Common Types of Unstable Slopes

Landslide – The vertical and horizontal displacement of a soil mass, under the influence of gravity, within a slope or embankment. Generally landslides can be divided into two categories based on failure geometry. Those landslide categories are circular and sliding block failures. The rate of movement of landslides can vary from very slow moving to very rapid.

Debris Flow – A rapidly moving fluid mass of rock fragments, soil, water, and organic material with more than half of the particles being larger than sand size. Generally debris flows occur on steep slopes or in gullies and can travel long distances. Typically, debris flows result from unusually high rainfall, or rain on snow events.

Rockfall – The fall of newly detached segments of bedrock of any size from a cliff or steep slope. The rockfall descends mostly through the air by free fall, bouncing, or rolling. Movements are very rapid to extremely rapid, and may not be preceded by minor movements.

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10-01-0001

Washington State Department of Transportation

January 2010

WSDOT's Unstable Slope Management Program

The Problem

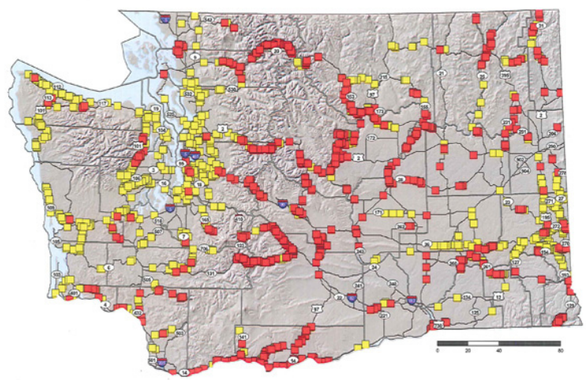
The Washington State Department of Transportation manages 7,048 miles of highway facilities that traverse widely varying terrains with complex geologic landforms. Unstable slopes, which include landslides, rock falls, and debris flows of all sizes, can impact highways when they fail. Failure of unstable slopes poses a potential safety risk to the traveling public and adversely affects regional commerce when resulting highway closures occur.

How We Manage Unstable Slopes

Prior to 1995, unstable slopes were stabilized reactively after they had failed. To address unstable slope issues with a proactive approach, a budget category in the Highway Preservation Program for Unstable Slopes was established in 1995. The target investment level for this category in the highway system was estimated at approximately $300 million over 10 biennia. WSDOT developed the Unstable Slope Management System (USMS) to provide a methodology to rationally evaluate known unstable slopes within the WSDOT highway system. The method focuses on balancing hazard and risk in prioritizing slopes for the allocation of funds for proactive stabilization efforts.

WSDOT regional offices in collaboration with Headquarters Geotechnical Division did the initial identification of unstable slopes. This resulted in a baseline inventory of over 2,500 sites. These known slopes are scored using a numerical rating system based on eleven criteria that identify the hazard and measure the potential risk factors to the highway facility if a slope fails. Based on the numerical rating system, a site may have a score ranging from 33 (lowest) to 891 (highest), with higher numbers representing a greater risk to the highway facility at that location. Table 1 identifies the rating factors. Since the inception of the USMS, the number of slopes in the inventory has increased to about 3,100. Detailed numerical ratings have been completed for almost all known unstable slopes statewide. Figure 1 identifies unstable slopes along state routes in Washington State.

Figure 1: Unstable Slopes along State Routes in Washington State



Rockfall Landslide/Debris Flows

Data Source: Unstable Slope Management System (USMS)
Date: 11/23/2005

The next part of the process is for geotechnical specialists with expertise in slope stability to provide a description of the slope stability problem and to develop conceptual slope mitigation designs and cost estimates. A simple benefit-cost analysis compares the cost of a 24-hour traffic delay and the maintenance costs over twenty years to the costs to mitigate the slope hazard. Based on this approximate benefit-cost comparison, sites with a ratio of 1 or greater are placed on a prioritized list of slopes to be programmed for remediation. Currently, WSDOT prioritizes and programs remediation for unstable slopes that have a numerical rating of 350 or greater along interstate highways, principal arterials, and other highway facilities with traffic volumes of 5,000 vehicles a day or greater, and a benefit-cost ratio of 1.0 or greater. Conceptual designs and cost estimates have been completed on 433 moderate to high-hazard unstable slopes as part of the ongoing prioritization process. Figure 2 identifies mitigated slopes along state routes in Washington State.

Processes Leading to Slope Instability

Slope instability is a category of natural hazard that refers to the movement of a soil or rock mass under the influence of gravity. Rock falls occur on both natural and excavated slopes. Causes of rock falls include a combination of natural processes and man-made influences, acting singly or in combination, to dislodge discrete blocks of rock. Usually planes of weakness termed "discontinuities" physically divide the rock mass into an assemblage of blocks.

Landslides are a category of natural hazards that involve the down slope movement of soil materials under the influence of gravity. Soil slope failures generally fall into two categories: 1) deep seated rotational failures or translational slides and 2) shallower debris flows and slides. Generally, rotational-type slope failures occur more slowly than debris flows and slides, which can occur rapidly. Landslide mechanisms involve either an increase in driving forces or a reduction of resisting forces (i.e., increased water pressure or loss of shear strength of the soil).

Distinction between Hazard and Risk

It is important to understand the terms "*hazard*" and "*risk*". Rock fall or soil slope failures are geologic processes categorized as natural hazards. These natural processes include landslides, debris avalanches, slope creep, soil piping, snow avalanches and so on. These events occur in nature and have done so since the geologic evolution of landforms began. In some cases, the activities of humans can influence the occurrence of natural hazard events. A reference to a high hazard means that there is a high likelihood an event will occur.

Risk refers to the consequences of a natural hazard event if it occurs. It is easy to envision an event that has absolutely no consequence in terms of human activity, for example a snow avalanche in the remote mountains. The same natural hazard perched above a ski resort would represent a significant risk.

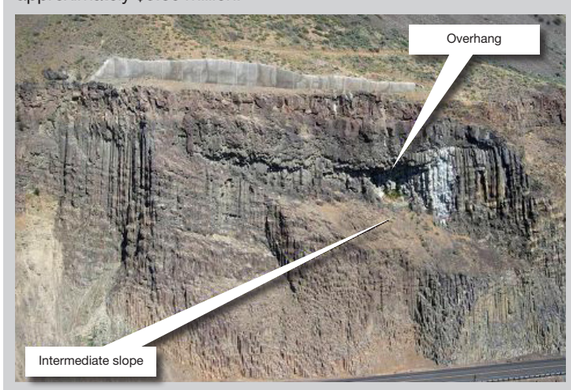
The hazards that most interest WSDOT are those that have both a high likelihood of occurrence and a high likelihood of causing damage, injuries, death or severe economic impacts. Applied to highway slopes, it is necessary to assess both the degree of hazard in terms of the rock or soil becoming dislodged from the slope and the potential damage (risk) it could inflict based on its energy, probable trajectory and the likelihood of something vulnerable being in its path.

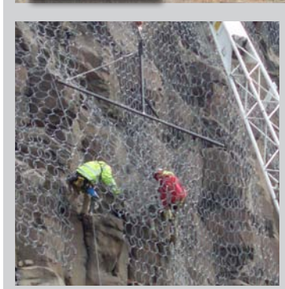
SR 28 Rock Island Slope Stabilization

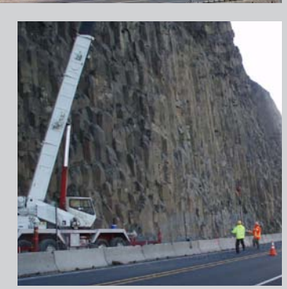
This rockfall site near Wenatchee is located along SR 28, just south of Rock Island Dam between MP 11.83 and MP 11.96. The two lane highway and a heavily used rail line are situated between a high basalt cliff and the Columbia River. The near vertical, 300-foot high unstable slope has an irregular slope configuration. It has an overhang with a moderately sloping intermediate bench approximately 130 feet above the highway. The average daily traffic through this section of highway is approximately 7,600 vehicles, 18% of which are trucks. WSDOT Maintenance personnel reported that three to four rockfall events occur every year, involving blocks 1 to 2 feet in size that reach the highway shoulders and travelled lanes, with smaller sized rockfall occurring more frequently.

The slope stabilization project removed 3,100 cubic yards of loose unstable rock from the slope. This was accomplished by the use of pry bars, pneumatic pillows, and hydraulic jacks operated by workers suspended from climbing ropes. Approximately 225,000 square feet of ring nets and wire mesh slope protection were draped on the slope to catch and contain rockfall so it would not enter the highway. The ring nets and wire mesh were lifted into place by a crane working from an upslope bench and the highway. The ring nets and wire mesh slope protection panels were seamed together by workmen suspended from climbing ropes.

The project provided WSDOT the opportunity to compare the attributes and performance of ring nets to more commonly used cable nets. WSDOT was able to secure Federal Experimental Feature status and funding for the project. Performance of the ring nets will be evaluated annually for the next five years. The final cost of the completed unstable slope mitigation project was approximately $3.89 million.







Solutions to Meet the Current Need to Reduce Public Risk

Present funding is for $25 million per biennium (projected to 2015) for planned work in the unstable slope management program. In preparing for the biennial budget development process, the Department reviews its current Asset Management Plan for unstable slope needs, adjusting it for the accomplishments of the past two years, adding any new needs, and evaluating the benefits of accelerating the rate at which unstable slope risks are addressed.

Some factors in this evaluation are the hardships for the public with travel delays, detours, and potential affect to local businesses, and the availability of having qualified contractors and workers to perform the work. WSDOT has identified the projects for the 09-11 biennium, and has developed the preliminary program through the 11-15 biennium. There will be continued scoping to identify needs and projects for the future biennia.

Future Needs

The Department has successfully mitigated over 228 high-risk unstable slopes over the last 15 years. However, more work remains to be done. Our goal is to mitigate all identified high and moderate risk unstable slopes on interstate highways, principal arterials and other roadways with moderate to high traffic volumes by 2020. At the same time, the Department will continue to conduct rock slope scaling as an interim measure on highway corridors with a high incidence of rockfall.

Geotechnical analysis and design of mitigation measures for 35 more high-risk unstable slopes is currently underway. Preliminary engineering to develop conceptual mitigation proposals and cost estimates for 64 moderate-risk slopes was begun in 2009. Additional engineering work to refine mitigation designs and improve cost estimates for theses unstable slopes is needed to ensure that we can continue to manage risk through an aggressive construction program. Sustained funding at the current $25 million per biennium level for unstable slope mitigation and $1.5 million per biennium level for rock slope scaling is needed to ensure that these goals can be met.

For more information

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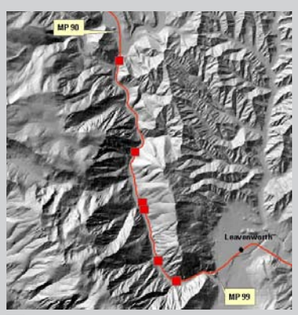
Tumwater Canyon.

Tumwater Canyon Rock Slopes Stabilization

US Highway 2, between MP 90.5 and MP 99, is in a narrow, steep-sided river valley known as Tumwater Canyon. Traffic volumes in the canyon average approximately 5,000 vehicles per day, with trucks comprising 15% of that volume. Rockfall-related incidents along this section of highway have been a significant concern because of the unfavorable geology, limited sight distance on the tight curves, very narrow shoulders and limited ditch capacity for rockfall catchment.

As part of the P3 Unstable Slope Program engineering geologists with the Geotechnical Division worked with Regional Maintenance staff to identify 14 unstable slopes where the risk of rockfall was high and the potential impacts from a rockslope failure could be significant. Conceptual designs were developed to mitigate these rockslopes. Rockslope mitigation included the use of scaling, rock dowels, rock bolts, fiber-reinforced shotcrete, wire mesh and cable nets. Project costs were prepared by the region and the slopes were prioritized for mitigation based on the calculated benefit/cost ratios.

The six highest priority slopes were programmed for mitigation beginning in 1995. These slope mitigation projects removed approximately 99,000 cubic yards of loose unstable rock from the slopes, installed 6,000 linear feet of rock bolts and dowels for rockslope reinforcement, and installed 99,000 square feet of wire mesh and cable net slope protection. The total project cost for this rockslope stabilization work was $1.9 million.



Mitigated Slopes

Map Source: Unstable Slope Management System (USMS)
Date: 12/04/2009

These slope mitigation projects have had a significant impact by reducing the number of rockfall related incidents in this corridor by approximately 80%. Two additional unstable slope projects in the canyon are currently in the final design phase and the slopes are scheduled for mitigation in 2010-11.

Midway Curve MP 66.

Midway Curves I-90 Project

Three unstable rock slopes, at approximately MP 66 in the Midway Curve area near Easton were identified for mitigation in the January 2006 I-90 unstable slope reassessment report to Governor Gregoire, following two major rockslides on Snoqualmie Pass in the fall of 2005. The bedrock exposed in the three existing cut slopes was highly fractured with large overhangs, and contained wide differentially weathered fault zones, and structurally controlled wedge blocks that dipped unfavorably toward the highway.

Rockzilla at work.

The western and middle rock slopes, which exceed 100 feet in height, were mitigated by extensive mechanical and hand scaling of approximately 45,000 cubic yards of loose unstable rock from the slopes, installing approximately 5,000 linear feet of tensioned rock bolts and untensioned rock dowels, and draping the slopes with approximately 141,000 square feet of wire mesh and cable net slope protection. The eastern slope was mitigated by flattening the slope, excavating a wider ditch and constructing a low concrete barrier wall. The total project cost for this rock slope stabilization work was approximately $6.6 million.

Three factors enabled the Department to successfully complete the $5 million unstable slope mitigation project in a single construction season in time for the winter travel season. They used digital imaging technology to accurately map and characterize the rock slopes under winter conditions, construction of a Mechanically Stabilized Earth wall to create a temporary detour during construction enabling crews to work with minimal traffic disruption, and large-volume mechanical scaling to remove loose rocks quickly and safely.

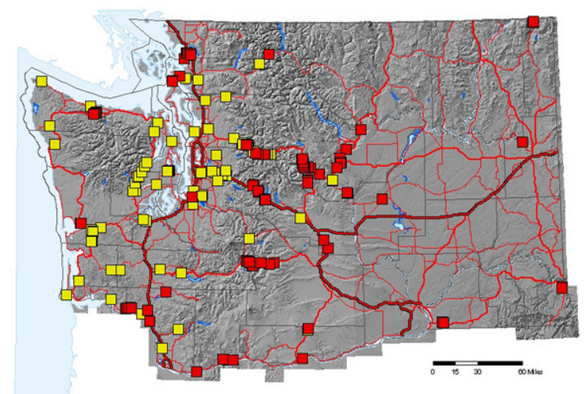
The American Council of Engineering Companies presented WSDOT and their consultants the Gold Award for "Social, Economic, and Sustainable Design Considerations" and the Silver Award for "Originality or Innovative Application of New or Existing Techniques" for the I-90 Snoqualmie Pass MP 66 rock slope mitigation project.

Table 1: USMS Rating Criteria

Category	Points = 3	Points = 9	Points = 27	Points = 81
Problem Type: Soil	Cut or Fill slope erosion	Settlement or piping	Slow moving landslides	Rapid landslides or debris flow
Problem Type: Rock	Minor rockfall Good catchment	Moderate rockfall Fair catchment	Major rockfall Limited catchment	Major rockfall No catchment
Average Daily Traffic	< 5,000	5,000 to 20,000	20,000 to 40,000	> 40,000
Decision Sight Distance	Adequate sight distance	Moderate sight distance	Limited sight distance	Very limited sight distance
Impact of Failure on Roadway	< 50 Feet	50 to 200 Feet	200 to 500 Feet	> 500 Feet
Roadway Impedence	Shoulder only	1/2 Roadway	3/4 Roadway	Full Roadway
Average Vehicle Risk	< 25% of the time	25% to 50% of the time	50% to 75% of the time	> 75% of the time
Pavement Damage	Minor - not noticeable	Moderate - driver must slow	Severe - driver must stop	Extreme - not traversable
Failure Frequency	No failures in last 5 years	One failure in last 5 years	One failure each year	More than one failure
Annual Maintenance Costs	< $5,000 per year	$5,000 to $10,000 per year	$10,000 to $50,000 per year	> $50,000 per year
Economic Factor	No detours required	Short detours < 3 Miles	Long detours > 3 Miles	Sole access - no detours
Accidents in Last 10 Years	0 to 1	2 to 3	4 to 5	> 5

WSDOT's Unstable Slope management program is a proactive, infrastructure- preservation program that seeks to cost-effectively reduce the risk of moderate- to high-hazard unstable slopes from adversely impacting our highest priority state highway facilities. The mitigation objective is to achieve long-term risk reduction. Therefore, the mitigation must either be a permanent solution or provide a reasonable performance life (>20 years).

Figure 2: Mitigated Slopes along State Routes in Washington State



Mitigated Rockfall Mitigated Landslide/Debris Flows

Data Source: Unstable Slope Management System (USMS)
Date: 12/08/2009

Under the existing USMS procedures, a slope that qualifies for stabilization receives a comprehensive (i.e., 20-year design life) treatment. In other words, stabilization is all or nothing at a given site. In some cases, a minimal amount of slope treatment can remediate a large component of the risk at a given site, for example, hand scaling of a rock slope. As part of the program WSDOT has also developed a risk reduction strategy that complements the current full slope stabilization program. On an annual basis WSDOT Geotechnical Division and regional personnel jointly determine the sites that will be included in this risk reduction strategy. An allocation of $1.5 million has been made available for risk reduction for each biennium beginning in 2007. This is in addition to the $20 million earmarked each biennium for programmed sites on the comprehensive slopes stabilization program.

Managing Risk

Between 1995 and 2009, WSDOT spent approximately $165 million on stabilizing more than 83 moderate to high-hazard programmed unstable slopes. In addition, the department spent another $208 million on unforeseen emergency slope corrections, for a total investment in unstable slopes of $26.6 million per year.

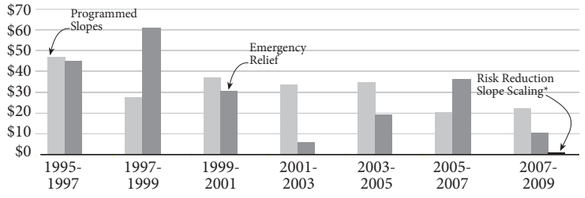
The Department's funding of non-dedicated dollars for the Highway Construction Program has decreased from approximately $1400 million in 2001-2003 to $650 million in 2009-2011. This reduction in non-dedicated State and Federal funds has made it essential for WSDOT to evaluate the performance of its highway system and determine how that performance will change in the future as a result of different investment alternatives.

In 2004, the Department began evaluating how the highway system was performing and developed a 10-year Asset Management Plan to identify the investment levels necessary for building the 2005-2007 Highway Preservation Program. At that time, the Department estimated that it would take an additional $100 million over the next 10 years to retrofit the currently identified high- and moderate-risk slopes. The evaluation recognized that emergency work, including slope failures, would probably continue, and WSDOT has set aside state funding to match federal emergency relief dollars and state declared emergencies. These funds are in addition to the $100 million for the planned unstable slope retrofit work.

Figure 3 shows the dollars spent on programmed and emergency unstable slopes projects from 1995 to 2009.

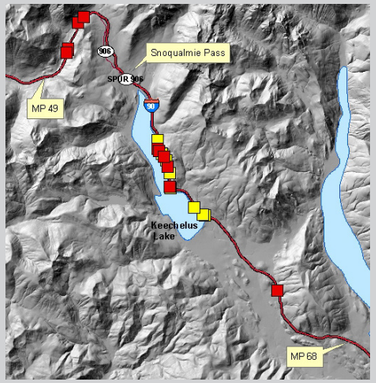
Figure 3: Unstable Slopes Projects - Actual Expenditures Emergency Relief vs. Programmed Project

Dollars in thousands



* New program implemented in 2007-2009
Source: WSDOT Capital Program Development and Management

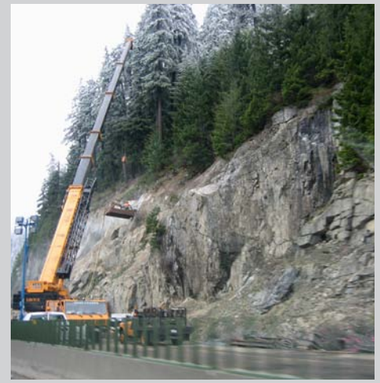
I-90 Snoqualmie Pass Corridor – Milepost 49 to Milepost 68



Mitigated Slopes Deferred Slopes

Map Source: Unstable Slope Management System (USMS)
Date: 12/04/2009

Scaling at Snoqualmie Pass.



Snoqualmie Pass.

Interstate 90, a multi-lane facility between MP 49 and MP 68, carries 30,500 vehicles per day across Snoqualmie Pass. It is the most heavily used east-west crossing of the Cascade Mountains, serving large volumes of recreational, business and freight traffic. Over 25% of the traffic is trucks bound for local, national and international markets.

The highway passes through widely varying geology and mountainous terrain requiring highway cuts in bedrock, some approaching 100 feet in height. The exposed geology has naturally occurring planes of weaknesses that often create a potential risk of rockslides and rockfalls. In the 1960s and 1970s, wide ditch catchments and concrete barriers were typically employed to minimize the risk of rockfall reaching the traveled lanes.

Ongoing unstable slope scoping work conducted by WSDOT's Geotechnical Division, including a 2006 reassessment of unstable slopes in the corridor, has identified 19 high priority unstable slopes along this portion of I-90. Seventeen of these unstable slopes are rockfall areas, one is a landslide area and one is a settlement area.

Of these identified high priority unstable slopes 11 have been mitigated since 1995. Mitigation has included the removal of approximately 75,000 cubic yards of loose unstable rock from the slopes, the installation of approximately 14,000 linear feet of rock bolts and rock dowels, and the installation of approximately 224,000 square feet of wire mesh and cable net slope protection. The total project cost for this rock slope stabilization work was $10.6 million.

A major highway improvement project planned for I-90 east of the Snoqualmie Pass summit in the late 1990s caused WSDOT to defer eight of the high priority slopes located between MP 49 and MP 68 from active consideration for mitigation in the Unstable Slopes Preservation Sub-program (P3). The proposed improvement project *I-90 Snoqualmie Pass East* will either stabilize these unstable slopes or realign the highway away from these hazards. In 2005, the legislature provided major funding for construction of two phases of the project. These reconstruction projects, *Hyak Snowshed Vicinity* and *Showshed to Keechelus Dam* between MP 55 and MP 60 will stabilize existing rock cuts and landslides in conjunction with highway widening and realignment work to reduce the hazards associated with the deferred unstable slopes. These projects will begin construction in the spring of 2010 and 2011, respectively.

Risk Reduction Rock Slope Scaling

In 2007, WSDOT initiated the Risk Reduction Rock Slope Scaling Program. The intent of this program is to reduce risk of rockfall along state highways. Risk reduction rock slope scaling entails the removal of loose unstable rock from a rock slope with the use of hand tools, such as scaling bars, hydraulic wedges, air pillows and in some cases with the use of mechanical equipment. These techniques can significantly reduce the likelihood of rockfall from reaching the highway where geologic site conditions make this type of work feasible.

The WSDOT Geotechnical Division works directly with the Region Maintenance and Materials Engineer's offices to identify the locations of rock slopes where risk reduction scaling would be beneficial. Typically these slopes have chronic rockfall problems with rocks reaching the highway numerous times during the year

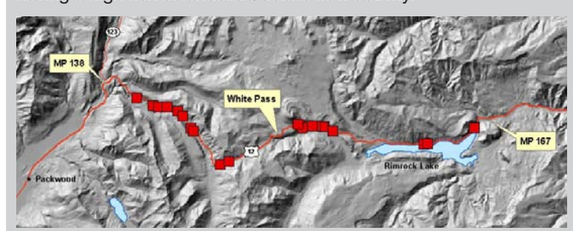
Scaling.

US 12 MP 146.

US Highway 12 – Milepost 138 to 167

Over White Pass US 12 is a two-lane principal arterial, one of three year-round passes that cross the Cascade Mountains. The narrow highway crosses below steep rock slopes and has long sections with limited site distance. Existing ditch and shoulder widths are limited in width and provide very limited catchment for rockfall. The highway carries an average of 3,240 vehicles per day, with trucks comprising approximately 27%.

Because of the large number of problematic rockfall areas located along the White Pass corridor, a focused rockfall corridor study was completed in 2003. The work entailed a check of the numerical rating for each slope, a detailed description of the slope instability/failure mechanism, a conceptual stabilization design and estimated quantities, and a cost estimate to mitigate the slope. WSDOT maintenance personnel provided information on frequency and size of rockfall or landslide events. Benefit-cost analyses were completed for each of these slopes to determine if they were cost effective to mitigate. As a result of this study, 153 unstable slopes have been identified and numerically rated along this corridor. Of these, 36 unstable slopes were identified as high risk slopes with a chronic history of rockfall, and two soil slopes were identified as having a high risk of landslide/debris flow activity.



Mitigated Slopes

Map Source: Unstable Slope Management System (USMS)
Date: 12/03/2009

Of the 38 identified high risk unstable slopes, 23 have been mitigated to date. These unstable slope mitigation projects included removal of approximately 19,600 cubic yards of loose unstable rock, installation of 7,000 linear feet of rock bolts and rock dowels for rockslope reinforcement, and installation of 257,000 square feet of wire mesh and cable net slope protection. The total project cost for this rock slope stabilization work was $9.1 million. Additional slope stabilization work is planned to address the remaining high risk unstable slopes. This stabilization work, which removes loose unstable material and prevents rockfall from reaching the highway, has significantly reduced the risk of highway closures and has improved safety for the traveling public.

and requiring multiple maintenance callouts to clear the highway of rockfall debris. These efforts have resulted in an extensive statewide list of candidate rock slopes that would benefit from rock slope scaling.

WSDOT engineering geologists assess the site conditions at each of the candidate slopes and determine the feasibility of rock slope scaling and whether or not rock slope scaling can effectively reduce the rockfall risk. These slopes are then rated utilizing a simple rating system based on eight criteria as shown in Table 2. The resulting total score is used to prioritize slopes for risk reduction scaling.

Table 2: Risk Reduction Rating Criteria

Category	Points = 3	Points = 9	Points = 27	Points = 81
Slope Height	< 25 ft.	25 to 50 ft.	50 to 75 ft.	> 75 ft.
Ditch Effectiveness	Good catchment	Moderate catchment	Limited catchment	No catchment
Total Roadway Width	< 40 ft.	32 ft.	24 ft.	< 24 ft.
Rockfall History	Few falls	Occasional falls	Many falls	Constant falls
Number of Maintenance Calls per Year	< 1	1 to 3	4 to 5	> 5
Rockfall Block Size	< 1 ft.	1 to 2 ft.	2 to 3 ft.	> 3 ft.
Volume of Rockfall per Year	< 3 cyd.	3 to cyd.	6 to 10 cyd.	> 10 cyd.
Average Daily Traffic	< 500	500 to 2,750	2,751-5,000	> 5,000

During the 2007-2009 biennium, 31 high priority rock slopes were identified as candidates for risk reduction scaling. Based on a biennial budget of $1.5 million, eight slopes on SR 2, 7, 20, 21, and 261 have been successfully scaled. An additional 44 slopes have been identified across the state and another $1.5 million has been allocated for risk reduction rock slope scaling in the 2009-2011 biennium.

Scaling.