Rockfall Control in Washington State

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The mountainous and rugged terrain of Washington State presents major and ongoing rockfall problems along transportation corridors. Rockfall control in Washington focuses on rockfall containment, identification, and prevention or minimization. Washington State Department of Transportation (WSDOT) has developed ditch design criteria for containing rockfall, which have been in use since 1963. The criteria address ditch design and rockfall fence placement for both rock and talus slopes. Rock slope design is a critical element of rockfall control in Washington. All new and upgraded construction of rock slopes is first evaluated for kinematic feasibility of rockfall. If applicable, cut-slope orientations are also based on kinematics. Highly fractured rock masses and those with random discontinuity orientation are designed using a nonlinear failure criterion. Controlled blasting methods are required on all WSDOT projects. Slope irregularities are kept to an absolute minimum and the use of a midslope benches for rockfall catchment has been eliminated. Commonly used stabilization methods are shotcreting, rock bolting and dowelling, slope trimming and scaling, and wire mesh. A priority rating system is also in use to direct proactive mitigation work in areas of high rockfall hazard around the state. In addition, WSDOT and Washington State University are developing an expert-type computer system, the unstable slope management system (USMS), for statewide use.

The mountainous and rugged terrain of Washington State presents major and ongoing rockfall problems along transportation corridors. A significant number of accidents and nearly a half dozen fatalities have occurred because of rockfall in the last 30 years on Washington highways. A preliminary statewide inventory revealed that 45 percent of all unstable slope problems (landslides, embankment failures, rockfall, etc.) are rockfall related.

Washington has a large highway infrastructure in place, and much of the present rockfall mitigation focuses on methods for control or containment. As the state highways are improved to meet current design standards, more of the mitigation work is focusing on rockfall identification and prevention. In this paper methods of rockfall control in Washington are addressed, as well as the proactive approach of prevention. Rockfall prevention includes the use of the most current standards for rock cut-slope designs, rockfall hazard priority rating, and development of a statewide unstable slope management system (USMS).

ROCKFALL DITCH DESIGN

In early Washington highway construction, methods of rockfall control included large flat ditch sections, wire mesh, midslope benches, and so on. However, there was little basis for the application of such rockfall designs, and designers relied on educated guesses about rockfall behavior on a particular slope. As early as 1959, engineers in the state of Washington began to realize the inadequacy of some design methods to control rockfall in deep cuts (*1*). The Washington Department of Highways [now the Washington State Department of Transportation (WSDOT)] recognized that little was known about the effectiveness of standard rockfall containment measures, and that even less was known about the mechanics of rockfall.

In 1961 the Washington State Highway Commission (WSHC) and the Bureau of Public Roads (BPR) funded a research project under the direction of Arthur Ritchie, chief geologist for WSHC (*2*) to study rockfall mechanics. In the research project full-scale rockfall observations were made under varying slope conditions and additional experiments were performed with portable ditch sections and rock fences.

With the conclusions from the research, Ritchie (*2*) developed a rockfall ditch design table that took into consideration the primary variables of the rockfall—slope height and slope angle. The ditch design contained three basic elements: fallout width, ditch depth, and a steep off-shoulder slope. In the case of natural slopes flatter than 1H:1V, on-slope rock protection fences were developed.

In 1963, WSDOT adopted a standard design for rockfall control that was based exclusively on this research. The standard roadway section contained two designs: one for rock slopes (Design A) and one for talus slopes (Design B). Subsequent to the original standard plan, Design A has been modified to allow for staged development of the rockfall ditch.

Design A—Rock Slopes

The staged development concept for Design A is to provide alternatives that are based on local site conditions and an estimate of the severity of future rockfall. The use of controlled blasting in developing the rock cut is recommended in conjunction with the ditch design. The width of the ditch is controlled primarily by the slope angle and slope height (see Table 1). Stage 1 design uses a standardized ditch section

TABLE 1 WSDOT DESIGN FOR ROCKFALL AREAS—DESIGN A

Slope	Height (ft)	Width (ft)
	20 - 30	12
Near	30 - 60	15
Vertical	>60	20
	20 - 30	12
0.25H:1V	30 - 60	15
or	60 - 100	20
flatter	>100	25

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(see Figure 1). Stage 2 and 3 designs use rock protection fences and deeper ditch sections for more severe applications (see Figures 2 and 3). Concrete barriers may be used instead of the rock protection fence. The concrete barrier alternative in Stage 2 and 3 designs is used only after an analysis of the site in which consideration is given to factors such as potential impact velocities, ditchy capacity, and size of rockfall.

Design B—Talus Slopes

Design B is used as a treatment for rockfall generated on talus slopes. Ritchie's (*2*) research revealed that rockfall on these slopes will generally roll and stay close to the slope. Rock protection fences are specified on these slopes because of the strong horizontal component of the trajectory. The purpose of a rock protection fence is to decelerate or catch the rolling rock before it enters the roadway. The ditch treatment calls for a steep 1.25H:1V foreslope into the ditch with a minimum depth of 4 ft. Design B allows for three positions of the rock protection fence (but never more than one position at any given site). Fence positions A, B, and C are shown in Figures 4, 5, and 6, respectively. Position B is the preferred fence location for most applications.

ROCKFALL HAZARD PRIORITY RATING

In 1988, WSDOT began using a priority rating system to address rockfall problems on existing facilities around the state. The goal of the system was to assess a large number of areas where rockfall occurred and to objectively rate the slopes in terms of potential hazard. The rating provides a basis for selecting potential sites that require rock slope remediation. Ideally, rock slope remediation would first focus on sites with the highest hazard ratings and then progress to lower-rated rock slopes as funds become available.

The rating system in use by WSDOT was developed by the Oregon Department of Transportation (*3*) and uses a matrix evaluation approach. Sites are rated on 11 criteria such as rock structure, highway geometrics, slope height, and rockfall frequency. Increasing levels of severity for each criterion are given greater point values using an exponential point scale. All the points for each of the 11 criteria are totaled for each investigated site. The site with the highest point total is theoretically the most hazardous and that with the lowest point total is theoretically the least hazardous. The rating system is not meant to predict which slope will fail first, but rather to provide a logical starting point for remediation work on a large number of rock slopes.

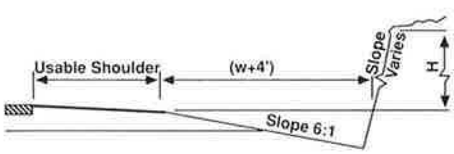

FIGURE 1 Roadway section on rock slope—Design A, Stage 1.

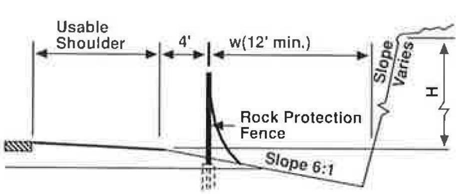

FIGURE 2 Roadway section on rock slope—Design A, Stage 2.

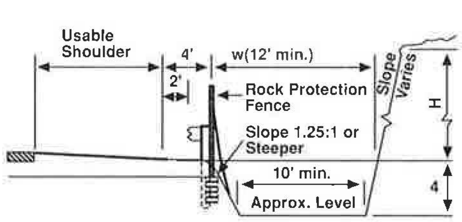

FIGURE 3 Roadway section on rock slope—Design A, Stage 3.

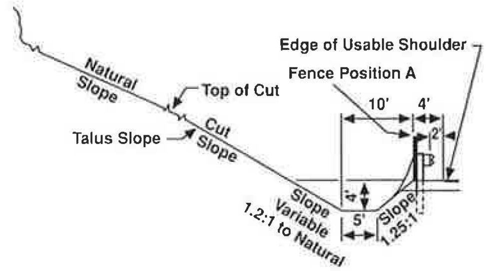

FIGURE 4 Roadway section on talus slope—Design B, fence position A.

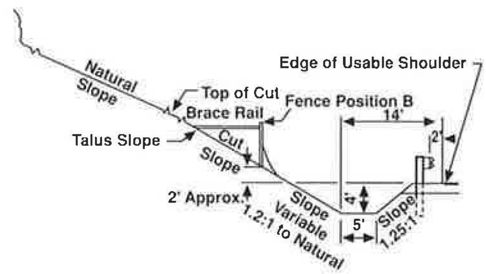

FIGURE 5 Roadway section on talus slope—Design B, fence position B.

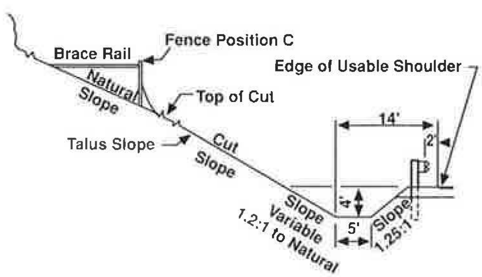

FIGURE 6 Roadway section on talus slope—Design B, fence position C.

The Geotechnical Branch of WSDOT completed a pilot project in 1989 using this rockfall hazard rating system in District 1 the northwest part of the state (*4*); 39 problem rockfall areas were identified by the four maintenance areas of the district. Phase I of the project consisted of rating and priority-ranking each of the 39 sites. The district then selected a group of high-ranking sites to address first. Phase II of the project consisted of providing final remediation design and cost estimates of the required work on the sites selected. The final remediation designs prepared in Phase II focused on long-term solutions. Final designs included work such as slope scaling and trimming, shotcreting weak zones in the rockmass, and rockbolting and dowelling. In 1990, the district appropriated $250,000 to begin work on the list. Additional funds for 1992 have been set up to continue remediation work on the list of 39 slopes.

Since this pilot project, the Geotechnical Branch has completed another rock slope priority-ranking study on a 10-mi length of Interstate in the northwestern portion of the state. Based on these pilot projects, at least three other major state highway routes representing approximately 180 mi of highway within the state are being considered for rock slope rating and ranking.

UNSTABLE SLOPE MANAGEMENT SYSTEM (USMS)

Under a research grant administered by the Washington State Transportation Commission (WSTC) and the Federal Highway Administration (FHWA), WSDOT and Washington State University (WSU) are developing the USMS (*5*). The research is being conducted by the WSU Civil Engineering Department. The USMS is a computer program consisting of a database and priority programs that prioritizes unstable slopes. Unstable slopes include not only rockfall, but also landslides, embankment failures, debris flows, etc. The priority programs are developed from the expert shell system CLIPS, a language developed by the National Aeronautics and Space Administration. The USMS identifies factors that determine the importance of a failure site such as the cause of instability, cost of repair, use of road, and safety to motorists. The data are collected and stored in the database by site. Using the priority programs, priority ratings are assigned to each site and then multiplied by a weight. The sum of the products yields the total priority, which ranges from a point value of 0 to 100, where 100 indicates the highest-priority site. The total priority of a site is independent of all other sites. The USMS develops a list of priority-ranked sites from which mitigation work can be selected.

ROCKFALL MODELLING

WSDOT has been using the Colorado Rockfall Simulation Program (CRSP) developed by the Colorado Department of Transportation to aid in rockfall mitigation design (*6*). The program allows the designer to input the geometry of the slope and define certain parameters of the slope. The program then simulates a number of rockfall events and provides output information on items such as impact force, trajectory path, and termination point. The program has provided WSDOT with design information for necessary length of a tunnel portal extension, rockfall protection fence placement, and ditch design verification.

ROCK SLOPE DESIGN

Rock slope design is a critical element of rockfall control in Washington State. The potential for rockfall can be dramatically reduced by the proper engineering of new and upgraded cut slopes. All proposed construction of rock slopes is reviewed by the Geotechnical Branch of WSDOT early in the design process.

Rock slopes are first evaluated for their potential for kinematic failure. Does the rockmass contain ordered sets of discontinuities (e.g., bedding surfaces, joints, faults) that could produce rockfall when the slope if excavated at a typically steep orientation? Rockmasses that appear to be kinematically controlled are evaluated for three failure conditions: planar failure, wedge failure, and toppling failure (see Figure 7). A nonkinematically controlled failure would more commonly fail as a circular failure. A statistically significant number of discontinuity orientations are gathered and then plotted on stereo nets. An evaluation can then be made as to whether the rockmass contains adverse discontinuity sets that could produce instability in the slope. Design slope orientation may then be adjusted to cut out many of these potentially unstable features. This design approach focuses on repeatable discontinuity sets. It does not attempt to address every possible joint set that may produce an isolated rockfall event.

Rock slopes that are not structurally controlled are also evaluated. However, the focus of rock slope engineering is on large-scale failures rather than small-scale events. Rockmasses that are not structurally controlled include ones that are highly fractured, massive slopes that contain no or few joint sets, highly weathered or hydrothermally altered rockmasses, and many Washington State sedimentary rockmasses. WSDOT uses Hoek and Brown's (*7*) nonlinear failure criteria to evaluate these rockmasses. In the evaluation, the quality of the rockmass is classified using the Council for Scientific and Industrial Research (CSIR), Geomechanics Classification of Jointed Rock Masses developed by Bieniawski (*8*), which

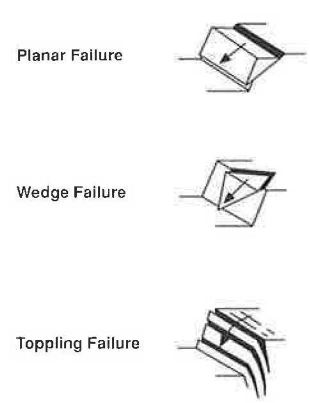

FIGURE 7 Kinematic failure conditions.

uses test hole and laboratory data from the rockmass. The Hoek-Brown (*7*) criteria then use empirically derived values for different rock types and rock quality conditions to develop a Mohr envelope. Corresponding strength parameters are then determined for a certain confining pressure and a computer-assisted stability analysis is performed using XSTABL or PCSTABL4. WSDOT has had excellent results using this method of analysis for nonkinematically controlled rockmasses.

Controlled Blasting

Many of the rockfall problems along Washington highways are a result of poor rock excavation methods used when the slopes were first constructed. Poorly designed blasting can result in excessive backbreak in the finished slope and continued rockfall problems for years after construction. Controlled blasting methods are required on all WSDOT projects for excavation in rock. These methods include the initiation of a preshear line along the finished slope before the production holes are detonated. WSDOT has had successful experience with preshearing slopes as flat as 1H:1V. Preshearing is not required by WSDOT for slopes flatter than 0.5H:1V and for burdens less than 10 ft. Before implementation, all blasting operations on state highway projects must submit a blasting plan for review by the Geotechnical Branch of WSDOT. When properties of the rockmass are sufficiently poor, mechanical excavation (e.g., ripping) is allowed, provided that finished slopes are approximately 0.5H:1V or flatter.

Midslope Benches

WSDOT designs rock slopes to be uniform, with as few slope irregularities as possible. The construction of 20-ft-wide midslope benches on steep rock slopes to catch rockfall is no longer practiced in Washington. Without continued maintenance, benches fill with rock debris. This results in a bench that is no longer flat but slopes outwards to the roadway. Rockfall striking these benches is no longer contained, and a significant horizontal component can be imparted to the trajectory path. Midslope benches are permitted only at the overburden-bedrock interface. When rockfall may originate from coarse overburden soils, a bench of 15-ft minimum width may be specified provided the soil slope is not over approximately 20 ft high. Vegetation is also stripped from the rock slope and 10-ft behind the upper catchpoint of the slope to prevent root wedging of blocks.

Rockfall Protection Fences

WSDOT uses rock protection fences for rockfall control and has developed standard plans for their construction. The fence is used in areas where rockfall would not be adequately contained by a ditch. These applications are generally used on flatter slopes such as talus slopes, where a horizontal component in the trajectory path is present. The standard plan for the fence consists of a 6-ft-high chain link fence fastened to steel posts with 2 to 3.5 in. inside diameter and 9 ft long. Upslope bracing is used for midslope anchor positions and impact attenuators are used to anchor the end of the fence.

WSDOT has had extremely good success with this rockfall protection fence. In addition to the standard plan for rock protection fences, WSDOT is considering the use of a proprietary rock protection fence developed in Europe. WSDOT would use this fence system for areas with high rockfall frequency and large rock size.

Wire Mesh Slope Protection

WSDOT uses wire mesh slope protection in areas where construction of an adequate ditch section is not feasible or where slope features would produce a large horizontal component in the rockfall. Wire mesh slope protection is used both to contain rockfall and to prevent ravelling of loose material. A typical wire mesh slope protection system consists of main vertical cable supports anchored at the top of the slope to which a wire mesh is attached, which is draped down the slope. The wire mesh is generally double twist gabion wire on galvanized chain link fence. The vertical wire mesh seams are wired or hog-ringed together to form a continuous blanket. WSDOT uses deadmans above the crest of the slope to anchor the wire mesh in overburden or weathered rock, and grouted rock anchors to attach the wire mesh in competent rock. The wire mesh typically extends downslope to within approximately 5 ft above the ditch. Wire mesh slope protection installed in mountainous areas is subject to heavy snow loads, and anchor systems are designed accordingly. WSDOT has effectively used wire mesh for near-vertical rock slopes and rock and talus slopes as flat as 1H:1V. For steep slopes it is important that rock sizes be less than 2 ft in diameter; larger rocks may have sufficient energy to break the mesh.

Gabion Barriers

WSDOT has also had extensive experience with gabion barriers for rockfall control on talus slopes. Their flexibility and relative ease of repair make them useful for areas with high rockfall frequency and very large rock size. Gabions are placed approximately 10 ft in front of the base of the slope and off the shoulder. Openings in the gabion wall are provided to allow for removal of the rock debris behind the wall. Gabions have proven to be very effective control for large rock size. In one instance, several rocks of more than 50 tons were retained by a two-tier-high gabion wall after the rocks had rolled several hundred feet down a steep talus chute.

Rock Debris Barriers

Rock debris barriers are also used in Washington State for containing rockfall. Rock debris barriers consist of 4- to 8-ft-high continuous mounds constructed of rock or soil debris near the base of the slope. These barriers provide the trapezoidal ditch section and energy attenuation required for containing rock fall with high energy and frequency. Rock debris barriers are typically used on talus slopes that produce a significant amount of rockfall containing large boulders.

Scaling and Trimming

Slope scaling and trimming are used extensively for rockfall control. Scaling consists of removing loose rock debris on a slope with scaling bars, hydraulic splitters, and so on. Trimming refers to removing sizable unstable blocks and slabs from a slope, generally by use of explosives. Scaling is done on almost all new construction and remediation work in Washington State. Scaling and trimming are generally the first order of work for rock slope remediation projects. Work always progresses from the top down, moving across the length of slope and is accomplished by a crew of at least two on-slope workers and a foreman. The work can be extremely hazardous and WSDOT requires that only experienced high scalers be allowed to perform it.

Rock Bolting and Doweling

Rock bolting and doweling are commonly used on both new construction and rock slope remediation work for controlling rockfall. Rock bolts are posttensioned steel bars and tendons that are used to anchor potentially unstable masses to the slope. Rock dowels are similar except that they are not posttensioned; stresses are mobilized in the steel bar when and if the potentially unstable mass begins to move. Rock bolts and dowels are anchored into the rock with either cement grout, two-stage polyester resin, or mechanical anchors. Bolting and doweling is performed after loose rock has been scaled from the slope and is accomplished from either a crane-supported work platform or off ropes by experienced high scalers. Crane-supported work platforms generally use an air track drill for advancing the bolt and dowel holes. Platforms are typically anchored to the slope to allow for some drilling resistance. Rock bolting operations require skilled workers to perform the work safely and effectively.

Horizontal Rock Drains

Horizontal rock drains are commonly used for rockfall control in both new construction and remediation work by WSDOT. Horizontal drains dewater rockmasses and lessens the driving forces leading to slope failure. Generally the drains are uncased holes drilled into the slope by an air track drill or a portable rock drill. When horizontal drains are installed in highly fractured rockmasses, it is often necessary to case the hole with slotted polyvinylchloride (pvc) pipe to maintain the drain opening. Since most water in a rock slope is carried within discontinuities, drains are installed to intersect as many discontiuities as possible. Drains are typically installed sloping down and out of the rockmass at approximately 5 degrees. Both straight and fan-shaped drain arrays are used.

Shotcrete

Shotcrete is used in both new construction and remediation work by WSDOT. Shotcrete is used in weak, highly weathered or hydrothermally altered zones to prevent differential erosion. It has also been used for interbedded sedimentary units in which differential weathering of poorly indurated units could undermine more resistance units. The shotcrete is reinforced either with wire mesh affixed to the slope or by the use of steel or polypropylene fibers incorporated into the shotcrete mixture. Adhesion of the shotcrete to the slope is lessened under excessive moisture conditions. Weep holes through the shotcrete are installed with every application. WSDOT prefers the use of fiber-reinforced shotcrete because it conforms better to slope irregularities and is simpler and less expensive to construct. Experienced workers are an important factor in the success of shotcreting for rock slope stabilization.

Rock Sheds and Tunnel Portal Extensions

Rock sheds are in place on Washington mountain passes where the highway crosses large talus and avalanche slopes. WSDOT also utilizes portal extensions for tunnels, where necessary, to minimize risk from rockfall.

Rock Patrols

The Maintenance Division of WSDOT plays a very important role in rockfall control along state highways. Rock patrols are run on certain sections of state highways 24 hrs a day, 7 days a week because of increased rockfall frequency during late fall and winter.

Rock Slope Remediation Specifications

Until 1986, WSDOT did not have specifications for rock slope remediation. WSDOT surveyed other western states and found that none had such specifications either. WSDOT has since developed standard special provisions for scaling and trimming operations, rock bolting and doweling, horizontal rock drains, and shotcreting. The emphasis of the special provisions is quality control and amount of work experience. Rock anchors and shotcrete have performance specifications to ensure quality installation and application. All of the specifications contain language requiring a minimum level of work experience for all workers involved in remediation. WSDOT believes that only experienced workers should be allowed to perform remediation because all phases of the work are potentially so hazardous.

CONCLUSIONS

WSDOT controls rockfall containment, as well as prevention and minimization. A full spectrum of rockfall ditches, fences, and rock slope stabilization methods is employed for controlling rockfall in Washington State. Increased interest in the state on maintenance issues has resulted in appropriation funds for rockfall mitigation for a proactive response to rockfall problems. WSDOT is using a rockfall priority-ranking system to identify rockfall problems on a regionwide basis and to provide a logical plan for mitigation. In addition, Washington State is developing an expert-type management system to address unstable slope problems on a statewide basis.

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