11 | 2,759 | 9.8 | 39 | 0.50 | 3.2 | 52.5 | 67.3 |
| 12 | 2,723 | 9.8 | 35 | 0.50 | 3.2 | 68.9 | 84.0 |
| 13 | 2,684 | 9.8 | 51 | 0.50 | 3.2 | 32.8 | 52.5 |

## 4.3 LAYOUT

The horizontal distance between structures, L' and slope distance between structures, L, were determined based on net height ($D_K$), slope angle (ψ), Glide Factor (N), and ground friction (tan Φ). Tables 3.1 and 3.2 of the Swiss Guidelines (Appendix B) were used to determine a spacing distance between rows of structures. Distances between structures are presented in Tables 7 and 8.

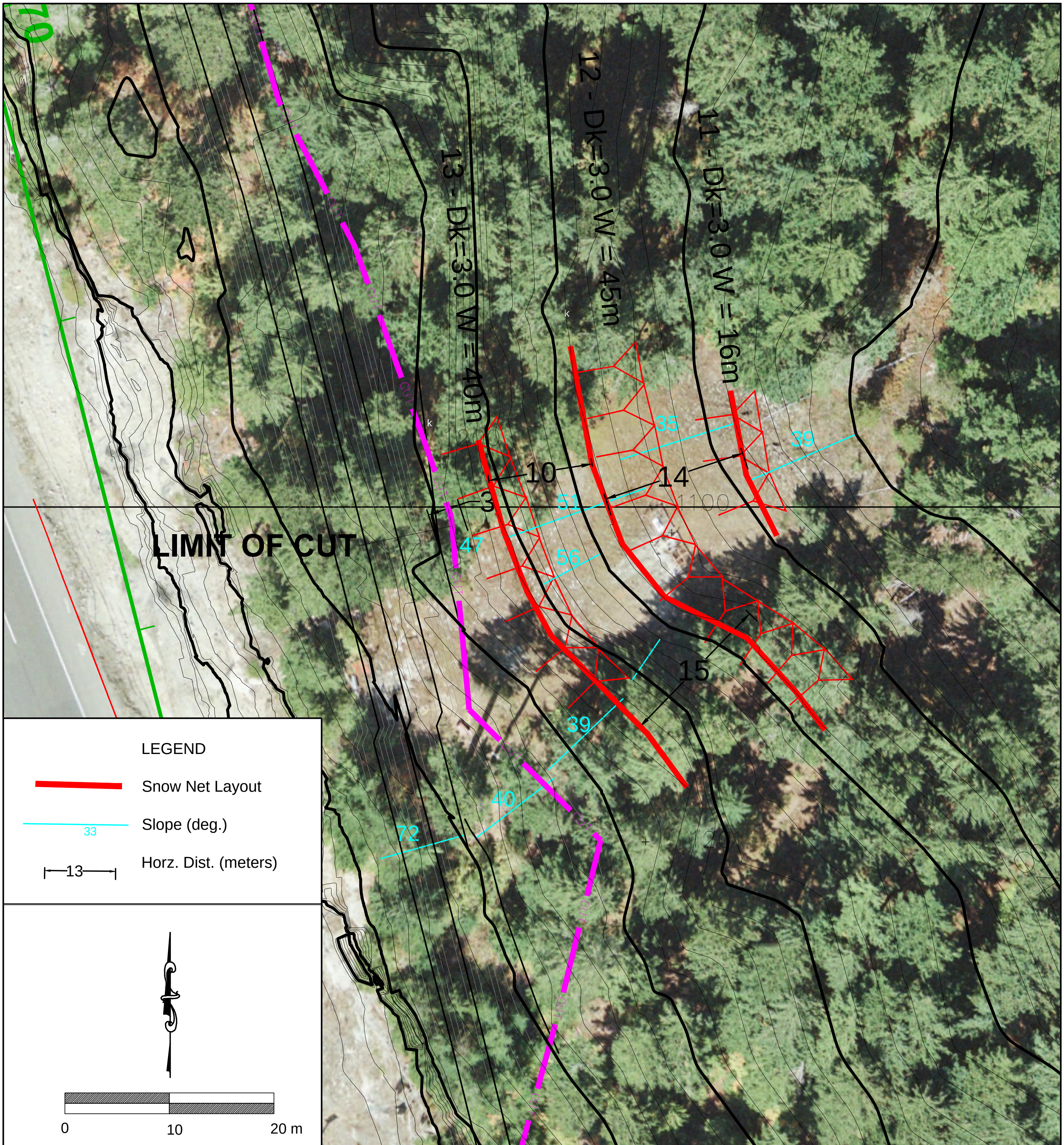
Figure 8 shows the Preliminary Layout for Structures in the starting zone of Bald Knob. Tables 9 and 10 present a summary of the Bald Knob layout. The preliminary coordinates for the structures, including end points, are presented in Appendix A.

**Table 9 [Metric]: Summary of Bald Knob Snow Net Layout**

| Line No. | $D_K$ (m) | Elevation (m) | Line Length (m) |
|---|---|---|---|
| 11 | 3.5 | 841 | 16 |
| 12 | 3.5 | 830 | 45 |
| 13 | 3.5 | 818 | 40 |
| | | **Total** | **101** |

**Table 10 [English]: Summary of Bald Knob Snow Net Layout**

| Line No. | $D_K$ (ft) | Elevation (ft) | Line Length (ft) |
|---|---|---|---|
| 11 | 11.5 | 2,759 | 53 |
| 12 | 11.5 | 2,723 | 148 |
| 13 | 11.5 | 2,684 | 131 |
| | | **Total** | **331** |




LEGEND

Snow Net Layout

33 Slope (deg.)

13 Horz. Dist. (meters)

0 10 20 m

Scale 1:500

Contour Interval 2 meters

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# Figure 8 - Bald Knob Snow Net Layout

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## 4.4 SNOW PRESSURES

Snow pressures parallel to the slope ($S'_N$) and perpendicular to the slope ($S'_Q$) are presented in Tables 11 and 12. A Glide Factor, N = 3.2 was assigned to areas of smooth steep bedrock. As explained in Subsection 3.4, snow creep factor, K, was assumed to be 1.05.

**Table 11 [Metric]: Snow Pressures at Bald Knob**

| Line No. | Glide Factor, N | Creep Factor, K | Slope (deg.) | Snow Depth (m) | Design Forces $S'_N$ (kN/m) | Design Forces $S'_Q$ (kN/m) |
|---|---|---|---|---|---|---|
| 11 | 3.2 | 1.05 | 39 | 3.5 | 103 | 19 |
| 12 | 3.2 | 1.05 | 35 | 3.5 | 103 | 23 |
| 13 | 3.2 | 1.05 | 51 | 3.5 | 103 | 13 |

**Table 12 [English]: Snow Pressures at Bald Knob**

| Line No. | Glide Factor, N | Creep Factor, K | Slope (deg.) | Snow Depth (ft) | Design Forces $S'_N$ (ton/ft) | Design Forces $S'_Q$ (ton/ft) |
|---|---|---|---|---|---|---|
| 11 | 3.2 | 1.05 | 39 | 11.5 | 3.5 | 0.65 |
| 12 | 3.2 | 1.05 | 35 | 11.5 | 3.5 | 0.79 |
| 13 | 3.2 | 1.05 | 51 | 11.5 | 3.5 | 0.45 |

# 5.0 EAST SHED MINUS ONE

Figure 9 shows the rock slopes that form the East Shed Minus One avalanche path between WB Sta. 1341+00 and 1344+00. The south portion (right portion of photo) of this path can reach the proposed WB lanes and requires mitigation. Topography and vegetation will prevent the north portion of this avalanche path from reaching the travel lanes, except in very rare circumstances. Based on field observations and input from WSDOT avalanche specialists, only the south portion of this avalanche path requires mitigation with snow nets.

## 5.1 EXTREME SNOW HEIGHT

The maximum vertical snow depths at East Shed Minus One are very similar to Slide Curve because of proximity, elevation and aspect. The proposed locations of the snow nets at East Shed Minus One lie at or below elevation 850 m (2790 ft), so an extreme vertical snow height of 3.5 m (11.5 ft) was used.

**Figure 9**: East Shed Minus One (Craig Wilbour, WSDOT photo)

## 5.2 GLIDE FACTORS AND ROW SPACING

The Glide Factor and ground friction were determined based on field observations of vegetation, ground roughness, and solar aspect in conjunction with Table 5, Reference 2 (included in Appendix B). Glide Factor for East Shed Minus One can be described as Class 4 for a west facing exposure. The ground friction (tan Φ) was determined based on the same observations, with consideration given to the maritime snow climate and glide measurements made on smooth rock face at Alpental (Ref. 5). Selected design parameters for snow nets at East Shed Minus One are shown in Tables 13 and 14.

**Table 13 [Metric]: Design Parameters for East Shed Minus One**

| Line No. | Elevation (m) | $D_K$ (m) | ψ (deg.) | Tan Φ (deg.) | Glide Factor, N | L' (m) | L (m) |
|---|---|---|---|---|---|---|---|
| 14 | 850 | 3.0 | 38 | 0.50 | 3.2 | 16.0 | 20.5 |
| 15 | 838 | 3.0 | 36 | 0.50 | 3.2 | 18.3 | 22.6 |

**Table 14 [English]: Design Parameters for East Shed Minus One**

| Line No. | Elevation (m) | $D_K$ (m) | ψ (deg.) | Tan Φ (deg.) | Glide Factor, N | L' (m) | L (m) |
|---|---|---|---|---|---|---|---|
| 14 | 2,789 | 9.8 | 38 | 0.50 | 3.2 | 52.5 | 67.3 |
| 15 | 2,749 | 9.8 | 36 | 0.50 | 3.2 | 60.0 | 74.2 |

## 5.3 LAYOUT

The horizontal distance between structures, L' and slope distance between structures, L were determined based on net height ($D_K$), slope angle ($\psi$), glide factor (N), and ground friction (tan $\Phi$). Tables 3.1 and 3.2 of the Swiss Guidelines (in Appendix B) were used to determine a spacing distance between rows of structures. Distances between structures are presented in Tables 13 and 14.

Figure 10 shows the Preliminary Layout for Structures in the starting zone of Slide Curve. Tables 15 and 16 present a summary of the layout. The preliminary coordinates for the structures, including end points, are presented in Appendix A.

**Table 15 [Metric]: East Shed Minus One Snow Net Layout Summary**

| Line No. | $D_K$ (m) | Elevation (m) | Line Length (m) |
|---|---|---|---|
| 14 | 3.5 | 850 | 27 |
| 15 | 3.5 | 830 | 30 |
| | | **Totals** | **57** |

**Table 16 [English]: East Shed Minus One Snow Net Layout Summary**

| Line No. | $D_K$ (ft) | Elevation (ft) | Line Length (ft) |
|---|---|---|---|
| 14 | 11.5 | 2,789 | 89 |
| 15 | 11.5 | 2,723 | 98 |
| | | **Totals** | 187 |

## 5.4 SNOW PRESSURES

Snow pressures parallel to the slope ($S'_N$) and perpendicular to the slope ($S'_Q$) are presented in Tables 17 and 18. A Glide Factor, N = 3.2 was assigned to areas of smooth steep bedrock. As explained in Subsection 3.4, snow creep factor, K, was assumed to be 1.05.

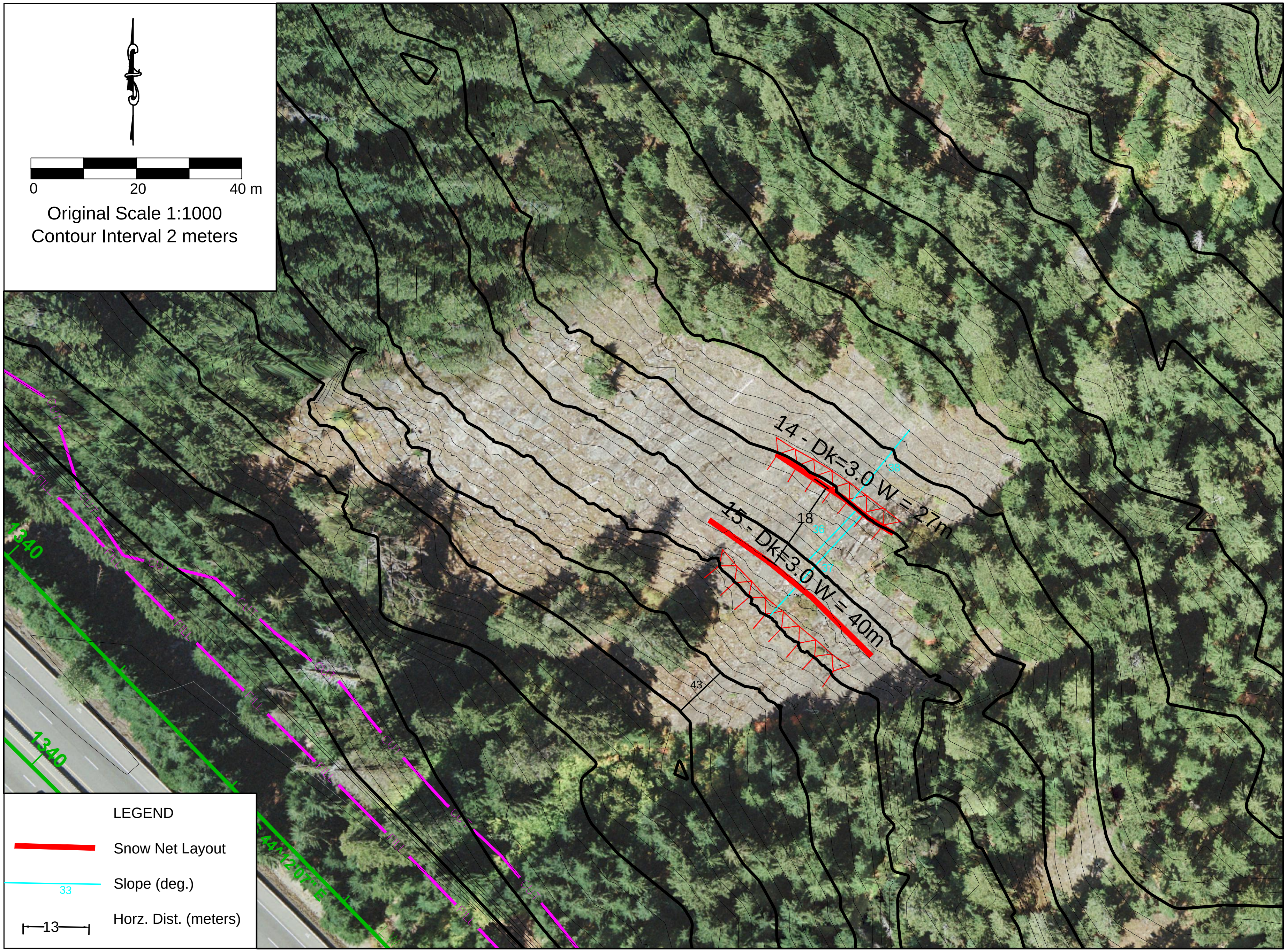


Figure 10 - East Shed Minus One Layout

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**Table 17 [Metric]: East Shed Minus One Snow Pressures**

| Line No. | Glide Factor, N | Creep Factor, K | Slope (deg.) | Snow Depth (m) | Design Forces $S'_N$ (kN/m) | Design Forces $S'_Q$ (kN/m) |
|---|---|---|---|---|---|---|
| 14 | 3.2 | 1.05 | 38 | 3.5 | 103 | 25 |
| 15 | 3.2 | 1.05 | 37 | 3.5 | 103 | 25 |

**Table 18 [English]: East Shed Minus One Snow Pressures**

| Line No. | Glide Factor, N | Creep Factor, K | Slope (deg.) | Snow Depth (ft) | Design Forces $S'_N$ (Tons/ft) | Design Forces $S'_Q$ (Tons/ft) |
|---|---|---|---|---|---|---|
| 14 | 3.2 | 1.05 | 38 | 11.5 | 3.53 | 0.86 |
| 15 | 3.2 | 1.05 | 37 | 11.5 | 3.53 | 0.86 |

# 6.0 AVALANCHE LOADING ANALYSIS – ROCKFALL CONTROL FENCE

## 6.1 EXPOSURE OF ROCKFALL FENCE TO AVALANCHES

A rockfall control fence was considered at the south side of the Slide Curve avalanche area at approximately 800 m (2630 ft) elevation (Figure 11; between approximately WB Sta. 1402 to 1411). A standard rockfall fence, such as the one originally proposed, would be used to attenuate rockfall point loads and protect the highway. However, it would also be subject to snowpack creep and glide loads and impact loads from small avalanches. The impact loads from avalanches may be larger than snowpack loads or rockfall point loads. As stated in Margreth and Roth (2006): "A rockfall event produces a large dynamic load on a relatively small barrier area. The interaction of the snowpack and avalanches with barriers is very different. Snowpack forces and dynamic avalanche pressures act over a larger area and over longer time periods. Thus, if not properly designed, rockfall barriers can be damaged." Therefore the fence would need to be specially designed if it is to remain functional as a rockfall control fence.

The proposed I-90 alignment will be supported on fill, located below the rockfall fence, and will also include a wide shoulder and drainage ditch. Based on this configuration, the travel lanes will not be impacted by the small avalanches beginning on rock slabs between 820 m (2690 ft) and 840 m (2760 ft) elevation, or by smaller avalanches beginning in other locations in the southern area of Slide Curve. Therefore, nets are not required to protect the highway from avalanches. The analysis presented in Sections 6.2 and 6.3 describes assumptions and methods used to evaluate the design loads on the proposed rockfall fence. This fence, however, would not be required to protect the highway from snow avalanches.

### 6.2 DETERMINATION OF THE DESIGN SNOW AVALANCHE

Avalanches beginning on the rock slabs 20 m (66 ft) to 40 m (130 ft) above the rockfall fence will constitute the design-loading case. Figure 11 shows the terrain subject to avalanches and rockfall above this fence. Based on the avalanche-dynamics analysis in the 2007 report, our knowledge of the snowpack depth distribution and study of avalanche photographs in the Slide Curve area, we assume the following slab release conditions for the design 30-100 year avalanche. We also assumed the design avalanche case at this location would consist of a water-saturated slab of high density.

Slab thickness: 1.2 m (3.9 ft.);
Slab density: 450 kg/m.$^3$ (28 lb/ft$^3$)

Design parameters at the proposed rockfall fence were first computed through AVAL-1D analysis to determine approximations of impact velocity at the rockfall fence and the time interval over which the maximum velocity at the fence occurs. From this analysis we determined an impact velocity of 9 m/s (30 ft/s) and a maximum-velocity time interval of approximately 1.0 seconds. The results of these design parameters are summarized below.

Impact velocity: 9.0 m/s (30 ft/s);
Flow thickness: 0.4 m (1.3 ft);
Maximum velocity interval at fence: 1.0 seconds.

AVAL-1D was developed in Switzerland for larger avalanches. It is, therefore, of questionable applicability for a small avalanche. Because of this limitation we also used a completely independent alternate graphical technique (Köner, 1980). Köner's "energy-line" method models an avalanche as a simple "sliding block," in which the energy dissipated along the path results from sliding friction and/or internal "inertial" deformation. We assumed that 60 percent of the initial potential energy at the starting zone was available as kinetic energy at the fence. This resulted in a design velocity of 12 m/s (39 ft/s) at the fence, somewhat larger than the 9 m/s (30 ft/s) velocity obtained by application of AVAL-1D.

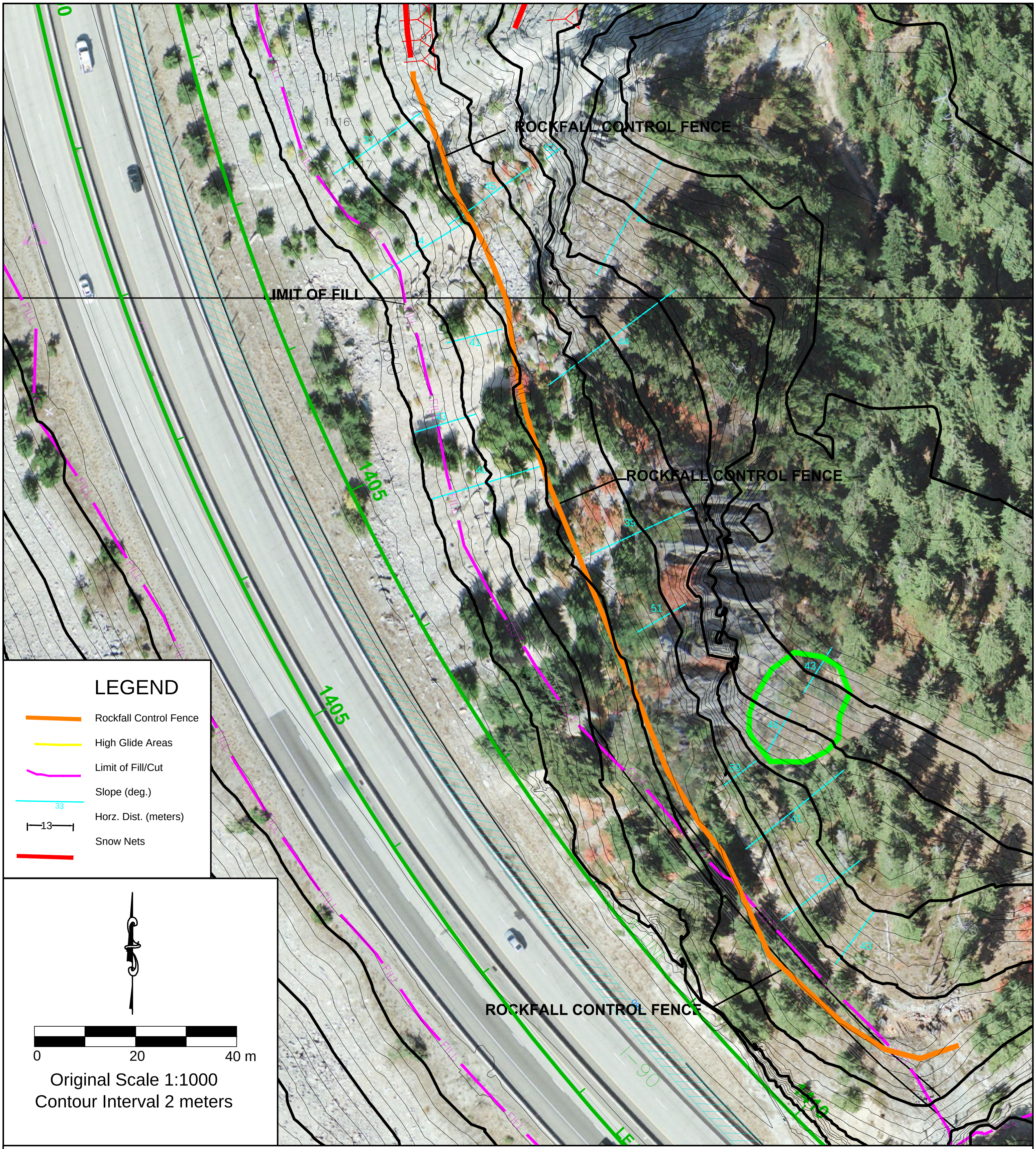
Combining the results of both methods enabled the following conclusions:

- Impact velocity at the fence 9 m/s (30 ft/s) $\leq V \leq$ 12 m/s (39 ft/s); and
- The time interval of maximum velocity is approximately 1.0 second.

These two conclusions provided us some boundaries on the assumptions we made in applying the "design energy" and "impulse-momentum" analyses that follow.

### 6.3 AVALANCHE KINETIC ENERGIES AND LOADS AT ROCKFALL FENCE

Commercially available rockfall attenuation fences are usually rated in terms of their capacity to resist kinetic energy of a rock impact. To determine the kinetic energy (K.E.) of the avalanche at the fence we assumed the parameters of a sliding, wet-slab avalanche 10 m (33 ft) wide as it impacts the fence, as shown in Tables 19 and 20.




URS
Arthur I. Mears, P.E., Inc.
*Wilbur Engineering, Inc.*

# Figure 11 - Slide Curve Rockfall Fence Avalanche Areas

July 2010

**Table 19 [Metric]: Rockfall fence design kinetic energies**

| V [1] (m/sec) | W (m) | L [2] (m) | D [3] (m) | Vol ($m^3$) | K.E. (kJ) |
|---|---|---|---|---|---|
| 8 | 10 | 8 | 0.3 | 24 | 346 |
| 9 | 10 | 9 | 0.4 | 36 | 656 |
| 10 | 10 | 10 | 0.5 | 50 | 1125 |
| 11 | 10 | 11 | 0.6 | 66 | 1797 |
| 12 | 10 | 12 | 0.7 | 84 | 2722 |
| 13 | 10 | 13 | 0.8 | 104 | 3955 |

**NOTES**
1. The velocity range of 8 to 13 m/sec slightly extends the limits provided by AVAL-1D and Energy-Line analyses discussed.
2. The upslope length (L) of the impacting slab avalanche equals V times 1.0 sec; this interval is the duration of the peak pressure curve from AVAL-1D.
3. We assumed an increased (D) is associated with increased velocity, as commonly observed.

**Table 20 [English]: Rockfall fence design kinetic energies**

| V [1] (ft/sec) | W (ft) | L [2] (ft) | D [3] (ft) | Vol ($ft^3$) | K.E. (ft-tons) |
|---|---|---|---|---|---|
| 26 | 33 | 26 | 1.0 | 847 | 127 |
| 30 | 33 | 30 | 1.3 | 1270 | 241 |
| 33 | 33 | 33 | 1.6 | 1764 | 414 |
| 36 | 33 | 36 | 2.0 | 2329 | 661 |
| 39 | 33 | 39 | 2.3 | 2964 | 1002 |
| 43 | 33 | 43 | 2.6 | 3670 | 1455 |

**NOTES:**
1. The velocity range of 26 to 43 ft/sec slightly extends the limits provided by AVAL-1D and Energy-Line analyses discussed.
2. The upslope length (L) of the impacting slab avalanche equals V times 1.0 sec; this interval is the duration of the peak pressure curve from AVAL-1D.
3. We assumed an increased (D) is associated with increased velocity, as commonly observed.

The kinetic energies in Tables 19 and 20 generally *exceed by a wide margin* the 400 kJ (150 ft-ton) capacity fence discussed during the April, 2010 site visit.

We also provided a design-loading analysis resulting from avalanche impact at the fence location. This analysis applied the impulse-momentum principle where the impulsive force, F, is determined from the momentum change ($\Delta P$) over time ($\Delta t$), therefore

$$F = \Delta P/\Delta t.$$

The impulsive force, F, per unit of fence length is summarized in Tables 21 for the small wet-slab avalanche described above. Note that an English conversion table from Table 21 was not included because there is not a direct correlation between metric and English units.

**Table 21 [Metric]: Impulsive Force, F, per unit of fence length**

| V (m/s) | Vol ($m^3$) | ρ ($kg/m^3$) | M (kg) | P (kg-m/s) | F (kN/m) |
|---|---|---|---|---|---|
| 8 | 24 | 450 | 10,800 | 86,400 | 8.6 |
| 9 | 36 | 450 | 16,200 | 145,800 | 14.6 |
| 10 | 50 | 450 | 22,500 | 225,000 | 22.5 |
| 11 | 66 | 450 | 29,700 | 326,700 | 32.7 |
| 12 | 84 | 450 | 37,800 | 453,600 | 45.4 |
| 13 | 104 | 450 | 46,800 | 608,400 | 60.8 |

The forces in column 6 and 7 (Tables 21) for slides > 11 m/s (36 ft/s) are similar to or exceed the unit forces we specified for *snow supporting structures* in the Slide Curve area. However, it should be noted that rockfall fences are designed differently from snowpack retention structures (e.g. nets), thus the forces appropriate for net design may not be applicable for a rockfall fence.

## 6.4 SUMMARY OF DESIGN CONSIDERATIONS

We have completed an analysis of design loads resulting from small, wet-slab avalanches at the proposed rockfall fence. Our analysis is subject to uncertainties due to the snow-climate characteristics in this maritime, wet-snow environment, the likely behavior of design avalanches in terrain with a small vertical drop, the presence of rock-slab surfaces that can promote water runoff and glide-induced avalanches in some starting zones, and the uncertainties in applying standard avalanche-dynamics modeling methods in small-scale avalanches. Nevertheless we believe our assumptions and methods are reasonable and not overly conservative.

Based on the analyses presented in Sections 6.2 and 6.3, the following design "suggestions" should be considered during the design of the proposed rockfall fence shown in Figure 11. They should not be considered "recommendations" because, as stated, snow avalanches do not affect the proposed highway alignment. The following suggestions (mostly from Margreth and Roth, 2006) are intended to provide guidance in design of a rockfall fence at this location.

a. The rockfall fence should be designed to resist at least 2,000 k-joules (> 750 ft-tons) of kinetic energy.
b. Retaining ropes should be installed in the direction of the slope.
c. Stronger break rings should be used for the retaining ropes.
d. Supporting ropes should be fixed directly to the posts without rated break points.
e. Break rings in the support ropes within the sections are not necessary.

f. Micropile and anchor foundations should be reinforced with a concrete base or a larger steel base plate must be considered.
g. A shorter than standard spacing of posts should be used.

Limited experience gained with the use of rockfall fences as avalanche barriers suggests costs may be as much as two to five times those of a standard rockfall fence of the same length. An accurate cost estimate would depend on the design details and is beyond the scope of our work.

## 7.0 EVALUATION OF VELA STRUCTURES

Figure 12 shows an installation of the relatively new Vela system starting zone structures made in Italy by Artigiana Construzioni S.R.L. and distributed in Europe by Technologie Alpine de Securte of France. The United States distributor is High Angle Construction, Inc. from California. The Vela system consists of individual panels connected to the ground by a single anchor. The Vela system has not been tested or approved by the Swiss Government.

The 2007 I-90 Avalanche Mitigation report (Ref. 1) recommended using a Swiss approved system. All systems that have met Swiss requirements have tension anchors on the uphill and downhill sides of the net and a compression foundation/base plate for the swivel post. Also, the Swiss-approved systems consist of continuous rows stitched together where the panels are joined. Adjacent Vela panels are not connected.

**Figure 12**: Loaded Vela Starting Zone Structure

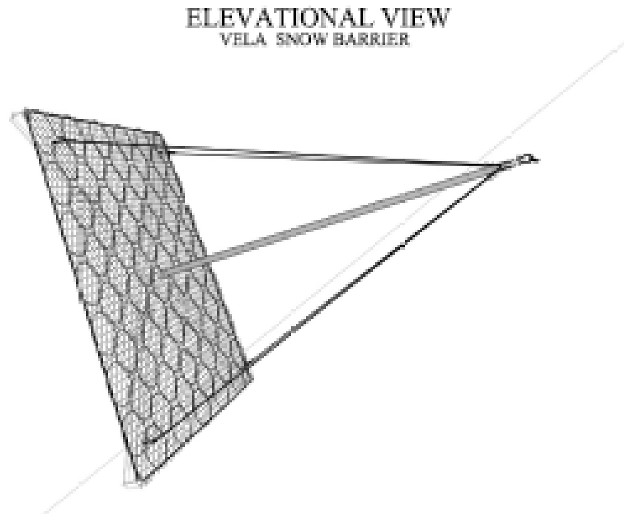



**Figure 13**: 3D View of Vela Starting Zone Structure
Photo & diagram provided by High Angle Construction, Inc., USA Representative for Vela

We reviewed calculation notes for a $D_K$ = 3.0 m (9.8 ft) system by Italian engineer Lionello Caproni, dated February 5, 2009. We also communicated with Eric Lieberman of High Angle Construction, Inc., the USA representative for Vela, and researched existing installations.

The first installation of Vela was in 2005 in Europe. The first, and only installation to date in the USA, was done at the Canyons Resort near Park City, Utah in 2009. The manufacturer provided a list of 25 installations from 2005 to 2009. Research on these installations revealed that some of these were earth retaining structures rather than avalanche starting zone structures. No installations have been made in wet heavy snow climates similar to the Washington Cascades.

Due to the fact that the Vela system has a very limited history (5 years), there were no installations in place during the heavy snow winter of 1999 in Europe, and it has not been field-tested in a climate similar to Snoqualmie Pass, it is not recommended for large scale use on the I-90 Snoqualmie Pass East project. If there are substantial cost or schedule savings with the Vela system, it should be used on a limited basis, where the consequences of a failure are small, and be considered as an experimental effort. Locations that might meet this criteria are Bald Knob (lines 11, 12, and 13), East Shed Minus One (lines 14 and 15), and the smooth Rock Slabs above the rockfall control fence southeast of Slide Curve at WB Sta. 1404+50 and Sta. 1407+50.

## 8.0 SNOW NET ANCHORS

Snow nets require anchor connections to the ground that include compressive and shear forces at the posts, and tension forces at the uphill and downhill anchor points. Due to the cyclical loading, high forces, variable load direction, and uncertainties related to ground conditions, anchors are often the most likely location for system failure. Such failures are costly to repair due to difficult access conditions and the need to mobilize specialized equipment. Consequently, anchor designs should include a generous factor of safety (at least 2:1) and a thorough testing program.

The snow climate at Snoqualmie Pass is expected to place unusually high loads on the net anchors due to high snow density, high glide rates and deep snow depths. The potential for high anchor loading is addressed partly by the reduced row spacing described in previous sections of this report. Additional considerations and recommendations related to snow net anchors are presented below.

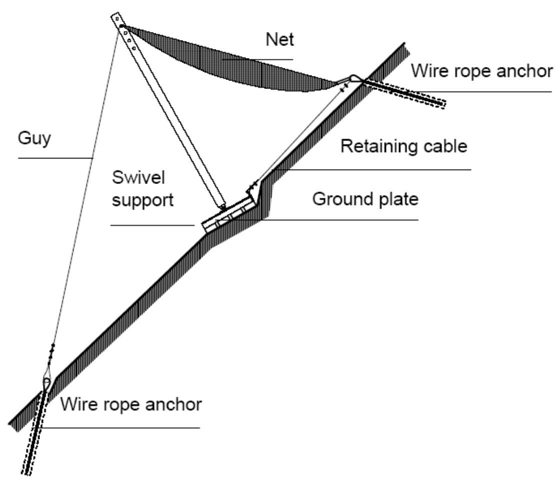



**Figure 14**: Typical Snow Net Anchor System

## 8.1 POST ANCHORS

The swivel posts for the snow nets must support compression and shear loads. The magnitude of these loads is expected to range from 220 kN to 370 kN (25 tons to 42 tons) for compression and from 70 kN to 110 kN (7.9 tons to 12.4 tons) for shear. Figure 14 shows a typical installation with a base plate embedded into the ground. Depending on loads and ground conditions, it may be necessary to construct concrete foundations or install drilled micropiles to support the shear and compressive forces. Each manufacturer provides base plates and options for various loading and ground conditions.

## 8.2 CABLE ANCHORS

Due to the variation in the direction of tension, grouted cable anchors are recommended for supporting the uphill and downhill guys. The uphill anchors experience the larger tensile forces than the downhill anchors. Loads are expected to range from 260 kN to 280 kN (29 tons to 31 tons) for the uphill anchors and from to 16 kN to 26 kN (1.8 tons to 2.9 tons) for the downhill anchors. The Swiss Guidelines recommend testing all anchors.

## 8.3 ROW END MEMBERS

The end members of snow net rows experience higher stresses than middle structures due to snow creep and glide in the unsupported adjacent areas. Figure 15 shows the approximate loading for end effects on snow nets.

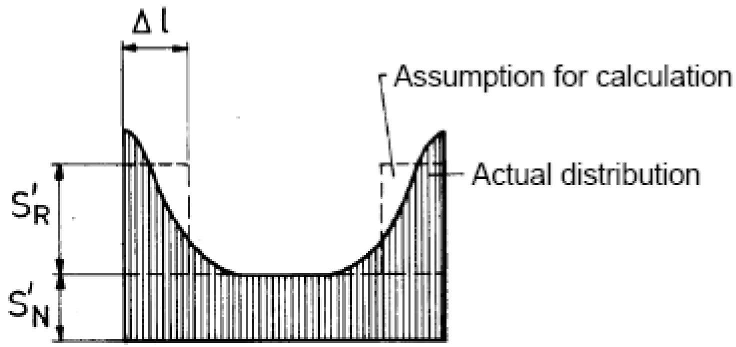



**Figure 15**: End Effect Loads

The Swiss Guidelines (Ref. 2) recommend increasing loads according to the following equations:

$$f_R = (0.92 + 0.65 \cdot N)\frac{A}{2} \leq (1.00 + 1.25 \cdot N)$$
$$\Delta l = 0.60 \cdot \frac{A}{2} \leq \frac{D_K}{3}$$

Assuming 2 meter gaps (A=2 m) at row breaks,

$$\Delta l = 0.6 \text{ m}$$

and

$$f_R = 1.7 \text{ for } N = 1.2$$
$$f_R = 3.0 \text{ for } N = 3.2$$

The snow net manufacturers recognize and account for end effects in their designs and anchor loads.

## 8.4 GROUTING

The quality of anchor grouting is critical for system performance and this dictates a high level of quality assurance and testing during grouting. Grouting should be done by pumping through a tremie hose to the bottom of the hole, such that grout fills the hole from the bottom to the top.

### 8.5 COATINGS

Snow nets typically use galvanized steel for corrosion protection, but special coatings for additional protection or aesthetics are available. Galvanized net components lose some of their brightness within a few years. Figure 16 shows galvanized snow nets with backgrounds of snow, sky and forest. Materials can be powder-coated or PVC-coated for color and additional protection. Forest re-growth and resulting improved snowpack stability may negate benefits from additional corrosion protection for most of the snow nets sites.

**Figure 16**: Galvanized Posts and Nets in Winter

## 9.0 REFERENCES

1. URS Corporation & Arthur I. Mears, P.E., Inc., *I-90 Snoqualmie Pass East Project Avalanche Mitigation Report and Avalanche Analyses*, December 2007.
2. Margreth, S. 2007: *Defense Structures in Avalanche Starting Zones, Technical Guideline as an Aid to Enforcement*. Environment in Practice no. 0704, Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos 134 pp.
3. Shaerer, Peter & Chris Stethem & Associates, Ltd. *Snow Avalanche Control Snoqualmie Pass East Shed Area*, May 2000
4. Stimberis, John; Rubin, Charles, *Glide avalanche response to an extreme rain on snow event, Snoqualmie Pass, Washington, USA*, International Snow Science Workshop, Davos, Switzerland Editors: Jürg Schweizer and Alec van Herwijnen , October 2009.

# APPENDIX A
# SNOW NET COORDINATES

| Snow Net Coordinates[1] | | | | |
|---|---|---|---|---|
| | | | **End Points** | |
| **Line No.** | **$D_K$ (m)** | **$D_K$ (ft)** | **Easting** | **Northing** |
| **Slide Curve** | | | | |
| **1** | 3.5 | 11.5 | 534919.4 | 324000.1 |
| | 3.5 | 11.5 | 534942.5 | 323987.7 |
| | 3.5 | 11.5 | 534943.6 | 323986.1 |
| | 3.5 | 11.5 | 534958.5 | 323962.2 |
| | 3.5 | 11.5 | 534959.3 | 323960.4 |
| | 3.5 | 11.5 | 534959.0 | 323947.2 |
| **2** | 3.5 | 11.5 | 534911.9 | 323990.4 |
| | 3.5 | 11.5 | 534938.1 | 323971.3 |
| | 3.5 | 11.5 | 534938.8 | 323970.0 |
| | 3.5 | 11.5 | 534942.6 | 323932.0 |
| **3** | 3.5 | 11.5 | 534900.1 | 323999.8 |
| | 3.5 | 11.5 | 534905.4 | 323982.1 |
| | 3.5 | 11.5 | 534909.1 | 323979.3 |
| | 3.5 | 11.5 | 534926.6 | 323963.3 |
| | 3.5 | 11.5 | 534928.8 | 323961.5 |
| | 3.5 | 11.5 | 534927.4 | 323928.1 |
| **4** | 3.5 | 11.5 | 534889.0 | 324004.9 |
| | 3.5 | 11.5 | 534902.6 | 323956.2 |
| | 3.5 | 11.5 | 534904.1 | 323954.4 |
| | 3.5 | 11.5 | 534912.7 | 323899.2 |
| **5** | 3.5 | 11.5 | 534870.1 | 324005.8 |
| | 3.5 | 11.5 | 534878.9 | 323959.0 |
| | 3.5 | 11.5 | 534879.5 | 323957.1 |
| | 3.5 | 11.5 | 534884.5 | 323916.0 |
| | 3.5 | 11.5 | 534884.9 | 323913.8 |
| | 3.5 | 11.5 | 534891.5 | 323875.0 |
| **6** | 3.0 | 9.8 | 534845.6 | 324002.6 |
| | 3.0 | 9.8 | 534853.1 | 323954.2 |
| | 3.0 | 9.8 | 534853.9 | 323952.4 |
| | 3.0 | 9.8 | 534857.6 | 323908.4 |
| | 3.0 | 9.8 | 534857.7 | 323905.8 |
| | 3.0 | 9.8 | 534865.3 | 323861.0 |

**Note**
1. Some adjustments will be required to address field conditions. Adjustments should be checked for conformance with the Swiss Federal Guidelines and to ensure that the design intent is met

| **Snow Net Coordinates** | | | | |
|---|---|---|---|---|
| | | | **End Points** | |
| **Line No.** | **$D_K$ (m)** | **$D_K$ (ft)** | **Easting** | **Northing** |
| **Slide Curve** (continued) | | | | |
| **7C** | 3.0 | 9.8 | 534833.5 | 324030.2 |
| | 3.0 | 9.8 | 534835.9 | 323999.5 |
| **7B** | 3.0 | 9.8 | 534851.8 | 324010.7 |
| | 3.0 | 9.8 | 534854.3 | 324049.2 |
| **7A** | 3.0 | 9.8 | 534871.2 | 324014.7 |
| | 3.0 | 9.8 | 534872.5 | 324039.1 |
| **8** | 3.0 | 9.8 | 534822.5 | 323995.9 |
| | 3.0 | 9.8 | 534825.4 | 323948.2 |
| | 3.0 | 9.8 | 534825.6 | 323945.9 |
| | 3.0 | 9.8 | 534830.9 | 323902.3 |
| | 3.0 | 9.8 | 534831.2 | 323900.4 |
| | 3.0 | 9.8 | 534831.4 | 323849.4 |
| **9** | 3.0 | 9.8 | 534799.3 | 323996.6 |
| | 3.0 | 9.8 | 534802.4 | 323946.4 |
| | 3.0 | 9.8 | 534802.8 | 323944.5 |
| | 3.0 | 9.8 | 534807.3 | 323895.9 |
| | 3.0 | 9.8 | 534807.5 | 323893.7 |
| | 3.0 | 9.8 | 534810.8 | 323843.6 |
| **Bald Knob** | | | | |
| **11** | 3.0 | 9.8 | 534798.9 | 324755.3 |
| | 3.0 | 9.8 | 534794.5 | 324769.2 |
| **12** | 3.0 | 9.8 | 534779.2 | 324773.4 |
| | 3.0 | 9.8 | 534803.5 | 324736.8 |
| **13** | 3.0 | 9.8 | 534770.4 | 324764.5 |
| | 3.0 | 9.8 | 534790.3 | 324731.3 |
| **East Shed Minus One** | | | | |
| **14** | 3.0 | 9.8 | 534457.6 | 325619.6 |
| | 3.0 | 9.8 | 534479.8 | 325604.5 |
| **15** | 3.0 | 9.8 | 534475.7 | 325581.2 |
| | 3.0 | 9.8 | 534444.9 | 325607.1 |

# APPENDIX B
# FIGURES AND TABLES FROM THE SWISS GUIDELINES (REF. 2)

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

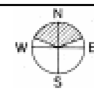
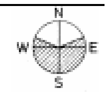
| Inclination of slope | $D_K$ [m] | $H_K$ [m] | L' = L · cos ψ [m] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N = 1.2 | | | N ≥ 1.3 | | |
| | | | tan φ = | | | tan φ = | | |
| | | | 0.60 | 0.55 | 0.50 | 0.60 | 0.55 | 0.50 |
| 60 % (31°) | 1.5 | 1.75 | | 13.1 | | | 15.8 | |
| | 2.0 | 2.33 | | 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 | |

**Technical Guideline for Defense Structures in Avalanche Starting Zones FOEN / WSL 2007**

**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 · cos ψ [m] | | |
|---|---|---|---|---|---|
| | | | N ≥ 1.2 | | |
| | | | tan φ = | | |
| | | | 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 | |

**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)<br>• 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<br>• Prominent mounds covered with grass and low bushes (height of mounds over 50 cm)<br>• Prominent cow trails<br>• 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)<br>• Fine scree (d* ≤ 10 cm) alternating with grass and low bushes<br>• 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<br>• Grass with shallow cow trails | 2.0 | 2.4 |
| **Class 4** | | |
| • Smooth, long-bladed, compact grass cover<br>• Smooth outcropping rock plates with stratification planes parallel to the slope<br>• Smooth scree mixed with earth<br>• Swampy depressions | 2.6 | 3.2 |

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