

Guidelines for Certification and Management of Rockfall Fence Systems

Final Report

Prepared for
National Cooperative Highway Research Program, Project 24-35
Transportation Research Board
of
The National Academies of Sciences, Engineering and Medicine

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ABSTRACT

Rockfall fence systems have been used throughout the world to mitigate rockfall from affecting structures and highways. The report consists of reviewing past and present guidelines for testing and certifying rockfall fence systems and reviewing management practices associated with these systems. The initial part of the study consisted of gathering data regarding rockfall systems in the form of survey questions from State and Federal transportation agencies, rockfall system design engineers, and rockfall system manufacturers. Based on review of the current European testing standards and results of this study, it is recommended to accept the European Standards with further documentation. The report also provides guidelines to assist transportation agencies to obtain the data necessary to evaluate the results of rockfall fence systems tested using the procedure recommended for acceptance.

Guidelines for asset management for rockfall fence systems were developed and are presented to assist transportation agencies in incorporating rockfall fence systems into existing transportation asset management plans. Asset management guidelines presented include inventory and condition assessment methods to assist transportation agencies in gathering the necessary information to perform life cycle analysis to evaluate and prioritize rockfall fence system projects. A case history of the proposed inventory and condition assessment is presented to validate the proposed methods.

SUMMARY

Rockfall fence systems have been in service along roadways in Europe and the United States for more than 40 years. In the United States, rockfalls occur each year along highways; consequently, rockfall fence systems have become an important component of highway safety and maintenance. Rockfall fence systems are usually designed and rated based on full scale testing of energy capacity or energy reduction of a single rockfall event with some consideration for serviceability after specific impacts.

Prior to 2003, no widely accepted means were available to test and certify flexible rockfall fence systems sold in the United States (U.S.). In 2003, the National Cooperative Highway Research Program (NCHRP) Project 20-07, Task 138, “Recommended Procedures for the Testing of Rockfall Barriers” (Higgins 2003) was submitted to the American Association of State Highway and Transportation Officials (AASHTO). This task report recommended acceptance of the Swiss testing standard and certification process (Gerber 2001).

In 2008, the European Union (EU) implemented standardized testing and certification of rockfall fences known as European Technical Approval Guideline (ETAG) 27. ETAG 27 differs from the Swiss standard making direct comparisons of test results reported from each standard more difficult. Most European manufacturers are certifying their products in accordance with ETAG 27 guidelines.

Currently, U.S. transportation agencies do not have testing standards and certification procedures for these flexible rockfall fence systems. Based on the research described in this report, acceptance of the ETAG 27 test procedure is proposed for use within the U.S. eliminating the need for manufacturers to perform additional testing. A request form has been developed for agencies to request data collected during an ETAG 27 test from manufacturers so the agency can evaluate the system for conformance with a project specific specification regarding the rockfall fence system performance.

In addition, the long-term performance and maintenance issues of flexible rockfall fence systems are a growing concern for many transportation agencies that have installed these systems and are faced with significant maintenance, repair, and/or replacement costs. Currently, there are no well-defined provisions or protocols for inventory, condition assessment, and life-cycle modeling of rockfall fence systems. Asset management offers a framework for monitoring performance of rockfall fence systems and understanding the condition/deterioration time-line so that transportation agencies can make informed life cycle cost-based decisions about these assets. Combining technical analysis with asset management principles can yield a more efficient and fiscally responsible transportation system that focuses on preservation of assets while maintaining the required level of service set by owners.

Guidelines are presented for the inventory and condition assessment of flexible rockfall fence systems to collect the data necessary for transportation agencies to perform life cycle and risk analysis to guide project evaluation and prioritization.

CHAPTER 1

Background

1.1 Problem Statement

1.1.1 Certification of Rockfall Fence Systems in the United States

Rockfall fence systems are used to mitigate rockfall and generally consist of flexible nets or panels that are connected to a post system with energy absorbing braking elements. Rockfall fence systems are currently designed and given an energy rating based on full-scale field testing to determine the energy capacity or energy reduction of a single rockfall event with variable considerations for serviceability after specific impacts. Most of the current tested and rated rockfall fence systems manufactured today were developed in Europe and are specific to a manufacturer system. Prior to 2003, no widely accepted means were available to test and certify fences sold in the United States (U.S.). In 2003, National Cooperative Highway Research Program (NCHRP) Project 20-07, Task 138, “Recommended Procedures for the Testing of Rockfall Barriers” (Higgins 2003) was submitted to the American Association of State Highway and Transportation Officials (AASHTO). This task report recommended acceptance of the Swiss testing standard and certification process developed by the Swiss Agency for the Environments, Forests and Landscape (SAEFL) and the Swiss Federal Research Institute (WSL) (Gerber 2001). In 2008, the European Union (E.U.) implemented standardized testing and certification of rockfall fences known as European Technical Approval Guideline 27 (ETAG 27) for Falling Rock Protection Kits (EOTA 2008). ETAG 27 differs significantly from the Swiss standard. Most European manufacturers are now certifying their products in accordance with ETAG 27. Currently, U.S. transportation agencies do not have testing standards and certification procedures for these rockfall fence systems.

1.1.2 Asset Management of Flexible Rockfall Fence Systems

MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), was signed into law on July 6, 2012 and took effect on October 1, 2012. The bill provides funds for surface transportation investments in fiscal years 2013-14, and also establishes a new performance-based management framework. While the language mandates an inventory of pavement and bridge assets on the National Highway System (NHS), it also encourages States to include all infrastructure assets within the right-of-way corridor and requires States to achieve or make significant progress toward achieving its performance targets; and establishes penalties for non-compliance. MAP-21 does not approve or certify a State’s asset management plans, but certifies the process used in developing such plans. At the time it did not specifically contain references for asset management related to geotechnical features but many DOTs are developing such processes. By including geotechnical assets within an agency’s asset management plan, the potential benefits and staying power of best-practice asset management are to be enhanced.

Overall the desired outcome of geotechnical asset management is the establishment of more predictable and sustainable funding allocation policies and program management decisions. A difficulty that will need to be overcome in developing asset management related to geotechnical features is that steel, concrete, and pavement have well defined and measureable parameters that relate well to performance

based management systems whereas, soil and rock are generally not well defined and have wide ranges in measurable and non-measurable parameters.

1.2 Research Objectives

The objective of this research was to produce guidelines on rockfall fence systems for transportation agencies that address the following:

- Testing, approval, and certification methodologies, as well as proposed performance-based specifications for flexible rockfall fence systems and components thereof.
- Inspection, maintenance, and repair procedures for flexible rockfall fence systems.
- Development of an asset management plan, including long-term performance and condition measures, and establishment of critical factors and key components in determining estimates of future performance, life-cycle cost, and cost/benefit analysis for maintenance, repair, and replacement decisions for flexible rockfall fence systems.

CHAPTER 2

Research Approach

2.1 Project Overview

The research effort was separated into four major tasks:

- Review Previous Rockfall Fence Testing Standards
- Review of Previous Geotechnical Asset Inventory and Assessment Systems
- Review of Transportation and Geotechnical Asset Management Systems
- Rockfall Fence System Survey of Transportation Agencies, Design Engineers, and Manufacturers

These tasks were developed to achieve the research objectives and to guide the research effort progressively to the development of an asset management plan for flexible rockfall fence systems. Much of the research conducted to accomplish these tasks included review of work previously completed for flexible rockfall protection systems; however, the findings have been applied specifically to rockfall fence systems.

2.2 Review Previous Rockfall Fence Testing Standards

Literature related to the development of rockfall fence testing procedures was reviewed. The literature review was intended to identify the methods used for rock or block delivery systems and the physical setup of these systems. This focused on advantages and disadvantages of previous rockfall fence testing procedures. Methods used for measurement and analysis of parameters important for evaluating systems effectiveness and cost associated with performing these tests were also reviewed. Special emphasis was placed on the most recent testing programs as they are likely to have the most well-developed testing procedures, delivery systems, and measurement techniques.

The literature review also consisted of a detailed review of the Swiss (SAEFL) guideline (Gerber 2001; FOEN 2006), the NCHRP 20-07 recommended test procedures (Higgins 2003), and the E.U. (ETAG 27) testing and approval guideline (EOTA 2008). The primary focus of this task was to identify test parameters in the existing guidelines and how they relate to the performance of fence systems. The test parameters were also evaluated for the advantages and disadvantages of using these parameters for the specified performance indicator. This included identifying parameters that are important to fence installation practice in the U.S. that are not evaluated in the ETAG 27 procedures. Additionally, publications discussing the experiences of using the test procedures and guidelines were reviewed to identify limitations of the existing test procedures.

2.3 Review of Previous Geotechnical Asset Inventory and Assessment Systems

Literature related to geotechnical asset inventory and assessment systems were reviewed to evaluate the current state of practice and methods used that may be applicable to flexible rockfall fence systems. This review included information from U.S. transportation agencies collected through surveys and published

information from other transportation agencies such as railroads. A review of European inventory and assessment systems was also conducted to the extent possible.

Existing retaining wall inventory and retaining wall assessment systems were reviewed to evaluate various methods used to perform these tasks. This information was intended to identify the procedures used, the detail required in the inventory, and the methodologies used for assessing walls based on the data collected during the inventory. Methods found in the literature review used for evaluation of retaining wall systems appeared to be directly applicable for use in inventory and assessment of flexible rockfall fence systems.

2.4 Review of Transportation and Geotechnical Asset Management

Currently there are no published examples of asset management plans in place or under development for rockfall protection systems. Nonetheless, a considerable body of work does exist in related fields, including mature asset management processes and tools for pavements and bridges, and new capabilities under development for geotechnical assets. Some of the most significant themes found in the literature review are:

- Implementation plans and guidance for transportation asset management
- Research and guidance documents on transportation levels of service and performance measures
- Inspection standards for other transportation assets, especially bridges
- Condition and performance assessment and communication practices for other assets
- Web sites of transportation agencies, particularly those with performance dashboards
- The extensive literature on safety, risk, and life cycle cost analysis
- Literature on multi-objective optimization
- Literature on program management and budgeting

Together, these information sources provide a variety of techniques that are potentially useful for discussion of rockfall fence asset management. Many states such as Colorado and Alaska are making progress on their Geotechnical Asset Management Plans, but they are still in development.

2.5 Survey Input from Transportation Agencies, Designers, and Manufacturers Regarding Rockfall Fence Systems

Surveys were sent to transportation agencies, design engineers, and rockfall fence manufacturers to evaluate the existing state of practice for testing, certification, inspection, maintenance, and asset management of rockfall fence systems and are outlined as follows:

- The surveys were separated into five sections consisting of Contact Information, Background, Standards and Certifications, Design and Construction, and Maintenance and Repair. Three similar surveys were created for each of the groups with specific questions directed toward each.
- The transportation agency survey was intended to be completed by the Rockfall Program Manager or someone in a similar position within transportation agencies and departments of transportation (DOTs).
- The design engineer survey was intended to be completed by engineers and other professionals who have experience with rockfall fence systems.
- The manufacturer survey was intended to be completed by a qualified engineer or someone in a similar position within a company that produces rockfall fence systems and components of those systems.

The Contact Information section gathered information on the person completing the survey and their role within their agency or firm. The Background section gathered information related to the agency's rockfall mitigation projects and the number and types of projects the agency designs and constructs per

year. The Standards and Certifications section collected information on any existing methodologies for testing and certification of rockfall protection systems. The Design and Construction section gathered information on existing practice for design and construction of various components related to rockfall protection systems. The Maintenance and Repair section collected information on how inspection, maintenance, and repair are generally performed and what criteria are used to initiate these tasks. This section also gathered information related to any existing asset management techniques used for flexible rockfall protection systems. The Transportation Agency, Design Engineers, and Manufacturers survey questions are provided in Appendix A.

CHAPTER 3

Review of Flexible Rockfall Fence Testing Definitions, Standards, and Guidelines

3.1 Rockfall Protection System Definitions

Rockfall systems have many definitions and descriptions. Where possible the definitions used in this document are defined based on descriptions in the Transportation Research Board (TRB) publication *Rockfall Characterization and Control* (Turner and Schuster 2012). However, within the TRB publication many of the definitions vary in use from chapter to chapter. The following are definitions of types of flexible rockfall protection systems as used in this study:

Rockfall Fences (Figure 3-1), also sometimes referred to as flexible rockfall barriers, are designed to stop individual rockfall events. As described by Duffy and Badger (2012), rockfall fences typically consist of panels (interception structure), infrastructure (support structure), friction brakes (energy-absorbing devices or connections), and foundations. These systems are commonly tested and certified by various European testing agencies and are rated between 100 and 8,000 kilojoules (kJ) for a single rockfall event.



Source: Photography courtesy of B. Arndt

Figure 3-1. Example of a flexible rockfall fence

Attenuators (Figure 3-2), also sometimes referred to as hybrid drapery, are a flexible rockfall panel system which consists of various combinations of panels and infrastructure that are intended to reduce the velocity and energy of a rockfall event initiating upslope of the installation, but are not intended to stop the rockfall completely. As described in Duffy and Badger (2012), these systems are intended to control the continued descent of the rockfall by attenuating the energy of the rock. These systems may or may not have braking elements.



Source: Photography courtesy of B. Arndt

Figure 3-2. Example of an attenuator

Drapery Systems (Figure 3-3), referred to as unsecured drapery by Badger and Duffy (2012), typically consist of single twist wire mesh, double twist wire mesh, cable mesh or net, or other panel systems that are attached to a top cable that is generally suspended from the top of a slope by ground anchors or posts in the case of a hybrid drapery. Hybrid drapery systems are similar to attenuator systems, but are generally used on steeper slopes compared to attenuator systems. Rockfall events generally initiate beneath these systems and potentially upslope of the installation in the case of a hybrid drapery system. These systems are typically designed to hang freely to allow migration of rock falling between the panel and slope guiding the rock into a catchment ditch.



Source: Photography courtesy of B. Arndt

Figure 3-3. Example of a drapery system with cable net panels

Anchored Mesh, also referred to as secured drapery (Badger and Duffy 2012), is a slope stabilization system that consists of single twist wire mesh, double twist wire mesh, cable mesh or net, or other panel systems that are pattern anchored with ground anchors and are used to retain debris between the mesh panel and slope.

Pierson and Vierling (2012) also describe many additional rockfall mitigation measures that are outside of the scope of this research.

3.2 Discussion on Rockfall Fence Testing Delivery Methods

3.2.1 Rock Rolling Tests

The first rockfall testing programs conducted in the U.S. used natural slopes for rolling rocks to evaluate rockfall trajectories as well as various mitigation techniques. This type of test was chosen for its simplicity as well as the ability of the test to match site specific conditions for rockfall events. This type of test is the most applicable for the purpose of evaluating site specific rockfall characteristics. Rock impacts with a test fence include both translational and rotational kinetic energy as would be the case in most real applications. However, this type of test is difficult to use for developing test procedures that are reproducible for the purpose of comparing the capacity and performance of fence systems.

The characteristics of the slope such as the length, height, surface roughness, and composition influence the rockfall trajectory and energy. Because rocks are not likely to follow the same trajectory down the slope, the location and angle of impact are not easily predicted or reproduced between tests. This makes it difficult to test the same or different fences consistently such that a comparison between capacity and performance is possible. Duffy (1992) and Duffy and Haller (1993) suggest that fence maintenance increases and efficiency decreases as rocks impact further from the center of the fence

panels. It is therefore important to be able to reproduce the impact location during testing such that different fences can be compared. In the application of fences for protection, impacts will not always occur near the center of panels making impact location important for the proper design of these systems.

In testing fences on slopes using rock rolling, it is possible for the rock to make contact with the ground after being intercepted by the fence, but before the fence has reached the maximum elongation. This ground impact absorbs some of the energy of the rolling rock leading to uncertainty in the amount of energy that is absorbed by the fence. This limitation could be avoided by having a sufficiently steep slope behind the test fence to prevent the rock from contacting the ground during elongation. Such a test setup is likely to make fence installation and maintenance more difficult. Also, this test setup requires increased effort to remove test rocks from the fence after impact. A crane may be the most useful equipment for rock removal; however, this will likely increase the cost of the testing program.

The velocities of rocks at impact using rock rolling tests are typically inconsistent. This makes it difficult to predict and reproduce tests using this method. For the purpose of evaluating the capacity of a fence, it is desirable to achieve a specific energy at impact. This requires an estimate of the velocity and mass of the rock at impact. While the mass of the rock can be obtained relatively easily, it is much more difficult to achieve the desired velocity at impact, making this test method problematic for testing energy capacity.

The uncertainty in the horizontal and vertical impact location, angle, and energy associated with rock rolling test methods typically prolong test programs because several rock rolls are typically required to achieve the desired impact energy and location. In many instances, rocks rolled may miss the test fence or stop on the slope before reaching the fence. Of data available from test programs using rock rolling, on average greater than 30 percent of the rocks rolled either missed or stopped before reaching the fence. It may be possible to conduct rock rolls before installing the test fence to better calibrate the necessary rock mass to achieve the desired energy levels and impact locations, but again, this could prolong testing and considerable uncertainty would still exist due to varying rock rolling trajectories.

The use of a smooth rock slope may help to reduce uncertainties in rockfall trajectories and energies. The availability of such a slope is likely limited and rocks rolling down a rock slope are more likely to fragment during the test making accurate evaluation of impact energies difficult. Another option to help reduce uncertainties in rockfall trajectories and energies may be to conduct testing by installing the test fence across a narrow gully to confine the rock trajectory laterally. The use of a spherical rock would help to control the vertical trajectory as well as reduce variation in impact velocities and energies. While these conditions may not represent realistic conditions, they would provide better control for a standardized test. Use of a narrow gully may complicate access for fence installation and measurements for the tests.

3.2.2 Inclined Cable Type Tests

An inclined cable system developed in Switzerland in 1991 allowed the rock to strike the ground in front of and then roll into the test fence (Baumann 2002). This method was intended to increase the velocity of the rocks at impact, but it was found that the energy absorbed by the single ground impact was similar to the energy absorbed during multiple ground impacts using the rolling rock method causing considerable velocity variation. This test procedure had the advantage of rotational energy imparted on the rock during the impact before reaching the test fence, although the rotational energy was likely highly variable.

The inclined cable system allowed for improved control over the lateral impact location, but the height and angle of impact were difficult to predict and reproduce. Both the height and angle of impact were dependent on the velocity of the rock before and after impact with the ground. While the consistency of the lateral impact location was improved, the ability of the lateral impact location to be varied was limited

due to the cable system. In order to test a different section of the fence, the location of cable system or the fence had to be modified.

Modifications were made to the inclined cable system test used in Switzerland and Italy in the 1990s (Baumann 2002 and Peila et al. 1998). This included launching rocks directly into the test fences, which allowed for a relatively narrow range of rock velocities that varied with the geometry of the test site. This allowed prediction and calculation of rock energies prior to tests and also made tests more reproducible. Impact locations and angles could also be predicted and reproduced making comparison of different products much easier than in previous test methods. However, the angle of impact may be reproducible at a single test site, but it may not be easily reproduced among different test sites. This could lead to differences in the capacity and performance of fences based on which test site is used. Additionally, allowing the rock to directly impact the fence results in only translational energy of the rock and rotational energy is not considered.

Limitations of this system still include the difficulty of varying the impact location, which could be reduced by redesign of the system. Other limitations include specialized equipment required to release the rock at the proper time before reaching the fence and the difficulty of handling large rocks required for high energy tests. An inclined cable system used in 2007 in Italy (Peila et al. 2007) was capable of producing energies in excess of 5,000 kJ (1,844 ft-tons). If fences are developed to absorb energies greater than 5,000 kJ, redesign of inclined cable type systems may be required to safely conduct testing.

As with the rock rolling method, this method must ensure that the rock does not make contact with the ground during elongation of the fence. The setup of this test method on a slope may make installation, maintenance, and rock removal more difficult. With the proper design, the inclined cable system could likely be used in fence installation and rock removal as well as delivering the rock to the fence during tests. Such a system would require extensive infrastructure that would be cost prohibitive for a temporary facility and would only be practical for a permanent facility.

3.2.3 Vertical Drop Tests

Researchers performing testing in Japan in 1998 (Muraishi and Sano 1999) chose a vertical drop test rather than a rolling rock because the location, angle, and energy of impact with a vertical drop test could be more easily controlled and was reproducible. This test has a very high accuracy and precision of impact location. Additionally, the impact location can easily be adjusted to test specific sections of a fence. The angle of impact can also be reproduced by installing different fences at a consistent angle relative to horizontal.

The vertical drop test allows for easy calculation of impact velocity and rock mass required to achieve a specific energy. This can be evaluated prior to the test. Also, each test can be conducted under exactly equal conditions without other factors significantly influencing the rock trajectory or energy. The mass of the test rock is limited by the capacity of the crane; however, the use of a crane is generally safer and allows for easy rock handling compared to inclined cable type systems. Additionally, the crane can be used to remove rocks from the fence after the test.

The vertical drop test does not include rotational energy of the rock, which is a limitation in the applicability of the test results for design of fences. The actual amount of total kinetic energy and rotational kinetic energy that a rock has is highly dependent on the rock dimensions and interaction with the slope during the rockfall event making it difficult to evaluate in a standardized test.

The vertical drop test can be setup to avoid rock contact with the ground during elongation of the fence requiring the fence to absorb all of the impact energy. This loading is likely the maximum possible from the test. However, it may not be representative of a natural event that has the same total kinetic energy but different components of translational and rotational kinetic energy. The rotational energy will cause different fence behavior than is observed during a vertical drop test.

The vertical drop test requires the fence to be installed on a near-vertical face. Additionally, the fence must be installed on the face high enough to avoid ground contact of the block during the elongation of the fence. Working at height on a near-vertical face requires specialized equipment and personnel to safely complete the fence installation and measurements for the test.

3.2.4 Pendulum Type Tests

Pendulum type tests have been used to test rockfall fences and individual components at relatively low energies up to several hundred kilojoules. The limitation of using this type of test for higher energies is the ability to construct a pendulum system large enough to produce velocities at impact similar to that of a natural rockfall event. Higher energies could be achieved by using excessively large rocks at lower velocities, but this does not necessarily represent conditions comparable to the majority of natural rockfall events that occur. Therefore, the results may not be applicable for the typical design of a rockfall fences.

Additional limitations include the specialized equipment necessary to release the rock to start the pendulum swing and another release device to allow the rock to fly freely into the test fence. The second release device must be capable of detaching the rock at the exact time to allow the rock to impact the fence. The release devices must also be rated for a capacity sufficient to withstand the forces exerted by the swinging rock. It may be possible to conduct a pendulum test were the rock is not released before impact; however, this may lead to uncertainty in the impact energy absorbed by the fence. The pendulum type test is also not capable of producing rotation of the rock at impact with the fence.

The pendulum type test can be useful for low energy tests as the impact location and angle are generally easily predicted prior to the test. Some initial tests may be required in order to calibrate the release devices to achieve the desired impact location and angle. The test is generally reproducible and energies can be easily calculated prior to the test.

3.2.5 Comparison of Rockfall Fence Testing Delivery Methods

Table 3-1 summarizes the advantages and disadvantages of various methods and procedures for rock delivery and physical setup of the delivery systems and the test site.

Table 3-1. Summary of advantages and disadvantages of various rock/block delivery methods

Rock/Block Delivery Method	Advantages	Disadvantages
Rock Rolling	<ul style="list-style-type: none"> • Simple • Represents real rockfall conditions • Includes translational and rotational energy 	<ul style="list-style-type: none"> • Tests not easily reproduced • Trajectory and energy influenced by slope characteristics • Location and angle of impact difficult to predict • Potential for ground contact during elongation
Inclined Cable	<ul style="list-style-type: none"> • Reproducible • Better control over impact velocity, energy, location, and angle • Cable system may also be used for installation, maintenance, and rock removal during testing 	<ul style="list-style-type: none"> • No rotational energy depending on test setup • Velocity and energy depend on test site and setup • May be difficult to vary impact location • Requires specialized equipment • Requires extensive infrastructure
Vertical Drop	<ul style="list-style-type: none"> • Reproducible • Better control over impact velocity, energy, location, and angle • High accuracy and precision 	<ul style="list-style-type: none"> • No rotational energy • Requires installation on near-vertical face • Requires specialized equipment
Pendulum	<ul style="list-style-type: none"> • Reproducible • Better control over impact velocity, energy, location, and angle 	<ul style="list-style-type: none"> • No rotational energy • Difficult to achieve high energies • Requires specialized equipment

3.3 Overview of Rockfall Fence Testing Programs, Standards, and Guidelines

The majority of rockfall testing programs in the U.S. have been conducted by transportation agencies in California, Colorado, Oregon, and Washington. Testing worldwide has been conducted in numerous countries including Austria, Italy, Japan, and Switzerland. The progression of rockfall testing is well documented in Rockfall Characterization and Control (Turner and Schuster 2012) and Duffy (2012). The scope of this study was to evaluate the specific testing programs and protocols used for testing and certifying flexible rockfall fence systems, but an overview of various testing programs that may have tested other types of rockfall protection systems is included.

During the development of early testing programs, fence testing and design changed rapidly but there was no standardized test procedure that allowed for comparison of capacity or performance of different fence systems. Due to the lack of any standardized procedures, some state transportation agencies, countries, and fence manufacturers developed their own testing procedures and performance criteria to evaluate various rockfall fence designs. These procedures and performance criteria are outlined below to follow their progression to the present state.

3.3.1 Rockfall Fence Testing In 1980s

The California Department of Transportation (CALTRANS) conducted a study in 1985 to evaluate the causes of rockfall in California, identify mitigation methods used, and evaluate the effectiveness of these

mitigation measures (McCauley et al. 1985). Testing was performed at 11 sites located along roadways. Numerous rocks were rolled down natural slopes with angles ranging from approximately 34 degrees to 63 degrees. Three berms and nine fences were placed at distances varying from 1.8 m (6 ft) to 12.8 m (42 ft) from the toe of the slope. Physical characteristics of the test sites and data for each rock rolled were recorded. Video of each test was recorded in slow-motion. Mitigation effectiveness was evaluated based on the system's ability to stop rocks, approximately 0.6 meters (2 feet) in diameter or smaller, before reaching the roadway. The conclusions of testing program were that the effectiveness of fence systems could be improved by eliminating gaps at the bottom of fence and placing the fence at the optimal distance from the toe of the slope. The effectiveness of the berms could be improved by using the appropriate height of berm and placing the berm at the optimal distance from the toe of the slope.

In 1988, the Colorado Department of Transportation (CDOT) began testing a variety of rockfall barrier systems at a site west of Rifle, Colorado (Pfeiffer 1989; Barrett et al., 1991; and Higgins, 2003). The tests consisted of rolling rocks down a 91-m (300-ft) high soil and rock slope. The first tests were performed to evaluate rockfall attenuator systems and to calibrate the Colorado Rockfall Simulation Program (CRSP). Rocks were dropped onto the slope above the attenuator systems using a front-end loader. The mass of rocks used during the testing were calculated by estimating the rock density and measuring the rock size. Video recordings of the tests were used to estimate velocities at impact and analyze rockfall behavior. The kinetic energy absorbed by the attenuator systems were assessed to an order of magnitude because of uncertainty in the parameters used in the calculations. From the testing program, Barrett et al. (1991) made the following suggestions to improve the quality of the data for future testing:

- Determine rock mass accurately.
- Videotape recordings should be made looking down along the top cable of the attenuator so that the impact may be viewed from the side.
- The slope should be marked in 10-foot increments on both sides of the attenuator with markings that can be clearly seen from the camera position.
- Analyze the test results from accurate as-constructed plans.

In 1989 and 1990, CALTRANS conducted a research project with the purpose of constructing, testing, and evaluating the effectiveness of rockfall nets from two manufacturers that would be used for rockfall hazard mitigation at selected sites in California (Smith and Duffy 1990). The tests were performed by rolling rocks down a 76-m (250-ft) long natural slope inclined at 34 degrees to impact fences installed at the base of the slope. Eighty (80) natural boulders weighing 136 to 5,897 kg (300 to 13,000 lb) were rolled into the test fences. The dimensions of each boulder were measured and the weight estimated prior to being rolled. Fifteen boulders were accurately weighted using a load cell and the actual weights were compared to the estimated weights to evaluate the accuracy of the estimated weights. It was found that estimated weights were within 10 percent of the actual rock weights.

The tests were recorded on video and high-speed film from four different locations along the slope to capture two side views, one oblique, and one front view. Reference lines were placed at various intervals perpendicular to the dip of the slope to allow for calculation of rockfall velocities using the video recordings. Rocks were initiated from the top of the slope by dropping from or pushing by a front-end loader. Rocks dropped from the loader were released from a consistent height for each test.

The nets were inspected periodically during testing and the net performance was recorded along with necessary repairs before the next rock was rolled. Maintenance of the net was evaluated based on ease and feasibility of repair and the replacement parts required for repairs. Data recorded for the tests included impact locations, net damage, and net repairs.

The total kinetic energy of each rockfall was calculated by summing the translational and the rotational kinetic energies, expressed as:

$$\text{Total Kinetic Energy} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$$

where m is the mass of the boulder, v is the translational velocity of the boulder just before impact, I is the moment of inertia of the boulder as it spins, and ω is the angular velocity of the spinning boulder just before impact. The translational velocity v was evaluated by measuring the time it took the boulder to travel the distance from a reference point to the fence. The angular velocity ω was evaluated by measuring the time it took the boulder to complete one revolution before hitting the net. The measurements were obtained from the video recordings and slow-motion film footage. The researchers used equations representing the moment of inertia for rectangular and spherical bodies based on the boulder dimensions and axes of rotation evaluated from the video recordings and slow-motion films in calculating the total kinetic energy of each test.

They also performed dynamic load path analysis to evaluate the forces within individual fence components. The analysis was used to balance the fence systems so that each component would function without failure at an optimum level for load-carrying capacity. This analysis consisted of evaluating momentum and impulse imparted on the fence system during impact. Friction brake analysis was also performed using a hydraulic machine to apply a load to the brakes until they activated.

The researchers concluded, in part, that modifications in design of many components of fence systems could reduce the required maintenance, secondary mesh was important to prevent small rock fragments from passing through the fence and limiting damage to the primary fence panel, and that detailed site investigation was required for the proper selection of a rockfall fence system. Based on the report, 22 of the 83 tests performed did not impact the fence systems illustrating the difficulty of impacting the fence in a specific location using the rock rolling test method.

In 1988, a fence testing program was conducted in Switzerland, which consisted of rolling rocks down a steep slope (Baumann 2002). It was found that a significant amount of energy was lost as the rock made contact with the slope and in many cases rock trajectories missed the test barriers. Also, rock velocities varied widely from 6 to 24 m/s (20 to 78 ft/s) and impact locations and angles were also widely variable. The kinetic energy absorbed by the barrier and the location and angle of impact could not be determined before the test making it difficult to obtain the desired and reproducible results (Baumann 2002 and Higgins 2003).

3.3.2 Rockfall Fence Testing In 1990s

Hearn (1991) reported on CDOT testing of flex-post fence systems in 1990 at the test site west of Rifle, Colorado. Two prototype fence designs were tested to evaluate the performance in terms of maximum rock mass and rockfall velocity intercepted by the fence systems. Rocks used for the tests were measured and weighed with weights ranging from 116 to 2,740 kg (256 to 6,040 lb). Two video cameras were used to record the tests with one following the rock down the slope and the other fixed on the fence system. The slope of the test site was marked with ribbons at approximately 3-m (10-ft) intervals extending upslope approximately 18-m (60-ft) from the fence. Ribbons were also placed on the fence to improve visibility. Analysis of the test videotapes was used to estimate rockfall translational and rotational velocities, trajectories and location of impact, kinetic energies, post rotation in response to impact, and fence damage, if any, of each test.

In 1991, CDOT conducted testing of geotextile rockfall barrier walls at the test site west of Rifle, Colorado (Parsons De Leuw 1992). For the testing program, a channel was dug at the base of the slope to guide the rolling rocks into the center of the wall. All tests were recorded on video cameras and reference lines were placed parallel to the wall at approximately 3-m (10-ft) intervals extending up the slope to assist in evaluating the velocities of the rolling rocks. Video cameras were also used to record the behavior of the wall during impact. Dimensions of the rocks used for the tests were measured prior to

testing. The weights of rocks were calculated using the average diameter of the rock and an estimated density.

A total of 18 rocks ranging in diameter from approximately 0.5 to 1.8 m (1.7 to 5.8 ft) and ranging in weight from 269 to 8,325 kg (592 to 18,354 lb) were used for the tests. The various sizes of rocks were selected to provide different levels of energy at impact with the wall. Rocks were released from the same point at the top of the slope starting with smaller and using larger rocks in each successive test to gradually increase the impact energy on the wall. Rocks were removed from the impact area after each test and damage to the wall was not repaired. Permanent wall deformations were measured on the front and rear faces of the wall and maximum deformations on the back face of the wall were measured after each impact.

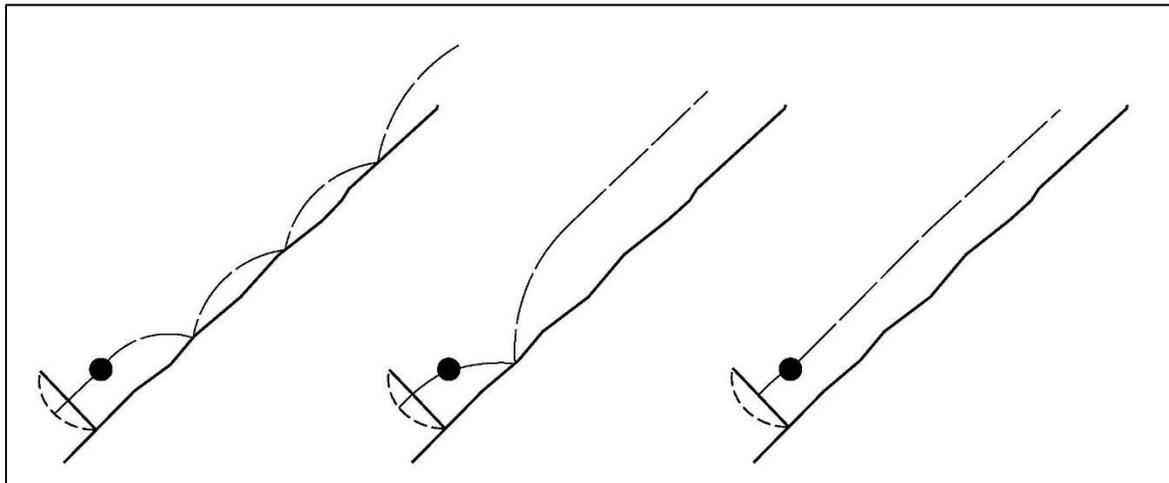
The kinetic energy of the rock was calculated using only the translation energy as the rotational component of the kinetic energy did not create large horizontal deformations of the wall. It was found, in part, that the accuracy of estimating the rock velocity could be improved by video recording at least the last approximately 9 m (30 ft) of rolling before the rock impacted the wall.

In 1991 and 1992, a testing program was conducted in Oberbuchsiten, Switzerland to evaluate the design of rockfall fence structures by balancing material properties to enhance overall flexibility (Duffy 1992). The test procedures were similar to those used in testing performed in Switzerland in 1988. The tests were conducted on a bare limestone rock slope 140 m (460-ft) long and 100-m (328 ft) high with an overall slope angle of 45 degrees. The rock initiation point on the slope was varied throughout the testing from 45 to 103 m (148 to 338 ft) up the slope depending on the desired rockfall velocity at impact with the fence. Rocks used for the testing were weighed and the principle axes were measured prior to the tests. Weighing and measuring of rocks were repeated if significant rock breakage occurred during testing. Tests were recorded on video from three different camera angles. One camera followed the rock down the slope, one was fixed on a side view of the fence, and the last camera was fixed on a front view of the fence and slope face. Video recordings were used to analyze rockfall trajectories, rockfall impacts, barrier behavior, and barrier performance (Duffy 1992 and Duffy and Haller 1993). Reference lines were placed on the slope above and below the barrier and were used in the video recordings to calculate rockfall velocities before and during impact with the barrier. The kinetic energy of the rockfall impact was calculated using methods similar to those described by Smith and Duffy (1990). Impact energies ranged from 14 to 1,000 kJ (5 to 369 ft-tons).

In 1991, a second testing program was conducted in Switzerland changing the procedure to reduce some of the limitations of the 1988 tests (Baumann 2002 and Gerber and Haller 1997). This test consisted of an inclined cable-crane aligned perpendicular to the test fence such that rocks hanging from the cable travelled downslope and were released after a certain distance was covered. The rocks then struck the ground in front of and rolled into the test fence. This test method was intended to increase the velocity of the rocks upon impact with the fence, but it was found that the energy absorbed by a single ground impact was similar to the energy absorption from multiple impacts as in the earlier tests. The velocities again varied widely from 10 to 22 m/s (32 to 72 ft/s). Using the inclined cable allowed for consistent impact locations in the center of the fence in the lateral direction, but height and angle of impact was still not easily controlled.

Also in 1991, a third testing program was conducted in Switzerland again modifying the procedure to reduce the limitations of the testing conducted in 1988 and 1991. The third test used an inclined cable-crane similar to the crane used in the second test procedure, but this system was setup to guide the rocks directly into test fences rather than allowing the rocks to impact the ground prior to reaching the fence (Baumann 2002). Figure 3-4 illustrates the progression of the testing methods used in Switzerland between 1988 and 1991. The third testing procedure allowed for a relatively narrow range of rock velocities that varied with the geometry of the test site. It was also possible to calculate the energy of the falling rocks prior to the test. This test procedure still had limitations in the ability of the cable-crane

system to release the rock before barrier impact and hazardous operating conditions with large rocks required for a high energy test. Also, it was difficult and costly to make modifications to the cable-crane system to vary the impact location and angle. While this test procedure improved reproducibility, the system required adjustments for each new fence tested and the accuracy of the impact location was not yet totally satisfactory.



Source: Adapted from Baumann 2002

Figure 3-4. Schematics of the progression of testing methods used in Switzerland

In 1992, the University of the Pacific and CALTRANS performed testing of low energy rope rock nets to stop approximately 68 kJ (25 ft-tons) of energy with minimal maintenance (Kane and Duffy 1993). The tests consisted of rolling rocks down a 20-m (66-ft) high and 27-m (89-ft) long slope with an average angle of 37 degrees. Reference lines were placed upslope of the test fence on approximately 1.5-m (5-ft) intervals for approximately 4.5 m (15 ft). Natural rock dimensions were measured in three directions and weights were calculated by estimating the unit weight of the rock. Two manufactured concrete cylinders of known weight were also used during the testing. Use of these cylinders allowed a more uniform roll down the slope than could be achieved with natural rocks. Three video cameras were used to record each test from a side view upslope, at, and downslope of the fence and one camera was used to record the overall test sequence. Video recordings of the tests were used to visually estimate the velocity of the rocks just prior to impact using the camera speed and reference marks on the slope. The kinetic energy at impact was calculated using the following equation:

$$\text{Kinetic Energy} = \frac{1}{2}mv^2$$

where m is the mass of the rock and v is the velocity of the rock just before impact.

Rocks were initiated from the top of the slope by either rolling by hand or pushing with a front-end loader. Small rocks were rolled first for the lowest energy impacts and successively larger rocks were rolled for higher energy impacts. Rocks were allowed to accumulate in the fence during the testing. Over 20 rocks were rolled into the test fences with kinetic energies ranging from approximately 13 to 136 kJ (5 to 50 ft-tons).

Additional rockfall fence testing was performed by CALTRANS in 1993 (Duffy 1996) using the test site described by Kane and Duffy (1993). The rocks used in this testing program were weighed using a load cell after impact to ensure the actual weight of the rock hitting the fence was recorded. In addition to reference lines upslope of the test fence, two reference lines were placed downslope of the test fence 0.5

m (1.6 ft) apart. Two video cameras were used to record the tests with one camera following the rock down the slope and the other fixed on the fence impact zone. Kinetic energies of rock impacts were calculated similar to the methods used by Smith and Duffy (1990) where the translational and rotation kinetic energies were summed.

In 1993, CDOT conducted additional testing of a high-capacity flex-post fence system (Hearn 1994). The tests were performed at the site located west of Rifle, Colorado. The test setup and procedures used were the same as those described by Hearn (1991). The test consisted of rolling 15 rocks ranging in diameter from approximately 1 to 1.7 m (3 to 5.5 ft). The weight of the rocks ranged from approximately 590 to 4,040 kg (1,300 to 8,910 lb). It was found that the rockfall capacity of the flex-post fence was controlled by rock size and kinetic energy. Rock size was important as the mesh fabric could not deform freely around large rocks limiting the ability of the fence to intercept the rockfall.

In 1996, CALTRANS conducted testing of two rockfall fence systems (Duffy and Hoon 1996) at the site described by Kane and Duffy (1993) and Duffy (1996). The procedure was similar to the procedure described by Duffy (1996) except that three video cameras were used to record the tests and additional reference lines were placed on the slope above and below the test fence.

In 1998, Chama Valley Productions, LLC conducted rockfall fence testing with the assistance of CDOT and Los Alamos National Laboratory (Andrew et al. 1998). The purpose of the tests was to validate the design concepts of four different rockfall fence systems. The tests were performed at the test site located near Rifle, Colorado previously used by CDOT. Rocks used for the testing were measured and weighed prior to being rolled down the slope. Each test was recorded using video cameras placed parallel to and upslope of the fence. Reference lines were placed upslope and downslope of the fence systems to aid in video analysis of rock velocities and deflection of the fences during impact. Translation and rotational velocities and the dimensions and weight of the rolling rocks were used to calculate the total kinetic energy using methods similar to those used by Smith and Duffy (1990).

The researchers noted that evaluating the velocities of rolling rocks was made more difficult due to blur of the video recordings when measuring over relatively small distances. Measuring over longer distances in the video recordings could reduce the error in velocity calculations; however, it was found during testing that slowing occurred in the final approximately 3 m (10 ft) before the fence, and using a longer distance to calculate the velocity of the rock could result in error from the actual velocity at impact of up to 25 percent.

Muraishi and Sano (1999) describe the testing procedures used to test rockfall fence designs for Japan's Railway Technical Institute. Static strength tests of individual fence components (wire rope anchors, brakes, etc.) and full-scale field testing were performed for certification of rockfall fence systems. Full-scale testing was performed by dropping a "rock weight" from a crane into a test fence constructed on a slope at 35 degrees above horizontal such that the impact of the rock with the fence was at a fixed angle of 55 degrees. The tests were recorded using high-speed video cameras for detailed analysis of the fence behavior.

Higgins (2003) describes the test as consisting of four parts which included a basic impact test, an accumulated impact test, a maximum load test, and a special test. The basic test was used to evaluate damage to the fence at energies less than the design value. The accumulated load test evaluated the performance of the barrier with accumulation of rocks. The maximum load test consisted of a test at the design energy level. The special test consisted of rocks impacting the retaining wire ropes and posts. Muraishi and Sano (1999) concluded that the vertical drop test was more desirable than the rock rolling on slopes because the location, angle, and energy of the impact could be easily reproduced and the accuracy of the vertical drop required fewer impacts to gather the necessary data.

Serafini et al. (1998) describe CALTRANS testing performed in 1998 of three rockfall barrier systems that were not originally designed as rockfall barriers. The tests were performed to evaluate the

constructability of the systems and to assess the ease of and requirements for maintenance to these systems.

The tests were performed by rolling natural rocks down a slope 27-meters (89-feet) long and 20-meters (66-feet) high with an overall slope angle of 36 degrees and a surface composed of soil and rock fragments. Rocks were dropped from the top of the slope using a front-end loader. Rocks were weighed using a load cell after impact in an attempt to evaluate the actual weight of the rock impacting the barrier. The dimensions of each test rock were also recorded after impact with the barrier. Tests were recorded on video from three different camera angles to allow analysis of rockfall trajectories, rockfall impact energies, and fence performance and behavior. Reference lines were placed on the slope above and below the fences to calculate rockfall velocities prior to and during impact. Rockfall energies were calculated using similar methods as described in Smith and Duffy (1990).

The entire system and individual components were evaluated based on ability to withstand rockfall impacts of kinetic energies ranging from 1.6 to 118 kJ (0.59 to 43 foot-tons). Performance of the fences was evaluated based on criteria for impact loading, maintenance, and efficiency. A detailed description of the performance criteria used by CALTRANS to evaluate the tests is included in Section 3.3.4.

Peila et al. (1998) describe full-scale rockfall testing programs performed in Italy in order to compare various systems as well as to develop a design procedure for rockfall fences. The tests were performed by attaching a trolley to a cable installed from the top to the bottom of a slope extending over the top of the test fence. The test rock was connected to the trolley by a cable. The trolley and rock travelled down the guide cable to a precise location where the connection cable was cut by an explosive charge sending the rock flying freely into the test fence. The cable delivery system was setup in a quarry and rocks used for the tests were from the quarry. The dimensions and weights of the rocks were measured prior to the tests. Tests were filmed using three video cameras and for some tests, the forces transmitted to various components of the fences were measured using dynamometers. The global behavior of the fence, the velocity and displacement of the block before and after the impact, and the reaction of the fence components during the impact were analyzed using the video recordings and other data

3.3.3 Rockfall Fence Testing In 2000 to Present

3.3.3.1 Swiss Testing

Grassl et al. (2002) describe testing of single and multi-field fences performed in Switzerland. The goal of this research project was to combine specialized field experiments and numerical modeling to optimize rockfall fence structures. Field tests were performed at the Swiss Federal Rockfall Test Site near Walenstadt, Switzerland. The test block consisted of a fiber reinforced concrete sphere with a mass of 825 kg (1,819 lb). The block was dropped from a crane into a test fence installed on a near-vertical rock face 15 m (49 ft) above the ground. A vertical drop was chosen for the reproducibility of the velocity, the trajectory, and the location of the impact of the block with the test fence. Forces were measured in the post foundations and anchor cables using load cells. The test block was instrumented with accelerometers to allow evaluation of the braking forces acting on the block from the fence. High-speed video cameras were also used to record the braking process and provide a measuring technique independent from the load cells and accelerometers.

3.3.3.2 Geobrugg North America Testing

In 2005, Geobrugg North America (Roth 2006) conducted testing of a rockfall fence using the NCHRP 20-07 guideline. The tests were performed at a temporary site located in an open-pit mine. The fence system was installed on a near-vertical face in the mine with a truck-mounted crane located on an access

road above the fence location (Figure 3-5). Load cells were installed on support ropes and lateral anchor ropes to measure tension forces during testing. Load cells were also mounted to the ground plate of the fence posts to measure forces on the posts during testing. One high-speed camera was used to record the test sequence. A height of fall of the test block of 32 m (105 ft) was used. The test was observed by Dr. Higgins and several other rockfall specialists to evaluate the NCHRP 20-07 guideline (Duffy and Badger 2012). Based on the test, modifications to the guideline were proposed and are discussed in Section 3.3.7.



Source: Photography courtesy of J.D. Higgins

Figure 3-5. Geobrigg temporary test site located in an open-pit mine

3.3.3.3 Italian Testing

Peila et al. (2007) describe testing conducted in Italy in 2007. Tests were performed to evaluate various reinforced embankments to stop rockfall. The test facility consisted of a cable system similar to the system described by Peila (1998). The system used in 2007 was capable of delivering concrete blocks weighing up to 10,000 kg (22,050 lb) with a speed of 32 m/s (105 ft/s).

Wienberg et al. (2008) describe another testing program conducted in Italy in 2007. The tests were generally conducted according to the SAEFL guideline except that a post spacing of 5 m (16 ft) was used instead of the standard 10 m (33 ft) post spacing. The intent of the program was to test a fence previously certified using the SAEFL guideline in special situations such as a direct impact to a post or rope or an impact in a peripheral panel. The test facility was located in an old quarry with the fence installed on a near-vertical rock face. Load cells were used to measure forces in retaining ropes and support rope anchorage and high-speed video cameras were used to record the tests. The researchers concluded that the fence tested according to the SAEFL guideline was able to withstand exceptional load cases that are not explicitly considered in the guideline.

Badger et al. (2008) describe testing conducted in Italy in 2007 to evaluate the performance of hybrid or attenuator type systems. The system consisted of three 6 m-wide by 4 m-high panels supported on four 4 m-high posts suspending an approximately 15 m-long drapery of ring nets. Tests were performed by rolling concrete “rocks” weighing up to 5 tonnes (11,020 lb) down a 45 degree slope. Impact energies of up to 500 kJ were estimated using high speed video. Load cells were installed on retaining and anchor ropes to measure impact loading of the attenuator systems.

3.3.3.4 Colorado Attenuator Testing

In 2007 and 2008, CDOT conducted testing to evaluate potential rockfall attenuator systems (Arndt et al. 2009). The test site consisted of a near-vertical rock face above a soil slope approximately 15-m (50-ft) long that was inclined at approximately 35 degrees. A concrete ramp was constructed on the upper portion of the soil slope with the test attenuators installed at the base of the ramp. Test rocks were dropped onto the rock face such that the impact would impart translational and rotational energy on the rock before travelling down the concrete ramp towards the attenuator. Concrete blocks of specific dimensions were used for the test rocks to provide characteristics similar to natural rocks and provide a consistent shape and weight. Each test was recorded by three high-speed video cameras placed to record front and side views of the ramp and attenuator. Video recordings were used to estimate translational and rotational velocities for some of the tests performed. Calculation of the kinetic energies was then possible with the known dimensions and weights of the test blocks. Figure 3-6 depicts a concrete block just before impact with the attenuator system.



Source: Photography courtesy of B. Arndt

Figure 3-6. Colorado attenuator testing with rock in motion prior to attenuator impact

3.3.3.5 Austrian Testing

Buzzi et al. (2012) describe testing conducted in Australia on low energy fences to evaluate system stiffness and transmission of load to components such as posts and cables. Testing was conducted using a pendulum system. The test block consisted of concrete constructed according to the ETAG 27 guideline. A quick release device was used to initiate the test block moving on the pendulum and a second quick

release device was used to automatically release the block allowing it to fly freely into the test fence. Testing was recorded using two high-speed cameras. Load cells were installed on cables and at the post bases to measure forces. The controlled release system was found to function consistently allowing easy comparison of test results.

3.3.3.6 Colorado Rockfall Fence and Post Foundation Systems Testing

CDOT performed full-scale rockfall fence tests based on ETAG 27 procedures, in an effort to limit outward deflection of the fence panels. In many instances in Colorado, the fence barriers are placed next to the roadway travel lane. Based on manufacture reported ETAG testing results, the outward deflections of the fence barriers could range from 3 to 8.5 meters for energies from 500 to 2,000 kJ. Manufactured rockfall fence systems deflect depending on the various proprietary braking elements developed by the manufacturers that are incorporated into the various retaining and support wire ropes that stretch and elongate during a rockfall impact.

The CDOT testing was undertaken to limit the outward deflection of the fence panel systems for energies up to 1,000 kJ with and without braking elements. A vertical test facility was constructed in Colorado and a two-post system with a single net panel and a four-post system with multiple attached net panels were tested. The tested systems were instrumented with load cells on the foundation elements and tension (link) cells in the wire rope anchors. Figure 3-7 depicts the rockfall fence test site. Based on the rockfall fence testing conducted the following selected observations were reported (Arndt et al. 2014):

- It was possible to achieve multiple passing tests in excess of 557 kJ without braking elements.
- It was not possible to achieve a 911 kJ non-failing test without utilizing a braking device.
- Overall outward panel deflections of the testing were as follows (approx.):
 - 1.4 m for 278 kJ (no braking system)
 - 2.0 m for 557 kJ (no braking system)
 - 4.2 m for 1,000 kJ (with braking system)

CDOT also performed post base foundation testing mainly due to lack of guidelines for post foundation systems since ETAG 27 has no specifically established foundation protocols. A pendulum test facility was constructed to test fixed and “floating” post bases. Figure 3-8 depicts the rockfall post foundation test site. The tested systems were instrumented with load cells on the foundation elements (when appropriate) and tension (link) cells in the wire rope anchors. Based on the post foundation testing conducted, the selected general observations were made (Arndt et al. 2014):

- The “floating” base foundation systems were best at absorbing impact energy with the least amount of damage (up to 3 times the impact energy of fixed rigid base systems).
- The stiffer the post foundation system, the more damage that was concentrated with respect to the structural elements.



Source: Photography courtesy of B. Arndt
Figure 3-7. Colorado rockfall fence test site



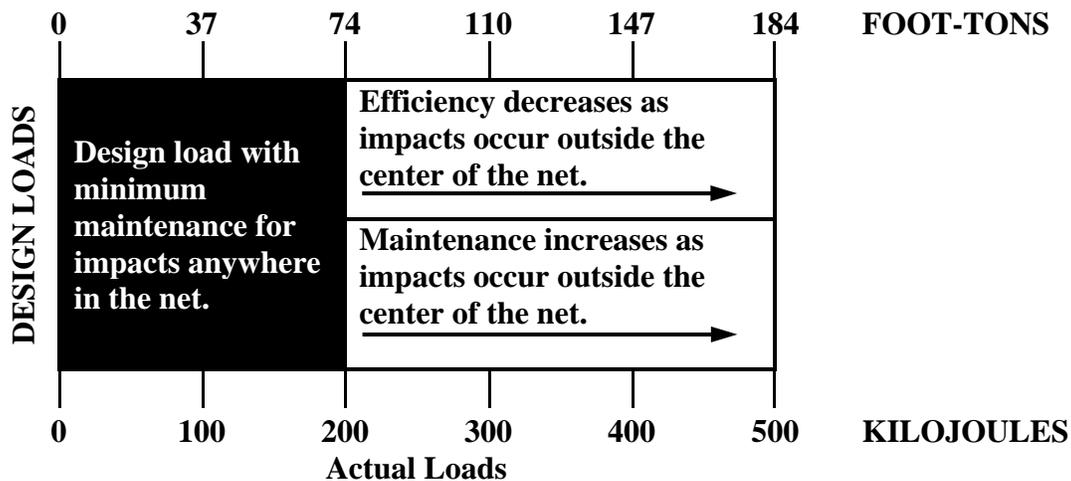
Source: Photography courtesy of B. Arndt
Figure 3-8. Colorado rockfall post foundation test site

3.3.4 Early United States Rockfall Fence Performance Standards and Guidelines

During the development of testing programs, fence testing and design changed rapidly but there was no standardized test procedure that allowed for comparison of capacity or performance of different fence systems. Due to the lack of any standardized procedures, some State transportation agencies, countries, and fence manufacturers developed their own testing procedures and performance criteria to evaluate various rockfall fence designs. These procedures and performance criteria are outlined below to follow their progression to the present state.

Testing performed in 1991 and 1992 described by Duffy (1992) and Duffy and Haller (1993) evaluated the performance of fence systems by comparing the relationships between impact loading, maintenance, and efficiency. Impact loading was the amount of energy absorbed by the fence at impact, maintenance was the repair required at various impact energies, and efficiency was the importance of impact location as fence flexibility was found to decrease outward from the center of the fence resulting in increased maintenance requirements. The performance criteria were compared using a chart illustrated in Figure 3-9.

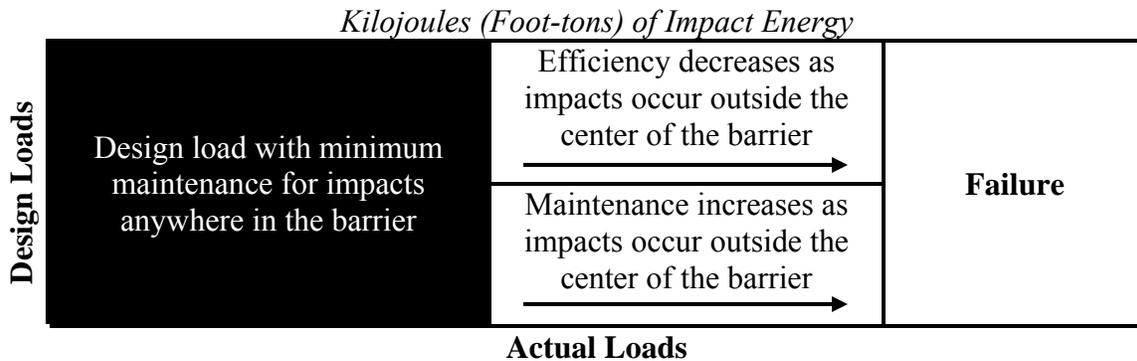
For impact loads less than the design load, the fence was capable of stopping repeated impacts with minimal maintenance. For impact loads greater than the design load, maintenance increased and efficiency decreased until the fence was no longer effective for design purposes. Impacts with loads greater than the design load would be stopped, but damage to the fence would likely be significant. Similar performance criteria were used in testing performed by Kane and Duffy (1993), Duffy (1996), and Andrew et al. (1998).



Source: Adapted from Duffy 1992

Figure 3-9. Design load and fence performance chart

Duffy and Hoon (1996) and Serafini et al. (1998) describe CALTRANS' evaluation of fence performance similar to Duffy (1992) and Duffy and Haller (1993) with the addition of a failure category (Figure 3-10).



Source: Adapted from Serafini et al. 1998

Figure 3-10. CALTRANS chart of fence performance criteria

Performance criteria and definitions used by Duffy and Hoon (1996) and Serafini et al. (1998) are outlined as follows:

- Acceptable Performance Criteria: The system’s ability to stop multiple impacts within design load levels without needing immediate maintenance.
- Immediate Maintenance: Immediate repairs required to restore the fence system to design load operational capabilities.
- Rock Stopped: In order to keep the traveled way clear at all times the final resting position of a rock must be within the shoulder. Commonly two meters of shoulder is available. Of these two meters, one meter is available for the fence system and one meter is available for flexing of the fence. Therefore, the final resting position of the rock must be less than one meter beyond the plane of the net. If not, the rock is considered not stopped.

In 1999, CALTRANS developed a guideline for rockfall fence testing based on the experience gained from the previous rockfall testing programs conducted by the agency (Duffy 1999; Higgins 2003; and Duffy and Badger 2012). The guideline was intended to test a product, evaluate the product per manufacturers’ expectations, and report the results of the test. The test consisted of rolling 20 rocks down a slope into the fence. Each successive rock rolled during the test was increased in size such that the test started with low impact energies and increased the impact energies to the design load of the fence by the end of the test. Rocks were allowed to accumulate behind the fence so that the cumulative effects of impact loading, maintenance, and efficiency could be evaluated similar to methods previously used by CALTRANS. Fence performance was deemed satisfactory if the fence stopped repeated rockfall within the design load without immediate maintenance needs.

Washington State Department of Transportation (WSDOT) developed procedures for approval of new rockfall fence products consisting of a questionnaire completed by subject matter experts (Higgins 2003; Duffy and Badger 2012). The questionnaire was based on criteria of the system being able to withstand multiple impacts at the rated capacity with little or no maintenance, the maintainability of the system, and a reasonable service life of at least 20 years. The subject matter experts made their recommendations for approval, modification, or rejection of the fence to a committee. The committee then corresponded with the manufacturer with the recommendations and, as necessary, requested additional information. No tests were performed by WSDOT, but the manufacturer was required to prove their products met the criteria. This often led to different tests being performed by different manufacturers making comparison between different systems difficult.

Oregon State Department of Transportation (ODOT) developed procedures consisting of specifications for individual rockfall protection projects. This required a “certificate of compliance” from the fence

manufacturer that stated that the fence was capable of absorbing multiple impacts at the design energy with little or no maintenance required and that the fence was thoroughly tested and performed satisfactorily in a similar application and capacity as its anticipated use on the ODOT project (Higgins 2003; Duffy and Badger 2012). Due to the lack of standard testing and certification procedures and the demonstration of satisfactory performance relying on successful application, this approval procedure was somewhat subjective.

3.3.5 Early Italian Rockfall Fence Testing Standards

Peila (1998) recognized the lack of a standardized method for the classification and use of rockfall fences that had led to the numerous procedures and guidelines used by different organizations. A procedural guideline was developed in Italy to eliminate the lack of a standard procedure. It contained the minimum requirements necessary for an optimal classification of fences and the specifications that should be considered when conducting fence tests. The guideline requested, from the manufacturer, fence specifications and parameters consisting of the maximum dispersible energy in safe conditions; maximum deformation and loads on the fence from the maximum impact energy; assembly specifications with mechanical and behavioral characteristics of the joints and brakes; and a guarantee of the quality relative to both the construction and installation stages. The procedures were developed specifically for fences capable of absorbing 200 to 5,000 kJ (74 to 1,844 ft-tons) of energy and rocks no larger than 5 m³ (177 ft³). Fences tested were classified based on energy categories and associated fence dimensions. The test used a natural rock or concrete block of unit weight between 2200 and 3200 kg/m³ (137 to 200 lb/ft³). The procedure required that the rock or block impact the fence at two thirds of the useful height of the fence and with an incidence angle between 10 and 60 degrees.

3.3.6 Swiss Rockfall Fence Performance Standards and Guidelines

In 1997 and 1998, a survey of European rockfall practitioners revealed the continued need for objective and standardized testing procedures for fences that would allow comparison of products and provide relevant information on fence capacity and maintenance (Baumann 2002; Higgins 2003). Development of the SAEFL test procedure and approval guideline began in 1999 and was completed in 2001 (Gerber 2001). An amendment to the guideline was published by the Federal Office for the Environment (FOEN) in 2006 (FOEN 2006). Testing and certification according to the guideline is still required for federally funded projects using rockfall fences in Switzerland. The guideline was established and is administered by a government agency to provide standardized and independent evaluation of the fence systems tested (Baumann 2002). It was intended to define the approval procedure, provide a basis for an objective comparison of different rockfall fences in specific energy classes, improve fence effectiveness, and provide information to practitioners in charge of project work, construction, and maintenance of the fence systems. The 2006 amendment was published to include knowledge gained since testing started in 2001. This included reducing the required residual useful height to be consistent with the ETAG 27 guideline in preparation at the time. The SAEFL guideline includes both administrative and testing procedures. Only the testing procedures are discussed here as the administrative procedures generally only apply to the government agency conducting the tests. Tests are conducted at a site located near Walenstadt, Switzerland and consist of dropping a concrete “rock” vertically from a crane into a test fence installed on a near-vertical rock face (Figure 3-11).



Source: Photograph courtesy of J.D. Higgins

Figure 3-11. SAEFL test site in Walenstadt, Switzerland

In developing the guideline, it was decided that fences should be able to absorb all of the kinetic energy of the test rock without energy absorption from the rock making contact with the ground. It was also decided that the fence system should not exceed a maximum deformation after impact and should retain a minimum residual useful height (Gerber 2001; Baumann 2002; Higgins 2003).

The following discussion of the SAEFL guideline is summarized from Gerber (2001) and FOEN (2006). The test fence is installed at a height of 15 m (49 ft.) above the ground with the posts inclined 20 degrees above horizontal and retaining ropes inclined approximately 40 degrees above horizontal. The test fence typically consists of three sections with a distance between posts of 10 m (33 ft.). The minimum fence height and lengths of the posts are defined based on the energy class being tested. Manufacturers are allowed to increase the post lengths by up to 1.5 times without being required to retest and certify the modified fence.

The fence systems are divided into nine energy classes ranging from 100 to 5,000 kJ (37 to 1,844 ft-tons) (Table 3-2). The test sequence is divided into four parts, A to D. Evaluation of tests A, B, and C is based on measurements taken during or after impacts to the fence. Test D consists of a qualitative assessment of the fence system and the fence performance during tests A to C. Concrete blocks of

specified dimensions (Figure 3-12) and mass are used depending on the energy class and the test. For the fence to pass, the concrete blocks must be decelerated and stopped by the fence within a distance specified by the energy class.

Table 3-2. SAEFL parameters for tests B and C

Class	Net Height h_v (m)	Test B (50%)			Test C (100%)				
		Energy (kJ)	Test Body		Energy (kJ)	Test Body		Braking Distance b_s (m)	Residual Useful Height h_n (m)
			Mass (kg)	Side Lengths (m)		Mass (kg)	Side Lengths (m)		
1	1.5	50	160	0.41	100	320	0.52	4.0	0.75
2	2.0	125	400	0.56	250	800	0.70	5.0	1.0
3	3.0	250	800	0.70	500	1,600	0.88	6.0	1.5
4	3.0	375	1,200	0.80	750	2,400	1.01	7.0	1.5
5	4.0	500	1,600	0.88	1,000	3,200	1.11	8.0	2.0
6	4.0	750	2,400	1.01	1,500	4,800	1.27	9.0	2.0
7	5.0	1,000	3,200	1.11	2,000	6,400	1.40	10.0	2.5
8	5.0	1,500	4,800	1.27	3,000	9,600	1.60	12.0	2.5
9	6.0	2,500	8,000	1.51	5,000	16,000	1.90	15.0	3.0

Source: Adapted from FOEN 2006



Source: Photograph courtesy of J.D. Duffy

Figure 3-12. Shape and geometry of SAEFL test blocks made of reinforced concrete

Test A is a preliminary test with low impact energies in a boundary section of the fence. This test is intended to evaluate the deformation of any applied mesh and to load individual ropes or rings in the fence system with several small rocks. Three drops are conducted with various numbers of rocks of specified size. Each bundle of rocks is dropped together into a boundary panel of the fence with an impact velocity of 25 m/s (82 ft/s). Deformations and damages of the applied mesh and the individual ropes and rings are measured and described for each drop. All rocks must be slowed by the fence without punctures of the applied mesh and no repair work is allowed between each drop.

Test B is a preliminary test using 50 percent of the specified energy for the class of the fence. The test rock (with the specified mass and dimensions) is dropped into the middle section of the fence at an impact velocity of 25 m/s (82 ft/s). This test is intended to evaluate the required repair effort, the ease of maintenance, and the braking distance at half the design energy. Prior to the test, the positions of the individual bearing elements are measured and recorded. The tests are filmed from two directions and tensile forces on the ropes are measured and recorded at approximately 10 anchor points during the test. The test rock must be stopped without puncture of the net panel. The fence is repaired after the test. The following data are gathered from the test:

- Deformation of the ropes, brake elements, posts, and nets
- Position of the block in the net
- Deformation of the net
- Changes in the positions of the posts
- Deformations of the individual brake elements
- Damage to and deformations of other structural elements
- Braking time (t_s) and the maximum braking distance (b_s) from video recordings
- Time and material for least possible repair effort required for full restoration of the structure

Test C is the main test at 100 percent of the specified energy for the class of the fence. The test rock (with the specified mass and dimensions) is dropped into the middle section of the repaired fence at an impact velocity of 25 m/s (82 ft/s). The full kinetic energy of the rock must be absorbed by the structure to evaluate the capacity and deformability of the fence system. The data recorded before, during, and after the test is identical to the data recorded in Test B except the time and material required for repairing the fence system is not recorded as no repair effort is made. The test rock must be stopped without puncture of the net panel. The maximum braking distance is required to be less than the value specified for the energy class of the test (Table 3-2). The residual useful height of the net in the middle section of the fence must be equal to or greater than the value specified for the energy class of the test (Table 3-2).

Test D is an overall assessment of the fence systems' performance during tests A, B and C. This includes an assessment of the documentation provided by the fence manufacturer to ensure that the fence installed for testing is the same as the fence described by the documentation. The fence system is also assessed for simplicity of construction, especially in difficult terrain. An assessment of the lifespan of the fence is made based on the lifespan of the individual components as indicated by the manufacturer.

Video cameras are used during the testing to record front and side views of the fence to allow for evaluation of the motion of the block and individual bearing elements of the system. The resulting forces acting on the rock can be calculated from the motion of the block and can be compared with the forces measured in the bearing ropes (Baumann 2002). The SAEFL guideline gives a general discussion of the importance of post foundations and anchorage and states that design relies on force measurements collected during approval tests.

Baumann (2002) claims that the test procedure has demonstrated that it meets the intended objectives and requirements stated during development of the guideline and the procedure is capable of differentiating between unsatisfactory products and those that perform as intended. The cost of conducting the SAEFL test is reported as approximately \$40,000 USD.

3.3.7 United States NCHRP 20-07 Testing Guidelines

In 2003, the NCHRP 20-07 guideline for testing of rockfall fences was developed to allow U.S. transportation agencies to make direct comparisons between fence systems with respect to capacity and maintenance (Higgins 2003). The test procedure was developed using the SAEFL guideline (Gerber 2001) as a model as it was the only “officially” recognized test and certification guideline for rockfall fence systems at the time. Additionally, this allowed a SAEFL certification to be substituted for the NCHRP 20-07 test procedure to avoid being cost prohibitive for manufacturers to perform separate testing. The terms and definitions used in the NCHRP 20-07 guideline are very similar to those used in the SAEFL guideline to avoid confusion between tests. The NCHRP 20-07 guideline does not include the 2006 amendments to the SAEFL guideline as the NCHRP 20-07 guideline was developed prior to 2006.

The primary differences between the NCHRP 20-07 and SAEFL guidelines are that manufacturers are responsible for conducting and documenting tests in the U.S., NCHRP 20-07 test procedure allows manufacturers to decide whether the test block is delivered to the fence by a vertical drop, rock roll, or an inclined cable system, and the rock body can be natural or manufactured of reinforced concrete (Higgins 2003). Additionally, the NCHRP 20-07 guideline allows for a temporary test site to be used and the equipment used for testing can be readily rented and transported to the site (Duffy and Badger 2012).

The following discussion is summarized from comparison of the SAEFL guideline (Gerber 2001; FOEN 2006) and the NCHRP 20-07 guideline (Higgins 2003). The fence system setup in the NCHRP 20-07 guideline is similar to that of the SAEFL guideline in that the system must consist of three panels with the associated posts, ropes, brakes, and foundation elements. In the NCHRP 20-07 guideline, the manufacturer is allowed to select the panel width.

The NCHRP 20-07 guideline requires the angle of impact of the test blocks to be in a vertical plane orthogonal to the line connecting the base of each post in the fence system. Also, the angle between the net plane, defined by the four edges of the net, and the block trajectory at impact must be between 70 and 90 degrees. The test block geometry is recommended to be similar to that used in the SAEFL guideline or the block may be nearly equi-dimensional with a determined density.

Energies of the test block at the moment of impact are required to be consistent with and within 5 percent of the required energies specified for the energy class being tested. The NCHRP 20-07 guideline also requires documentation of the foundation design and construction for the posts and cables in the test report.

The energy categories used in the NCHRP 20-07 guideline are the same as in the SAEFL guideline with 9 energy categories ranging from 100 to 5,000 kJ (37 to 1,844 ft-tons). These categories are based on the original SAEFL guideline and not the 2006 amendment. As in the SAEFL guideline, the NCHRP 20-07 test sequence consists of four tests, A to D. In general, the objectives, implementation, measurements, and performance standards for each test in the NCHRP 20-07 guideline are the same as in the SAEFL guideline. An exception is that when test blocks are delivered by inclined slope or inclined cable, the test is required to be conducted such that the fence is subjected to similar energies and test block sizes as for the vertical drop test used in the SAEFL guideline. Also, measurements are required to be documented by photos taken before and after the test in the NCHRP 20-07 guideline.

Modifications to the NCHRP 20-07 guideline were made in 2005 after Geobrugg North America (Roth 2006) conducted tests using the guideline. The tests were observed by Dr. Higgins and several other rockfall specialists who recommended the modifications to the NCHRP 20-07 guideline. These modifications have not been widely distributed. The following discussion of the modifications to the NCHRP 20-07 guideline is summarized from Higgins (2013). The original NCHRP 20-07 guideline stated that test results were only valid for the tested panel width. Modifications to the guideline allow the panel width to be increased or decreased by up to 1.15 times without additional testing. Modifications to some of the definitions used in the guideline were also made. These modifications included defining test

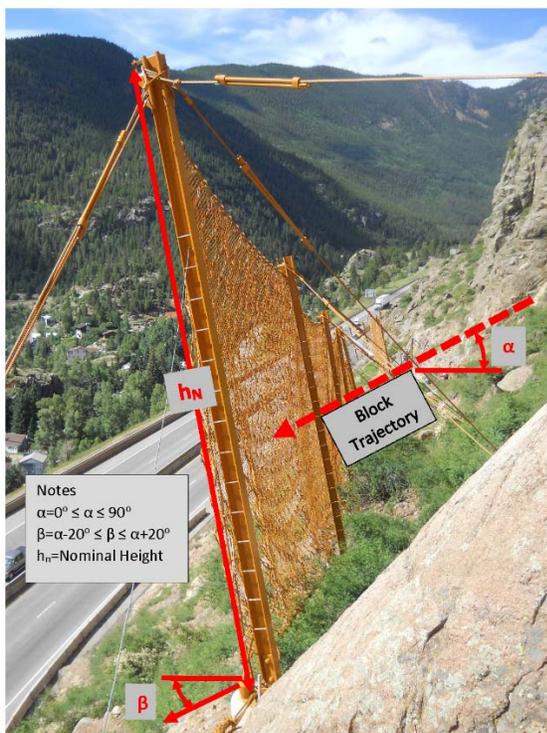
B at 50 percent energy as the service energy level (SEL) test and defining test C at 100 percent energy as the maximum energy level (MEL) test.

Modifications to the test sequence include measurement and description of the height of drop, weight of test body, and impact locations for all tests. The guideline was also modified to reduce the number of force measurements required during tests B and C (SEL and MEL tests, respectively). The original guideline required tensile force measurements at approximately 10 anchor points. Modifications require force measurements at a minimum of three locations including a post foundation, an upslope anchor, and a lateral anchor. Recording of the camera locations and film speed used to film the tests was also added to the guideline during modification.

3.3.8 European ETAG 27 Testing Standards

In 2008, ETAG 27 became effective in the E.U. The guideline includes material conformity guidelines and identification tests, which are not summarized here as they apply to specific European standards. The terms and definitions used and the criteria evaluated by ETAG 27 are somewhat similar to those of the SAEFL and NCHRP 20-07 guidelines.

The following discussion of ETAG 27 is summarized from EOTA (2008) and Peila and Ronco (2009). The test site must consist of a structure capable of accelerating a concrete block to the test speed and delivering the concrete block into the fence with the necessary precision. The slope downhill of the fence, referred to as the reference slope, must be within 20 degrees of parallel to the block trajectory in the last one meter before the impact of the block with the fence (Figure 3-13). The trajectory of the block may be vertical or inclined (Figure 3-14 and Figure 3-15) and inscribed in a vertical plane orthogonal to the line connecting the post bases.



Source: Photograph courtesy of B. Arndt

Figure 3-13. Section view of the relationship between the block trajectory and reference slope in ETAG 27



Source: Photograph courtesy of B. Arndt

Figure 3-14. Test facility in Italy set up according to the ETAG 27 guideline for a vertical drop test



Source: Photograph courtesy of B. Arndt

Figure 3-15. Styrian Erzberg test facility in Eisenerz, Austria set up according to the ETAG 27 guideline for an inclined test

The test fence is required to consist of three functional modules or panels with four posts. The manufacturer is allowed to decide the installation geometry and post spacing. The height of the fence cannot be reduced from that of the tested height and cannot be raised more than 0.5 m (1.6 ft) for fences with a tested height of less than 4 m (13 ft) or 1 meter (3 ft) for fences with a tested height of greater than or equal to 4 m (13 ft). Modification of the post spacing and the inclination of the main ropes from those tested are allowed within a tolerance specified by the manufacturer. The manufacturer is responsible for evaluating the forces acting on the structure to demonstrate the fitness for use of any modified fence.

An installation manual is required as part of the certification process and it is required that the manufacturer follow the manual in installing the fence at the test site. The block used for testing can be unreinforced or reinforced concrete in a polyhedral shape (Figure 3-16). The density of the block is required to be between 2,500 and 3,000 kg/m³ (156 and 187 lb/ft³). The maximum size of the block is required to be 3 times smaller than the nominal height of the fence. The mass and size of the block is measured before each test. The average velocity of the block within the last one meter from the fence must be greater than or equal to 25 m/s (82 ft/s) for all tests. The impact energy is calculated as the translational kinetic energy of the block at impact.



Source: Photograph courtesy of B. Arndt

Figure 3-16. Shape and geometry of ETAG 27 test blocks made of unreinforced or reinforced concrete

The test procedure consists of two SEL tests and one MEL test. The MEL test is chosen by the manufacturer prior to the test and is required to be greater than or equal to three times the SEL test. There are nine classifications for MEL ranging from 100 to greater than 4,500 kJ (37 to greater than 1,660 ft-tons) (Table 3-3).

Table 3-3. ETAG 27 energy level classifications

Energy level classification	0	1	2	3	4	5	6	7	8
SEL (kJ)	-	85	170	330	500	660	1,000	1,500	>1,500
MEL ≥ (kJ)	100	250	500	1,000	1,500	2,000	3,000	4,500	>4,500

Note: No test performed at SEL for Energy level classification 0
 Source: Adapted from EOTA 2008

The test and fence characteristics recorded prior to each test include:

- Mass of the test block
- Nominal height of the fence
- Photographs of the position and construction of the fence
- Geometric parameters of the fence
- Mechanical and physical characteristics of fence components

The test and fence characteristics recorded during each test include:

- Block speed evaluated in the last one meter before impact with the fence
- Block trajectory
- Maximum elongation of the fence
- Photographic records to give a complete record of the fence behavior including deformation, deflections, braking time, and proof that no ground contact occurred before the maximum elongation is reached
- Foundation peak forces and time-force diagrams

The test and fence characteristics recorded after each test includes:

- Residual height of the fence
- Description and photographic records of damages to the fence

Block speed measurements are performed from at least one high-speed video camera and additional cameras are considered for covering areas of special interest. Measurement of forces on anchorage and ropes is adapted to the specific fence with at least 3 measurements on the main ropes of the center fence panel.

The SEL tests are conducted with two launches of a block at the same kinetic energy as specified by the energy level classification. The objective of the tests is to evaluate the ability of the fence system to intercept and contain successive impacts within specified performance criteria. The first SEL test is required to impact the center of the fence system. The test is passed if:

- The block is stopped by the fence.
- No ruptures occur in the connection components and the opening of the panel mesh is less than two times larger than the initial size of the mesh openings.
- The residual height of the fence after the test (without removing the block) is greater than or equal to 70 percent of the nominal height of the fence.
- The block has not touched the ground until the fence has reached the maximum elongation during the test.

The block is then removed from the fence and no maintenance is allowed. The second SEL test is also required to impact the center of the fence. This test is passed if:

- The block is stopped by the fence.
- The block has not touched the ground until the fence has reached the maximum elongation during the test.

The MEL test is conducted with one launch of the test block into the test fence at the energy specified. The objective of the test is to characterize the maximum energy capacity of the fence system. The manufacturer of the fence is allowed to decide whether the MEL test is conducted using the same fence as used for the SEL tests after being repaired or on a new fence. The test block is launched into the center of the new or repaired fence and the test is passed if:

- The block is stopped by the fence.
- The block has not touched the ground until the fence has reached the maximum elongation during the test.

The classification of the residual height of the fence measured after the MEL tests is outlined in Table 3-4.

Table 3-4. ETAG 27 residual height categories for MEL test

Category	Residual Height
A	≥ 50% of nominal height
B	Between 30 and 50% of nominal height
C	≤ 30% of nominal height

Source: Adapted from EOTA 2008

3.4 Comparison of SAEFL, NCHRP 20-07, and ETAG 27

A summary and comparison of the SAEFL, NCHRP 20-07, and ETAG 27 guidelines previously discussed is provided in Table 3-5. Table 3-6 summarizes the advantages and disadvantages of these guidelines.

The significant differences between the existing rockfall fence testing systems which include SAEFL, NCHRP 20-07, and ETAG 27 have made it difficult to compare the results of the various guidelines. Some of these differences stem from the testing procedures while others stem from the performance criteria used to evaluate the test results. Also, the terms and definitions used in the guidelines have slightly different definitions in some cases that could potentially lead to confusion when comparing test results. Overall some highlighted considerations when discussing or comparing the various rockfall testing protocols are as follows:

Test Responsible Party

Similar to the SAEFL guideline, the ETAG 27 test is conducted by a governing body and is considered to be an independent evaluation. According to Higgins (2003), manufacturers were given responsibility for the tests in the NCHRP 20-07 guideline because there were likely to be very few tests conducted in the U.S. in any one year and a national test facility with infrastructure and staff was not justifiable. Additionally, funding a national facility was not practical. The solution at the time was to develop a guideline that was simple and could be conducted by the manufacturer with readily available and portable equipment.

Fence Height

The ETAG 27 guideline does not limit the height of the test fence as do the SAEFL and NCHRP 20-07 guidelines. However, the ETAG 27 guideline does limit modification of the height after testing has been performed. If the manufacturer modifies the height by more than the specified amount, retesting is required for certification. This is similar to limitations used in the SAEFL and NCHRP 20-07 guidelines, but the specific limitations vary. The ETAG 27 limitations are generally stricter than those used in the SAEFL and NCHRP 20-07 guidelines.

Post Spacing

As with the SAEFL and NCHRP 20-07 guidelines, the ETAG 27 guideline requires the test fence to consist of three net panels and four posts. The ETAG 27 guideline allows the manufacturer to select the panel width and post spacing for the test. The limitations on the number of panels and posts are important for being able to compare different test results as fences consisting of different numbers of these components are likely to behave differently. Allowing the manufacturer to select the panel width and post spacing allows freedom to design new fence systems; however, this may make comparison of test results more difficult. Modification of the panel width and post spacing from that tested is allowed in the ETAG 27 guideline within a tolerance specified by the manufacturer. Many DOTs however have opinions on maximum post spacing based on their experience and site conditions.

Service and Maximum Energy Levels

The intended results of the Service Energy Level (SEL) tests in the ETAG 27 guideline and test B in the SAEFL and NCHRP 20-07 guidelines are similar, but the impact energies and the number of tests performed differ. The ETAG 27 guideline requires two SEL tests to be conducted at one third of the Maximum Energy Level (MEL) while the SAEFL and NCHRP 20-07 guidelines require one SEL test to be conducted at one half of the MEL. Using a lower SEL limits the ability to achieve the objective of the test in evaluating the residual height of the fence at a lower energy level.

Residual Height

The ETAG 27 guideline includes residual height categories for evaluating fence performance at the MEL. Residual height categories range from greater than 50 percent to less than 30 percent of the nominal fence height. These criteria are less strict than those used in the SAEFL and NCHRP 20-07 guidelines, which generally require that the residual height be greater than 50 percent of the nominal fence height. Typical ETAG 27 certification documents give the residual height category for the MEL test, but they do not provide the actual value of residual height. This makes comparison of the residual height of different fences tested using the various guidelines difficult. Additionally, the residual height is recorded for the SEL tests, but is not typically reported on certification documents, which also makes comparison difficult.

Elongation

For a fence to pass the MEL test in ETAG 27, the fence must stop the test rock, but can deform an unlimited amount. The elongation of the fence during impact is not limited in the ETAG 27 guideline as it is in the SAEFL and NCHRP 20-07 guidelines. This has led to some fences having significant elongation lengths and some manufactures designing more plastic type deformable systems with lighter weight materials. Deformation of the fence panels can be greater than 10 m (33 ft) for the highest energy level classifications for many current systems. Additionally, fences may require extensive repair or replacement after one impact at the MEL. The inconsistency in limiting elongation in the various guidelines makes direct comparison of tests more difficult. Comparison is also made more difficult in some instances by the lack of reporting of the actual maximum elongation value on typical ETAG 27 certification documents.

Maintenance

A zero maintenance level (ZML) test was considered during the development of the ETAG 27 guideline, but was not included in the final guideline (Spang 2002 and Viktorovitch 2002). This test was being considered to define the energy level for which no maintenance would be required between multiple rockfall impacts. This type of test may have been useful for evaluating fences for sites that may have limitations on the ability to perform maintenance on the fence. A fence with the appropriate ZML could theoretically be chosen and installed without requiring maintenance for the service life of the fence for a given energy level. The current ETAG 27 guideline does not carry this concept further.

After the SEL tests in the ETAG 27 guideline, the fence manufacturer is allowed to decide whether the MEL test is conducted on a new fence or the fence tested at the SEL with repairs, which can create

confusion when reviewing the test results. The ETAG 27 guideline does however require documentation of damages to the fence, but in many cases there may not be clear documentation or evaluation of the level of maintenance that the fence requires after the SEL tests as is the case in the SAEFL and NCHRP 20-07 guidelines. Documentation of damage may be used to evaluate maintenance that would be required after a low energy impact, but it does not allow a direct evaluation that would be possible if the manufacturer was not allowed to replace the fence for the MEL test.

Table 3-5. Summary and comparison of the SAEFL, NCHRP 20-07, and ETAG 27 guidelines

	Guideline		
	SAEFL	NCHRP 20-07	ETAG 27
Location of Development	Switzerland	United States	European Union
Test Responsibility	Governing Body	Manufacturer	Governing Body
Rock/Block Delivery Method	Vertical Drop	Vertical drop, inclined cable, and rock rolling	Vertical drop or inclined cable
Rock/Block Type	Manufactured	Manufactured or natural	Manufactured
Fence Height	Limited	Limited	Unlimited
Post Spacing/Panel Width	Limited	Unlimited	Unlimited
Small Diameter Rock/Block Test	Yes	Yes	No
MEL/SEL	2	2	3
Tests at Low Energy (SEL)	1	1	2
Tests at High Energy (MEL)	1	1	1
Residual Height			
at SEL	Unlimited	Unlimited	1 st Test: > 70% 2 nd Test: Unlimited
at MEL	>50%	>60%	Categories A, B, C
Elongation			
at SEL	Unlimited	Unlimited	Unlimited
at MEL	Limited	Limited	Unlimited
Maintenance	Evaluated	Evaluated	Not evaluated

Table 3-6. Summary of advantages and disadvantages of SAEFL, NCHRP 20-07, and ETAG 27 guidelines

Guideline	Advantages	Disadvantages
SAEFL	<ul style="list-style-type: none"> • Tests easily reproduced • Small diameter rock/block test • Maintenance evaluated • Elongation limited • Force measurements on ropes and anchorage 	<ul style="list-style-type: none"> • Limits post spacing and panel widths • 50% residual height limitation • Requires force measurements at 10 locations • No force measurements on foundations • Vertical drop test does not represent real conditions
NCHRP 20-07	<ul style="list-style-type: none"> • Can be conducted by manufacturers with readily available and portable equipment • Multiple rock/block delivery options • Post spacing/panel width decided by manufacturer with limitations on post-testing modifications • Documentation of foundation and anchorage design • Requires force measurements at post foundation, lateral anchor, and upslope anchor 	<ul style="list-style-type: none"> • Potential for bias of results • 60% residual height limitation • Allows rock rolling tests, which can be difficult to reproduce • Vertical drop tests does not represent real conditions
ETAG 27	<ul style="list-style-type: none"> • Widely used in Europe • Multiple rock/block delivery options • Post spacing/panel width decided by manufacturer • Requires force measurements at post foundation, lateral anchor, and upslope anchor 	<ul style="list-style-type: none"> • Differs from SAEFL and NCHRP 20-07 guidelines • Does not limit elongation • No limitations on allowable modification of post spacing/panel width • 50% residual height limitation • No evaluation of maintenance

CHAPTER 4

Review of Flexible Rockfall Fence Inventory, Assessment and Management Systems

4.1 Overview Asset Management

Transportation Asset Management (TAM) is a strategic and systematic process of maintaining and managing infrastructure assets throughout their life cycle, focusing on business and engineering practices for resource allocation and utilization. It uses data and analysis to improve decision making, with the objective of providing the required level of service in the most cost effective manner (Gordon et al. 2011).

TAM incorporates a set of best practices that maximize transportation system performance, minimize long-term costs, and manage risks. These practices are widely implemented all over the world and are codified in international and AASHTO manuals (NAMS 2006 and Gordon et al. 2011). They influence asset-level decisions about performance evaluation and treatment selection, as well as network level decisions about program development and resource allocation.

The Moving Ahead for Progress in the 21st Century Act, known as MAP-21, calls on state Departments of Transportation to prepare risk-based Transportation Asset Management Plans (TAM Plans) for the National Highway System to “improve or preserve the condition of the assets and the performance of the system”. The legislation mandates the establishment of condition and performance targets for at least pavements and bridges, and requires the TAM Plan “to include strategies leading to a program of projects that would make progress toward achievement of the targets.” Although only pavements and bridges are mandatory in the TAM Plans, states are encouraged “to include all infrastructure assets within the right-of-way corridor in such plan” (23 USC 119(e)). FHWA has published draft guidance on TAM Plan development (FHWA 2015a and 2015b).

Many states in their TAM Plans have decided to go well beyond pavements and bridges, and many are covering all state-maintained roads on and off the National Highway System. Examples of these plans can be found at:

- <http://www.fhwa.dot.gov/asset/plans.cfm>
- <http://www.tamtemplate.org/>

Although the coverage of geotechnical assets is optional, MAP-21 and the proposed regulations provide considerable incentive to include geotechnical assets. The TAM Plan is designed to provide the strategy and justification for projects in the Statewide Transportation Improvement Program (STIP), and agencies will be required to document this justification. MAP-21 allows National Highway Performance Program (NHPP) funding to be used for the necessary data collection and tools. Techniques are available, as documented in the Appendix C, to develop the necessary information in a way that is simple and focused, and completely compatible with accepted practice in pavements and bridges.

By providing an objective, data-driven justification for the funding and selection of geotechnical investments, and by including these investments in the STIP process, incorporation of geotechnical assets

within the TAM Plan gives this asset class a seat at the table in preservation strategy, funding allocation, and investment programming decisions. In exchange for this benefit, the proposed rules mandate that the TAM Plan address all covered assets using the same types of best practices.

Asset management is based on a process of measuring performance, and then making decisions in a manner that optimizes performance. MAP-21 lists seven national goals in 23 USC 150(b): safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. At the same time, agencies are expected to minimize life cycle cost and risk. Most state DOTs have mission statements, strategic plans, state laws, or administrative codes that specify a similar list of goals. Performance measures attempt to summarize how well a given asset is contributing to those goals.

Rockfall fence systems affect the performance goals in two primary ways.

- Physical condition of these assets tends to deteriorate, a fact that necessitates occasional maintenance and preservation activities in order to extend service life and minimize life cycle costs.
- Incidents of rockfall sometimes cause a disruption of transportation service: this reduces network safety, reliability, and sustainability; and causes recovery expenses. Such adverse events can be analyzed using the principles of risk analysis. The likelihood of these events is influenced by the presence of appropriate rockfall protection features, and by the condition of these assets.

By including geotechnical assets within an agency's TAM Plan, the potential benefits and staying power of best-practice asset management are enhanced. The TAM Plan describes several essential aspects of these assets:

- Objectives, performance measures, levels of service, and targets;
- Inventory, condition, and performance gaps;
- Analysis of life cycle costs and risks, including the cost and effectiveness of treatments;
- Fiscal scenarios and anticipated performance for each scenario.

A desired outcome of geotechnical asset management is:

- the establishment of more predictable and sustainable funding allocation policies and program management decisions, which may serve to allocate risk more uniformly across all asset classes,
- to ensure that geotechnical assets are preserved to minimize life cycle cost,
- to enable long-range investments in improved agency capabilities, and
- to encourage improved contractor capabilities.

4.2 Austrian Rockfall System Inspection and Maintenance Guidelines

Based on review of European based publications one notable document was developed by the Austrian Standard Institute to go beyond the ETAG 27 document, which they described as primarily focusing on material aspects of rockfall barriers rather than long term implementation and formed a document known as "ONR 24810 - Technical protection against rockfall – Terms and definitions, effects of actions, design, monitoring and maintenance" (Austrian Standards Institute 2013). The guidelines focus on the site investigation, design, construction and maintenance of rockfall mitigation measures such as stabilization with anchoring and mesh/nets, embankments, galleries and rockfall catchment fences. The main document is in German and the following outline of the document has been summarized from Stelzer and Bichler (2013a and 2013b).

After a rockfall mitigation system is implemented, detailed documentation of the structures is necessary so that the condition of the system can be evaluated during future inspections and maintenance can be performed as required. The ONR 24810 inspection procedures consist of four inspection protocols:

- On-going inspection – inspections performed annually by experts or trained personnel. Inspection includes checking brake functionality, elongation and residual capacity, net deformation and damage, damages to ropes, verification of nominal height, and evaluation of debris in the system.
- Control inspection – inspections performed every 5 to 10 years by experts. Inspection includes on-going inspection items and evaluation of general condition and possible corrosion of components such as brake elements, nets, ropes, posts and base plates, foundations, and other system components. A general evaluation of the state of the system compared to the most recent inspection is performed. Based on the evaluation, a State Class is assigned to the system.
- Post-event inspection – inspections performed by an expert after a rockfall event. This inspection is independent from scheduled inspections and is intended to evaluate the status of the mitigation system. A test inspection may be recommended after the post-event inspection.
- Test inspection – inspection is performed by an expert or by an inter-disciplinary expert team. It is conducted when other inspections cannot evaluate the condition of the system. The inspection procedure is specific to the components being inspected and may include testing to evaluate the overall safety and condition of the system. For example, anchor pull tests may be performed to evaluate anchor capacity.

The inspection protocols outlined in the ONR 24810 guideline suggest useful procedures for U.S. transportation agencies to gather information necessary to maintain mitigation systems and to develop asset management plans for these systems. However, most agencies will likely want more flexibility in the inspection schedule and procedure. Agencies may desire to inspect systems in higher risk areas such as heavily traveled highways more often than systems installed in lower risk areas such as rural roads. This prioritization may also help agencies perform inspections with often limited resources.

Additionally, a typical obstacle to inspection is getting personnel to rockfall sites to perform inspection. It is therefore beneficial for full inspections such as the control inspection described in ONR 24810 to be performed each time personnel visit the site. Post-event type inspections can be initiated by reports of rockfall events from highway maintenance crews who regularly travel roadways to perform other tasks. Testing type inspections as described in ONR 24810 should be evaluated for cost effectiveness as it may be only slightly more expensive to replace potentially damaged components compared to performing specialized testing to evaluate the capacity of a component.

4.3 Canadian Rockfall Site and System Inspection and Maintenance Practices

Based on available literature and discussion with rockfall experts, the current state of practice within Canadian transportation agencies pertaining to rockfall site and system inspection and maintenance consists of slope and mitigation inventories and use of databases to retain information and evaluate high priority sites (Wyllie 2015). According to Wyllie and Mah (2004), high priority sites can be identified by assigning each slope an “Inspection Rating” and corresponding “Required Action”. Inspection ratings range from “Urgent” with recent movement or rockfall activity to “Okay” with no evidence of slope movement. Required action ratings range from limit service and perform mitigation work within one month to no action. Wyllie and Mah suggest that this information can be stored within a database and can be analyzed to identify the most hazardous sites, correlate rockfall frequency with other factors and slope attributes, assess impacts of rockfalls on mobility, and assess effectiveness of stabilization work based on frequency of rockfalls.

4.4 Comparison with Retaining Wall Inventory and Condition Assessment Methods

An inventory system that is comparable to rockfall protection system inventories is the manual for the Retaining Wall Inventory and Condition Assessment Program for the National Parks Service (NPS) developed by Central Federal Lands (CFL) (DeMarco et al. 2010). The purpose of the manual was to develop, define, quantify, and assess wall assets associated with park roadways in terms of their location, geometry, construction attributes, geotechnical and structural condition, failure consequence, cultural aspects, apparent design criteria, and cost of structure maintenance/repair/replacement. The procedures manual documents the data collection and management processes, wall attribute and element definitions, and team member responsibilities for conducting retaining wall inventories and condition assessments. The NPS Wall Inventory Program (WIP) was used to assess nearly 3,500 walls within 32 national parks. The manual describes the development of a comprehensive training program for field inspectors, a Microsoft Access-based database, unique data collection forms, a supporting field guide, and a wall repair/replacement cost estimation guide.

4.4.1 Examples of WIP Field Forms for Wall Systems

The following figures depict the forms used in the WIP manual that have been considered as a basis for developing a procedure for evaluating and inventorying of rockfall fence systems. Figure 4-1 depicts the field form with replacement cost estimates for damaged systems and Figure 4-2 depicts the form used to collect condition narrative and ratings.

-NPS RETAINING WALL INVENTORY PROGRAM (WIP) FIELD FORM-					
NPS Park Name		Route/Parking No.		Wall Start Milepoint	
Inspected By		Route/Parking Name		Wall End Milepoint	
Inspection Date		Side of Centerline	(R/L/P# #)	Visidata Event Milepoint	
WALL FUNCTION, DIMENSIONS, and DESCRIPTION					
Wall Function		Primary Wall Type		Architectural Facings	
Approx. Year Built		Secondary Wall Types		Surface Treatments	
Wall General Description Notes: (e.g., wall purpose, setting, construction, consequence of failure, special design, etc.)					
Wall Length (ft)		Wall Face Area (ft ²)		Wall Start Offset (ft)	
Max. Wall Height (ft)		Vertical Offset (+/- ft)		Wall End Offset (ft)	
Photo Description/No. (e.g., approach, elevation, wall top, alignment, face detail deficiencies, etc.)				Face Angle (deg)	
Park Designated Wall ID					
REPAIR /REPLACE RECOMMENDATIONS AND WORK ORDER					
Wall Condition Rating		Design Criteria		Failure Consequence	
Investigation Req'd?	(Y/N)	Cultural Concern?	(Y/N)	Action	
Brief Work Order Description (5-10 word maximum, key work elements)					
Repair/Replace Recommendations (itemized description of wall repairs, methods, estimated quantities, and costs per repair item, including consideration of constructability issues such as access, traffic control, staging, safety hazards, etc.)					
Rev. 07-10-2007				Repair/Replace COST:	

Source: DeMarco et al. 2010

Figure 4-1. WIP field form and estimated repair replacement

Element	Condition Narrative	Condition Rating	Weighting Factor	Condition Score	Data Reliability
Primary Wall Elements					
Piles and Shafts		1-10	8		1-3
Lagging		1-10	8		1-3
Anchor Heads		1-10	8		1-3
Wire/Geosynthetic Facing Elements		1-10	8		1-3
Bin or Crib		1-10	8		1-3
Concrete		1-10	8		1-3
Shotcrete		1-10	8		1-3
Mortar		1-10	8		1-3
Manufactured Block/Brick		1-10	8		1-3
Placed Stone		1-10	8		1-3
Stone Masonry		1-10	8		1-3
Wall Foundation Material		1-10	8		1-3
Other Primary Wall Element		1-10	8		1-3
Secondary Wall Elements (WF=0.5 for CR=8-10/WF=1.0 for CR=4-7/WF=5 for CR=1-3)					
Wall Drains		1-10	0.5-5		1-3
Architectural Facing		1-10	0.5-5		1-3
Traffic Barrier/Fence		1-10	0.5-5		1-3
Road/Sidewalk/Shoulder		1-10	0.5-5		1-3
Upslope		1-10	0.5-5		1-3
Downslope		1-10	0.5-5		1-3
Lateral Slope		1-10	0.5-5		1-3
Vegetation		1-10	0.5-5		1-3
Culvert		1-10	0.5-5		1-3
Curb/Berm/Ditch		1-10	0.5-5		1-3
Other Secondary Wall Elements		1-10	0.5-5		1-3
Wall Performance					
Performance		1-10	8		
WALL RATING	Weighting Factor (x10) and Condition Score Totals				
	Wall Condition Rating := [Condition Score Total/Weighting Factor Total (x10)] X 100				

Source: DeMarco et al. 2010

Figure 4-2. WIP condition narrative and condition rating

4.4.2 Example of Definitions, Conditions and Performance Ratings for Wall Systems

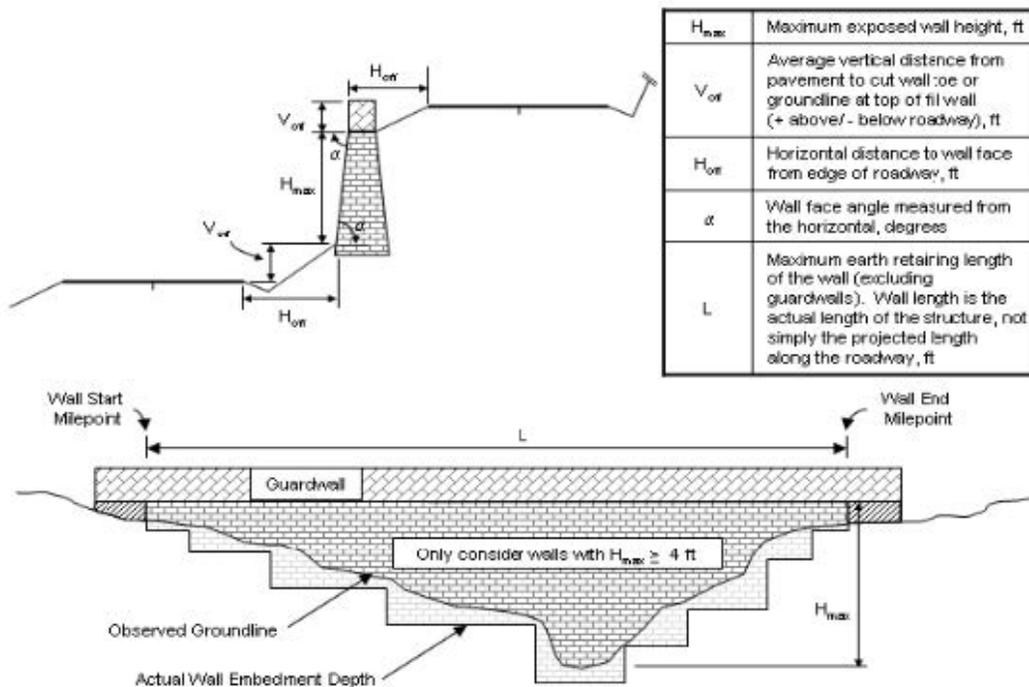
Figure 4-3 depicts the criteria and definitions used in evaluating wall systems and Figure 4-4 depicts wall condition rating definitions.

- NPS Retaining Wall Inventory Program Field Guide (WIFG)-		
Retaining Wall Acceptance Criteria		
<p>*All classes of paved roadways and parking areas included in the RIP Route Investigation Report and/or identified by Park staff.</p> <p>*Walls must reside within the constructed roadway/parking area prism.</p> <p>*Maximum wall height, including only that portion actively retaining soil and/or rock, must be ≥ 4 ft (≥ 6 ft for culvert headwalls).</p> <p>*Consider known/verifiable wall embedment in determining maximum retaining wall height. Include fully buried retaining structures.</p> <p>*Walls have an internal wall face angle $\geq 45^\circ$ ($\geq 1H:1V$ face slope ratio).</p> <p>*Include all walls where the intent is to support/protect the travelway, and where failure would require replacement with a retaining wall.</p>		
Definitions		
Design Criteria	Measure of how well current design criteria are satisfied: None - Does not meet any known standards. Non-AASHTO - Does not meet AASHTO, but is consistent with other structures of its type/period with good performance. AASHTO - Apparently meets current AASHTO Geometric, Design, Materials, and Construction Standards.	
Consequence of Failure	Low - No loss of roadway, no to low public risk, no impact to traffic during wall repair/replacement Moderate - Hourly to short-term closure of roadway, low-to-moderate public risk, multiple alternate routes available High - Seasonal to long-term loss of roadway, substantial loss-of-life risk, no alternate routes available	
Action	Select from: No Action, Monitor, Maintenance, Repair Elements, Replace Elements, and Replace Wall	
Weighting Factor	Weighting Factor to be applied to the Condition Rating (CR). When indicated on the Condition Assessment Input Form: WF=0.5 for CR=8-10; WF=1.0 for CR=4-7; and WF=5 for CR=1-3.	
Data Reliability	Estimate of how well observed conditions represent wall performance, and if additional investigations may be warranted. 1-Poor Conditions cannot be sufficiently observed to rate element(s), warranting additional investigations to better define element performance and/or to determine the cause(s) or poor performance. 2-Good Observed conditions are sufficient to rate the conditions of wall element(s); however, additional investigations would be useful to better understand element performance. 3-Very Good Observed conditions clearly describe wall performance. Additional investigations are not needed.	
Wall Function Codes		
[FW] Fill Wall [CW] Cut Wall [BW] Bridge Wall [SW] Switchback Wall [HW] Head Wall [SP] Slope Protection [FL] Flood Wall		
Wall Type Codes		
[AH] Anchor, Tieback H-Pile	[CC] Crib, Concrete	[MG] MSE, Geosynthetic Wrapped Face
[AM] Anchor, Micropile	[CM] Crib, Metal	[MP] MSE, Precast Panel
[AS] Anchor, Tieback Sheet Pile	[CT] Crib, Timber	[MS] MSE, Segmental Block
[BC] Bin, Concrete	[GB] Gravity, Concrete Block/ Brick	[MW] MSE, Welded Wire Face
[BM] Bin, Metal	[GC] Gravity, Mass Concrete	[SN] Soil Nail
[CL] Cantilever, Concrete	[GD] Gravity, Dry Stone	[TP] Tangent/ Secant Pile
[CP] Cantilever, Soldier Pile	[GG] Gravity, Gabion	[OT] Other, User Defined
[CS] Cantilever, Sheet Pile	[GM] Gravity, Mortared Stone	[NO] None
Architectural Facing Type Codes		
[BV] Brick Veneer	[PF] Planted Face	[SS] Simulated Stone
[CO] Cementitious Overlay	[SC] Sculpted Shotcrete	[SV] Stone Veneer
[FF] Fractured Fin Concrete	[SH] Shotcrete (nozzle finish)	[TI] Timber
[FL] Formlined Concrete	[SM] Steel/Metal	[OT] Other, User Defined
[PC] Plain Concrete (float finish or light texture)	[SO] Stone	[NO] None
Surface Treatment Codes		
[BG] Bush Gun (tool-textured concrete)	[PS] Preservative	[WS] Weathering Steel
[CA] Color Additive	[SE] Silane Sealer	[OT] Other, User Defined
[GL] Galvanized	[ST] Stain	[NO] None
[PA] Painted	[TR] Tar Coated	

Source: DeMarco et al. 2010

Figure 4-3. WIP definitions

Condition Ratings	
Condition Ratings apply to all Primary and Secondary Wall Elements, and are intended to assist in consistently defining element severity, extent, and repair/replace urgency of wall element distresses.	
9-10 (Excellent)	-Any defects are minor and are within normal range for newly constructed or fabricated elements. -Defects may include those typically caused from fabrication or construction.
7-8 (Good)	-Low-to-moderate extent of low severity distress. -Distress present does not significantly compromise the element function, nor is there significantly severe distress to major structural components of an element.
5-6 (Fair)	-High extent of low severity distress and/or low-to-medium extent of medium to high severity distress. -Distress present does not compromise element function, but lack of treatment may lead to impaired function/elevated risk of element failure in the near term.
3-4 (Poor)	-Medium-to-high extent of medium-to-high severity distress. -Distress present threatens element function, and strength is obviously compromised and/or structural analysis is warranted. -The element condition does not pose an immediate threat to wall stability and road closure is not necessary.
1-2 (Critical)	-Medium-to-high extent of high severity distress. -Element is no longer serving intended function. Element performance threatening overall stability of the wall at the time of inspection.
Wall Performance Condition Ratings	
Performance	Evaluation of overall wall performance as indicated by observations not necessarily captured by observed distresses for specific elements, including global wall distresses (rotation, settlement, translation, displacement, etc.) and/or evidence of prior repairs that may further indicate component problems.
	Good to Excellent - No observation of distresses not already captured by individual element condition assessment. No combination of element distresses indicating unseen problems or creating significant performance problems. No history of remediation or repair to wall or adjacent elements.
	Fair - Some observed global distress is not associated with specific elements. Some observation of element distress combinations that indicate wall component problems. Minor work on primary elements or major work on secondary elements has occurred improving overall wall function.
	Poor to Critical - Global wall rotation, settlement, and/or overturning is readily apparent. Combined element distresses clearly indicate serious stability problems with components or global wall stability. Major repairs have occurred to wall structural elements, though functionality has not improved significantly.



Source: DeMarco et al. 2010

Figure 4-4. WIP condition ratings

CHAPTER 5

Research Results

5.1 Overview

This section presents the results of the research study and is divided into eight sections:

- Survey - Results of the rockfall system survey for agencies, manufacturers and design engineers.
- Proposed ETAG 27 Acceptance Procedures - Acceptance of ETAG 27 certification with manufacturer certified forms to capture data from original ETAG 27 certification.
- Discussion of ASTM rockfall fence testing considerations and challenges.
- Proposed Inventory and Condition Assessment of Rockfall Fence Systems.
- Case Study of Colorado Project using Inventory and Condition Assessment.
- Discussion of Asset Management of Rockfall Fence Systems.
- Discussion of Maintenance and Repair of Rockfall Fence Systems.
- Proposed Performance Based Special Provision for Rockfall Fence Systems.

5.2 Survey Results

A total of 32 responses from transportation agencies, design engineers, and rockfall fence manufacturers were received. The surveys were completed by 16 representatives of transportation agencies, 10 design engineers, and 6 representatives of rockfall fence manufacturers. The responses are summarized in the sections below. A detailed summary of the survey responses is provided in Appendix B.

5.2.1 Background Section Results

The majority of transportation agencies indicated that they have less than 10 rockfall mitigation projects per year. Four agencies indicated that they have more than 10 projects per year. The majority of agencies and design engineers surveyed indicated that less than 10 percent of their rockfall mitigation projects are related to systems such as fences, attenuators, drapery systems, and anchored mesh. Agencies indicated that over 70 percent of projects are related to other types of mitigation such as resloping, scaling, bolting, catchment ditches, concrete roadside barriers, and mechanically stabilized earth (MSE) barrier walls. Four rockfall fence manufacturers indicated that they sell less than 10 fence systems per year in the U.S. while 2 manufacturers indicated that they sell more than 10 fence systems per year in the U.S. Agencies and design engineers indicated that, on average, greater than 70 percent of rockfall protection systems in the U.S. are installed within approximately 9 m (30 ft.) of a roadway or other structure. This is important when evaluating the ability of flexible rockfall fence systems to contain and stop rocks within a limited shoulder distance.

Some agencies indicated the annual programmed budgets for rockfall mitigation projects are generally less than \$5 million. Many agencies indicated that they do not have a programmed budget for rockfall projects, but these projects are generally included with other projects. The majority of agencies indicated that they spend less than \$1 million per year for emergency rockfall projects, but there is no programmed

rockfall emergency budget. Rockfall emergency money generally comes from maintenance funds or a general emergency fund.

The majority of agencies indicated that they or a consultant typically write specifications related to their rockfall mitigation projects. The majority of design engineers indicated that they or the owner typically write the specifications. However, the majority of manufacturers indicate that greater than 80 percent of public sector customers request that the manufacturer write specifications for rockfall fence systems while less than 20 percent of private sector customers make this request.

The majority of agencies and design engineers indicated that they typically design permanent rockfall protection systems for a certain life-span rather than one-time use. Agencies and design engineers indicated that the design life-span varied depending on the type of system, but a minimum design life of 25 years is common.

5.2.2 Standards and Certifications Section Results

The majority of transportation agencies indicated that they do not have their own design or performance standards or certifications for flexible rockfall protection systems. Some agencies require information or a “certificate of compliance” for these systems from the manufacturer.

The majority of agencies and design engineers indicated that they were familiar with the existing NCHRP 20-07 and ETAG 27 guidelines for testing of fence systems. Manufacturers appear to be more familiar with the SAEFL and ETAG 27 guidelines. The majority of agencies and design engineers were also familiar with other publications related to flexible rockfall protection while few manufacturers were familiar with these publications. Of the existing testing guidelines, agencies appear not to have a preference for using or specifying any specific guideline. Design engineers and manufacturers appear to prefer the use or specification of ETAG 27 over the SAEFL and NCHRP 20-07 guidelines. Agencies and design engineers indicate they use or specify other related publications while no manufacturers appear to use these publications.

Half of agencies surveyed indicated that they do not require or request any documentation of testing and certification of fence systems under any of the existing guidelines. Agencies who do request documentation do not appear to have a specific preference for any of the existing guidelines. The majority of design engineers indicated that their firm requires or requests documentation from the ETAG 27 guideline or they rely on the owner of the rockfall protection system to specify whether any documentation is required. The majority of manufacturers indicated that most customers request documentation from the ETAG 27 guideline and occasionally from the SAEFL guidelines.

Transportation agencies indicated that they would like a new U.S. testing guideline that reflects the ETAG 27 guideline rather than the SAEFL guideline. Agencies perceive the primary advantages of the ETAG 27 guideline are that it is widely used and has general applicability. Agencies indicate the disadvantages of ETAG 27 are that the test procedures do not necessarily represent real conditions, the guideline does not consider ease of installation or maintenance, and the guideline does not consider small diameter rocks. In general, agencies perceive limitations in the lack of consistency between each guideline in terms of performance criteria and allowable modifications to tested systems.

Design engineers have similar perceived advantages and limitations of the existing testing guidelines. Specifically, design engineers perceive a significant obstacle in the lack of standardized terminology in the guidelines and the lack of accounting for rotation of rocks during impact with the fence systems or direct impacts to post systems.

Some manufacturers indicated that the SAEFL and ETAG 27 guidelines give an unfair advantage to larger manufacturers based in European countries because it is not feasible for smaller U.S. manufacturers to have testing performed in European countries. Manufacturers also indicated that the SAEFL guideline

has the advantages of being conducted at one test site, there are limits on fence deflection, only a vertical drop test is allowed, and maintenance is considered in the guideline. Manufacturers indicated advantages of ETAG 27 include the flexibility of tests to be performed by inclined systems or vertical drop and the ability to use independent test facilities. Manufacturers' perceived limitations of ETAG 27 include that there are a large number of agencies who can perform rockfall fence testing, but some agencies have no experience in testing. Also, manufacturers perceive the limitations on allowable fence modifications before retesting is required as a shortcoming of the guideline.

Three manufacturers indicated that they have performed or have considered performing certification-type testing in the U.S. One response includes testing performed by Geobruigg North America in 2005 using the NCHRP 20-07 guideline. Manufacturers indicated that cost is a significant obstacle to performing testing in the U.S. and even if testing is performed, it may not be accepted by all U.S. transportation agencies. Additionally, the cost of performing testing in multiple countries is redundant and cost prohibitive. Manufacturers prefer that testing in the U.S. only include U.S. specific requirements and not duplicate the results of SAEFL or ETAG 27 tests. Manufacturers would like SAEFL or ETAG 27 to serve as the basis for application in the U.S. with modifications for specific U.S. requirements.

Of the agencies that have a pre-approved product list, the majority indicate that they do not have any flexible rockfall protection systems included in this list. When agencies and manufacturers were asked if they see an opportunity or necessity for developing testing and certification procedures for other types of systems such as anchored mesh, attenuator, drapery systems, mesh fabrics, or components of these systems, they generally indicated all would be helpful. This information may be useful in evaluating areas of future research.

5.2.3 Design and Construction Section Results

The majority of agencies indicated that they or their consultant typically design post foundations for their agency's rockfall protection systems. Most design engineers indicated that they, the system owner, or the system manufacturer typically design the foundations. The majority of agencies indicated that the design of foundations is typically site specific; however, many agencies also indicated that a standard design for rock or soil conditions is used. The majority of design engineers indicated that they typically use a site-specific foundation design while manufacturers indicated that they generally use a standard design for rock or soil conditions.

When asked whether a fixed or pinned post to foundation connection is used in their projects, the majority of agencies indicated fixed connections are typically used, design engineers indicated they use each type approximately equally, and the majority of manufacturers indicated pinned connections are typically used. Agencies indicated that in-house designs typically use a fixed connection while systems designed by manufacturers typically use a pinned connection. Agencies also state that if they require a fence system to be certified, the connection must be the same as was used during the certification testing. Some agencies indicated that it is generally easier to install and maintain a fixed connection system than a pinned connection system. Several design engineers and manufacturers stated that pinned connections allow more movement to occur without damage to the foundation and the load transferred to the foundation using a pinned connection is generally less than with a fixed connection.

The majority of agencies indicated that they or their consultant typically design the anchorage system for their agency's rockfall protection systems. Most design engineers indicated that they, the system owner, or the system manufacturer typically design the anchorage systems. The majority of agencies indicated that the design of anchorage is typically site specific; however, many agencies also indicated that a standard design for rock or soil conditions is used. Design engineers and manufacturers indicated that site specific and standard designs are used approximately equally. Agencies and design engineers indicated that the agency typically specifies the procedure for anchor pullout testing for rockfall

protection systems. Manufacturers indicated that customers typically request that they specify anchor pullout capacities. When asked what, if any, anchor pullout testing procedures are used for rockfall protection systems, many agencies indicated that they generally use procedures outlined by the Post-Tensioning Institute (PTI) while some use their own specifications. Design engineers indicated they use PTI procedures and other project specific procedures approximately equally. Manufacturers indicated that they generally use procedures other than those outlined by PTI.

5.2.4 Maintenance and Repair Section Results

When asked whether agencies have developed procedures for inspection of rockfall protection systems, the majority indicated that they have not. Agencies that indicated that they had inspected systems stated that they had no formal procedures. Several design engineers indicated that they have developed in-house methods; however, they also indicated that the procedures would not likely apply to this research. Manufacturers indicated that they have maintenance manuals for all systems; however, these manuals are specific to each manufacturer and are likely too specific to use in a general inspection procedure. Of the agencies that have performed inspections, most indicated that they inspected systems every few years and after rockfall events. Manufacturers indicated that they recommend that systems be inspected annually and after rockfall events.

The majority of agencies indicated that they do not have standard repair procedures for rockfall protection systems. Manufacturers also indicated that they have not developed standard repair procedures because they depend on the type of system and extent of damage.

Several design engineers indicated that they have been involved in inventorying existing rockfall systems, but only a few design engineers indicated that they have been involved in creating databases of past inspections and repairs made to existing systems. Some agencies indicated that they or a consultant working for their agency maintain an inventory of existing rockfall protection systems. Some agencies also indicated that their inventory is incorporated into the agencies' Rockfall Hazard Rating System (RHRS). Approximately half of the agencies that responded to the survey indicated that they maintain a database of past inspections of rockfall protection systems. Most agencies indicated that they do not maintain a database of repairs made to existing systems; however, several agencies indicated they do have a database of past repairs. These survey responses indicated that very few agencies have all of the information necessary to perform asset management for rockfall protection systems.

5.3 Proposed ETAG 27 Acceptance Procedures for Agencies

5.3.1 Discussion of Acceptance Conditions for Agencies

Table 5-1 summarizes the proposed guideline using the framework of the ETAG 27 guideline. The proposed guideline has been developed to be consistent with the ETAG 27 guideline to allow for acceptance of ETAG 27 testing for rockfall fence systems installed in the U.S. The primary differences between the proposed guideline and the ETAG 27 guideline are:

- If performing testing in the U.S., the manufacturer would be responsible for performing the test as there are currently no governing bodies for rockfall fence testing in the U.S.
- The test rock or block may be natural or manufactured.

An obstacle currently faced by agencies is that certification documentation of ETAG 27 tests that is provided by manufacturers typically lacks the details necessary for agencies to fully evaluate the acceptability of the rockfall fence system to meet their project specific requirements. However, per the ETAG 27 guidelines, much of this information is recorded during the test and could be made available at the request of the agency as discussed in Section 5.3.2.

Table 5-1. Summary and comparison of the SAEFL, NCHRP 20-07, ETAG 27, and the proposed guidelines

	Guideline			
	SAEFL	NCHRP 20-07	ETAG 27	Proposed (Accept ETAG 27)
Location of Development	Switzerland	United States	European Union	United States
Test Responsibility	Governing Body	Manufacturer	Governing Body	Manufacturer
Rock/Block Delivery Method	Vertical Drop	Vertical drop, inclined cable, and rock rolling	Vertical drop or inclined cable	Vertical drop or inclined cable
Rock/Block Type	Manufactured	Manufactured or natural	Manufactured	Manufactured or natural
Fence Height	Limited	Limited	Unlimited	Unlimited
Post Spacing/Panel Width	Limited	Unlimited	Unlimited	Unlimited
Small Diameter Rock/Block Test	Yes	Yes	No	No
MEL/SEL	2	2	3	3
Tests at Low Energy (SEL)	1	1	2	2
Tests at High Energy (MEL)	1	1	1	1
Residual Height				
at SEL	Unlimited	Unlimited	1 st Test: > 70% 2 nd Test: Unlimited	1 st Test: > 70% 2 nd Test: Unlimited
at MEL	>50%	>60%	Category A, B, C	Category A, B, C
Elongation				
at SEL	Unlimited	Unlimited	Unlimited	Unlimited
at MEL	Limited	Limited	Unlimited	Unlimited
Maintenance	Evaluated	Evaluated	Not evaluated	Not evaluated

5.3.2 Proposed Data Request Form for ETAG 27 Tested Systems

The proposed data request form (Table 5-2) would allow agencies to request information and data that is required per the ETAG 27 guideline, but may not be included in typical certification or test documentation. With this information, agencies can evaluate the ETAG 27 tested system for conformance with a project specific specification regarding the rockfall fence system performance. It may be useful for agencies to include this form in their rockfall fence system specifications.

Table 5-2. Proposed data request form for ETAG 27 rockfall fence testing

ETAG 27 ROCKFALL FENCE TEST DATA REQUEST FORM			
This form is intended to be used by Federal and State transportation agencies to request rockfall fence test data for fences that have been tested and approved according to ETAG 27. Agencies may send this form to the fence manufacturer to request the documentation and data described below. The manufacturer may fill in the appropriate information and complete the checklist providing the requested information or the manufacturer may provide a separate report containing the requested information.			
Manufacturer		Fence Model/Type	
Energy Level Classification/Energy		Test Institution	
Test Location		Rock/Block Delivery Method	<input type="checkbox"/> Vertical Drop <input type="checkbox"/> Inclined Cable
Date of Testing		Date of Approval	
DOCUMENTATION AND TEST DATA CHECKLIST			
	Provide system documentation including plans, installation manual/guide, and description of system components.		
	Verify and document that ropes, cables, nets, posts, and other components used in the U.S. have equivalent strength as those tested according to ETAG 27.		
Nominal Height		Post Dimensions (Width/Flange/Thickness)	
Post to Foundation Connection Type		Panel Width/Post Spacing	
Panel Type		Applied Mesh Type	
Retaining Rope Dimensions		Anchor Type and Diameter	
Type and locations of Energy Dissipating Devices			
First Service Energy Level (SEL) Test Data			
Block Energy at Impact		Residual Height	
Maximum Elongation		Braking Time	
Force Measurements			
	Provide a description below of fence behavior including damages and deformations of components.		

Table 5-2. Proposed data request form for ETAG 27 rockfall fence testing (continued)

ETAG 27 ROCKFALL FENCE TEST DATA REQUEST FORM (CONTINUED)			
Second Service Energy Level (SEL) Test Data			
Block Energy at Impact		Residual Height	
Maximum Elongation		Braking Time	
Force Measurements			
Provide a description below of fence behavior including damages and deformations of components.			
Maximum Energy Level (MEL) Test Data			
Maintenance performed after SEL tests	<input type="checkbox"/> Repair <input type="checkbox"/> Replacement <input type="checkbox"/> None		
Block Energy at Impact		Residual Height Category	<input type="checkbox"/> A <input type="checkbox"/> B <input type="checkbox"/> C
Residual Height		Maximum Elongation	
Braking Time			
Force Measurements			
Provide a description below of fence behavior including damages and deformations of components.			
Manufacturer Representative Signature and Date (Attach Original ETAG 27 Document)			

5.4 Discussion of ASTM Rockfall Fence Testing

Based on the survey, three of the rockfall fence manufacturers indicated that they have performed or have considered performing certification-type testing in the U.S. However, because there are no widely accepted testing guidelines, tests may not be performed such that comparison of different systems is possible. The basis for American Society of Testing and Materials (ASTM) is that a system or product can be tested and the test procedure is repeatable allowing for comparison of different products regardless of who performs the testing. Currently, there are no maintained facilities for testing rockfall systems in the U.S. Specific DOTs and manufacturers have performed testing at selected sites, but these sites are typically for individual tests and are not generally available. Overall, the survey results from the manufacturers indicated that they would like SAEFL or ETAG 27 to serve as the basis for application in the U.S. with modifications for specific U.S. requirements presumably since testing requires significant investment on the manufacturer's part. Additionally, manufacturers indicated that they would like a U.S. guideline to be widely accepted. An ASTM standard for testing of rockfall fence systems has been suggested as a possible solution and ASTM Subcommittee D18.25.06 on Geohazard Protection Systems may consider development of a standard.

Reviewing the need for ASTM specific testing in the U.S., the following are considerations that present challenges to the establishment of an ASTM rockfall fence testing standard:

- The majority of transportation agencies indicated from the survey results that they have less than 10 rockfall mitigation projects per year of which less than 30 percent involve rockfall fence systems.
- The majority of agencies indicated from the survey that they do not have a programmed budget for rockfall projects, do not have a programmed budget for emergency rockfall projects, and spend less than \$1 million per year for emergency rockfall projects.
- Currently, there are no known maintained rockfall fence test sites in the U.S.
- Based on historic information, performing one (1) rockfall fence test per current ETAG 27 guidelines can cost from \$200,000 to \$500,000 (USD).
- ASTM testing protocols generally are for testing of materials in which the testing can range from a \$100 to \$1,000 (USD) compared to hundreds of thousands for one rockfall fence test.
- For manufacturers to invest in an ASTM specific test it would either need to be a much less expensive test than current ETAG 27 guidelines or there would need to be a significantly increased demand in rockfall fence systems from agencies and DOTs to offset the high cost of testing the systems in the U.S.

Conversely, using ETAG 27 as the basis for acceptance as a certified rockfall fence system in the U.S. presents the following concerns and issues:

- European testing commonly refers to International Standards developed for use in the European Union (ISO Standards) which are very different from ASTM Standards.
- ISO standards are in metric.
- ISO standards use different steel type, strength, and manufacturing than U.S. manufactured steel.
- It can be difficult to substitute U.S. steel products for European ISO steel products based on either strength or dimension.
- "Buy America" mandated requirements for DOTs restrict the materials that can be supplied to U.S. rockfall fence manufacturers further creating differences in the steel product types and grades when comparing to materials reported in ETAG 27 test results.

For instance, it may not be advisable to try to match only wire rope diameters since in many cases the metric versus imperial strength differences may be more significant than the diameters. In some cases, it may not be advisable to specify a stronger wire rope for an ETAG 27 tested system using an U.S. steel since this may actually change the overall rockfall fence system performance by changing the deflections

of the braking elements. Stronger is not always better in rockfall systems as deflection and deformation are important aspects in maintaining flexibility in the systems. Overall, it is possible to substitute U.S. manufactured steel materials for European manufactured and tested materials, but there can be significant differences.

If an ASTM committee or other governing body was to specify a testing method in the U.S., it could generally follow the guidelines in ETAG 27; however the panel or committee overseeing such a testing method might consider the following additions or modifications:

- Testing sequence. Currently ETAG 27 does not specify the sequence for the maximum energy and service energy testing; tests can be performed in any order with or without replacing or repairing the system. A more representative testing sequence could be specified such as having three (3) SEL tests in a row with no modifications to the system to provide data on serviceability, resilience, and maintenance requirements. One (1) separate MEL test could be specified after the SEL tests to also provide an overview of the resilience, and maintenance requirements of the system.
- Residual Height. Requirements for residual height after the test could also be reviewed as a system that is less than 50% or 70% of the design height is typically not effective for future rockfall events.
- More thought could be placed on maintenance requirements and resiliency of the system rather than creating a rockfall system that would need to be replaced after a single rockfall impact event. Single impact systems may generally have lower initial costs, but may not be less costly when evaluating asset management for long term goals and performance measures.
- The specific overall costs of the rockfall fence system are generally minor compared to the overall project costs accounting for traffic control, overhead costs, construction observation, etc. Paying an extra cost for a more resilient system can greatly outweigh the nominal cost difference between a resilient system and a single impact system especially over a longer time period.

5.5 Proposed Inventory and Condition Assessment of Rockfall Fence Systems for Agencies

The following forms are proposed for use in inspecting, inventorying, and assessing flexible rockfall fence systems. The NPS Wall Inventory Program was used as a basis for developing the proposed methodology.

5.5.1 Condition Rating of Rockfall System Elements

Rockfall systems are composed of elements that contribute to the function and performance of the system. These elements have been divided into primary and secondary elements based on the importance of the element in the ability of the system to function as designed. The primary and secondary element methodology has been adapted from the NPS Wall Inventory Program. Primary elements are components of the system that if damaged significantly reduce the functionality of the system. Secondary elements are components that are important in the functionality of the system to perform as designed, but the system would likely still provide protection from an impact near the design energy level even if the secondary element is damaged.

Condition ratings of primary elements and secondary elements range from 10 (excellent) to 1 (critical). Table 5-3 and Table 5-4 describe the condition state of primary and secondary elements, respectively, and the associated condition rating that would be assigned based on observation during the field inspection. Condition ratings are recorded on the Rockfall System Inventory Form described in Section 5.5.7.

Table 5-3. Proposed rockfall system condition rating – primary elements

ROCKFALL SYSTEM CONDITION RATING PRIMARY ELEMENTS			
Element	Condition Ratings		
	10 to 8	7 to 6	5 to 1
	GOOD TO EXCELLENT (A to B)	FAIR (C to D)	POOR TO CRITICAL (F)
Primary System Elements			
Panel	Panel elements are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Panel elements show signs of rockfall impacts that resulted in moderate damage, but can still contain a rockfall event.	Panel elements show signs of rockfall impacts that resulted in severe damage and likely cannot contain a rockfall event.
Post	Posts are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Posts show signs of rockfall impacts that resulted in moderate damage, but are still functional.	Posts show signs of rockfall impacts that resulted in significant damage and are not fully functional.
Bearing/ Retaining Ropes and Anchors	Wire ropes and anchors are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Wire ropes and anchors show signs of rockfall impacts that resulted in moderate damage but are still functional.	Wire ropes and anchors show signs of rockfall impacts that resulted in severe damage and are not fully functional.
Post Foundation	Foundations are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Foundations show signs of rockfall impacts that resulted in moderate damage, but are still functional.	Foundations show signs of rockfall impacts that resulted in severe damage and are not fully functional.
Braking Elements	Braking elements are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Braking elements show signs of rockfall impacts that resulted in engagement, but are still functional.	Braking elements show signs of rockfall impacts that resulted in engagement and are not functional.

Table 5-4. Proposed rockfall system condition rating – secondary elements

ROCKFALL SYSTEM CONDITION RATING SECONDARY ELEMENTS			
Element	Condition Ratings		
	10 to 8	7 to 6	5 to 1
	GOOD TO EXCELLENT (A to B)	FAIR (C to D)	POOR TO CRITICAL (F)
Secondary System Elements			
Panel Secondary Mesh	Panel elements are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Panel elements show signs of rockfall impacts that resulted in moderate damage, but can still contain a rockfall event.	Panel elements show signs of rockfall impacts that resulted in severe damage and likely cannot contain a rockfall event.
Shackles, Clips, Connections	Elements are as constructed, and no elements are missing.	Elements show signs of moderate damage, but are still functional. Minor elements are missing creating gaps < 3 inches wide.	Elements show signs of severe damage and are not functional. Major elements are missing creating gaps ≥ 6 inches wide.
Corrosion	No evidence of corrosion, staining, contamination, or crack/spalling due to weathering or chemical attack.	Minor evidence of corrosion, staining, contamination, or cracking/spalling due to weathering or chemical attack.	System is compromised by corrosion, staining, contamination, or cracking/spalling due to weathering or chemical attack.
Foundation Protection Systems	Systems are as constructed and show no signs of rockfall impacts that resulted in significant damage.	Systems show signs of rockfall impacts that resulted in moderate damage, but are still functional.	Systems show signs of rockfall impacts that resulted in severe damage and are not functional.
Other	As constructed.	Moderate damage, but still functional.	Severe damage, not functional.

5.5.2 Rockfall System Performance Rating

In addition to primary and secondary condition ratings, the overall performance of the system is evaluated. The performance rating is intended to capture the condition of the system related to items and elements that are not captured by the primary and secondary element condition ratings. As with the condition element ratings, performance ratings vary from 10 (excellent) to 1 (critical). Table 5-5 describes the condition state and the associated condition rating for performance.

Table 5-5. Proposed rockfall system performance rating

ROCKFALL SYSTEM CONDITION RATING PERFORMANCE ELEMENTS			
Element	Condition Ratings		
	10 to 8	7 to 6	5 to 1
	GOOD TO EXCELLENT (A to B)	FAIR (C to D)	POOR TO CRITICAL (F)
System Performance			
Performance	No combinations of element distresses are observed indicating unseen problems or creating significant performance problems. No history of remediation or repair to adjacent elements is observed. No impacts from rockfall accumulation or vegetation noted within the system or within adjacent elements.	Some observed distresses to specific elements. Some element distress combinations are observed that indicate fence component problems. Minor work on primary elements or major work on secondary elements has occurred improving overall system function. Minor impacts from rockfall accumulation or vegetation noted within the system or within adjacent elements.	System elements that have failed are apparent, rockfall impacts significantly damaged system. Distresses clearly indicate serious stability problems with components. Major repairs have occurred to structural elements, though functionality has not improved. Adverse impacts from rockfall accumulation or vegetation noted within the system or within adjacent elements interfering with system.

5.5.3 Rockfall System Condition and Performance Weighting Factors

Weighting factors are used to account for various levels of element importance in the overall system rating. Proposed weighting factors presented in Table 5-6 are based on experience and calibration using this system to evaluate various rockfall protection measures that are discussed in a case history in Section 5.6. Proposed weighting factors for primary elements range from 3 to 10 to reflect the overall importance of the element in the ability of the system to function as designed. A weighting factor of 10 is proposed for elements that are essential to the performance of the system such as panels, posts, bearing ropes, and lateral anchors.

A weighting factor of 1 is proposed for secondary elements as these elements are typically not essential to the function of the system. A weighting factor of 10 is proposed for the performance rating of the system as the overall performance of the system is important in ensuring that the system functions as designed.

The proposed weighting factors may need to be adjusted as the system is implemented and more experience is gained in using the system. Additionally, weighting factors will need to be adjusted to calibrate the system to the practices of specific agencies to account for the varying use of elements and the importance of the elements in the system performance.

Table 5-6. Proposed rockfall system weighting factor

ROCKFALL SYSTEM WEIGHTING FACTOR GUIDANCE	
Suggested Weighting Factor	Weighting Factor Definition
3 to 10	Primary Elements (Panel, Posts, Top Bearing Rope, Lateral Anchors)
1	Secondary Elements (Other Elements)
10	Performance

5.5.4 Rockfall System Inventory and Assessment Data Reliability Rating

Data reliability ratings are also included in the condition assessment forms to capture the level of confidence in the data that is used to evaluate the overall system condition. Table 5-7 summarizes data reliability rating guidance.

Table 5-7. Proposed rockfall system data reliability rating

ROCKFALL SYSTEM DATA RELIABILITY RATING GUIDANCE	
Data Reliability Factor	Data Reliability Factor Definition
1	Very Good Observed conditions clearly describe system performance. Additional investigations are not needed.
2	Good Observed conditions are sufficient to rate the condition of element(s); however, additional investigations would be useful to better understand element performance.
3	Poor Conditions cannot be sufficiently observed to rate element(s), warranting additional investigations to better define element performance and/or to determine the cause(s) of poor performance.

5.5.5 Rockfall System Failure Consequence Rating

The Rockfall System Failure Consequence Rating (Table 5-8) is based on the impact to roadway users, public safety, and availability of alternate routes.

Table 5-8. Proposed rockfall system failure consequence rating

ROCKFALL SYSTEM FAILURE CONSEQUENCE RATING GUIDANCE	
Definitions:	
Consequence of Failure	<p>Low - No loss of roadway, no to low public risk, no impact to traffic during construction</p> <p>Moderate - Hourly to short-term closure, low to moderate public risk, multiple alternative routes</p> <p>High - Seasonal to long-term loss of roadway, substantial loss or public risk, no alternative routes</p>

5.5.6 Rockfall System Condition Rating

The overall system condition rating is evaluated using the total of the condition scores and the total of the weighting factors and assigned a letter grade based on the criteria outlined in Table 5-9. As with the weighting factors, the criteria used to assign grades are based on experience and should be reevaluated as additional data becomes available and to suit specific agencies.

Table 5-9. Proposed rockfall fence system rating criteria

ROCKFALL FENCE SYSTEM CONDITION RATING CRITERIA	
Grade	Criteria
A	Fence condition ≥ 9
B	Fence condition rating between 8 and < 9
C	Fence condition rating between 7 and < 8
D	Fence condition between 6 and < 7
F	Fence condition < 6

5.5.7 Proposed Rockfall System Inventory Form

The Rockfall System Inventory Form (Table 5-10) gathers information about the system identification, location, type of components, dimensions, and a summary of the overall system condition based on the detailed condition assessment.

5.5.8 Proposed Rockfall System Condition Assessment Form

The Rockfall Fence Condition Assessment form (Table 5-11) is used to guide detailed inspection and documentation of the condition of individual elements of the system. A description of the condition of the elements is recorded and a condition rating and data reliability score are assigned. The condition score is calculated as the condition rating multiplied by the weighting factor.

Table 5-10. Proposed rockfall system inventory form

ROCKFALL SYSTEM INVENTORY FORM					
Rockfall System ID		Chute or Pathway Location		Roadway and MM Start (Approx)	
Manufacturer		Station		Roadway and MM End (Approx)	
Inspected By		Distance Centerline		Latitude	
Inspected Date		Left or Right of Centerline		Longitude	
Approx. Year Built		Project Code for System		Elevation	
SYSTEM FUNCTION, DIMENSIONS, and DESCRIPTION					
Rockfall Mitigation Type		Panel Lacing Rope Dia.		Post to Foundation (Fixed/Pinned /Hinged)	
Panel Type		Ring Net Designation		Uphill Retaining Anchor Dia.	
Panel Aperture Opening		Post Flange Dimension (bf)		Lateral Retaining Anchor Dia.	
Panel Wire Thickness		Post Depth Dimension (d)		Type and Dia of Anchors	
Secondary Mesh Clip Spacing (ft)		Post Thickness (tf)		Secondary Panel Cover Type	
Rockfall Accumulation (cy)		Post Foundation Diameter, Size and No. bars		Painting/Powder Coating	
Fence General Description Notes (draw in Post/Foundation/Anchors if necessary):					
System Length (ft)		System Panel Face Area (sf)			
System Height (ft)		Vertical Offset (+/- ft)			
Photo Description/No.		Post Batter Down Slope (deg)			
REPAIR/REPLACE RECOMMENDATIONS AND WORK ORDER					
Further Investigation?		Failure Consequence			
System Condition Rating	(Insert From Inspection Form)	Action			
Maintenance/Repair/Replace Recommendations:					

Table 5-11. Proposed rockfall system condition assessment form

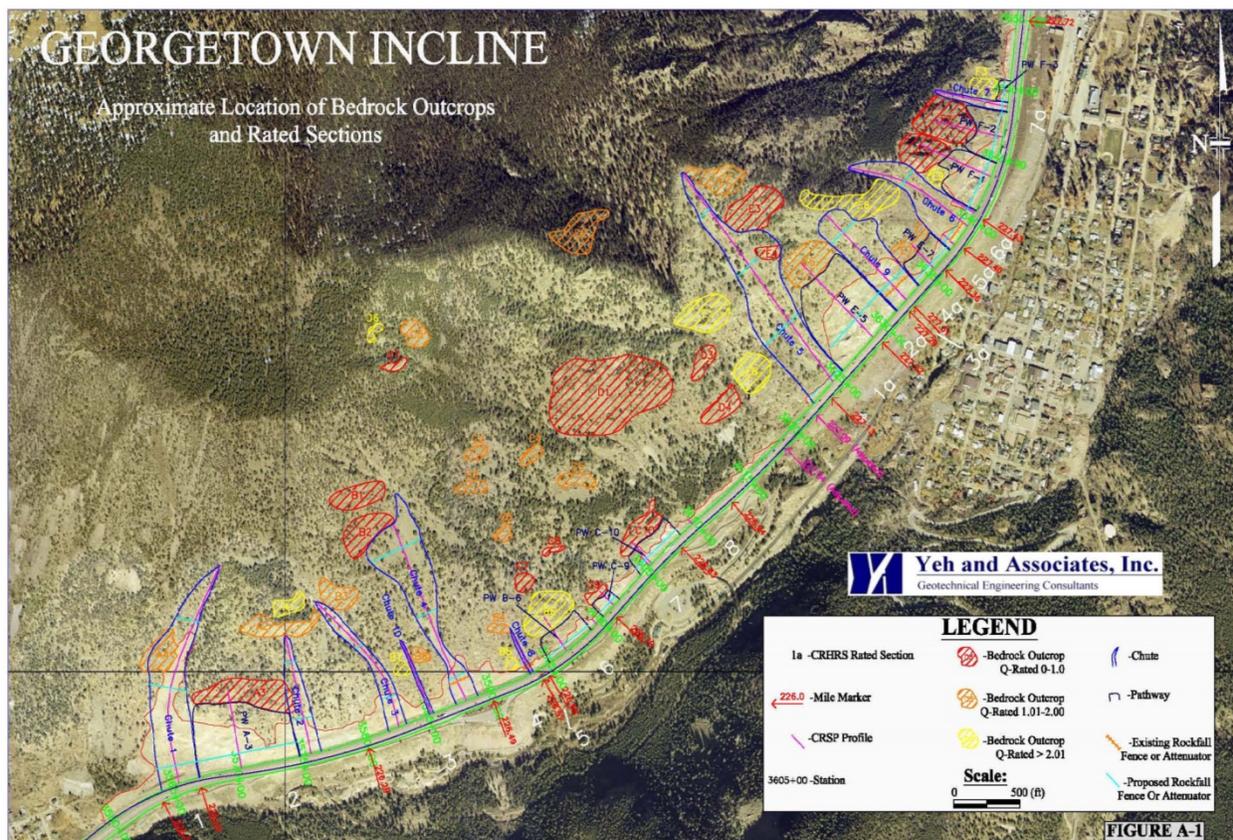
ROCKFALL SYSTEM CONDITION ASSESSMENT						
Element	Photo Number	Condition Narrative	Condition Rating	Weighting Factor	Condition Score	Data Reliability
Primary System Elements						
Panel				10	0	
Post				10	0	
Top Bearing Rope and Anchors				10	0	
Lateral Retaining Rope and Anchors				10	0	
Uphill Retaining Rope and Anchors				7	0	
Post Foundation				3	0	
Braking Elements				3	0	
Secondary System Elements						
Panel Secondary Mesh				1	0	
Shackles, Clips, Connections				1	0	
Corrosion				1	0	
Foundation Protection Systems				1	0	
Other				1	0	
System Performance						
Performance				10	0	
System Rating		Weighting Factor (x10) and Condition Score Totals		0.0	0	0.0
		Fence Condition Rating (=[Condition Score Total/Weighting Factor Total (x10)]X100)		0.0	System Grade	Data Reliability

5.6 Case History – Colorado Rockfall System Inventory and Assessment

The prototype of proposed inventory and assessment forms and procedures outlined in Section 5.5 have been implemented in the field in 2013 and 2015 for the Colorado Department of Transportation (CDOT) along a 2.2 mile segment of Interstate 70 (I-70) between Georgetown and Silver Plume, Colorado commonly referred to as the Georgetown Incline. Over the past 10 years, CDOT has installed various rockfall mitigation systems along this 2.2 mile segment of I-70 including 21 rockfall fence systems. CDOT requested Yeh and Associates, Inc. to inventory and assess the existing systems to aid in asset management and future maintenance of the systems.

5.6.1 Previous Site Characterization Work

Figure 5-1 provides an overview map of the Georgetown Incline created as part of a rockslope assessment system to program funding for the corridor. The system used a combination of the Colorado Rockslope Hazard Rating System (CRHRS) and bedrock outcrop rating system. The CRHRS was previously modified from the original Rockfall Hazard Rating System (RHRS). The bedrock outcrop rating system used consisted of a version of a Q- rating system used in tunneling and modified for application to rockfall by Harp and Noble (1993). The procedure used to evaluate the rockslope has been described in detail in Chapter 6 – Site Characterization (Higgins and Andrew 2012) in Rockfall Characterization and Control (Turner and Schuster 2012).



Source: Yeh and Associates, Inc. (2005)

Figure 5-1. Overview of Georgetown Incline slope rating described in Rockfall Characterization and Control



Source: Photography courtesy of B. Arndt
Figure 5-3. Rockfall fence RBIF_5

Table 5-12. RBIF_5 inventory form

ROCKFALL SYSTEM INVENTORY FORM					
Rockfall System ID	5	Chute or Pathway Location	Chute 2a	Roadway and MM Start (Approx)	
Manufacturer	-	Station	3574+60	Roadway and MM End (Approx)	
Inspected By	WH	Distance Centerline		Latitude	
Inspected Date	-	Left or Right of Centerline	LT	Longitude	
Approx. Year Built	2013	Project Code for System	18853	Elevation	
SYSTEM FUNCTION, DIMENSIONS, and DESCRIPTION					
Rockfall Mitigation Type	Barrier Fence	Panel Lacing Rope Dia.	NA	Post to Foundation (Fixed/Pinned /Hinged)	Hinged
Panel Type	Ring Net	Ring Net Designation	12 wires, 2mm 14" dia	Uphill Retaining Anchor Dia.	3/4"
Panel Aperture Opening	14"	Post Flange Dimension (bf)	6"	Lateral Retaining Anchor Dia.	3/4" and 7/8"
Panel Wire Thickness		Post Depth Dimension (d)	6 1/2"	Type and Dia of Anchors	1" cable
Secondary Mesh Clip Spacing (ft)	1' - 1.5'	Post Thickness (tf)	7/16"	Secondary Panel Cover Type	chain link
Rockfall Accumulation (cy)	0	Post Foundation Diameter, Size and No. bars	36"PCC 4 - #8 bars 16"x22" plate	Painting/Powder Coating	yellow brown paint
Fence General Description Notes (draw in Post/Foundation/Anchors if necessary): New Construction					
System Length (ft)	270'	System Panel Face Area (sf)	5400 sq ft		
System Height (ft)	20'	Vertical Offset (+/- ft)			
Photo Description/No.		Post Batter Down Slope (deg)	Vert		
Rockfall System ID					
REPAIR/REPLACE RECOMMENDATIONS AND WORK ORDER					
Further Investigation?	No	Consequence of Failure	Moderate		
Fence Condition Rating	Good	Action	None		
Maintenance/Repair/Replace Recommendations: No issues					

Table 5-13. RBIF_5 condition assessment form

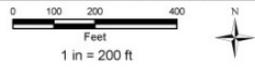
ROCKFALL SYSTEM CONDITION ASSESSMENT						
Element	Photo Number	Condition Narrative	Condition Rating (1 to 10)	Weighting Factor	Condition Score (Auto Calculates)	Data Reliability
Primary System Elements						
Panel	181-186	Excellent condition, brand new ring net barrier fence	10	10	100	1
Post	182	Excellent condition, brand new ring net barrier fence	10	10	100	1
Top Bearing Rope and Anchors	184	Excellent condition, brand new ring net barrier fence	10	10	100	1
Lateral Retaining Rope and Anchors	183	Excellent condition, brand new ring net barrier fence	10	10	100	1
Uphill Retaining Rope and Anchors	186	Excellent condition, brand new ring net barrier fence	10	7	70	1
Post Foundations	185	Excellent condition, brand new ring net barrier fence	10	3	30	1
Braking Elements	187-195	Excellent condition, brand new ring net barrier fence	10	3	30	1
Secondary System Elements						
Panel Secondary Mesh	187-195	Excellent condition, brand new ring net barrier fence	10	1	10	1
Shackles, Clips, Connections	187-195	Excellent condition, brand new ring net barrier fence	10	1	10	1
Corrosion	187-195	Excellent condition, brand new ring net barrier fence	10	1	10	1
Color	187-195	Excellent condition, brand new ring net barrier fence	10	1	10	1
Foundation Protection Systems	187-195	none	10	1	10	1
Other	187-195	none	10	1	10	1
System Performance						
Performance		Good overall condition	10	10	100	1
Weighting Factor (x10) and Condition Score Totals				690	690	1.0
System Rating		Fence Condition Rating (=[Condition Score Total/Weighting Factor Total (x10)]X100)		10.0	System Rating A	Very Good Data

5.6.2.2 Condition Assessment of RBIF_24

Figure 5-4 provides an overview of the northeastern end of the project area with identified rockfall mitigation system locations. The rockfall system identified as RBIF_24 (Figure 5-5) is an attenuator that prior to inspection had been impacted by a rockfall event damaging a post (Figure 5-6) and post support base and capturing rockfall debris beneath the cable net panel (Figure 5-7). Table 5-14 and Table 5-15 illustrate the inventory form and the condition assessment form, respectively, completed for RBIF_24.



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Source: Courtesy of the Colorado Department of Transportation
Figure 5-4. RBIF_24 rockfall attenuator location depicted by yellow arrow



Source: Photography courtesy of B. Arndt
Figure 5-5. RBIF_24 rockfall attenuator system



Source: Photography courtesy of B. Arndt

Figure 5-6. RBIF_24 rockfall attenuator damaged post and post support base



Source: Photography courtesy of B. Arndt

Figure 5-7. RBIF_24 rockfall attenuator with rock debris captured beneath cable net panel

Table 5-14. RBIF_24 inventory form

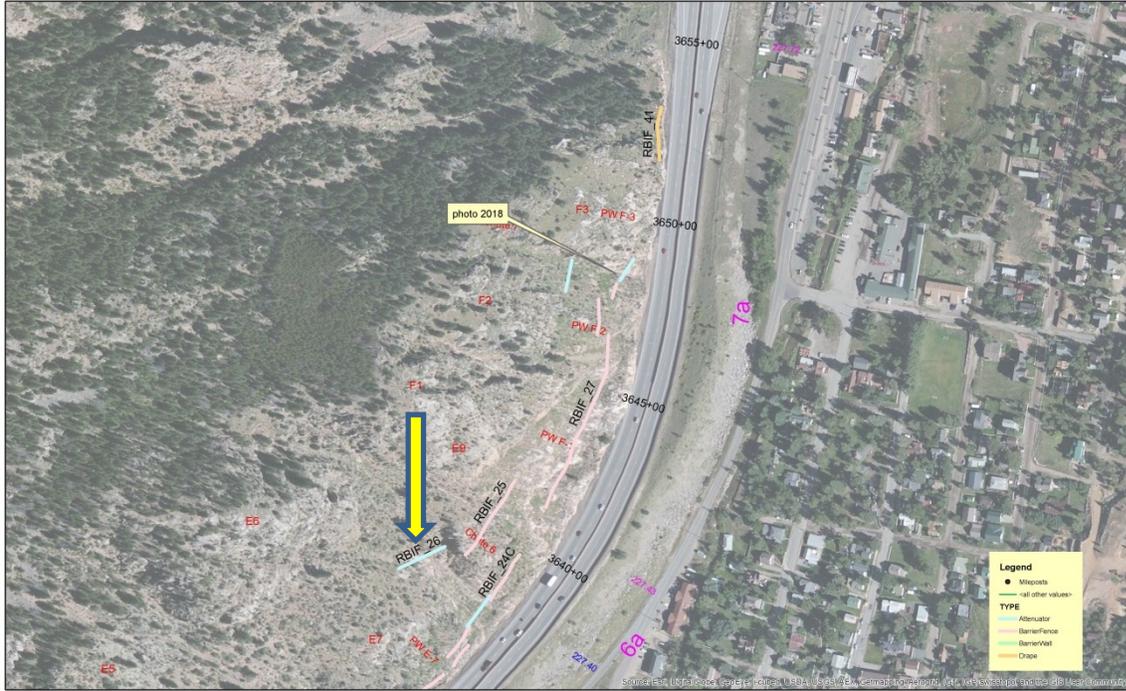
ROCKFALL SYSTEM INVENTORY FORM					
Rockfall System ID	24B	Chute or Pathway Location	Chute 6	Roadway and MM Start (Approx)	
Manufacturer	-	Station	3638+00	Roadway and MM End (Approx)	
Inspected By	WH/TH	Distance Centerline		Latitude	
Inspected Date	6/1/2015	Left or Right of Centerline	Left	Longitude	
Approx. Year Built	2011	Project Code for System	18099	Elevation	
SYSTEM FUNCTION, DIMENSIONS, and DESCRIPTION					
Rockfall Mitigation Type	Attenuator	Panel Lacing Rope Dia.	na	Post to Foundation (Fixed/Pinned /Hinged)	Fixed
Panel Type	Cable Net	Ring Net Designation	na	Uphill Retaining Anchor Dia.	1"
Panel Aperture Opening	9" x 9"	Post Flange Dimension (bf)	8"	Lateral Retaining Anchor Dia.	1"
Panel Wire Thickness	1/2"	Post Depth Dimension (d)	8.5"	Type and Dia of Anchors	Cable 1"
Secondary Mesh Clip Spacing (ft)	1 ft	Post Thickness (tf)	5/8"	Secondary Panel Cover Type	Chain Link
Rockfall Accumulation (cy)	1	Post Foundation Diameter, Size and No. bars	36" concrete 20"x20" plate 4x #8 bars	Painting/Powder Coating	Paint - Light Brown
Fence General Description Notes (draw in Post/Foundation/Anchors if necessary): Repair/Replace middle post and post foundation. Repair secondary chain link mesh. Remove rocks caught in attenuator system.					
System Length (ft)	100	System Panel Face Area (sf)	3000		
System Height (ft)	30	Vertical Offset (+/- ft)			
Photo Description/No.		Post Batter Down Slope (deg)	Vert		
Rockfall System ID					
REPAIR/REPLACE RECOMMENDATIONS AND WORK ORDER					
Further Investigation?	Yes	Consequence of Failure	High		
Fence Condition Rating	C	Action	Repair		
Maintenance/Repair/Replace Recommendations: Repair/Replace middle post and post foundation. Repair secondary chain link mesh. Remove rocks caught in attenuator system.					

Table 5-15. RBIF_24 condition assessment form

ROCKFALL SYSTEM CONDITION ASSESSMENT						
Element	Photo Number	Condition Narrative	Condition Rating (1 to 10)	Weighting Factor	Condition Score (Auto Calculates)	Data Reliability
Primary System Elements						
Panel	181-186	Some distortion from impact	9	10	90	1
Post	182	3 posts: middle post impacted and bent	7	10	70	1
Top Bearing Rope and Anchors	184	OK	9	10	90	1
Lateral Retaining Rope and Anchors	183	As built; slight sag from impact	8	10	80	1
Uphill Retaining Rope and Anchors	186	As built	9	7	63	1
Post Foundations	185	3 fnd: Outers good. Middle concrete shattered and rebar bent, wobbly	3	3	9	1
Braking Elements	187-195	na	0	0	0	1
Secondary System Elements						
Panel Secondary Mesh	187-195	Torn off from impact	7	1	7	1
Shackles, Clips, Connections	187-195	Shackles span both top ropes	8	1	8	1
Corrosion	187-195	Minor	8	1	8	1
Color	187-195	Good	8	1	8	1
Foundation Protection Systems	187-195	na	0	0	0	1
Other	187-195	na	0	0	0	1
System Performance						
Performance		System withstood impact - review maintenance needs	2	10	20	1
Weighting Factor (x10) and Condition Score Totals				640	453	1.0
System Rating	Fence Condition Rating ($=\frac{\text{Condition Score Total}}{\text{Weighting Factor Total (x10)}} \times 100$)			7.1	System Rating C	Very Good Data

5.6.2.3 Condition Assessment of RBIF_26

Figure 5-8 provides an overview of the northeastern end of the project area with identified rockfall mitigation system locations. The system identified as RBIF_26 (Figure 5-9) is an attenuator that prior to inspection had been impacted by a rockfall event that ruptured the top supporting wire ropes (Figure 5-10 and Figure 5-11). Table 5-16 and Table 5-17 illustrate the inventory form and the condition assessment form, respectively, completed for RBIF_26.



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0 100 200 400
Feet
1 in = 200 ft

Source: Courtesy of the Colorado Department of Transportation
Figure 5-8. RBIF_26 rockfall attenuator location depicted by yellow arrow



Source: Photography courtesy of B. Arndt
Figure 5-9. RBIF_26 rockfall attenuator with ruptured top support wire ropes



Source: Photography courtesy of B. Arndt

Figure 5-10. RBIF_26 rockfall attenuator with ruptured top support wire ropes



Source: Photography courtesy of B. Arndt

Figure 5-11. RBIF_26 ruptured top support wire ropes

Table 5-16. RBIF_26 inventory form

ROCKFALL SYSTEM INVENTORY FORM					
Rockfall System ID	26	Chute or Pathway Location	Chute 6	Roadway and MM Start (Approx)	
Manufacturer	-	Station	3639+00	Roadway and MM End (Approx)	
Inspected By	WH/TGH	Distance Centerline		Latitude	
Inspected Date	-	Left or Right of Centerline	Left	Longitude	
Approx. Year Built	2011	Project Code for System	18099	Elevation	
SYSTEM FUNCTION, DIMENSIONS, and DESCRIPTION					
Rockfall Mitigation Type	Attenuator	Panel Lacing Rope Dia.	N/A	Post to Foundation (Fixed/Pinned /Hinged)	N/A
Panel Type	Cable Net	Ring Net Designation	N/A	Uphill Retaining Anchor Dia.	N/A
Panel Aperture Opening	8" x 8"	Post Flange Dimension (bf)	N/A	Lateral Retaining Anchor Dia.	Cable 1"
Panel Wire Thickness	1/2"	Post Depth Dimension (d)	N/A	Type and Dia of Anchors	Cable 1"
Secondary Mesh Clip Spacing (ft)	1 to 2 ft	Post Thickness (tf)	N/A	Secondary Panel Cover Type	Chain Link
Rockfall Accumulation (cy)	0	Post Foundation Diameter, Size and No. bars	N/A	Painting/Powder Coating	Paint - Gray
Fence General Description Notes (draw in Post/Foundation/Anchors if necessary): Cable net attenuator - Chute 6 wall to wall, no posts. Upper most attenuator in chute. Debris/rockfall impacted attenuator twice and failed the twin 1-inch cable top bearing ropes. System is severely damaged and out of service.					
System Length (ft)	120	System Panel Face Area (sf)	14400		
System Height (ft)	120	Vertical Offset (+/- ft)			
Photo Description/No.		Post Batter Down Slope (deg)			
Rockfall System ID					
REPAIR/REPLACE RECOMMENDATIONS AND WORK ORDER					
Further Investigation?	Yes	Consequence of Failure	Moderate		
Fence Condition Rating	F	Action	Replace		
Maintenance/Repair/Replace Recommendations: Repair/Replace top bearing rope and reset attenuator system. Remove rocks caught in attenuator system.					

Table 5-17. RBIF_26 condition assessment form

ROCKFALL SYSTEM CONDITION ASSESSMENT						
Element	Photo Number	Condition Narrative	Condition Rating (1 to 10)	Weighting Factor	Condition Score (Auto Calculates)	Data Reliability
Primary System Elements						
Panel	181-186	Minor observed damage to panel, needs to be reset and cleared of debris	9	10	90	1
Post	182	N/A	0	0	0	1
Top Bearing Rope and Anchors	184	Top bearing rope has failed completely, anchors and cable clips held	1	10	10	1
Lateral Retaining Rope and Anchors	183	Anchors appear to be functional although should be tested	8	10	80	1
Uphill Retaining Rope and Anchors	186	N/A	0	0	0	1
Post Foundations	185	N/A	0	0	0	1
Braking Elements	187-195	N/A	0	0	0	1
Secondary System Elements						
Panel Secondary Mesh	187-195	Repair/Replace impacted chain link, 2 panels require chain link mesh reversal	5	1	5	1
Shackles, Clips, Connections	187-195	repair as required	7	1	7	1
Corrosion	187-195		9	1	9	1
Color	187-195	fading/chipping	8	1	8	1
Foundation Protection Systems	187-195	N/A	0	0	0	1
Other	187-195	N/A	0	0	0	1
System Performance						
Performance		Not performing presently - repair needed	1	10	10	1
System Rating						
System Rating	Weighting Factor (x10) and Condition Score Totals			440	219	1.0
	Fence Condition Rating (=[Condition Score Total/Weighting Factor Total (x10)]X100)			5.0	System Rating F	Very Good Data

5.6.3 Summary of Condition Assessment

Table 5-18 summarizes the condition rating grades for the systems assessed in 2013 and 2015. The majority of systems were in “A” or “B” condition and two systems were in “D” or “F” condition at the time of the 2013 assessment. At the time of the 2015 assessment, the majority of systems were still in “A” or “B” condition however 6 systems were in “D” or “F” condition. The percentage change in each condition category from 2013 to 2015 is also summarized in Table 5-18. Overall, there was a net decrease in the condition of the systems assessed with an additional four percent of systems deteriorating into the “D” and “F” conditions. This trend in deteriorating condition is illustrated by the decrease in systems in the “A” category and the corresponding increase in system grades less than “A”.

Table 5-18. Summary of condition rating grades

System Grade	2013 Rating		2015 Rating		% Change
	Number Systems	Percentage	Number Systems	Percentage	
A	25	47%	13	25%	-22%
B	22	42%	27	51%	9%
C	4	8%	7	13%	5%
D	2	4%	5	9%	6%
F	0	0%	1	2%	2%

5.7 Discussion of Management of Rockfall Fence Systems After Inventory

After completion of the inventory and condition assessment phase of an asset management plan, the data is analyzed using life cycle cost models to forecast future investments. The life cycle cost analysis principles for assets such as pavement are well developed with readily defined variables. However, the data required to perform a life cycle analysis for a rockfall fence system is not as readily defined as for pavement as illustrated in the following comparison.

5.7.1 Pavement Asset Management Concept

For pavement asset management most variables can be quantified or tested. The specific items associated with pavement design and construction include:

- pavement thickness
- mix types
- aggregate types
- binders
- compaction
- density testing

The preceding quantities are measurable items associated with pavement asset and used in modeling and design, however the one item that specifically affects the asset is:

- traffic volume

The traffic volume is also a measurable element that can be quantified in real time relatively inexpensively compared to the cost of an overall pavement project. With the above information and a well-defined deterioration model, a life cycle analysis can be performed to evaluate treatment options for the short-term and long-term. This analysis guides the decision making process to maintain the pavement in the best condition possible given budgetary and other constraints.

Figure 5-12 depicts a generalized life cycle activity profile that ties pavement performance to traffic volume which causes pavement deterioration over time.

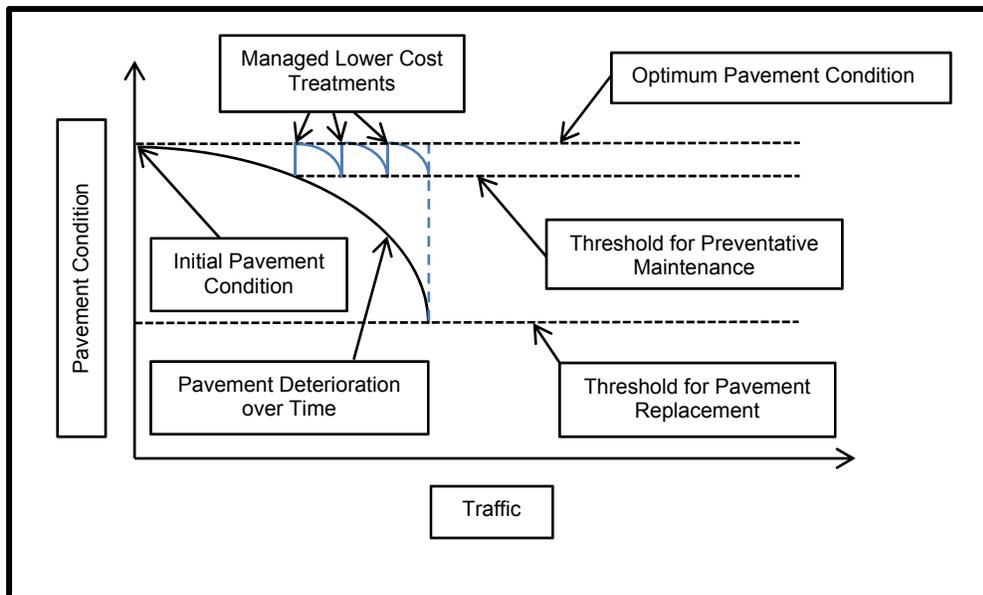


Figure 5-12. Generalized pavement life cycle activity profile

The example life cycle activity profile for pavement illustrates pavement deterioration to the replacement threshold versus performing several surface treatments to maintain the pavement in a better condition over the life cycle. The deterioration models and treatment alternatives that are incorporated into the life cycle analysis are relatively well known based on the current knowledge of pavement performance.

This concept fits well into asset management and programming of funding given that the parameters are measurable and well defined and can be anticipated and predicted to a reasonable confidence level.

5.7.2 Rockfall Fence Asset Management Concept

For rockfall fence asset management most variables cannot be readily quantified. The main variables associated with rockfall fence design include:

- the estimated design rock diameter
- the estimated design impact energy level associated with a given design rock diameter
- the estimated bounce height for the design rock diameter

These quantities are used in modeling and design of the rockfall fence asset; however, these events would need to be measured to provide a basis for managing the rockfall system.

The rockfall energy, frequency and bounce height are not readily measurable elements that can be quantified for use in asset management of rockfall fences. These events are more analogous to a catastrophic event for pavements such as a water main break that undermines the pavement section.

To anticipate and attempt to predict the actual rockfall size, frequency, and bounce height is not readily performed. Typically rockfall systems are located in historic rockfall areas, but the time, intensity, frequency, and amount of rockfall from the event cannot be predicted with a reasonable confidence level such as can be performed with traffic volumes.

There are systems that can be used to anticipate and predict rock slope failures, but these are generally expensive real-time monitoring systems that collect data on an ongoing basis. For example, the data collection for evaluating stability of a rock slope in an open pit mine may occur for years or even decades

in an effort to predict an impending rock slope failure. The prediction of the rock slope failure becomes more accurate as the time nears to the actual failure; however, vast amounts of data are required over long time-periods to determine what the threshold may be for an impending rock slope failure. These methods to anticipate and predict rockfall by gathering data are generally many times the cost of the actual rockfall system. For example, in many cases the rockfall fence system may be less than \$60,000, but to gather actual data on the rock slope or rockfall activity using radar or LiDAR methods may be in excess of \$10,000 to 60,000 a month depending on the system.

To further clarify the comparison between pavement asset management and rockfall fence asset management, the following three (3) scenarios are presented for a rockfall fence system. Figure 5-13 depicts a life cycle activity profile in which a rockfall event impacts a rockfall fence system with energy in excess of the system capacity. After one large rockfall event the entire system requires repair or replacement. This is similar to the Condition Assessment of RBIF_26 presented in the case history.

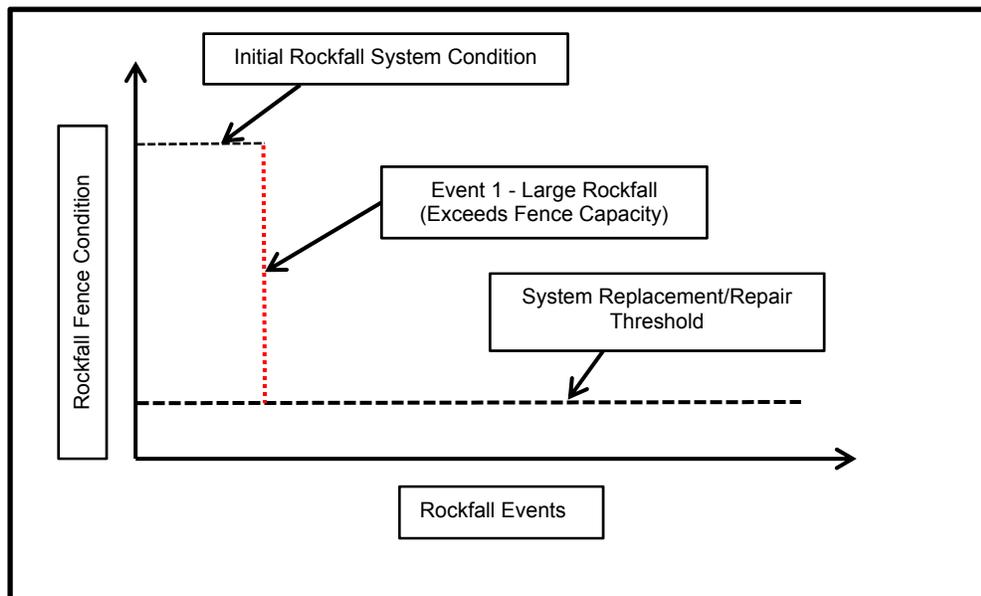


Figure 5-13. Life cycle activity profile for a rockfall event that exceeds rockfall system capacity

Figure 5-14 depicts a life cycle active profile for multiple smaller rockfall events that are within the system capacity but due to the frequency of events the condition of the system deteriorates to the point of requiring repair or replacement. Figure 5-15 depicts a life cycle activity profile for a single rockfall event at the service energy level resulting in a slight reduction in fence condition followed by a large rockfall event exceeding the system capacity requiring system repair or replacement.

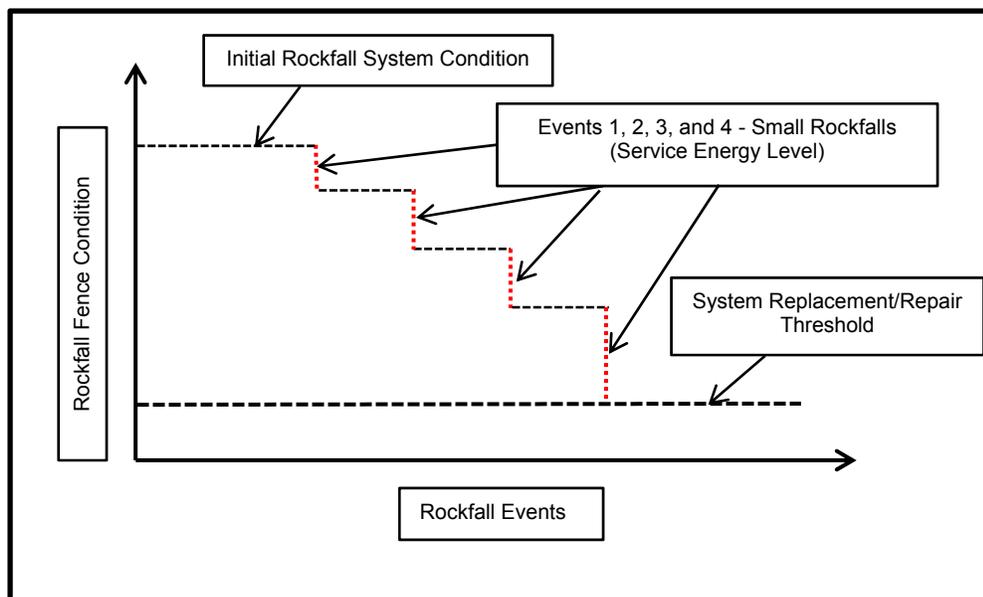


Figure 5-14. Life cycle activity profile for multiple smaller rockfall events that require repair or replacement of the system

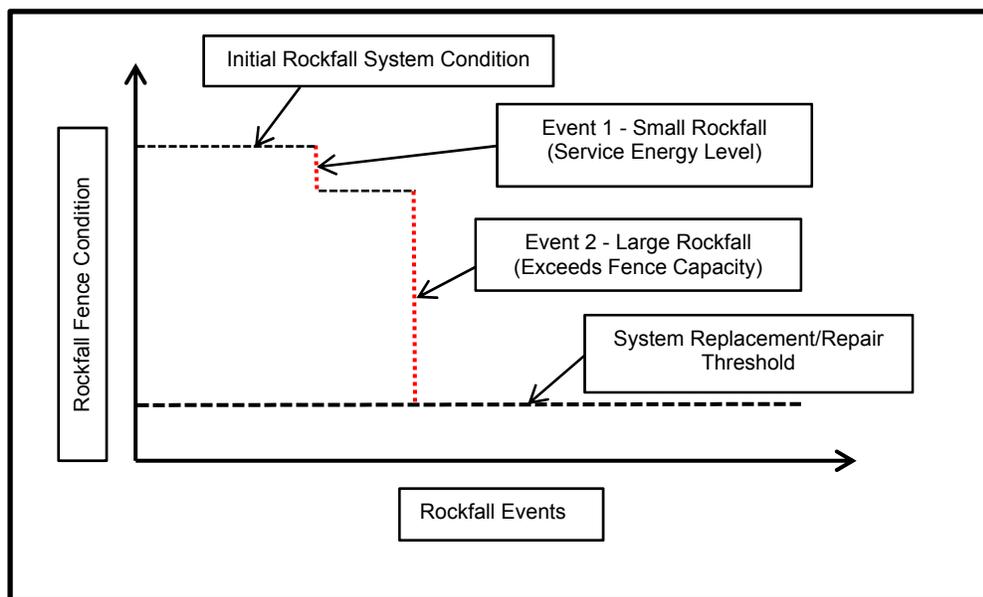


Figure 5-15. Life cycle activity profile for one smaller rockfall event and one larger rockfall event that requires repair or replacement of the system

5.7.3 Rockfall Fence Asset Management Practice

The preceding example illustrates the difficulty of applying a well know concept that works well for pavements to rockfall fences. For an agency to apply the principles and concepts of asset management from pavement design to rockfall fences, the following elements would need to be addressed:

- Frequency of rockfall impacts of varies energies
- Location of rockfall impacts within the system

- Bounce height of the rockfall
- Climatic conditions including high precipitation events and freeze-thaw cycles which affect rockfall frequency

In lieu of gathering this information through relatively expensive data gathering systems, an agency can estimate the measurements by the following:

- Perform an inventory and condition assessment of the rockfall systems on a periodic basis such as yearly or every two years to obtain basic information on the status of the systems
- Review the inventories and compare the change in system conditions in the time between assessments
- Program funding based on the rate at which system conditions fall below a threshold defined by the agency

During project evaluation and prioritization based on condition assessment data and analysis, agencies should consider the following:

- Cost of system repair or replacement versus overall construction contract costs as rockfall fence systems are typically relative inexpensive compared to project costs including traffic control, mobilization, inspection, etc.
- Cost of repairing a rockfall fence system from an unacceptable condition to an acceptable condition versus complete system replacement
- Potential cost savings of repairing or replacing multiple systems under one project

As agencies collect additional condition assessment data, they can develop deterioration models for life cycle analysis that will help guide the decision making process. More elaborate models can be developed over time as described in Appendix C. The initial process is dependent on creating a condition inventory and database of the rockfall fence systems and evaluating the performance over time. Rockfall fences in less active areas will require little to no maintenance whereas rockfall fences in highly active areas may require yearly maintenance or repair and funding can be programmed accordingly.

5.8 Discussion of Maintenance and Repair of Rockfall Fence Systems

Based on the survey results from the manufacturers, there does not appear to be a standard maintenance and repair protocol for rockfall fence systems. There are many issues and challenges surrounding a set guideline or protocol for a fence system including but not limited to the following:

- Rockfall fence systems are proprietary and have specific manufacturer designed elements such as braking systems, posts, wire rope anchors, etc. that if damaged or broken, would require the manufacturer to provide feedback or specialty parts for a particular system.
- Specific elements of propriety rockfall fence systems may be extremely critical to the manufacturers' tested system whereas similar elements on a competitors system may not be as critical for a given system.
- Agencies may have spare rockfall fence parts at their disposal and may choose to replace a damaged panel but then would be modifying the manufacturers system. This may or may not be an issue with an agency maintaining the rockfall fence systems.

Overall, the maintenance of rockfall fence systems needs to be performed on a case-by-case basis, as it will be necessary for the reviewers to evaluate the need to repair and maintain a system rather than attempting to generalize all rockfall damage into one set of pre-determined protocols. An agency will need to assess the amount of repair or replacement necessary and how it aligns with the asset management plan.

5.9 Proposed Performance Based Special Provision for Rockfall Fence Systems

The following is a proposed performance based special provisions for rockfall fence systems for guidance for agencies in bidding and contracting rockfall fence system work.

REVISION OF SECTION XXX.XX

(Commentary: A performance specification is provided. This is intended to be modified for use with standard or special provisions per agency requirements. Various Federal and State agencies have specific standard or special provisions relating to rockfall fences based on design assumptions, past experiences, and in-house procedures and protocols per specific agency requirements).

ROCKFALL FENCE

Section XXX of the Standard Specifications is hereby revised for this project to include the following:

DESCRIPTION

This work consists of construction of a rockfall fence to mitigate potential rockfall as designated on the Plans. Installation shall be at the locations designated on the Plans unless otherwise directed.

(Commentary: Definitions of the systems vary from region to region and state to state. Clarify what the system is such as Flexible Rockfall Fence, Rockfall Fence, or Rockfall Barrier).

DEFINITIONS

The bid item for Rockfall Fence is considered a _____ kJ, ____ high, tested rockfall fence system.

(Commentary: The agency or designer typically assesses the energy requirements of the rockfall fence based on an evaluation of the site conditions and rockfall energies using appropriate methods for Design-Bid-Build (DBB) projects. Other contracting methods may have different requirements)

CONSTRUCTION REQUIREMENTS

The rockfall fence shall be installed in accordance with the submitted Shop Drawings and in the locations shown on the plans or as marked by the Engineer for the specified rockfall fence system as shown on the Plans.

(Commentary: The agency or designer typically evaluates the energy requirements of the rockfall fence based on an evaluation of the site conditions and rockfall energies using appropriate methods for Design-Bid-Build (DBB) projects. Other contracting methods may have different requirements)

SUBMITTALS

Shop drawings shall be in accordance with Standard Specification _____.

(Commentary: Agencies typically have shop drawing standard provisions. The requirement for a Professional Engineer seal on the Shop Drawings can be evaluated by the agency).

At least _____ days prior to the beginning of construction the Contractor shall submit detailed Shop Drawings of the Rockfall Fence System.

The diameters and dimensions of materials in the submitted shop drawing system shall be equal strengths to the metric equivalents for the submitted ETAG 27 tested systems and requirements of this special provision (i.e. diameter of wire rope in fence panels, diameter of lacing ropes, and diameter of anchor ropes shall be sized for equal strength to the metric equivalents). The Contractor and/or Rockfall Fence Manufacturer shall outline differences (if any) between the two systems. If the differences are significant, the Engineer may require written justification for the change or require the tested elements be incorporated into the shop drawings.

The shop drawings shall include the following minimum information:

- a) Plan view locations for the rockfall fence system showing location of all elements associated with the rockfall system.
- b) Description of the construction sequence.
- c) Details for the fence panel system.
- d) Details for the fence panel mesh layer connection to the fence net panel.
- e) Details of the connection between the fence panel and wire support rope.
- f) Details for the supporting posts.
- g) Details of the net panel's lateral and retaining wire ropes with brakes.
- h) Details of the rock and/or soil anchor systems with applicable design pullout loads.
- i) Details of the post support and base.
- j) Required torque for all bolts and fasteners
- k) Grout and concrete requirements (per Agencies requirements).
- l) Documentation that the Rockfall Fence System has been tested in accordance with ETAG 27.
- m) A completed ETAG 27 Rockfall Fence Test Data Request Form

ETAG 27 ROCKFALL FENCE TEST DATA REQUEST FORM

This form is intended to be used by Federal and State transportation agencies to request rockfall fence test data for fences that have been tested and approved according to ETAG 27. Agencies may send this form to the fence manufacturer to request the documentation and data described below. The manufacturer may fill in the appropriate information and complete the checklist providing the requested information or the manufacturer may provide a separate report containing the requested information.

Manufacturer		Fence Model/Type	
Energy Level Classification/Energy		Test Institution	
Test Location		Rock/Block Delivery Method	<input type="checkbox"/> Vertical Drop <input type="checkbox"/> Inclined Cable
Date of Testing		Date of Approval	

DOCUMENTATION AND TEST DATA CHECKLIST

	Provide system documentation including plans, installation manual/guide, and description of system components.		
	Verify and document that ropes, cables, nets, posts, and other components used in the U.S. have equivalent strength as those tested according to ETAG 27.		
Nominal Height		Post Dimensions (Width/Flange/Thickness)	
Post to Foundation Connection Type		Panel Width/Post Spacing	
Panel Type		Applied Mesh Type	
Retaining Rope Dimensions		Anchor Type and Diameter	
Type and locations of Energy Dissipating Devices			

First Service Energy Level (SEL) Test Data

Block Energy at Impact		Residual Height	
Maximum Elongation		Braking Time	
Force Measurements			

Provide a description below of fence behavior including damages and deformations of components.

ETAG 27 ROCKFALL FENCE TEST DATA REQUEST FORM (CONTINUED)

Second Service Energy Level (SEL) Test Data

Block Energy at Impact		Residual Height	
Maximum Elongation		Braking Time	
Force Measurements			

Provide a description below of fence behavior including damages and deformations of components.

Maximum Energy Level (MEL) Test Data

Maintenance performed after SEL tests	<input type="checkbox"/> Repair <input type="checkbox"/> Replacement <input type="checkbox"/> None		
Block Energy at Impact		Residual Height Category	<input type="checkbox"/> A <input type="checkbox"/> B <input type="checkbox"/> C
Residual Height		Maximum Elongation	
Braking Time			

Force Measurements

Provide a description below of fence behavior including damages and deformations of components.

Manufacturer Representative Signature and Date
 (Attach Original ETAG 27 Document)

METHOD OF MEASUREMENT

Rockfall Fence will be measured and paid by the linear feet that are installed and accepted.

BASIS OF PAYMENT

The accepted quantity of work will be paid for at the contract price per unit of measurement for the pay items listed below. Payment for a _____ kJ system will be made under Rockfall Fence.

PAY ITEM

Rockfall Fence

PAY UNIT

Linear Foot

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APPENDIX A

Transportation Agency, Design Engineers, and Manufacturers Rockfall Fence Surveys

A.1 Transportation Agency Survey

A.1.1 Introduction

This survey is being conducted by Yeh and Associates, Inc. under contract to the National Cooperative Highway Research Program, for NCHRP Project 24-35: Guidelines for Certification and Management of Flexible Rockfall Protection Systems. The objective of this survey is to evaluate the existing state of practice within DOTs and other government agencies in the U.S for testing and certification of flexible rockfall protection systems as well as to evaluate existing procedures for inspection, maintenance, and repair of these systems. This survey is meant to be completed by the Rockfall Program manager or someone in a similar position.

The survey consists of various questions separated into five parts: Contact Information, Background Information, Standards and Certifications, Design and Construction, and Maintenance and Repair.

To help obtain consistent and accurate results from the survey, the following are definitions of types of flexible rockfall protection systems as used in this survey. It may be useful to copy these definitions into a document so that they can be referenced while taking the survey.

- Barriers – a flexible rockfall fence that is designed to stop an individual rockfall event. Barriers consist of various combinations of components including panels, posts, and braking elements. These systems are commonly tested and certified by various European testing agencies and are rated between 100 and 8,000 kJ for a single rockfall event.
- Attenuators – a flexible rockfall panel system which consists of various combinations of panels and posts that are intended to reduce the velocity and energy of a rockfall event initiating upslope of the installation but are not intended to stop the rockfall completely. These systems generally do not have braking elements.
- Drapery Systems – rockfall systems that consist of chain link, double twist, cable net, or other panel systems that are attached to a top cable that is generally suspended from the top of a slope by ground anchors or posts in the case of a hybrid drapery. Hybrid drapery systems are similar to attenuator systems but are generally used on steeper slopes compared to attenuator systems. Rockfall events generally initiate beneath these systems and potentially upslope of the installation in the case of a hybrid drapery system. These systems generally are designed to hang freely to allow migration of rock falling between the panel and slope guiding the rock into a catchment ditch.
- Anchored Mesh – generally slope stabilization systems that consist of chain link, double twist, cable net, or other panel systems that are pattern anchored with ground anchors and are used to stabilize a slope or hold debris between the mesh panel and slope.

A.1.2 Contact Information

Please provide your contact information so that we may contact you for more information or to clarify a survey response.

Name: _____

Title: _____

Agency: _____

Email Address: _____

Phone Number: _____

Mailing Address: _____

A.1.3 Background Information

For each question, please select all answers that apply, except where indicated, and give additional information as requested or if it is important for clarifying the answer.

1. How many rockfall mitigation projects does your agency have per year (including flexible protection systems, resloping, catchment ditches, concrete roadside barriers, scaling, bolting, emergency work, rockfall mitigation as part of larger projects, etc.)? (select one answer)
 - Less than 3 projects per year
 - Between 3 and 10 projects per year
 - Between 10 and 20 projects per year
 - More than 20 projects per year

2. What is the approximate average annual programmed budget for your agency's rockfall mitigation projects? (select one answer, please specify if this cost is for total project costs or for mitigation items only)
 - Less than \$1 Million
 - Between \$1 to \$5 Million
 - Between \$5 to \$10 Million
 - Greater than \$10 Million

3. What is the approximate average annual emergency budget for your agency's emergency rockfall mitigation projects? (select one answer, please specify if this cost is for total project costs or for mitigation items only)
 - Less than \$1 Million
 - Between \$1 to \$5 Million
 - Between \$5 to \$10 Million
 - Greater than \$10 Million

4. Of all of your agency's rockfall mitigation projects, approximately what percentages of the projects are related to each type of rockfall protection system listed below (for projects that include more than one type include the project in all appropriate types, percentages do not need to total to 100%)? Please refer to the system type definitions in the Introduction, if necessary.
 - ____% Barriers
 - ____% Attenuators
 - ____% Drapery systems
 - ____% Anchored mesh
 - ____% Other (resloping, scaling, bolting, catchment ditches, concrete roadside barriers, MSE barrier walls, etc.)

5. Of all of your agency's rockfall mitigation projects, approximately what percentages of the rockfall protection systems are typically in the following areas?
 - ____% Within 30 feet of the edge of a roadway or other structure
 - ____% Greater than 30 feet from the edge of a roadway or other structure
 - ____% Other (such as systems in both areas, please give details in Comments)

6. Who typically writes specifications related to your agency's rockfall mitigation projects? (select all that apply)
 - Owner/Agency/DOT
 - Consultant
 - Manufacturer of rockfall protection system
 - Other (please specify in Comments)

7. Does your agency typically design permanent rockfall protection systems for a certain life-span, or for one-time use? (select one answer)
 - Life-span (please specify what life-span is typically used in Comments)
 - One-time use
 - Depends on the project (please briefly explain in Comments)

A.1.4 Flexible Rockfall Protection System Standards and Certifications

8. Does your agency have its own design or performance standards or certifications for flexible rockfall protection systems?
 - Yes
 - No

9. Are you familiar with any of the following guidelines, procedures, and publications related to flexible rockfall protection systems? (select all that apply)
 - Guideline for the Approval of Rockfall Protection Kits by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers (Higgins, 2003)
 - Guideline for European Technical Approval of Falling Rock Protection Kits (ETAG 27)
 - Transportation Research Circular Number E-C141: Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems
 - Analysis and Design of Wire Mesh/Cable Net Slope Protection (WA-RD 612.1) and Design Guidelines for Wire Mesh/Cable Net Slope Protection (WA-RD 612.2)
 - Not familiar with any of these guidelines, procedures, or publications

Please provide comments on any perceived advantages and shortcomings of the guidelines, procedures, and publications that you are familiar with:

10. Does your agency use or specify any of the following guidelines, procedures, or publications for standards, certifications, or design of flexible rockfall protection systems? (select all that apply)
 - Guideline for the Approval of Rockfall Protection Kits by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)

- NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers (Higgins, 2003)
 - Guideline for European Technical Approval of Falling Rock Protection Kits (ETAG 27)
 - Transportation Research Circular Number E-C141: Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems
 - Analysis and Design of Wire Mesh/Cable Net Slope Protection (WA-RD 612.1) and Design Guidelines for Wire Mesh/Cable Net Slope Protection (WA-RD 612.2)
 - We do not use or specify any of these guidelines, procedures, or publications
11. Does your agency require documentation from manufacturers for testing and certification of flexible rockfall protection systems under any of the following guidelines? (select all that apply)
- Guideline for the Approval of Rockfall Protection Kits by SAEFL
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers
 - ETAG 27
 - Other (please specify)
 - We do not require documentation for testing and certification
12. Are any flexible rockfall protection systems included in your agency's pre-approved product list? If yes, please specify in the Comments which type(s) of systems are on the list (please refer to definitions of types in the Introduction, if necessary).
- Yes
 - No
 - We do not have a pre-approved product list
13. Existing testing and certification procedures have principally focused on flexible rockfall barriers. Do you see an opportunity or necessity for developing testing and/or certification procedures for any of the following systems or components? (select all that apply)
- Anchored Mesh
 - Attenuators
 - Drapery Systems (including hybrid systems)
 - Mesh Fabrics
 - Other systems components (i.e. brakes, ropes, anchors, post, etc.)

A.1.5 Flexible Rockfall Protection System Design and Construction

14. Who typically designs foundations for posts in your agency's rockfall protection systems (attenuators, barriers, and other systems)? (select all that apply)
- Owner/Agency/DOT
 - Consultant
 - Contractor
 - Manufacturer of the system
 - Other (please specify in Comments)
15. Is the design of foundations for posts in your agency's rockfall protection systems typically site specific or is a standard foundation design for rock or soil conditions used? (select all that apply)
- Site specific foundation design
 - Standard foundation design for rock or soil conditions
 - Other (please specify in comments)

16. Of your agency's rockfall protection systems that require posts, approximately what percentages of the following post to foundation connections are used?

____% Pinned posts (i.e. post can rotate about a horizontal pin installed through its base)

____% Fixed posts (i.e. posts are fixed so rotation is not possible)

Please briefly describe the experience of your agency in using pinned versus fixed posts:

17. Who typically designs the anchorage systems (i.e. rock and soil anchors which attach cables, wire ropes, or other elements to the ground) for your agency's rockfall protection systems? (select all that apply)

- Owner/Agency/DOT
- Consultant
- Contractor
- Manufacturer of the system
- Other (please specify in Comments)

18. Is the design of anchorage systems for your agency's rockfall protection systems typically site specific or is a standard anchorage system design for rock or soil conditions used? (select all that apply)

- Site specific anchorage system design
- Standard anchorage system design for rock or soil conditions
- Other (please specify in comments)

19. Who specifies the procedure for anchor pullout testing on your agency's rockfall protection systems? (select all that apply)

- Owner/Agency/DOT
- Consultant
- Contractor
- Manufacturer of the rockfall protection system
- Other (please specify in Comments)

20. What, if any, anchor pullout testing procedures are used for your agency's rockfall protection systems? (select all that apply)

- Procedures recommended by the Post-Tensioning Institute (PTI)
- Other (please specify in Comments)
- None

A.1.6 Rockfall Protection System Maintenance and Repair

21. Does your agency have standard periodic inspection procedures for rockfall protection systems?

- Yes
- No

22. What best describes the timing of inspections of rockfall protection systems in your agency? (select all that apply)

- Scheduled
 - Annually

- Quarterly
- Other (please specify): _____
- After rockfall events
- No inspections
- Other (please specify in Comments)

23. Does your agency have standard repair procedures for rockfall protection systems?

- Yes
- No

24. Which components of your rockfall barrier systems are most commonly in need of repair?

24a. How frequently do these repair needs arise in a typical installation?

25. Which components of your agency's rockfall barrier systems are least frequently in need of repair?

26. Does your agency have funding dedicated to the maintenance of existing rockfall protection systems?

- Yes
- No

27. Please describe what thresholds (i.e. damage, impact, aesthetic, age, or other), if any, your agency uses to initiate maintenance/repair of rockfall protection systems:

28. Are there situations where more than one alternative repair action may be feasible at a given time (other than do nothing)? Please describe the alternatives and the typical basis for selecting a repair alternative.

29. Have you experienced any total failures (i.e. system is no longer effective in its intended purpose) of rockfall barrier systems?

- Yes
- No

If yes, which component(s) of the system failed first, and what was the most significant failure mode?

30. Does your agency (or a consultant working for your agency) maintain an inventory of existing rockfall protection systems?

- Yes
- No

31. Does your agency (or a consultant working for your agency) maintain a database of past inspections of rockfall protection systems?

- Yes
- No

32. Does your agency (or a consultant working for your agency) maintain any type of database of repairs made to existing rockfall protection systems?

- Yes
- No

33. Does your agency (or a consultant working for your agency) maintain any type of an asset management plan for rockfall protection systems?

- Yes
- No

A.2 Manufacturer Survey

A.2.1 Contact Information

Please provide your contact information so that we may contact you for more information or to clarify a survey response.

Name: _____
Title: _____
Manufacturer: _____
Email Address: _____
Phone Number: _____
Mailing Address: _____

A.2.2 Background Information

For each question, please select all answers that apply, except where indicated, and give additional information as requested or if it is important for clarifying the answer.

1. Approximately how many rockfall barrier systems do you sell each year in the U.S.?
 - 0-10 Systems
 - 11-100 Systems
 - More than 100 Systems

2. Approximately what percentage of the following types of customers request that you write specifications for the rockfall barrier systems you sell?
 - _____ % of public customers
 - _____ % of private customers
 - _____ % other (not known, etc., please give details in Comments)

A.2.3 Flexible Rockfall Protection System Standards and Certifications

3. Are you familiar with any of the following guidelines, procedures, and publications related to flexible rockfall protection systems? (select all that apply)
 - Guideline for the Approval of Rockfall Protection Kits by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)
 - NCHRP 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers (Higgins, 2003)
 - Guideline for European Technical Approval of Falling Rock Protection Kits (ETAG 27)
 - Transportation Research Circular Number E-C141: Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems

- Analysis and Design of Wire Mesh/Cable Net Slope Protection (WA-RD 612.1) and Design Guidelines for Wire Mesh/Cable Net Slope Protection (WA-RD 612.2)
- Not familiar with any of these guidelines, procedures, or publications

Please provide comments on any perceived advantages and shortcomings of the guidelines, procedures, and publications that you are familiar with:

4. Have you submitted any of your products for certification under any of the following testing guidelines? (Please mark all that apply)
 - Guideline for the Approval of Rockfall Protection Kits by SAEFL
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers
 - ETAG 27
 - Other (please specify)
 - No products have been submitted

5. Have you performed or considered performing certification-type testing in the U.S.?
 - Yes
 - No

6. What obstacles do you foresee in performing the necessary testing for certification in the U.S. and what solutions would you propose to overcome these obstacles?

7. Do customers typically request documentation for testing and certification of flexible rockfall protection systems from any of the following standards or certification guidelines? (select all that apply)
 - Guideline for the Approval of Rockfall Protection Kits by SAEFL
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers
 - ETAG 27
 - Other (please specify)
 - Customers do not request documentation of testing and certification

8. Existing testing and certification procedures have principally focused on flexible rockfall barriers. Do you see an opportunity or necessity for developing testing and/or certification procedures for any of the following systems or components? (select all that apply)
 - Anchored Mesh
 - Attenuators
 - Drapery Systems (including hybrid systems)
 - Mesh Fabrics
 - Other systems components (i.e. brakes, ropes, anchors, post, etc.)

A.2.4 Flexible Rockfall Protection System Design and Construction

9. Do customers typically request that you design foundations for posts for rockfall protection systems (attenuators, barriers, and other systems) using a site specific design or a standard foundation design for rock or soil conditions? (select all that apply)
 - Site specific foundation design
 - Standard foundation design for rock or soil conditions

- Customers typically do not request that we design the foundations
- Other (please specify in Comments)

10. Of the systems you sell that require posts, approximately what percentages of the following post to foundation connections are used?

____% Pinned posts (i.e. post can rotate about a horizontal pin installed through its base)

____% Fixed posts (i.e. posts are fixed so rotation is not possible)

Please briefly describe your experience in using pinned versus fixed posts:

11. Do customers typically request that you design anchorage systems (i.e. rock or soil anchors which attach cables, wire ropes, or other elements to the ground) for rockfall protection systems using a site specific design or a standard design for rock or soil conditions? (select all that apply)

- Site specific anchorage system design
- Standard anchorage system design for rock or soil conditions
- Customers typically do not request that we design the anchorage systems
- Other (please specify in Comments)

12. Do customers typically request that you specify anchor pullout capacities?

- Yes
- No

13. What, if any, anchor pullout testing procedures do you specify for rockfall protection systems? (select all that apply)

- Procedures recommended by the Post-Tensioning Institute (PTI)
- Other (please specify in Comments)
- None

A.2.5 Rockfall Protection System Maintenance and Repair

14. Have you developed any recommended inspection procedures for rockfall protection systems you sell?

- Yes
- No

If yes, how often do you recommend that customers should inspect rockfall protection systems purchased from you?

- Annually
- Quarterly
- After rockfall events
- No inspections
- Other (please specify in Comments)

15. Do you recommend any particular repair procedures for rockfall protection systems you sell?

- Yes
- No

16. Please describe what thresholds (i.e. damage, impact, aesthetic, age, or other), if any, you recommend customers use to initiate maintenance/repair of rockfall protection systems you sell:

A.3 Design Engineer Survey

A.3.1 Contact Information

Please provide your contact information so that we may contact you for more information or to clarify a survey response.

Name: _____
Title: _____
Company: _____
Email Address: _____
Phone Number: _____
Mailing Address: _____

A.3.2 Background Information

For each question, please select all answers that apply, except where indicated, and give additional information as requested or if it is important for clarifying the answer.

1. Of all of your firm's rockfall mitigation design projects, approximately what percentages of the projects are related to each type of rockfall protection system listed below (for projects that include more than one type include the project in all appropriate types, percentages do not need to total to 100%)? Please refer to the system type definitions in the Introduction, if necessary.
 - ____% Barriers
 - ____% Attenuators
 - ____% Drapery systems
 - ____% Anchored mesh
 - ____% Other (resloping, scaling, bolting, catchment ditches, concrete roadside barriers, MSE barrier walls, etc.)

2. Of all of your firm's rockfall mitigation design projects, approximately what percentages of the rockfall protection systems are typically in the following areas?
 - ____% Within 30 feet of the edge of a roadway or other structure
 - ____% Greater than 30 feet from the edge of a roadway or other structure
 - ____% Other (such as systems in both areas, please give details in Comments)

3. Who typically writes specifications related to your firm's rockfall mitigation design projects? (select all that apply)
 - Your firm
 - Owner/Agency/DOT
 - Manufacturer of rockfall protection system
 - Other (please specify in Comments)

4. Does your firm typically design permanent rockfall protection systems for a certain life-span, or for one-time use? (select one answer)
 - Life-span (please specify what life-span is typically used in Comments)
 - One-time use

- Depends on the project (please briefly explain in Comments)

A.3.3 Flexible Rockfall Protection System Standards and Certifications

5. Are you familiar with any of the following guidelines, procedures, and publications related to flexible rockfall protection systems? (select all that apply)
- Guideline for the Approval of Rockfall Protection Kits by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers (Higgins, 2003)
 - Guideline for European Technical Approval of Falling Rock Protection Kits (ETAG 27)
 - Transportation Research Circular Number E-C141: Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems
 - Analysis and Design of Wire Mesh/Cable Net Slope Protection (WA-RD 612.1) and Design Guidelines for Wire Mesh/Cable Net Slope Protection (WA-RD 612.2)
 - Not familiar with any of these guidelines, procedures, or publications

Please provide comments on any perceived advantages and shortcomings of the guidelines, procedures, and publications that you are familiar with:

6. Does your firm use or specify any of the following guidelines, procedures, or publications for standards, certifications, or design of flexible rockfall protection systems? (select all that apply)
- Guideline for the Approval of Rockfall Protection Kits by the Swiss Agency for the Environment, Forests and Landscape (SAEFL)
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers (Higgins, 2003)
 - Guideline for European Technical Approval of Falling Rock Protection Kits (ETAG 27)
 - Transportation Research Circular Number E-C141: Colorado's Full-Scale Field Testing of Rockfall Attenuator Systems
 - Analysis and Design of Wire Mesh/Cable Net Slope Protection (WA-RD 612.1) and Design Guidelines for Wire Mesh/Cable Net Slope Protection (WA-RD 612.2)
 - We do not use or specify any of these guidelines, procedures, or publications
7. As a designer, do you require documentation from manufacturers for testing and certification of flexible rockfall protection systems under any of the following guidelines? (select all that apply)
- Guideline for the Approval of Rockfall Protection Kits by SAEFL
 - NCHRP Project 20-07, Task 138: Recommended Procedures for the Testing of Rock-fall Barriers
 - ETAG 27
 - Other (please specify)
 - We do not require documentation for testing and certification

A.3.4 Flexible Rockfall Protection System Design and Construction

8. Who typically designs foundations for posts in your firm's rockfall protection systems (attenuators, barriers, and other systems)? (select all that apply)
- Your firm
 - Owner/Agency/DOT

- Contractor
- Manufacturer of the system
- Other (please specify in Comments)

9. Is the design of foundations for posts in your firm's rockfall protection systems typically site specific or is a standard foundation design for rock or soil conditions used? (select all that apply)

- Site specific foundation design
- Standard foundation design for rock or soil conditions
- Other (please specify in comments)

10. Of your firm's rockfall protection system designs that require posts, approximately what percentages of the following post to foundation connections are used?

____% Pinned posts (i.e. post can rotate about a horizontal pin installed through its base)

____% Fixed posts (i.e. posts are fixed so rotation is not possible)

Please briefly describe the experience of your firm in using pinned versus fixed posts:

11. Who typically designs the anchorage systems (i.e. rock and soil anchors which attach cables, wire ropes, or other elements to the ground) for your firm's rockfall protection systems? (select all that apply)

- Your firm
- Owner/Agency/DOT
- Contractor
- Manufacturer of the system
- Other (please specify in Comments)

12. Is the design of anchorage systems for your firm's rockfall protection systems typically site specific or is a standard anchorage system design for rock or soil conditions used? (select all that apply)

- Site specific anchorage system design
- Standard anchorage system design for rock or soil conditions
- Other (please specify in comments)

13. Who specifies the procedure for anchor pullout testing on your firm's rockfall protection systems? (select all that apply)

- Your firm
- Owner/Agency/DOT
- Contractor
- Manufacturer of the rockfall protection system
- Other (please specify in Comments)

14. What, if any, anchor pullout testing procedures does your firm recommend for rockfall protection system anchors? (select all that apply)

- Procedures recommended by the Post-Tensioning Institute (PTI)
- Other (please specify in Comments)
- None

A.3.5 Rockfall Protection System Maintenance and Repair

15. Has your firm ever participated in inspection of rockfall protection systems?
- Yes
 - No
16. Has your firm ever been asked to maintain an inventory of existing rockfall protection systems, a database of past inspections of these systems, and/or a database of repairs made to existing systems? (Select all that apply)
- Inventory of existing systems
 - Database of past inspections
 - Database of repairs to existing systems
 - We have never been asked to perform these tasks
17. Has your firm ever been asked to develop any type of an asset management plan for rockfall protection systems?
- Yes
 - No
18. Please use the space below to provide any additional comments or questions that you feel would be helpful in evaluating the existing state of practice in rockfall protection system design.

APPENDIX B

Summary of Survey Results

B.1 Background Information

Question 1

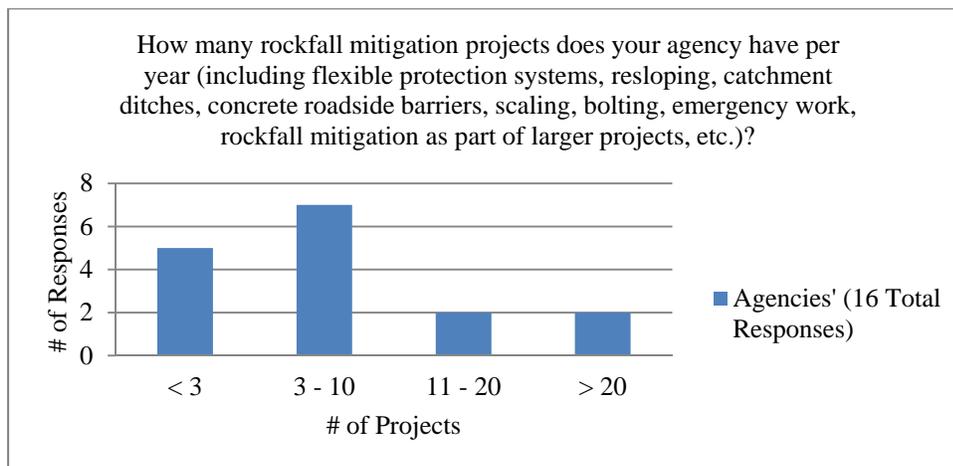


Figure B-1. Number of DOT rockfall mitigation projects per year.

Agencies' Comments:

- We have no standalone rockfall mitigation projects, rockfall is usually addressed as part of a larger roadway project.
- Rockfall mitigation is incorporated in to projects for new alignments and cuts and where project fall within existing RHRS sites.
- Mostly slope scaling, ditch rehab, and slope reconstruction. Partner agencies restrict opportunities for installed slope appurtenances such as bolts, mesh, barriers, etc.

Question 2

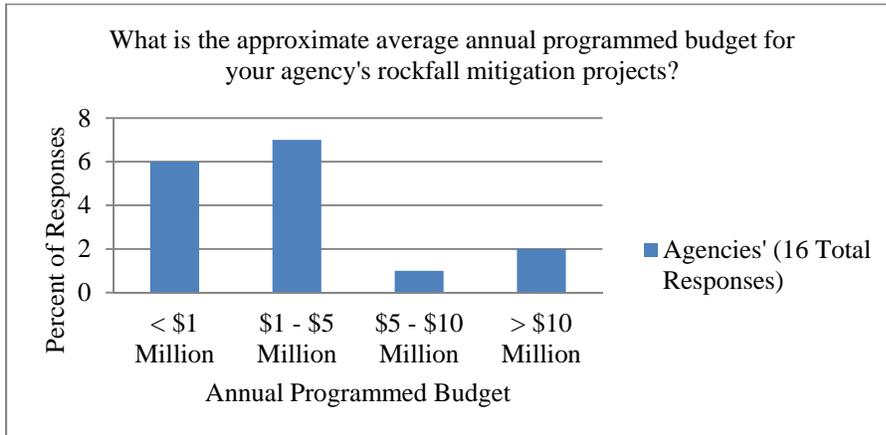


Figure B-2. DOT annual programmed budget for rockfall mitigation projects.

Agencies' Comments:

- Calif. DOT does not have a programmed budget for rockfall.
- CDOT's Rockfall Program budget is between \$5M and \$10M but if STIP projects are included, then the amount of funding spent on rockfall is much higher depending on the number of projects fall within RHRS sites or involve new rock cuts.
- There is no budget programmed for rock slope remediation. It's combined with resurfacing projects.
- Total project costs. ODOT rockfall work is not programmed separately; rockfall competes with other safety items.
- This is the total of projects that have some component of rock work included in the overall cost.
- Mitigation items only.
- Mitigation items - there is no annual budget.
- Total of all rockfall mitigation on all projects annually, including PE/CE costs.

Question 3

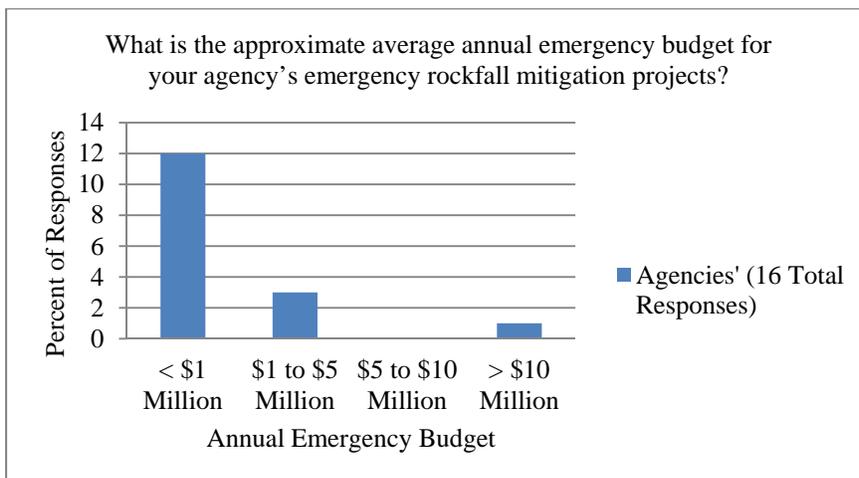


Figure B-3. DOT annual emergency budget for rockfall mitigation projects.

Agencies' Comments:

- Calif. DOT does not have an emergency budget for rockfall.
- This is for mitigation only and this money comes from maintenance budgets and is not specified as "rockfall" money.
- Not applicable. CDOT does not specify an amount of emergency funding for any one special event. An amount of funding is available for all emergencies. Emergency funding sources also vary in response to the urgency of the situation and the amount of funding required. If looking for an average amount spent on rockfall emergencies over the last several years, then the amount is less than \$1M.
- We have not budget for emergency work. Emergency work is paid for by maintenance through their funds. Equipment/contractors are used who have a rental agreement with DOT.
- No emergency budget. Usually part of Maintenance activity.
- Mitigation items only.
- \$2M for all kinds of emergency repairs - under M&O control.
- Varies. Monies come through different funding streams, but generally under the Emergency Repairs on Federally Owned roads (ERFO) program. No set aside specifically for the annual purpose of mitigating rockfall - as needed on developing projects or in response to emergencies.

Question 4

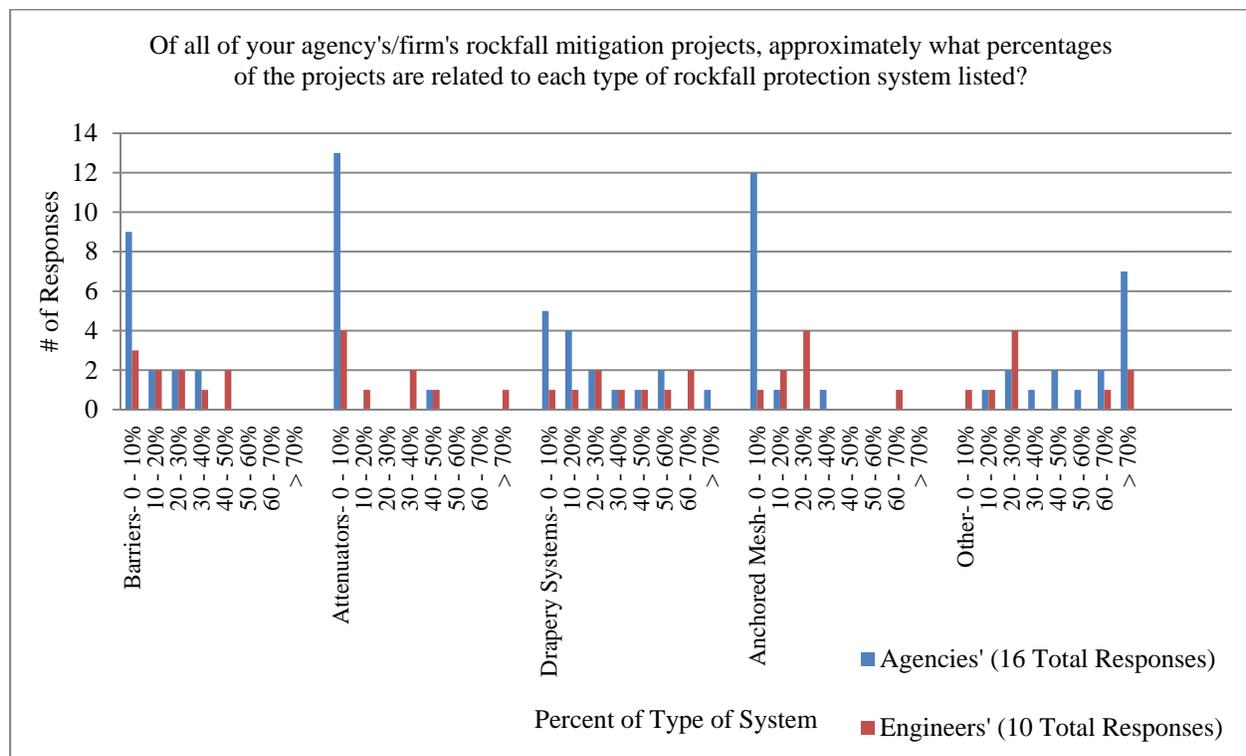


Figure B-4. Types of rockfall mitigation projects.

Agencies' Comments:

- Nearly all projects involve rock scaling.
- Primary mitigation measures are scaling and ditch rehab, with some bolting. Anchored mesh and some drapery work in recent years. Only two jobs in a 14 state region are fences/attenuators. Occasional temporary barrier applications.

Engineers' Comments:

- Mitigation work at most sites involves both on-slope stabilization (scaling, bolts etc.) and protection structures (barriers etc.).
- Typically for tunnel portals, etc.
- Catchment ditches and rockfall galleries (both flexible and massive structures).
- Attenuators are difficult to calculate and thus are hard to get approved by regulatory agencies.
- In the last five years, more like a 10 to 1 ratio of attenuators to barriers due to R-O-W and permitting issues. Easier to work in existing R-O-W.

Question 5

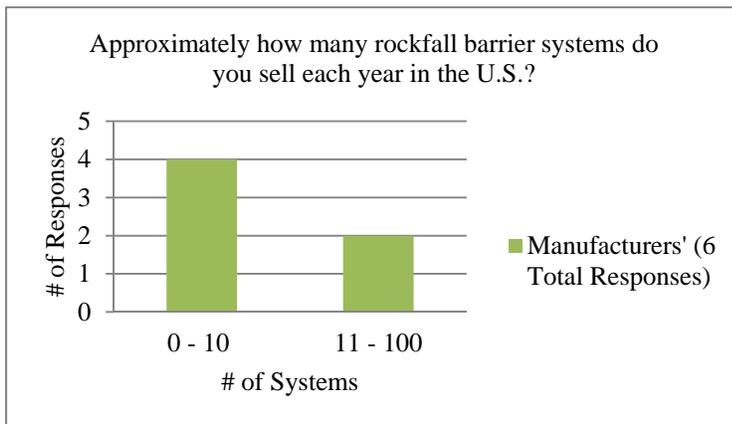


Figure B-5. Number of rockfall barrier systems manufacturers sell each year.

Manufacturers' Comments:

- It is increasing difficult to sell fence systems due to competitors' newer systems being much lighter and cheaper.
- Our company has just set up an office in the USA. Throughout the world we sell more than 100 systems.

Question 6

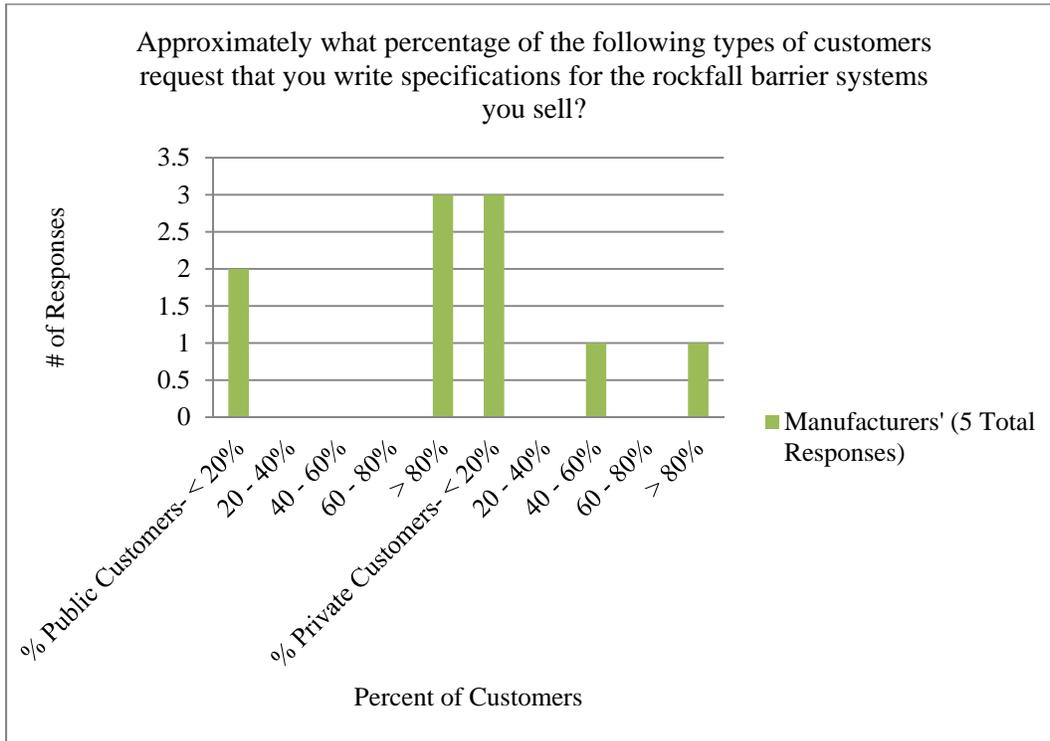


Figure B-6. Type and percentage of customers requesting specifications from manufacturers.

Question 7

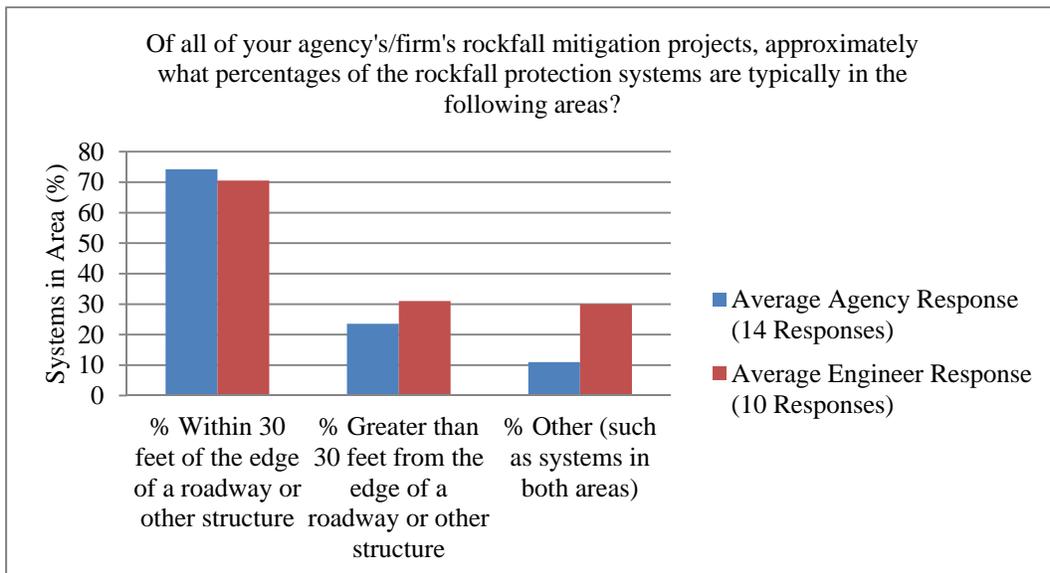


Figure B-7. Location of rockfall protection systems in relation to roadway or other structure.

Agencies' Comments:

- 20% are in both.
- Some rigid barriers within 30ft of track; net systems can be within 30ft or greater.
- 20% are drapery or hybrids that cross the 30' boundary.

Engineers' Comments:

- In general, this is dictated by our clients due to R-O-W, permitting, and environmental considerations.

Question 8

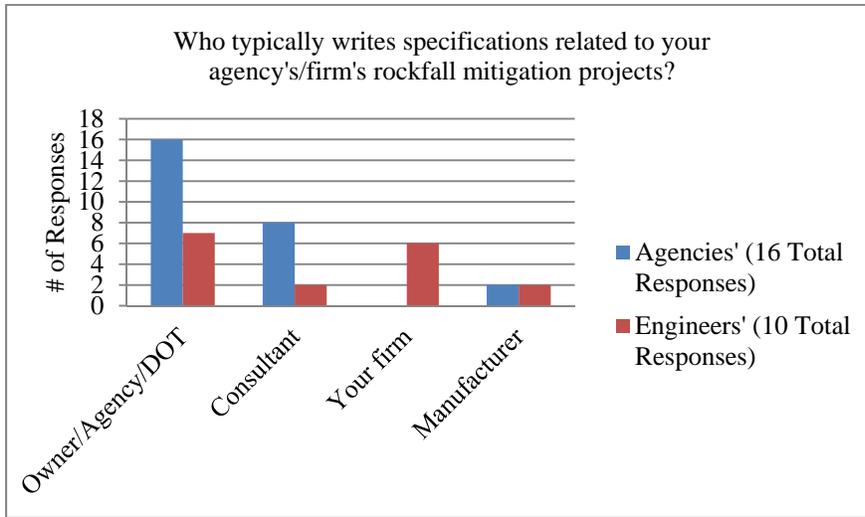


Figure B-8. Specifications for rockfall mitigation projects.

Agencies' Comments:

- We reference information provided by manufacturers and solicit information from other DOT's.
- Consultant prepared with owner oversight and review.
- No standing FP specification currently exists, and none will be included in the soon to be released FP-14. FHWA provides special contract requirements for in-house jobs and A/E full-service contractor provides for contracted jobs.

Engineers' Comments:

- Most of our mitigation measures are custom designs.
- Consultants.
- Geotechnical Consulting Firms.
- Only competent engineers/geologists should be allowed to write specs. Manufacturers should not be allowed.

Question 9

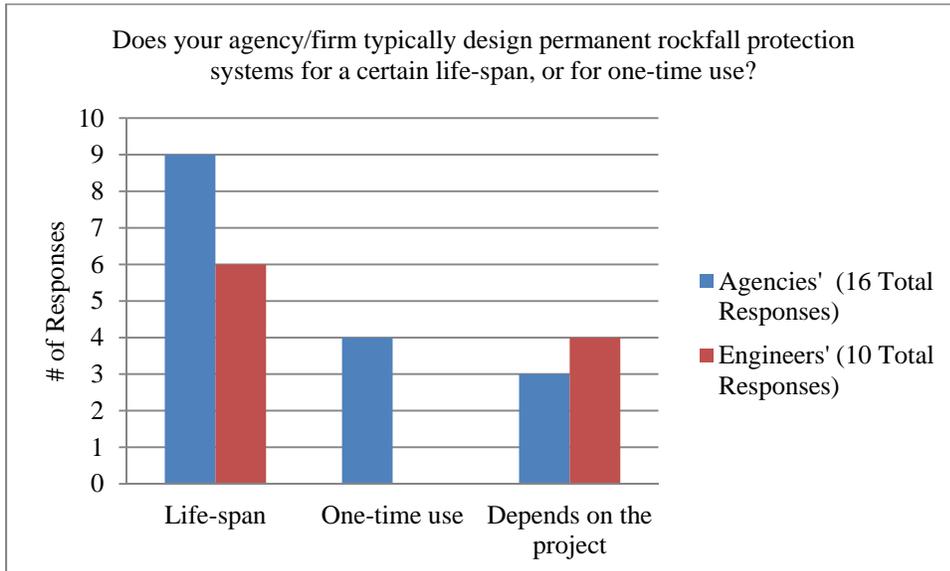


Figure B-9. Rockfall protection system life-span design.

Agencies' Comments:

- Dowels/bolts ~50 yrs, drapery/fences ~30 yrs, scaling < 10yrs.
- Temporary Construction is considered a one timer.
- Service life not yet defined.
- 20-30 Years.
- Manufacturers specs for life expectancy but we have no maintenance plan.
- 50 years.
- Systems are considered to be permanent, but designed to be repaired on occasion.
- Barriers and Net systems if hit will need maintenance; permanent structures such as sheds have 50-100yr life span.
- Life-span includes repair and/or cleanup after a rockfall event, i.e. replacing a section of rock catchment fence.
- 25 to 50 yrs.
- 20 years without major maintenance.
- We don't have a good handle yet on the life of the mitigation systems we have installed.
- I assume that "one-time use" means build and forget. That's primarily what we do.
- What work we do is for long-term use.

Engineers' Comments:

- Minimum 25 year design life.
- Drapes & anchored systems are life span, were barriers are done at max. energy (with anticipation of repairs).
- Project specifications typically suggest techniques and materials with a 30-50 year life.
- Correlated with design life of structure, i.e. 30 years for Interstate (with maintenance).
- 30 to 50 years.
- Designed with longevity for a common rockfall event, and a one use case for extreme events (the ~10th percentile).
- Some temporary construction protection, mostly 50 year lifespan.

- Typically, design for a 25 to 50 year life span with maintenance. Occasionally, asked by utility companies to provide "short-term rockfall protection" for workers to repair damage to structures from rockfall event; however, client does not want to make the capital investment to mitigate entire rockfall problem.

B.2 Flexible Rockfall Protection System Standards and Certifications

Question 10

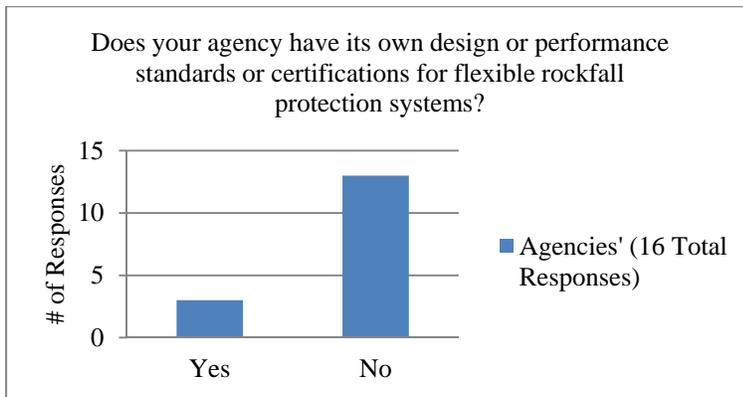


Figure B-10. DOT design or performance standards or certifications.

Agencies' Comments:

- We require a certification of compliance.
- Official standards do not exist current practice is based on empirical experience.
- ODOT relies on manufacturers' testing results.
- Follow manufacturers' performance certifications.
- Designed with various methods meeting standard of care for the application. No set standards for the design (e.g. AASHTO). Certs are limited to material certs for constructed structures.

Question 11

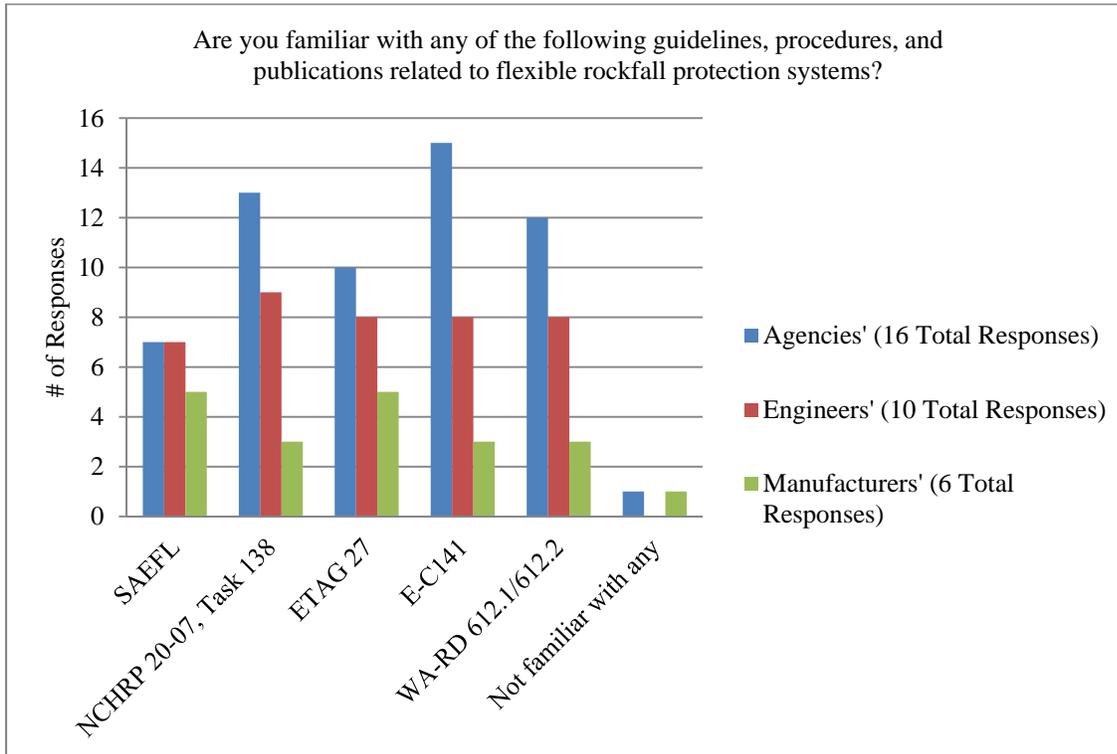


Figure B-11. Familiarity with guidelines, procedures, and publications.

Agencies' Comments:

- Limited knowledge due to limited application.

Engineers' Comments:

- Although familiar with the first two, they have never been utilized. I do consult the last two documents regularly.

Manufacturers' Comments:

- SAEFL is mandatory in Switzerland and ETAG in some European countries.
- Another to be considered is the ONR 24810.
- UNI 11211:4-2012 - Italian std. for design of rockfall barrier.

Question 12

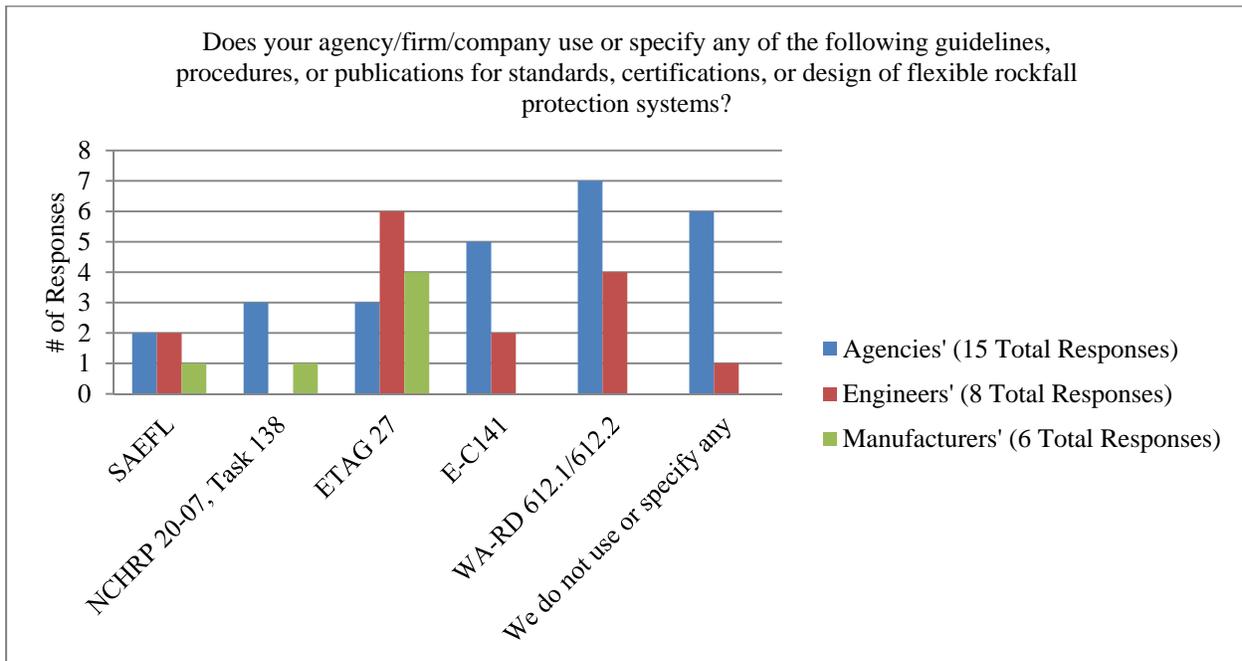


Figure B-12. Use of guidelines, procedures, and publications.

Agencies' Comments:

- Specs and standard details for Drapery systems are based on WSDOT reports.
- We incorporate elements of some of these publications into our in-house specifications.

Engineers' Comments:

- Does not regularly apply - we recommend the use of those checked, largely rely on Manufacturers.
- We have a VDOT-authored design guide written with respect to various industry references.

Manufacturers' Comments:

- Rockfall testing was done in 1998 with CDOT and Los Alamos National Laboratory. Test results are submitted for approval.
- Barrier test 100 kJ with Dr. Higgins in New Mexico according to NCHRP.
- WLW, Austria.
- Following my company's self-established guideline.

Question 13

Please provide comments on any perceived advantages and shortcomings of the guidelines, procedures, and publications listed in the previous question that you are familiar with:

Agencies' Comments:

- NCHRP 20-7 reflects the older SAEFL and we would like to see a guideline that reflects the newer ETAG testing guideline.

- Guidelines are often specific to the location of the sponsor. Barrier guidelines are not consistent with each other regarding pass fail criteria and regarding deviation from tested system.
- More standardization of anchorage systems in soil and mixed soil/rock situations. Better ice and snow load design parameters and defined analysis method for drapery and attenuator systems. Better affordability of high capacity flexible barrier systems.
- Most of the ETAG guidelines for system capacity and strength are based on documented crash tests or drop tests which don't necessarily reflect what will happen in our real life situations. However, the given strength capacity of a system can be used when an expected design load has been determined.
- WA-RD 612.2 was very useful when we were updating our specifications for drapery systems.
- ETAG 27 advantages: Widely used by suppliers, generally applicable ETAG 27 disadvantages: Does not specify or suggest minimum size or strength of components (eg: column size weight/length), does not consider ease of installation or maintenance, does not specify net flexibility characteristics, does not consider rock fall frequency, does not consider sharpness of impact rock, does not consider smaller diameter rocks, does not consider redundancy requirements for tieback cables, does not consider snow avalanche impact, does not consider rock impact directly on columns.
- As an agency we do not have the training and experience to take advantage of most of the guides, etc., except in a general way to understand at some level what our consultants are doing for us. Our geotechnical designers do use information from the WSDOT research publications on wire mesh as a basis for specifications that we sometimes create or specifications from consultants that we review. However, roadside barriers are usually "designed" by M&O forces acting on their own. We are also constrained by our nearly autonomous regional structure - each of our three regions acts independently so each region is free to use the guides as they desire. The principal shortcomings of the listed guides are the differences between them and the lack of recognizable authority from an organization such as AASHTO.

Engineers' Comments:

- Advantages - Tested Products - Certifications of Products Dis-Advantages - not one standard for certification, specs, etc. - testing varies for each.
- The major obstacle is lack of standardized terminology.
- The biggest shortfall of rockfall barriers are the post which are not considered within the design parameters.
- The testing of rockfall barriers to a maximum load case (while it should be done); it is often misleading to the hazard engineer who is designing a fence for 90% of the rockfall cases. It is often sufficient that a lower energy rock fall barrier is selected. It must be noted that it is useful to know what the maximum load of the system. Therefore the current testing method is valid (I refer to vertical testing). What vertical testing fails to do is account for the energy absorbing effect of the ground, often you have ground impacts with rockfall barrier. However the vertical case without ground contact tests the entire system strength, which is useful to investigate the ultimate strength of the system (highly applicable to flexible rock galleries). Another point that all testing methods fail to do is account for rotations of impacting rocks and their shape which can lead to puncturing and lacerations to the netting. While before this area of rockfall is included into a standard test procedure, it is an area of rockfall barrier research in its self to ascertain the significance of this effect.
- These are all good references. The downside is that inexperienced personnel will quote verbatim from these guidelines and write a spec which is virtually impossible to meet.

Manufacturers' Comments:

- The use of the European and/or Swiss guidelines for Rockfall Fence systems gives an unfair advantage to larger companies which are based in European countries. It is not feasible for smaller US based companies to have testing done in European countries.

- SAEFL: - All goes through one government agency and one test site --> totally comparable - Deflection limits have to be followed - Maintenance is considered - Only vertical tests allowed - Barrier height and post spacing to be tested is clearly defined. ETAG: - Factory production control is clearly defined - It does allow inclined and vertical testing, so some barriers have higher residual safety than others - Approvals can come from more than 20 agencies, some of them without any experience in rockfall barrier testing - Test heights vary from manufacturer to manufacturer - Only small variations from test to commercial height allowed.
- SAEFL requires that testing is carried out in Walenstadt which is partially owned by Geobruigg and so is not accepted as an independent test site - ETAG 27 provides a level playing field with regards to the collection of test and material data so that many manufacturers products can be compared - ONR 24810 provides a basis for evaluating the level of safety of the systems (e.g. Appendix E).
- ETAG 27: the stricter one to understand the performances of the rockfall barriers. UNI 11211:4-2012: only standard (around the world) that describes the procedure to design rockfall barriers.

Question 14

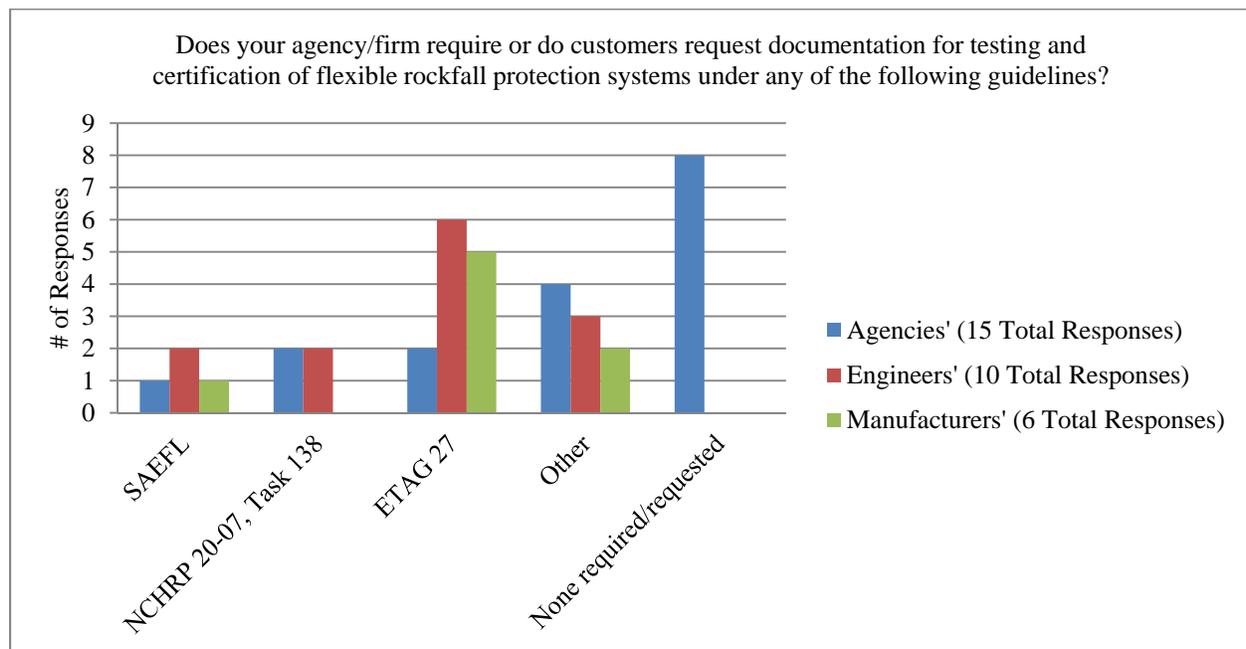


Figure B-13. Requested documentation for testing and certification.

Agencies' Comments:

- The fence shall be capable of absorbing repeated impact loads of at least 295 FT*TONS of kinetic energy with little or no maintenance and without passage of particles greater than 1 inch in size through the barrier. The fence shall be constructed using interlocking ring or wire rope net panels backed with a 9 gage, galvanized chainlink fabric. The contractor shall provide written evidence that the fence has performed satisfactorily in similar capacities elsewhere. This documentation shall include full-scale field testing and multi-year performance history. The fence shall be capable of absorbing repeated impact to the kinetic energy specified in the Contract Plans with little to no maintenance required or damage to the fence. The fence shall not pass particles greater than 2 inches in size. The fence shall be constructed using interlocking rings (min. 12 inch diameter) or wire rope net panels. The fence shall be backed with a 9-gauge, galvanized chain link fabric. A. The supplier

must be a pre-approved provider of rockfall protection fences and be included in the New Products List. Suppliers that are not pre-approved must provide written evidence that the fence has performed satisfactorily in similar capacities elsewhere. This documentation shall include full-scale field testing and multi-year performance history.

- We have not installed any of these systems for many years.
- Require testing from a recognized facility according to standard criteria.
- Manufacturers' Certification.
- No testing certifications required. Manufacturers' brochure required for proprietary rockfall barriers.

Engineers' Comments:

- We rely on the manufacturers of barrier systems to carry out tests that meet certification requirements.
- Does not regularly apply - we recommend the use of those checked, largely rely on Manufacturers.
- We require that they certify the material and methods for certain DOT-determined standards, such as an X kilojoule impact.
- I rely a lot on the manufacturer for product info.; however, not for technical assistance. Mainly use GeoBrugg if allowed by the client.

Manufacturers' Comments:

- The ETAG 27 seems to currently be specified more often, although other testing is sometimes accepted depending on the purchasing agency.
- Mainly documents on the approvals are required and should be asked for by the customer. The list of EOTA approvals can be seen online on www.eota.eu.
- Often they may ask for WLV certification instead of ETAG 27.
- Japanese customers request actual impact testing certification by my company.

Question 15

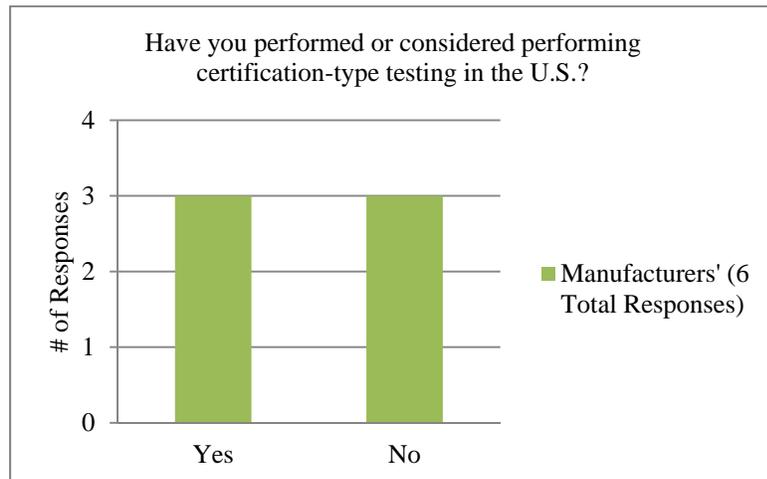


Figure B-14. U.S. certification-type testing.

Manufacturers' Comments:

- Field testing was performed in 1998 with CDOT and Los Alamos National Laboratory.
- NCHRP 100 kJ.
- ETAG is stricter.

Question 16

What obstacles do you foresee in performing the necessary testing for certification in the U.S. and what solutions would you propose to overcome these obstacles?

Manufacturers' Comments:

- Cost is probably the largest obstacle. Testing is very expensive. Additionally without specific guidelines, testing can be done but not accepted by all of the various agencies.
- Testing and certification in the US should only include US specific requirements (e.g. maintenance, residual safety, anchor and foundation design) and not duplicate results of SAEFL or ETAG. SAEFL and ETAG should serve as base for the application in the US.
- The cost of performing multiple tests in multiple countries is redundant and cost prohibitive for manufacturers which would lead to slower product development without any foreseeable benefits.
- Use the ETAG.

Question 17

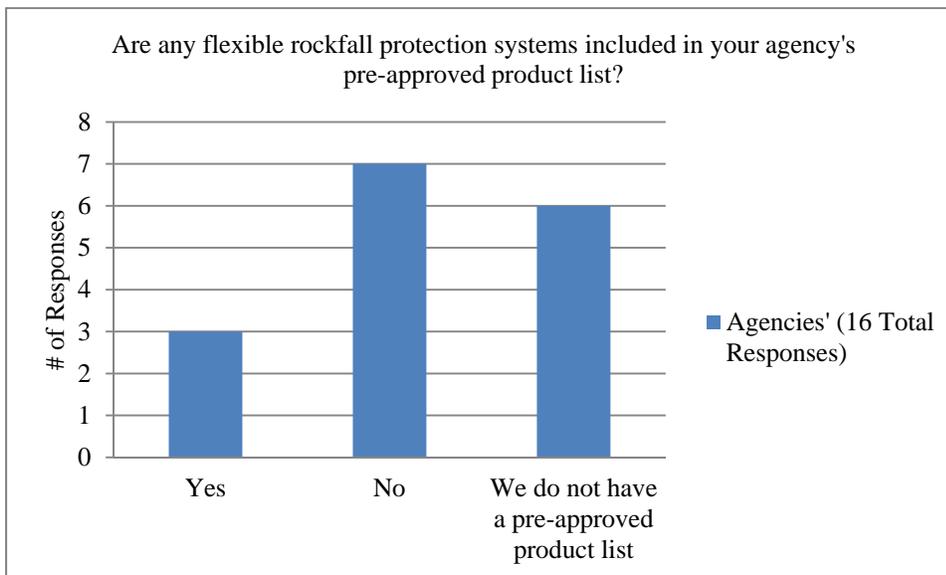


Figure B-15. Flexible rockfall protection systems on DOT pre-approved product lists.

Agencies' Comments:

- Geobruigg rockfall protection barriers.
- Flexible Rockfall Fences.
- We do not have an official pre-approved list. But with limited manufacturers, a de-facto one exists for flexible rockfall barriers and attenuators.
- Geobruigg, Trumer.
- We are not allowed under the FAR to preapprove, but can direct performance requirements through submittal requirements.

Question 18

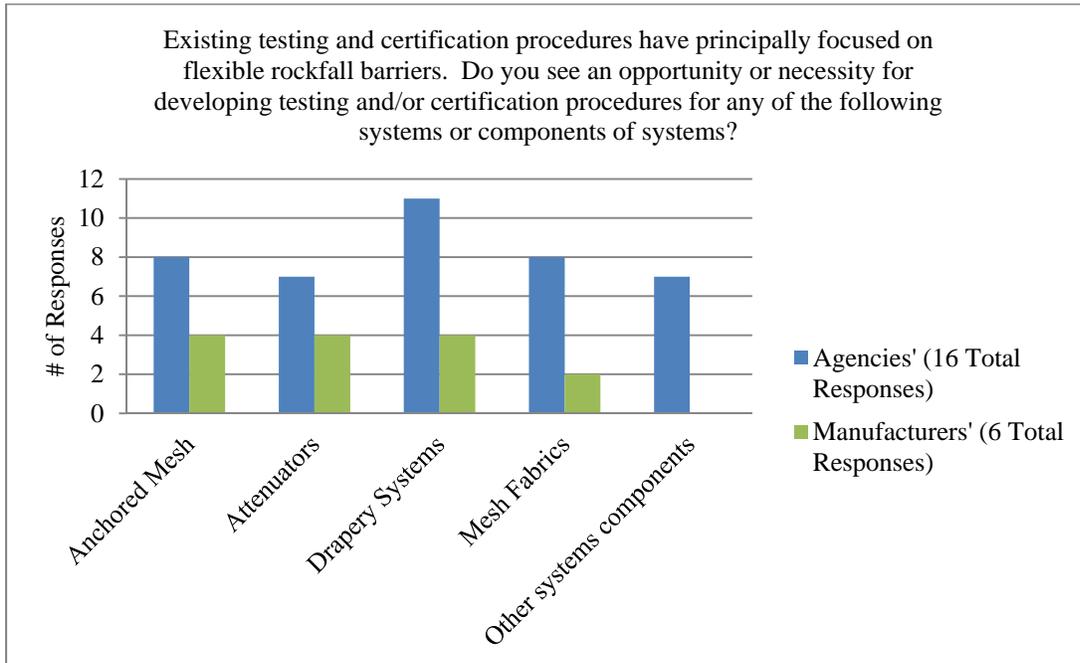


Figure B-16. Opportunity for testing and certification procedures for other systems.

Agencies' Comments:

- Design guidelines for mitigation systems would be beneficial.
- We use a "hanging net" system a lot, the closest type given is a drapery system. We would like to see testing of our type of net to determine expected capacities.
- Would like to see some studies on the evaluation of shotcrete-based rock slope treatments.
- If we have one class of rockfall mitigation systems with testing and certification, I would want to have the same for other types of systems, but my agency is unlikely to have much interest in certifying components of these systems.
- These are the items we may actually begin using in the near future.

Manufacturers' Comments:

- I think barriers need the most testing because of the wide range of products. Most of the other systems the owner specifically states what is required. There are many other variables involved in fence systems.
- In order to understand the real behavior of the mesh in situ in terms of deformation (difference between lab test and in situ evidence!).

B.3 Flexible Rockfall Protection System Design and Construction

Question 19

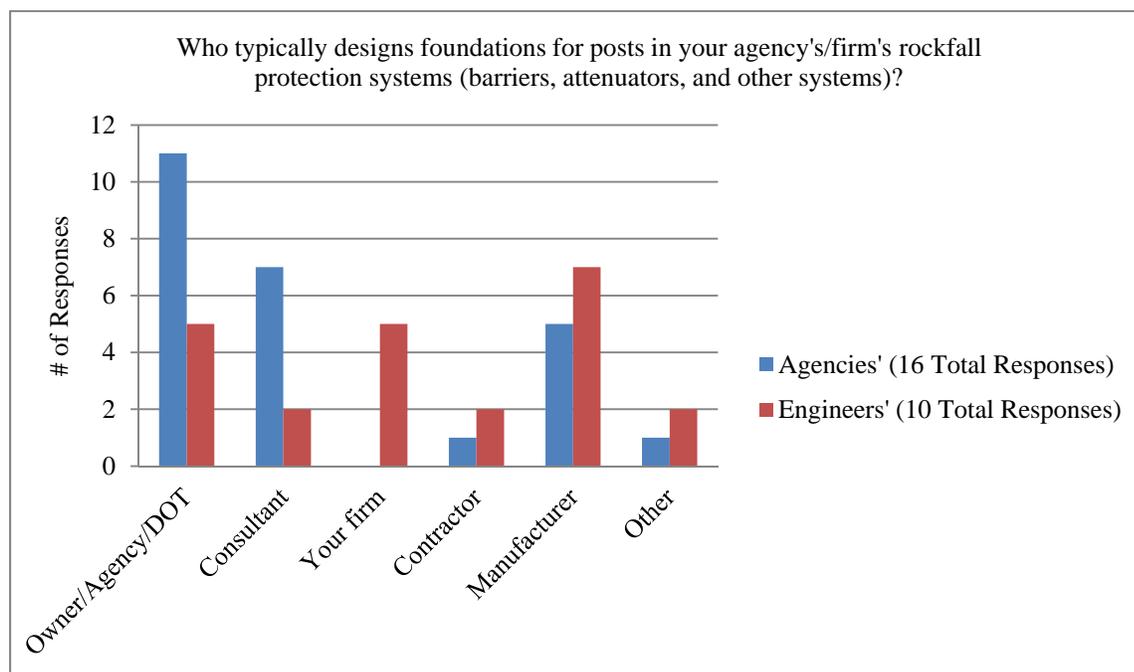


Figure B-17. Post foundation designers.

Agencies' Comments:

- Consultant design with owner review.
- I'm not aware of any specific foundation design for posts for any of our installations. We would be unlikely to do our own design, but might specify design by the other three types of entities.
- We would design (typically) for in-house; A/E for full-service design projects. We may spec contractor-furnished designs, which are akin to design-build features on a job. We can only do this for proprietary systems (similar to the internal reinforcement systems of proprietary MSE walls).

Engineers Comments:

- Engineering Consultants.
- Geotechnical consulting firms.
- Manufacturers and contractors should not be allowed to do this.
- Also rely on guidance from the manufacturer (force requirements).

Question 20

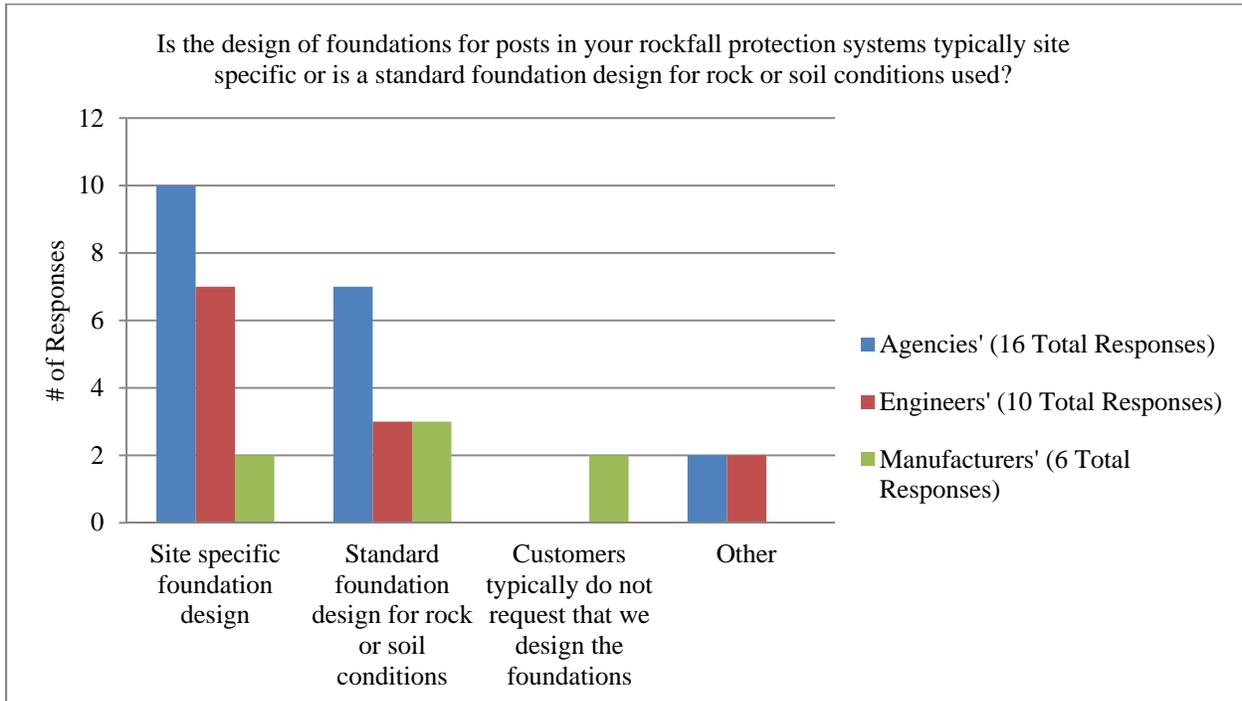


Figure B-18. Type of post foundation design.

Agencies' Comments:

- Dependent on site conditions.
- If we had a standard, it would probably be site specific, but we don't.
- More designer-specific. With no guidance to fall back on it is left up to the engineer to determine foundation designs. Issues with structures folks over-designing foundations would not be an issue if Geotech directed otherwise.

Engineers' Comments:

- Largely Site Specific, while we do use the standards. Largely dependent on the need for Stamped Engineered Plans.
- Also for the design of foundations for snow retaining structures. Not that selecting site specific foundation designs, I understand this as being tuned to the rock and soil conditions.
- Since manufacturer's supply forces, and engineer must design the foundations and the must be site specific.
- Typically standard; however, do take into consideration characteristics/strength of subsurface materials and use Eng. Judgement.

Manufacturers' Comments:

- Standard foundations are normally accepted.
- We provide standard foundation for rock and soil, and also the load transmitted from the barrier to the foundations (recorded during the crash test). Then, the designer/consultant has to validate the foundation proposed.

Question 21

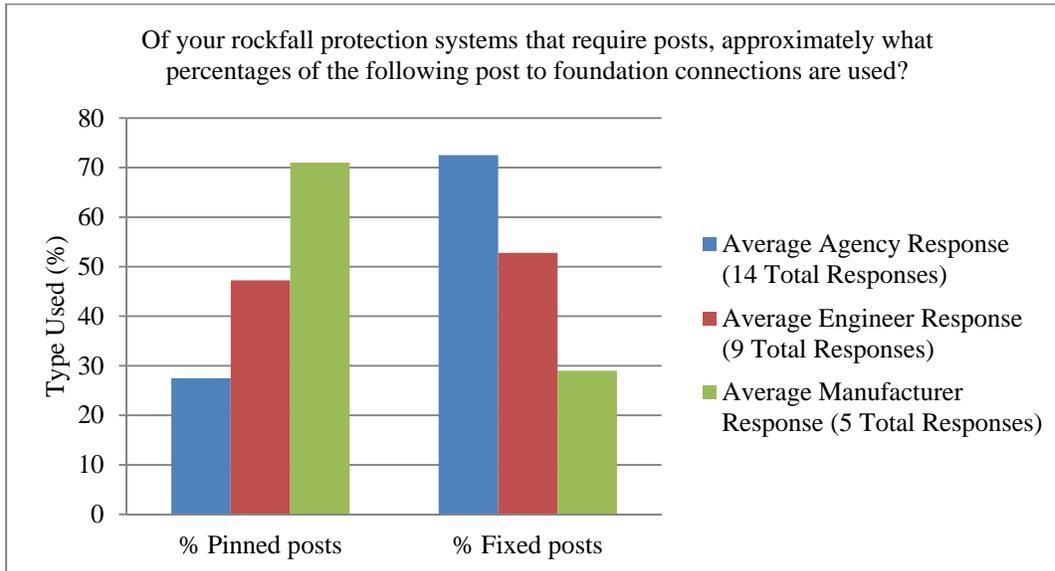


Figure B-19. Type of post to foundation connection.

Question 22

Please briefly describe your experience in using pinned versus fixed posts:

Agencies' Comments:

- Our agency designed post foundations are fixed (i.e. for hybrid systems). We have used pinned posts on fences designed by manufacturers (i.e. Geobruigg).
- FIXED. We preferred fixed in many cases because installation is easier and it's easier to maintain the post in a plumb position. In general fixed posts have less maintenance. PINNED. Less loads on the foundation but more difficult to install and requires more maintenance. But easier to batter.
- We only have a handful of installations and they are fixed.
- We prefer fixed post connections but for tested fences where a testing certification is required we are obligated to use the type of post that is tested, which is most often one using a pinned post to base connection. When designing systems independently of a manufacturer nearly all posts use a fixed post to base connection.
- We've had problems with maintenance for both systems but pinned systems have been more difficult. Maintenance units don't have a source for replacement parts or operations and maintenance guidance.
- Only have used fixed post type.
- Pinned posts are more efficient for our "hanging nets. Fixed posts are more useful for track level barrier fences.
- We generally place barriers near the traveling lane of the highway, so that large-deflection systems are not practical.
- Good performance in both systems. Pinned systems (Trumer): Attenuator posts 500 kJ, catch fences 2000 kJ. Fixed posts (Brugg, Chama): Catch fences 250 kJ, 500 kJ.
- Recently installed pinned posts on hybrid (fence/attenuator). Not in service long enough to evaluate.
- Don't know what types we have used.
- No real experience since we don't own the final installation or maintain them. Designer selects the system. No preference as such.

Engineers' Comments:

- All our installations are in active rock fall locations where they are subject to many hundreds of impacts. Where the impact energy exceeds the service energy limit, the hinged posts allow movement to occur without damage to the foundations. This facilitates repair of the structure.
- The problem with fixed posts is that the foundations are very costly because of the load transfer to the foundation that you would not have with a pinned post.
- I have little experience with this area of rockfall protection system design.
- The forces on the foundation are different and it is sometimes difficult to get the point through to clients, contractors, and even engineers/geologists.
- Depends on system. Some barrier systems do use pinned post, but always use system from manufacturer. All in-house designed systems used fixed posts.

Manufacturers' Comments:

- All of our systems were tested using fixed posts. We do not offer pinned.
- The pinned post system is the more common and is used in most projects. Fixed post systems are only applicable for energies up to 500 kJ and require stronger posts and stronger foundations. Mainly in use along roads and railways or if there is no possibility to drill upslope anchors (either technically not possible or because of land rights).
- Each system has its own advantages and disadvantages depending on the client's needs. Fixed systems have lower maintenance costs, better access but often higher installation costs. Hinged systems have lower installation costs, are more versatile with regards to adapting to difficult topography and are capable of higher energy absorption but have higher maintenance costs and more difficult access for clean out.
- Give the possibility to the post to move, and so help to absorb the impact. Even if the foundation collapses a bit in the soil, it is not a big issue! Big foundations are not effective!
- As the structure of flexible fence, the post and foundation should be hinge structure. Because on the slope, the reaction force of rockfall impact of fence should be minimized transmitted to foundation.

Question 23

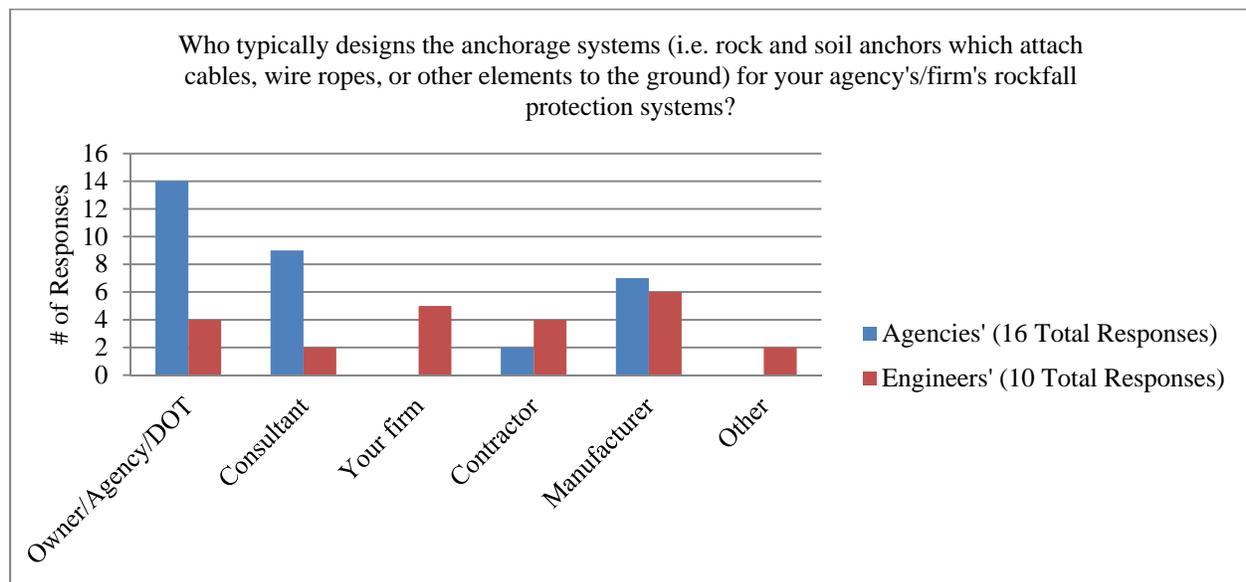


Figure B-20. Anchorage system designers.

Agencies' Comments:

- Consultant design with owner oversight.
- For flexible barriers, manufacturer designs anchorage. For all other systems, ODOT or consultant designs anchorage.
- Usually a consultant, sometimes for drapery, we have "designed" our own.
- We would design (typically) for in-house; A/E for full-service design projects. We may spec contractor-furnished designs, which are akin to design-build features on a job. We can only do this for proprietary systems (similar to the internal reinforcement systems of proprietary MSE walls).

Engineers' Comments:

- Consultants.
- Geotechnical consulting firms.
- Manufacturers and contractors should not be allowed to do this.
- Rely on the manufacturer to supply the required forces.

Question 24

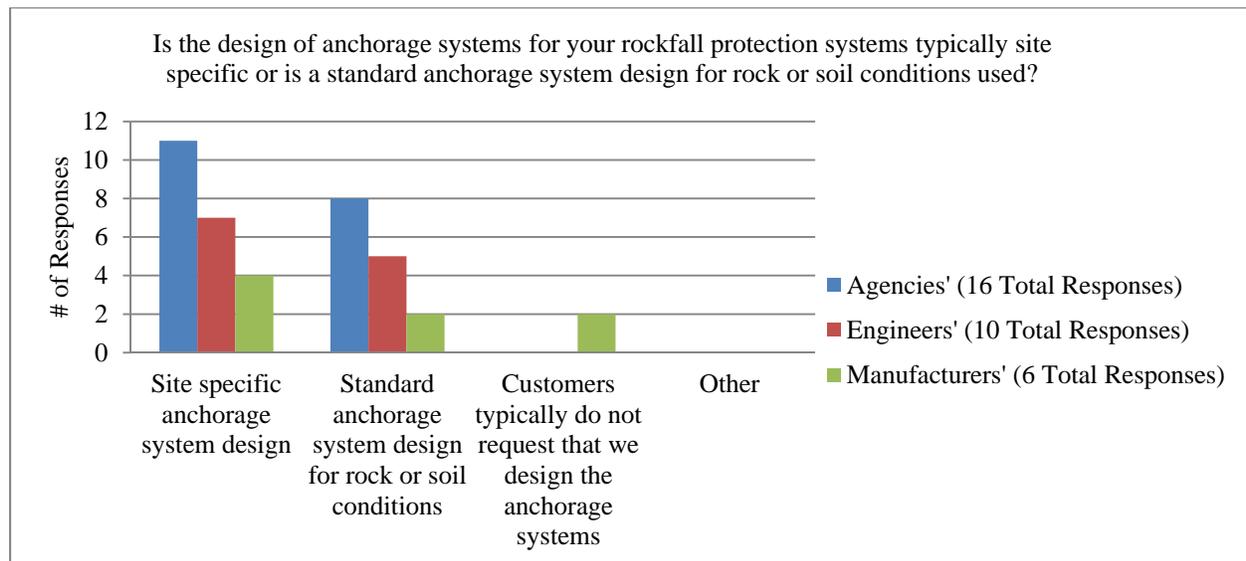


Figure B-21. Type of anchorage system design.

Agencies' Comments:

- A standard system is available for various rock and soil conditions.
- Where we have designed anchorage, we have probably done site specific design.

Manufacturers' Comments:

- Type of anchor used is based upon pullout capacity required for the system.
- It is important to design the anchors every time! It is not possible to have a specification that can be applied at any time!

Question 25

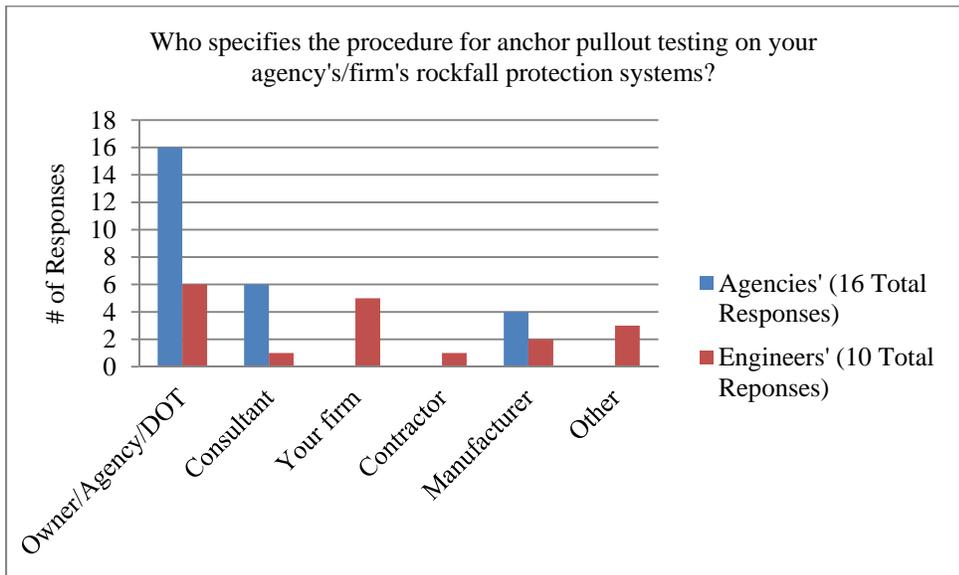


Figure B-22. Specification of anchor pullout testing.

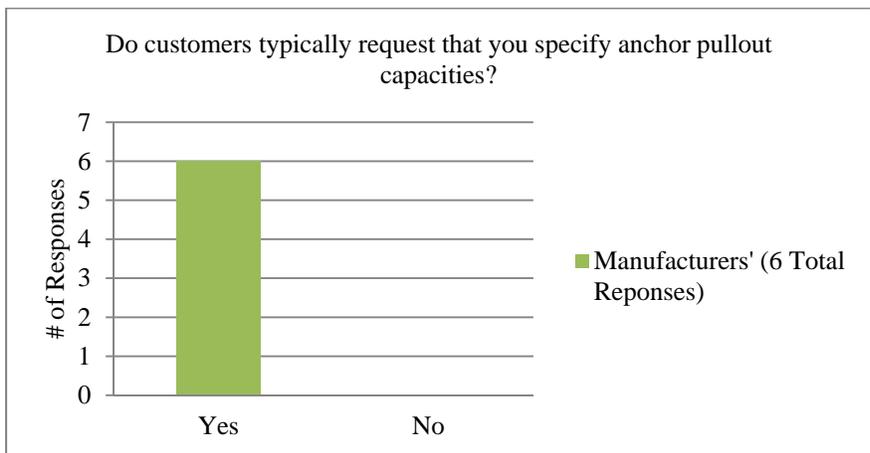


Figure B-23. Requests for anchor pullout capacities.

Agencies' Comments:

- Testing specs are usually by the consultant with owner oversight and review.
- All anchorage assemblies are specified in the FP-03 (-14).

Engineers' Comments:

- When Specs not available we refer to DOT Specs.
- Geotechnical consulting firms.
- I do not know the answer to this for the case in Switzerland. Testing is however conducted here.
- Anchor testing should be standardized. It is not necessary to pretend these are tie-back anchors and tested as such.

Manufacturers' Comments:

- Characteristic load.
- For rockfall barrier foundations! Not for pinned drapery, where the pull out is not so important and it has to be defined by the design.

Question 26

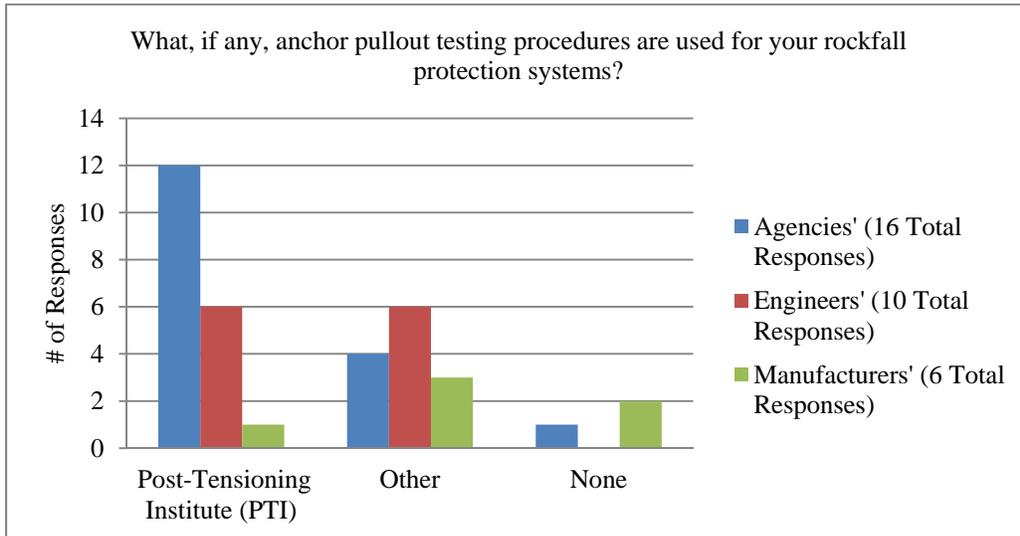


Figure B-24. Anchor pullout testing procedures.

Agencies' Comments:

- Calif. DOT has its own spec.
- PTI used as a reference.
- Contractor-submitted.
- Based on WSDOT Wire Mesh reports and PTI.
- We have probably adapted specifications from other sources, such as consultant recommendations and other state specifications.
- Generally follow PTI, but have some variances.

Engineers' Comments:

- WA DOT Specs.
- Generally follow PTI, but will decrease requirement if necessary. ie.: creep based plus 120% of DL.
- VDOT internal standard.
- Geotechnical consulting firms.
- Not sure of the current standards on this.
- We have developed our own based on a rational, common-sense approach with input from PTI, etc.
- PTI with modifications (using Eng. Judgment). Factors include time, access, etc.

Manufacturers' Comments:

- Normally pull testing procedures are outlined in project specifications.
- Recommendations based on experience and European codes.
- ONR 24810.
- ONR 24810 is a good Austrian reference for this.
- Follow to Japanese regulation.

B.4 Rockfall Protection System Maintenance and Repair

Question 27

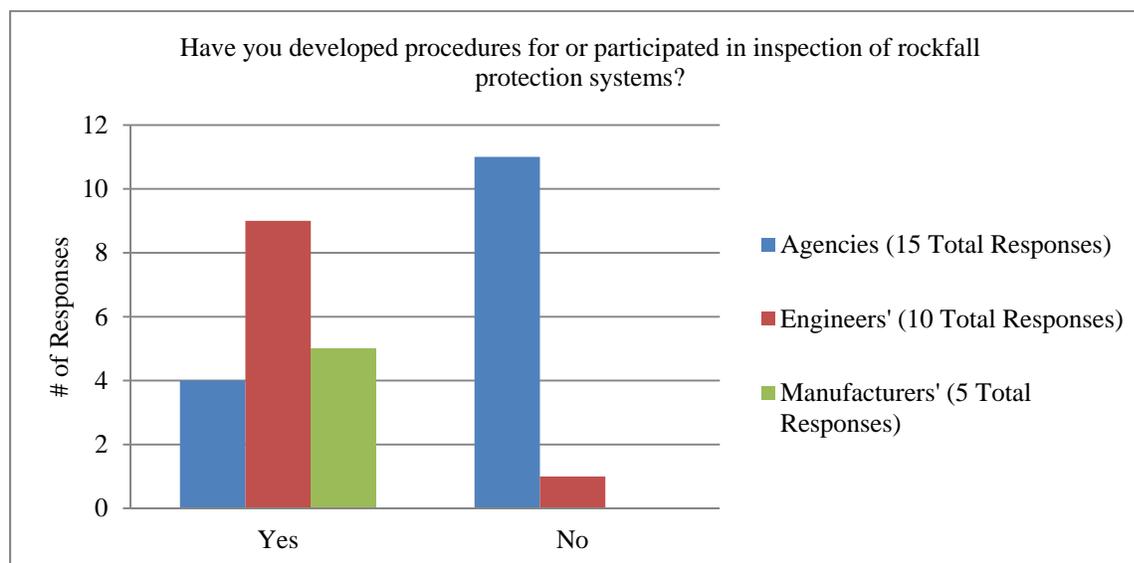


Figure B-25. Development of procedures for inspection.

Agencies' Comments:

- Nothing formal. There are no standardized procedures. In general the inspection is from road level by maintenance patrols. In some instances certain districts have maintenance design and geotechnical units who do annual inspections
- Annual Inspections.
- Inspection when convenient, generally annual to every 5 years or so.
- Handed off to the owning agency.

Engineers' Comments:

- This may not apply in this form.
- Inspection along rail ways of the stat of repair of rockfall barrier systems, contracted by the SBB rail way. Internal WSL report (in German).
- Often we observe existing mitigation systems for our long-term clients. In general, we document findings with field notes and photographs and make maintenance recommendations in a memo or email.

Manufacturers' Comments:

- There are maintenance manuals for all systems.
- ONR 24810
- Maintenance manual for all the rockfall barriers.

Question 28

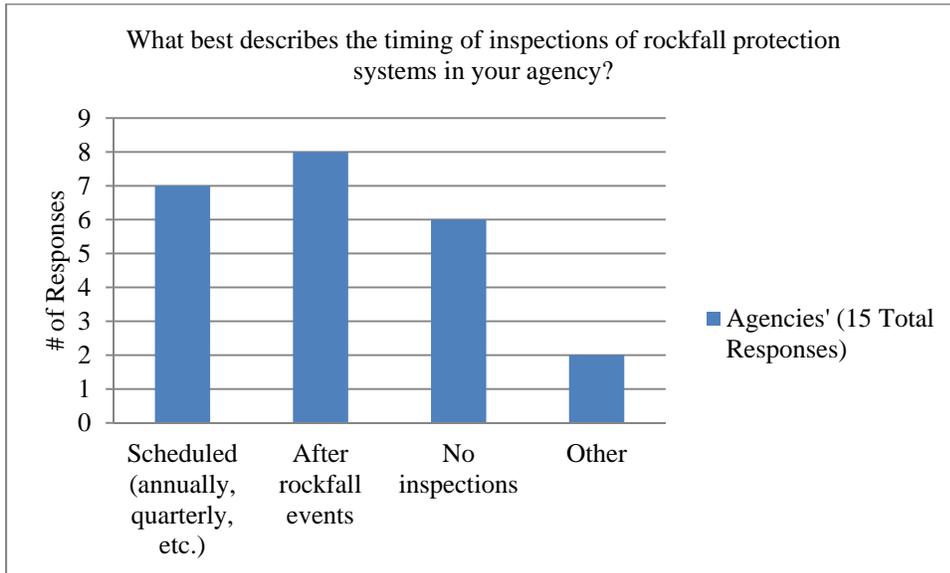


Figure B-26. Timing of inspections.

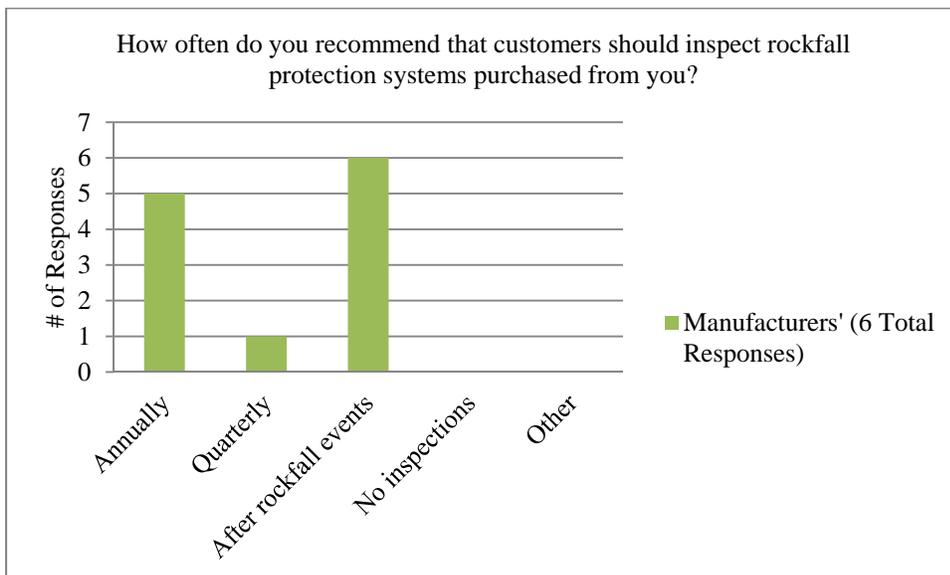


Figure B-27. Manufacturer recommended timing of inspections.

Agencies' Comments:

- Maintenance usually notifies the Geotechnical Office if there are problems with our rockfall mitigation installations.
- Nothing formal. Only certain projects get annual inspections. Otherwise inspections occur after an event.
- Annual inspection of all roadway items by maintenance crews.
- Depending on the corridor inspection will vary from yearly to every few years unless notified of failure through other methods.

- Generally on an as-necessary basis, by maintenance personnel.
- They are inspected after a rockfall impact, to evaluate the extent of the repairs needed.
- I'm only guessing...the few fences/drapes we have installed are not in our care, but I can imagine that unless there is visible sign of distress within the system that no further inspections are being conducted.

Manufacturers' Comments:

- Systems should be inspected annually at a minimum and after any rockfall event.

Question 29

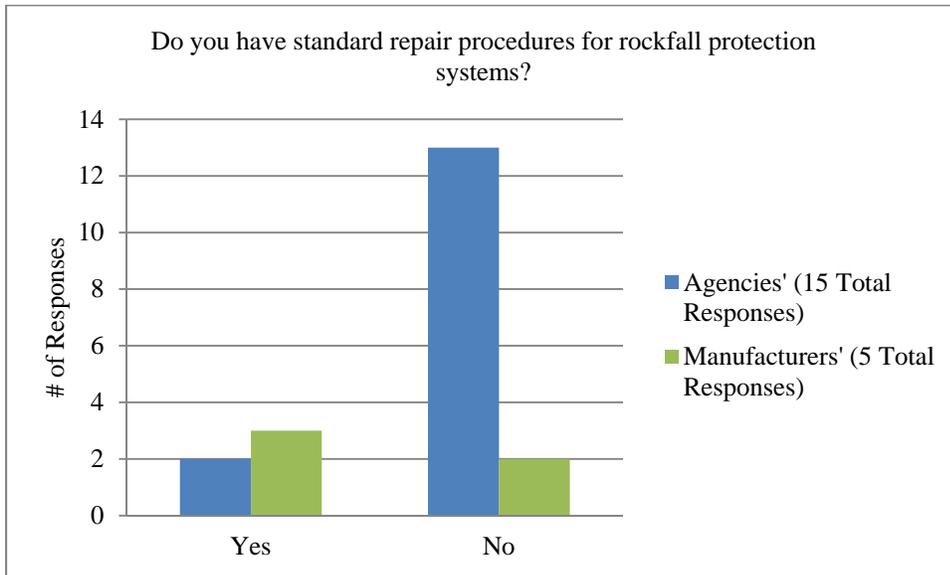


Figure B-28. Standard repair procedures.

Agencies' Comments:

- Nothing formal.
- Depends on system type, extent of damage, cost, and risk of further rockfall.
- Each repair is usually different.
- We have an in-house design for medium impact that can be repaired by DOT forces. If it is a Brugg fence, Brugg can make repair recommendations.

Manufacturers' Comments:

- Based upon damage sustained during an event.
- Also included in maintenance manuals.
- Each case is consulted with the client upon their request as no one procedure fits every site.
- It depends on the impact. Every time there is a different approach!

Question 30

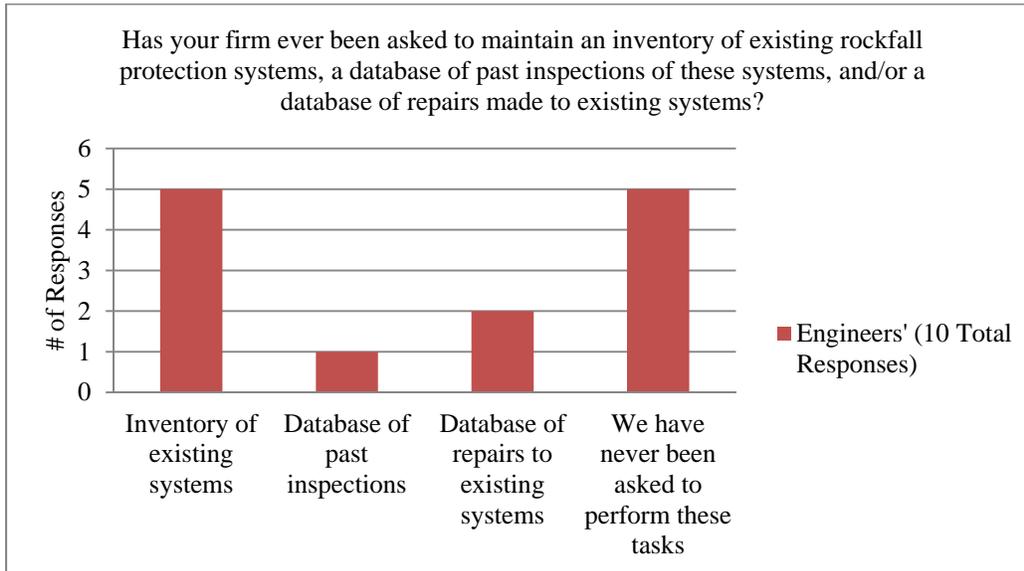


Figure B-29. Inventory of existing rockfall protection systems, database of past inspections of these systems, and/or database of repairs made to these systems.

Engineers' Comments:

- All protection structures (and other mitigation measures) are maintained in a database that includes all significant impacts and the repairs necessary.
- This may not apply in this form.
- As noted in previous, details are in the internal report.
- We are currently in the process of doing this for a large mining company who sees a cost savings in preventative maintenance.
- We often do it on our own while working on another part of the facility/asset. But we have also participated in AM types of inventories and geohazard assessments.

Question 31

Which components of your agency's rockfall barrier systems are most commonly in need of repair?

Agencies' Comments:

- Netting, posts, anchors, and brakes.
- FENCES. Energy absorbing brakes, replacing shear bolts on break away posts, re-tensioning infrastructure, replace fine mesh backing, and clean out debris. DTWM DRAPERY AND DTWM ATTENUATORS. Repair torn mesh, seams and clean out accumulated debris.
- Clean out of material retained by fencing or barrier.
- Posts, post foundations and nets for fences, nets for draped and anchored systems.
- Screen elements.
- Mesh, posts and anchors.
- Post base connection, support ropes, anchors, braking elements.
- Chain link mesh; brake components; For major damage after a large event, posts and foundations.
- Wire mesh or wire rope can be torn or punctured, and the braking elements need to be reset.

- Braking elements and support ropes (cables typically loosen in rigid systems). No problems with pinned systems.
- Drapery mesh primarily from snow load, or erosion undercutting anchors.
- Cables, panels.
- Mesh.
- Not sure, but would imagine the mesh and splice connections.

Question 32

Referring to the components discussed in the previous question, how frequently do these repair needs arise in a typical installation?

Agencies' Comments:

- Not often enough because there is very little funding available.
- It depends on the frequency of rockfall events. In some locations 2 times a year, in others every 5 years and in some cases never.
- Multiple times per year behind roadside barrier in places, areas of fencing may require attention once every few years.
- Yearly.
- Site-dependent. Some sites require annual repair, others have never needed repair.
- 1 or 2 years.
- Braking elements and support ropes more often than others.
- Generally we have one location per year that needs repair.
- Two or three per installation.
- Every 10 years or so.
- Typically once.
- Every couple of years.
- As a guess, every 2-3 years. But since the installations are not inspected, the "repair needs" only arise when an event occurs and a barrier allows rock-on-road or the barrier falls on the road. And, even if a "need" arises, there is no connection with subsequent repairs. Many of our draperies, e.g., are at least partially failed and have been for years with no effort (no budget) to repair them.
- Unknown.

Question 33

Which components of your agency's rockfall barrier systems are least frequently in need of repair?

Agencies' Comments:

- Top horizontal support cables and post support cables.
- Anchored mesh, cable drapery and cable attenuators.
- Draperies with open bottoms.
- Retaining rope and bearing ropes.
- Anchors.
- Foundations.
- Mesh and high capacity netting.
- Nets.
- Posts.

- Nets, anchors, posts.
- The ring nets.
- Foundation.
- Anchors and posts.
- Unknown, but likely the ground anchor.

Question 34

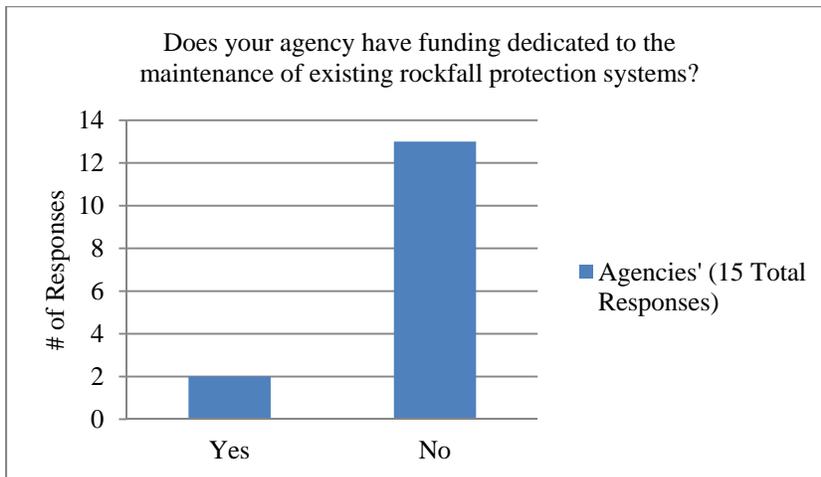


Figure B-30. Dedicated maintenance funding.

Agencies' Comments:

- We don't maintain the features. No additional funds would be allocated specifically for this purpose by one of our partner agencies either - simply added to the list of maintainable features along a roadway.

Question 35

Please describe what thresholds (i.e. damage, impact, aesthetic, age, or other), if any, you use to initiate maintenance/repair of rockfall protection systems:

Agencies' Comments:

- The Geotechnical Office needs to recommend that the installation is no longer functioning as intended and that repairs are needed to bring the installation back to its originally intended design criteria.
- Damage and volume of material required to clean out.
- Based on visual inspection to determine if the system needs attention to function properly.
- Maintenance recommendations are currently based on experience of inspector.
- Damage to the system to where it is no longer functional.
- Damage and Age.
- Damage.
- Related to extent of damage. If system is not functioning or in danger of falling onto the roadway then repairs are done. Minor distortion of posts or draped mesh is not usually significant to require repair. Seldom is a system repaired or replaced due to age or aesthetics.
- For catchment nets, percentage of debris filling net say 25-30% full.

- If the area behind the fence holds a significant amount of fallen rock, or if any element of the fence is damaged, the fence repair may be added to another nearby, unrelated contract.
- Generally level of damage, braking element activation, degree of sagging in nets, after significant rock impact.
- No set policy.
- When damage to system is found to compromise proper function.
- Whatever the threshold might be, we have rarely reached it. We do have some installations of chainlink panels on top of concrete Jersey barriers for which we have replaced panels and barriers when damaged.
- Visual distress from drive-by survey would be my guess.

Manufacturers' Comments:

- Damage must be repaired as required to maintain the integrity of the system.
- This is dependent on the component. There is threshold of elongation of brake elements, residual height of the barrier, filling up of the barrier by debris etc. This is all defined product specific in the maintenance manuals.
- This is dependent on the component and damages. For example, any broken or fractured component needs to be replaced. If, for example, it is a matter of a brake element that has been activated only slightly, it becomes a question of the owner's willingness to accept risk of a system that is not operating at 100% capacity. Again, this is consulted with the client on an individual basis.
- Impact, age.
- Damage, impact and age.

Question 36

Are there situations where more than one alternative repair action may be feasible at a given time (other than doing nothing)? Please describe the alternatives and the typical basis for selecting a repair alternative.

Agencies' Comments:

- An alternative to the original design would only occur if the assumptions for the original design have proven to be inadequate (i.e. capacity was not high enough).
- Fix or replace or if the repair and replacement becomes very frequent then we consider a new mitigation measure.
- Repairs may range from patching holes in the net to system removal and replacement if it is determined that the existing system is inadequate for the current conditions.
- Scaling is typically done in conjunction with barrier installation. Environmental/aesthetic considerations usually drive the repair alternatives.
- Improving fallout areas by excavation at the base of a slope, cleaning ditch areas, or construction of concrete barriers or walls next to the roadway are very common, usually because they are more maintainable than rockfall protection systems.
- Sometimes just cleaning out accumulated rock and not repairing mesh or brakes depending on available budget.
- If DOT Maintenance forces can do the repair, that would be the most cost-effective method. If the repair exceeds their capability, a contractor must be used.
- No.
- Not usually.
- We have repaired one flexible fence system two times in the 17 years the system has been installed.

- We do so few repairs that we haven't assessed alternatives.
- Yes. In the case of a significant system failure we may get one-time funding to effect additional slope stabilization measures. We may be allowed, for example, to systematically bolt a slope or use grouting.

Question 37

Have you experienced any total failures of rockfall barrier systems (i.e. system is no longer effective in performing its intended task)? If yes, please describe which component(s) of the system failed, and what was the most significant failure mode?

Agencies' Comments:

- Some of our fences have taken direct rockfall hits. The fence stopped the rock(s) but repairs to the fence were needed (i.e. replacement of anchors, brakes, and netting).
- When a rockfall event exceeds the design capacity. In the case of flexible fences energies above 1000 kilojoules usually requires extensive maintenance and in some cases replacement. This includes posts, energy absorbing brakes, infrastructure, replacement or extensive repair.
- Yes, a drapery systems failed due to larger than anticipated material being wrapped up in the fabric and pulling it down. The wrong draping material was used in this location.
- Yes, have had situations where all components have failed but most common components to fail are post to base connections, post foundations and netting.
- Yes. Barrier posts get hit by rocks and leave large sections of fence unsupported.
- Anchors failed when impacted by rock.
- Not aware of any total failures in ODOT.
- Yes 1, however, failure was from snow avalanche not rock fall, so impact was very high. Snow filled net system and exceeded system capacity twisting posts and bending foundation anchors. Yes 2, Net system designed for 500KJ was overwhelmed by major slope failure and ended up on the railway track.
- Have not yet seen a total failure.
- No failures within design parameters. Total failure from large volume impact well over design level.
- No.
- We have had a very few drapery systems that were overwhelmed by rock fall, tearing mesh and breaking cables. Not sure if we had any anchors pulled out or broken.
- None to date.

Question 38

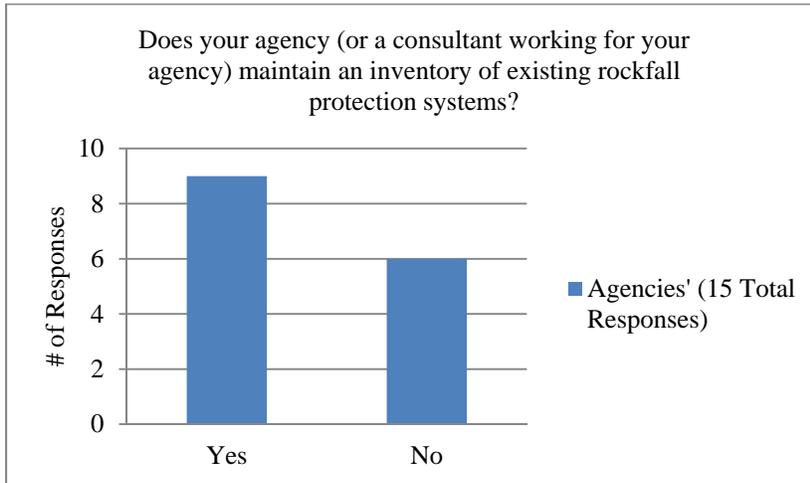


Figure B-31. Inventory of existing rockfall protection systems.

Agencies' Comments:

- Incorporated into the RHRS.
- And I doubt any of our partners inventory any of these features either.

Question 39

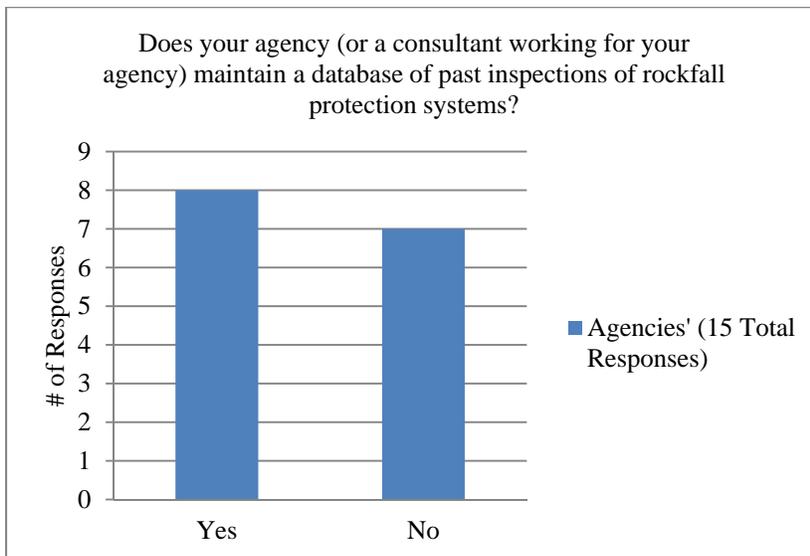


Figure B-32. Database of past inspections.

Agencies' Comments:

- Inspection process is in its infancy and will include inspection history when fully developed.
- Incorporated in RHRS.

Question 40

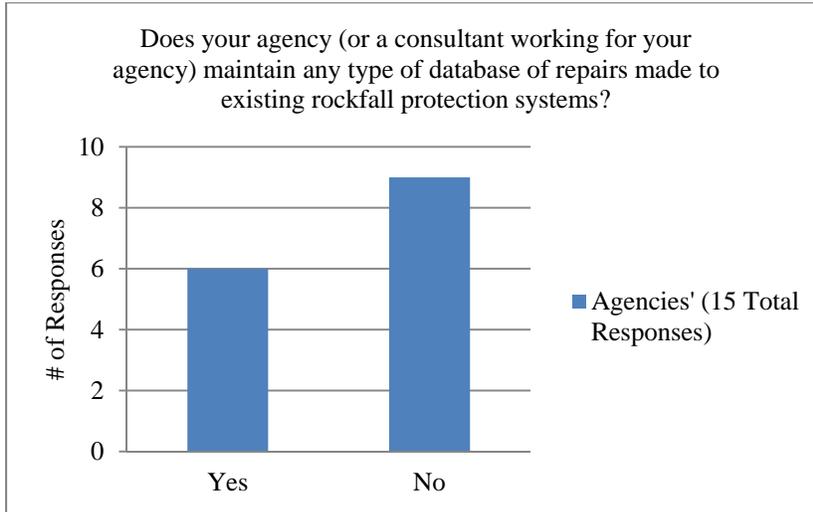


Figure B-33. Database of repairs.

Agencies' Comments:

- Incorporated in RHRS.

Question 41

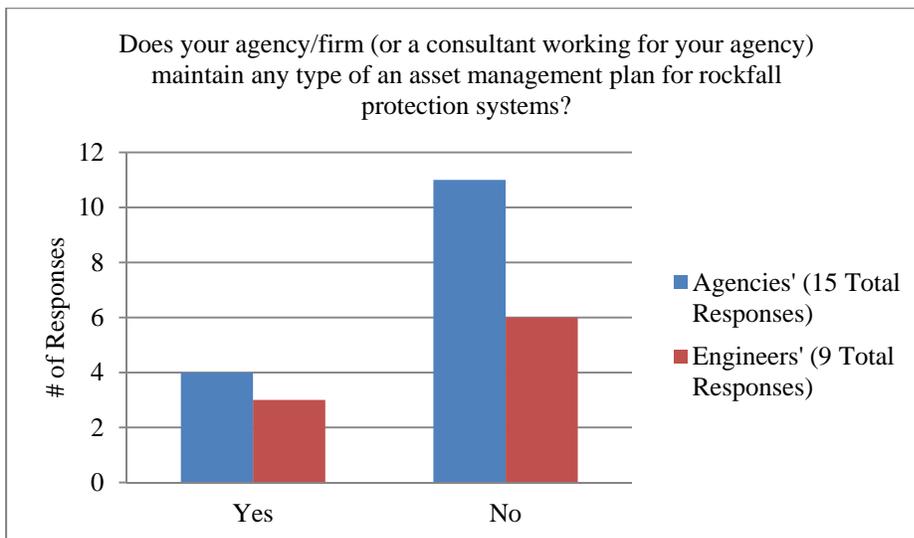


Figure B-34. Asset management plan.

Agencies' Comments:

- We maintain a database of the locations of rockfall mesh.
- We are conducting inventory and condition survey of unstable slopes and rockfall mitigation is noted as part of the inventory process, but do not have separate inventory.

- But beginning to implement on a site specific basis.

Engineers' Comments:

- We regard entire slopes as assets with the RPS being part of the overall asset.
- Although I understand one is in development.
- For a large mining firm.

Question 42

Please use the space below to provide any additional comments or questions that you feel would be helpful in evaluating the existing state of practice in rockfall protection system design.

Engineers' Comments:

- The barrier systems now available from the manufacturers are very valuable in providing rockfall protection, and we have found that their performance meets the energy capacity quoted in the product literature.
- I have seen a lot of instances where solid structures are put in place within the reaction zone of flexible rockfall barriers which completely changes the dynamics of the system. An example of such structures is Jersey Barriers that are put there to protect the oncoming traffic from driving into one of these barriers.
- I think that engineers and geologists should be responsible for analyzing for and specifying systems along with foundation and anchor designs based on loads provided by the manufacturer. The fact that unlicensed manufacturers' representatives and contractors(!) are doing this is reckless and dangerous. Good survey! Thanks!
- Believe that some of the foundations being designed by SEs for established barrier systems getting out of hand. We need to encourage existing barrier manufactures to produce "standardized" attenuator systems. Using many more attenuator systems these days as compared to barrier systems. Main reasons: R-O-W and permitting issues, plus difficulty in getting maintenance crews to clean out behind the barrier. Would also like to see more research/advancement in low-deflection fences. However, fear that the foundation requirements if reviewed or designed by local SEs (not familiar with manufactured barrier system kits) would make these types of system to cost prohibitive or feasible to construct. Miss the days of the skookum, old GeoBrugg systems that had a Design Load and an Ultimate Load (with God knows how much FOS built in). Always slept better after one of those systems were installed.

APPENDIX C

Asset Management for Rockfall Fence Systems

Transportation Asset Management (TAM) is a strategic and systematic process of maintaining and managing infrastructure assets throughout their life cycle, focusing on business and engineering practices for resource allocation and utilization. It uses data and analysis to improve decision making, with the objective of providing the required level of service in the most cost effective manner (Gordon et al 2011).

Because of its inclusion in Federal legislation regarding pavements and bridges (23 USC 190(e)), asset management may sometimes be regarded as a formality applying only to those more expensive assets. However, in reality asset management is merely a collection of management best practices, many of which have been in existence for decades.

All of the basic components of asset management have been codified in various standards documents in recent years (Figure C-1). In the United Kingdom, the authoritative source is Publicly Available Specification 55, volumes 1 and 2 (BSI 2008). In the United States, a basic framework is described in a financial management context in Government Accounting Standards Board Statement 34 (GASB 1999), and in a strategic planning context in Volume 1 of the AASHTO Guide for Asset Management (Cambridge et al 2002). A more detailed adaptation of the same principles is New Zealand's International Infrastructure Management Manual (IIMM, NAMS 2006). For bridges specifically, AASHTO has published a guide for bridge management systems, which focuses on the requirements of databases, models, and information systems appropriate for long-lived assets (Thompson and Hyman 1992).

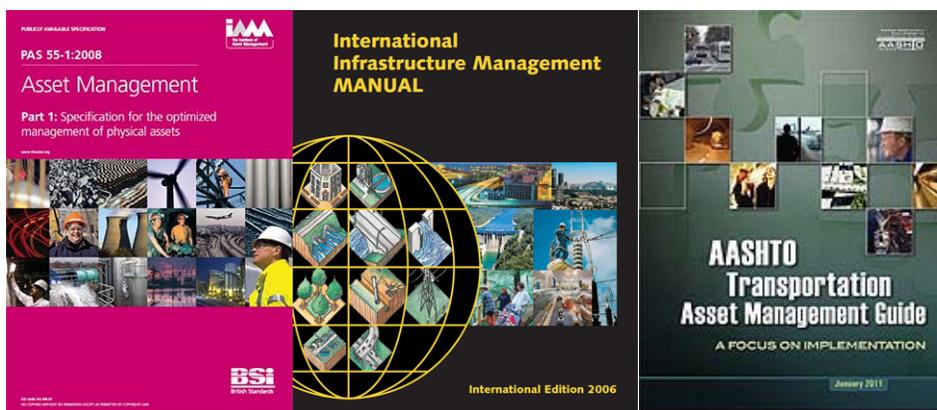


Figure C-1. International asset management standards

All of these documents offer advice and specifications for what an agency should do in order to be successful. What has been missing until recently is guidance on how to implement these requirements. The IIMM introduces a concept of self-assessment and gap analysis, to help agencies to plot a course toward implementation of improved asset management processes. In 2011, AASHTO built on this concept by publishing the AASHTO Transportation Asset Management Guide, Volume 2: A Focus on

Implementation (Gordon et al 2011), a more detailed guide focused on transportation infrastructure, informed by experiences worldwide in developing and implementing transportation asset management processes and systems.

A key aspect of successful asset management implementation, brought out in the IIMM and the AASHTO Guide, is the notion of continuous improvement. A variety of human and automated ingredients need to be improved in tandem. The amount of progress that can be made in asset management tools is limited by the human and organizational readiness to use the technology, and vice versa. In a more tangible sense, the technology to produce quality asset management information depends on management willingness to accept asset management information in decision-making (and to see the value and pay the cost of producing this information). Management acceptance, in turn, depends on the quality of information that can be produced. A small improvement in the decision making process must be matched by an incremental improvement in technology, which then spurs the next small improvement in decision making.

The Moving Ahead for Progress in the 21st Century Act, known as MAP-21, calls on state Departments of Transportation to prepare risk-based Transportation Asset Management Plans (TAM Plans) for the National Highway System to “improve or preserve the condition of the assets and the performance of the system”. The legislation mandates the establishment of condition and performance targets for at least pavements and bridges, and requires the TAM Plan “to include strategies leading to a program of projects that would make progress toward achievement of the targets.” Although only pavements and bridges are mandatory in the TAM Plans, states are encouraged “to include all infrastructure assets within the right-of-way corridor in such plan.” (23 USC 119(e))

FHWA has published draft guidance on TAM Plan development (FHWA 2015a and 2015b). Examples, many of which include assets other than pavements and bridges, can be found online from many states (See <http://www.fhwa.dot.gov/asset/plans.cfm> and <http://www.tamptemplate.org/>). Geotechnical assets are included in some of these efforts (ODOT 2011). Application of asset management concepts to geotechnical assets is relatively new (Hawkins and Smadi 2013). Some of the important considerations are:

- What is a geotechnical asset from the TAM perspective?
- How do geotechnical assets affect transportation system performance?
- How can this performance be measured?
- How can this performance be forecast, so it can be used in decision making to optimize performance?

The Central Federal Lands Division of FHWA gave these questions considerable thought in the preparation of its Implementation Concepts and Strategies document (Vessely 2013). The document describes numerous case studies where asset management thinking could help agencies make better long-term decisions about geotechnical assets. It visualizes GAM as a major driver of transportation system risk, with the corridor as the major unit of risk analysis. The report offers many practical ideas on establishing a GAM program.

Washington State DOT has published a brochure describing how it has implemented many of these ideas (WSDOT 2010). The Alaska Department of Transportation and Public Facilities has a Geotechnical Asset Management Plan under development for rock slopes, unstable soil slopes, retaining walls, and material sites. Colorado DOT is developing a plan for its retaining walls (unpublished work in progress).

C.1 Establishing an Asset Management Process for Rockfall Fence Systems

As is the case with pavements, bridges, and all other asset classes, quantifying the performance benefits of rockfall fence systems is a necessary part of justifying investment in the assets as a part of an enterprise-wide transportation asset management plan. An agency’s ability to develop performance

Forecasting and feedback. Proficient asset management includes the ability to make proactive decisions; that is, decisions that anticipate future performance and act to shape that future in a desired direction. This means the ability to forecast deterioration of slopes and rockfall fence systems, to estimate the cost and effectiveness of the various corrective actions, and to make a reasonable prediction of important future events such as future replacement actions and the work required because of future deterioration. It includes the periodic use of historical inspection and maintenance data to improve the quality of predictive models and to adjust them to reflect changes in agency maintenance capabilities.

Project development. When a rockfall fence system installation fails or reaches a deteriorated condition state, the agency may respond by planning a replacement or corrective action. As a slope deteriorates due to weathering or erosion, the need may arise for new rockfall fence system units in places where they were not needed previously. Effective asset management includes the ability to anticipate the scope and timing of these needs, to find the most effective solution for a given site. In addition, many projects that repair or improve rockfall fence system installations also include work on other elements of the road section. Rockfall fence system work planning will need to fit into a larger work planning process for road sections or corridors.

Program development. Each agency will already have a program development process, which may or may not include routine replacement or corrective work on rockfall fence systems. The process usually includes a means of setting priorities, matching funding with projects, and scheduling of the work. The asset management plan for rockfall fence systems will need to fit within this framework.

Network level analysis. An important part of asset management is developing an understanding of the inter-relationships between funding and performance. Funding for rockfall fence system work is not usually set by legislative action or by any external stakeholder, but is a result of internal decision making. Rockfall fence system investments therefore compete with a variety of other investments for limited funding. Future performance of rockfall fence system installations is affected by the amount of money spent on these assets to maintain or improve their performance, so performance targets are resource-constrained.

Choices and tradeoffs. If the measurement of performance can be standardized in useful ways across all asset types, then the funding vs performance tradeoff can be analyzed using relatively simple tools. The agency can develop a consistent set of performance targets for all the elements of a road section and corridor. When new investments are under consideration, these tools can help inform decision makers about the costs and changes in performance that might be expected.

All of these capabilities are made up of a combination of procedures, data, and tools. These are listed in the Ingredients section of Figure C-2. When an agency seeks to advance its asset management maturity by implementing new capabilities, the list of capabilities can be used as a checklist of implementation concerns to be evaluated and managed. The AASHTO Asset Management Guide (Gordon 2011) provides a variety of case studies and examples.

At the same time that the agency is developing its TAM capabilities, it should also seek to improve the catalysts supporting TAM in general and rockfall fence system TAM in particular. Most of these catalysts are based, in part, outside the agency. Nonetheless they are important for successful implementation. For example:

- Agency strategic planning documents (such as the statewide policy plan) should describe how the performance of geotechnical assets affects the resilience of the network and thus the quality of service provided to the public. It should describe the amount spent on these assets and the quantitative performance benefits.
- Having internal policy documents in place to describe asset management processes will help new employees to integrate constructively into the agency, and will help to resolve conflicts about difficult issues such as resource allocation, data ownership, and quality assurance. A complete and up-to-date library of policy documents helps to limit the agency's liability when natural

events cause rockfall incidents. This counter-acts the concern that having better information about hazards could increase liability.

- TAM is an effective focal point for initiatives to improve agency relationships with outside stakeholders. If stakeholders are regularly provided with performance information relevant to their concerns, and the agency shows how it manages and optimizes that performance, then stakeholders are more likely to feel constructively involved and valued. This is just as true for rockfall fence systems as for other asset types. The International Infrastructure Management Manual especially provides an extensive set of ideas and case studies on this aspect of TAM implementation (NAMS 2006).

Successful implementation of rockfall fence system asset management is aided substantially if TAM implementation is ongoing across the agency. When employees talk about performance, measure it, work to improve it, and are accountable for it, then they tend to value performance. In this way, an agency can develop a performance-oriented culture (Gordon et al 2011).

C.1.1 Performance Management

Transportation Asset Management supports decision making and accountability driven by measurable transportation system performance. Agencies with a functional TAM capability measure performance in terms of the agency's mission and objectives, attempting to make decisions that maximize the desired performance outcomes (Gordon et al 2011). Examples of the types of desirable system outcomes are (23 USC 150(b):

- (1) *SAFETY.—To achieve a significant reduction in traffic fatalities and serious injuries on all public roads.*
- (2) *INFRASTRUCTURE CONDITION.—To maintain the highway infrastructure asset system in a state of good repair.*
- (3) *CONGESTION REDUCTION.—To achieve a significant reduction in congestion on the National Highway System.*
- (4) *SYSTEM RELIABILITY.—To improve the efficiency of the surface transportation system.*
- (5) *FREIGHT MOVEMENT AND ECONOMIC VITALITY.—To improve the national freight network, strengthen the ability of rural communities to access national and international trade markets, and support regional economic development.*
- (6) *ENVIRONMENTAL SUSTAINABILITY.—To enhance the performance of the transportation system while protecting and enhancing the natural environment.*
- (7) *REDUCED PROJECT DELIVERY DELAYS.—To reduce project costs, promote jobs and the economy, and expedite the movement of people and goods by accelerating project completion through eliminating delays in the project development and delivery process, including reducing regulatory burdens and improving agencies' work practices.*

As a part of maximizing these system objectives, each asset makes its contribution by satisfying various criteria for its level of service:

- Condition (lack of material defects or performance deficiencies that occur with age and usage);
- Functionality (ability of an asset to perform the functions for which it was designed);
- Resilience (asset characteristics which minimize the likelihood of service disruption).

In exchange for the service provided by each asset, the agency incurs a cost. This includes the initial cost of constructing the asset, and the cost of ongoing work to keep the asset in service and functioning as designed. Typically an agency will seek to minimize the life cycle cost of keeping assets performing acceptably according to level of service criteria. These criteria can vary depending on the asset's role in the overall transportation system.

As agencies mature in their TAM capabilities, they become more adept at quantifying their performance objectives and routinely evaluating actual performance of their assets. Then they maintain

decision making processes that can be shown to improve performance, even (in best practice) to optimize it.

C.1.2 Measuring Performance

Rockfall fence systems affect transportation system performance primarily through the possibility of service disruption caused by rockfall, which may decrease network safety, mobility, and/or sustainability, and which may increase life cycle costs. Disruptions to service are typically uncommon and unexpected, but costly when they occur. As a result, geotechnical asset performance is typically managed using the principles of risk management.

Through its maintenance forces and contractors, a transportation agency implements treatments that maintain or enhance the characteristics of its geotechnical assets which minimize the frequency of disruptions. These characteristics make up a property called resilience. For geotechnical assets, resilience can be defined as follows:

... the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must (Allenby and Fink 2005).

'Vulnerability' seems largely to imply an inability to cope and 'resilience' seems to broadly imply an ability to cope. They may be viewed as two ends of a spectrum (Levina and Tirpak 2006).

“Internal and external change” can be interpreted in the context of geotechnical assets as changes caused within the asset itself (i.e. normal deterioration) and change caused by external forces (natural extreme events). “Maintain its functions and structure” can be interpreted as the avoidance of transportation service disruptions. “Service disruptions,” in turn, can be interpreted as unintended changes in the safety, mobility, or economic performance of the roadway. Based on this reasoning, a rock slope may be considered to have high resilience to the extent that it is sufficiently able to refrain from service disruptions caused by normal deterioration or by adverse events. An effective rockfall fence system may contribute to the resilience of the slope, and thereby contribute to desirable transportation service outcomes.

To analyze the performance of a rockfall fence system quantitatively, a logical approach is to estimate the likelihood of transportation service disruption as a function of the resilience of the rock slope, which depends in part on existence, condition, and performance of appropriate rockfall fence system features. A rock slope with good resilience has the following characteristics:

- Is in good condition (minimal damage, degradation, disintegration, or deformation relative to a newly cut slope);
- Has appropriate catchment ditch and/or mitigation features, including rockfall fence systems;
- Lacks characteristics of geology or geometry that are associated with catchment failure or slope collapse during foreseeable (but uncommon) seismic or weather events;

If a slope has poor resilience and therefore a high frequency of rock reaching the road, the addition of a rockfall fence system may improve its resilience. If a rockfall fence system is in place but in poor condition, repairs or replacement of the system may improve the resilience of the slope and reduce the frequency of rock reaching the road.

Assessment of the resilience and/or condition of a rock slope may contribute to the justification for installation of a new rockfall protection system. Rockfall hazard rating systems, used in approximately half of the states, can contribute to this decision on specific sites (Pierson and Turner 2012). Alaska DOT&PF is developing a simplified condition inspection process for rock slopes using five condition states and a Good-Fair-Poor characterization suitable for statewide application to all rock slopes. This can be used with deterioration and cost models to estimate the rate at which new needs for rockfall mitigation may arise.

For existing rockfall fence systems, the primary indication of resilience is the condition of these assets, and their functionality as affected by condition. The discussion of data and analysis, below, describes the

condition assessment process developed under this study. The process defines four condition states in terms of applicable components and properties. The condition states may be summarized as follows:

- Good to Excellent: Identified defects, if any, are minor and do not require corrective action. Asset performance, resilience, and life cycle cost are not adversely impacted by condition.
- Fair: Moderate damage and/or deterioration has been identified. Corrective maintenance action is feasible and would extend the service life and/or improve the performance of the asset.
- Poor to Critical: Significant damage and/or deterioration has occurred. Major corrective action is warranted.

Individual rockfall fence systems would be assessed in one of these four states using the criteria described in this Guide. Rockfall fence system condition can be summarized over a network or statewide using the percent good or percent poor/critical, in the same manner as documented in federal rules for pavements and bridges (FHWA 2015a). By adopting these existing definitions, rockfall fence system conditions and strategies are compatible with Transportation Asset Management Plans (FHWA 2015b).

C.1.3 Performance Targets and Gap Analysis

Proactive asset management at the statewide level requires investment strategies that are calibrated to feasible investment levels, which lead over time to reasonable performance goals, and which guide the preparation of near-term projects and programs. Quantitative performance goals are expressed as performance targets, in terms of a desired percentage of the inventory in good or poor condition. Two kinds of performance targets are commonly developed in asset management:

- Aspirational targets describe the agency's policy or judgment of the network-wide condition that would be expected if the agency is adequately-funded and its infrastructure is well preserved over the long term. Aspirational targets are a matter of judgment, and are generally not analyzed in a rigorous way. They do not have a timeframe and are not conditional on any specific financial scenario. In some cases they might not be literally achievable (e.g. "zero traffic deaths"), but represent the desired long-term direction of progress.
- Fiscally-constrained targets are developed from an analysis of asset deterioration rates and preservation effectiveness, as described in the next chapter. They have a fixed timeframe (usually ten years) and are conditional on a given fiscal scenario describing expected or proposed funding. They help to inform decisions about the funding vs performance tradeoff, and they set expectations about the ability to make progress toward aspirational targets.

A gap analysis, as described in the federal rules, measures the distance between current conditions and pre-existing aspirational or fiscally-constrained targets. If a gap exists, then achievement of the target will require enough funding to offset ongoing deterioration, plus additional funding to improve condition to the target level. The 10-year TAM Plan and the four-year Statewide Transportation Improvement Plan (STIP) would need to describe a program of sufficient size and effectiveness to fill the gap over time.

C.1.4 Communicating Performance

Using actual or forecast percent in good or poor condition, it is relatively simple to develop graphic representations for reports and web sites, showing statewide trends as well as a breakdown by asset class (pavement, bridges, geotechnical, etc.), corridor, and/or region. An interactive map display can allow the end user to select any type of performance and any asset class to gain a deep understanding of the network and its current issues.

When communicating performance, it is important to have a context and a message (Zmud et al 2009). The term "chartjunk" is often used when elaborately decorated graphics present numbers without any context or message, thus communicating nothing. Placing a performance measure in context means providing a basis for comparison: current vs. past performance, current vs benchmark (peer states or

national average), forecast vs. actual, future performance vs targets, etc. Having a message means telling the viewers what they should do, or what the agency is planning to do, as a result of the reported performance. Some good examples of simple context and message can readily be found online:

- Michigan (<http://www.michigan.gov/midashboard/0,4624,7-256-59297---,00.html>)
- Minnesota (http://www.dot.state.mn.us/measures/pdf/2011_Scorecard_10-19-12.pdf)
- Oregon (Figure C-3) (http://www.dot.state.mn.us/measures/pdf/2011_Scorecard_10-19-12.pdf)
- Utah (<http://performance.utah.gov/agencies/udot.shtml>)
- Wisconsin (<http://www.dot.wisconsin.gov/about/performance/docs/scorecard.pdf>)

For asset management purposes, the emphasis is on outcome measures, describing the service as perceived by stakeholders and the public. Many agencies also track input and output measures, so they can report on internal issues such as productivity, resource usage, project delivery, etc. (Poister 1997). Missouri and Washington have particularly extensive examples, which also demonstrate thorough use of context and message, albeit in a rather lengthy document (123 and 92 pages, respectively).

Effective communication entails finding the right balance of content — not too much and not too little — to fit the needs of the audience. The art of effective communication of quantitative information is widely explored in the literature (Tufte 2001, Eckerson 2006, Zmud et al 2009).

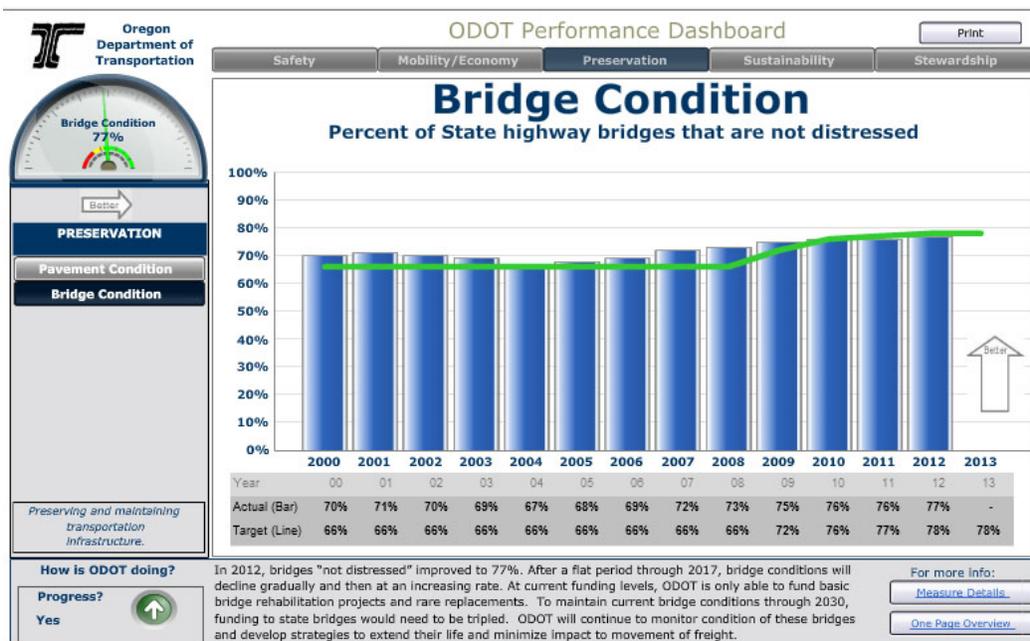


Figure C-3. Example performance dashboard from Oregon DOT

C.1.5 Self-Assessment

The incremental process of advancement in asset management necessarily occurs in phases spread over many years. During that time, much can change in an agency’s institutional and economic environment, in the needs of stakeholders, in the agency’s delivery capability, and in technology. Implementation may start and stop, even run backward at times. At any given time it is possible to sketch a roadmap to improved asset management, but only its initial steps are near enough in time to plan implementation.

A useful general approach to commence or resume the implementation of improved asset management is self-assessment. Agencies typically start with a relatively quick analysis at the strategic level, which helps in deciding which parts of the organization are ahead or behind, identifying barriers, and setting

some initial priorities. Table C-1 summarizes a strategic self-assessment presented in Volume 1 of the AASHTO Asset Management Guide (Cambridge 2002).

Table C-1. Outline of AASHTO TAM strategic self-assessment

Part A. Policy Guidance. <i>How does policy guidance benefit from improved asset management practice?</i> Policy guidance benefitting from good asset management practice Strong framework for performance-based resource allocation Proactive role in policy formulation
Part B. Planning and Programming <i>Do Resource allocation decisions reflect good practice in asset management?</i> Consideration of alternatives in planning and programming Performance-based planning and a clear linkage among policy, planning and programming Performance-based programming processes
Part C. Program Delivery <i>Are appropriate program delivery processes that reflect industry good practices being implemented?</i> Consideration of alternative project delivery mechanisms Effective program management Cost tracking and estimating
Part D. Information and Analysis <i>Do information resources effectively support asset management policies and decisions?</i> Effective and efficient data collection Information integration and access Use of decision-support tools System monitoring and feedback

The Strategic Self-Assessment is couched in very general terms in order to be applicable to all transportation agencies and all types of assets. Volume 2 of the AASHTO Asset Management Guide provides more detail (Gordon et al 2011). In the specific domain of rockfall fence systems, it is useful to think about how information about rockfall fence systems enters into each of the business processes addressed in the strategic assessment. For example:

- Does the agency have written internal policies and procedures that govern how geotechnical asset needs are identified and prioritized, which include rockfall fence systems? Are there quantitative criteria defined in the policies and procedures, which can be computed and used with inventory and inspection data about rockfall fence systems? Do policies and procedures support reliable updating of quality rockfall fence systems inventory and inspection data?
- Do projects focused on geotechnical assets and especially on rockfall fence systems make it into the Statewide Transportation Improvement Program (STIP), and what barriers exist in making sure needed projects are programmed? Is it certain that all rockfall fence system needs are identified? Do corridor-based projects focused on other asset types (e.g. pavements and bridges) also routinely and reliably consider rockfall-related needs in project scoping? Are there reliable processes to include routine maintenance of rockfall fence systems in the operating budget?
- Does the agency have the necessary delivery capability to inspect, maintain, and install rockfall fence systems in the places where it may be needed? Is agency capability kept up-to-date with the worldwide state of the practice? Are both internal and external resources fully developed and leveraged to support the rockfall fence system program? Are rockfall fence system work

accomplishments reliably recorded from planning to construction to performance monitoring? Are appropriate cost factors from rockfall fence system work captured and used to update forecasting models?

- Is there a complete inventory database of rockfall fence system features? Can rockfall fence system conditions be plotted on a map along with other asset types? Can future deterioration of rockfall fence systems be reliably forecast? Is there a process that can forecast future rockfall fence system needs?
- Do project planners and designers have readily-accessible data, which they can understand and rely upon, to include rockfall fence system needs when planning new work?
- When new routes are constructed or existing routes are improved, does the agency consider rockfall risk and life cycle cost as part of the evaluation of alternatives, and does it provide for appropriate expenditures to maintain new assets after they are opened?

Clearly many of these questions apply to all geotechnical and hydraulic assets, so in many agencies it may be more cost-effective to consider all such elements in the same self-assessment. This would be a prelude to developing a coordinated multi-year program that can fill all the gaps.

C.2 Data and Analysis for Rockfall Fence Asset Management

A key requirement of transportation asset management is the use of data and analysis to support long-range decision making. The result should be to minimize long-term costs of maintenance, preservation, and service disruption. The essential ingredients of a complete, professional asset management process for rockfall fence systems, as for all asset classes, can be summarized as follows:

Data	An inventory database listing all the assets to be managed A periodic condition assessment and inventory update
Analysis	Life cycle cost models to forecast future investments Risk models to estimate hazard effects on the public
Implementation	Software tools, manuals, training, quality assurance Decision-making processes that rely on TAM information

These ingredients are widespread today in pavement and bridge management systems, but it is not always necessary to develop a large information system to do asset management. For geotechnical assets it is most common to use an existing geographic information system database to house the inventory and inspection process, and spreadsheets to do the analysis.

C.2.1 Inventory and Condition Assessment

Recommendations are presented earlier in this report for a proposed inventory and condition assessment process for rockfall fence systems. A prototype data collection form was presented, which could be used as a template to design the rockfall fence system inventory database. It contains the following types of data:

- Identification and location of the feature
- System function, dimensions, and description
- Maintenance recommendations noted by inspector
- Condition states of system elements:
 - Panels
 - Posts and foundations
 - Ropes and anchors
 - Braking elements
 - Secondary elements
- Assessment of overall system performance

The three condition states — Good to Excellent, Fair, and Poor to Critical — have precise definitions for each category of element, based on visual evidence. They follow the same pattern as the AASHTO Manual for Bridge Element Inspection (AASHTO 2013) and are designed to be compatible with existing bridge inspection practice. Condition assessments and inventory data should be updated periodically, on an interval of 1 to 6 years depending on the risk assessment.

It is common for geotechnical asset data to be managed as part of an agency’s geographic information system. Figure C-4 shows an example of such a system, from the Alaska Department of Transportation and Public Facilities. The map shows the location of unstable slopes, using symbols to indicate the type of slope and color to represent condition states. This is a simple but very effective means of presenting asset information to decision makers and the public.

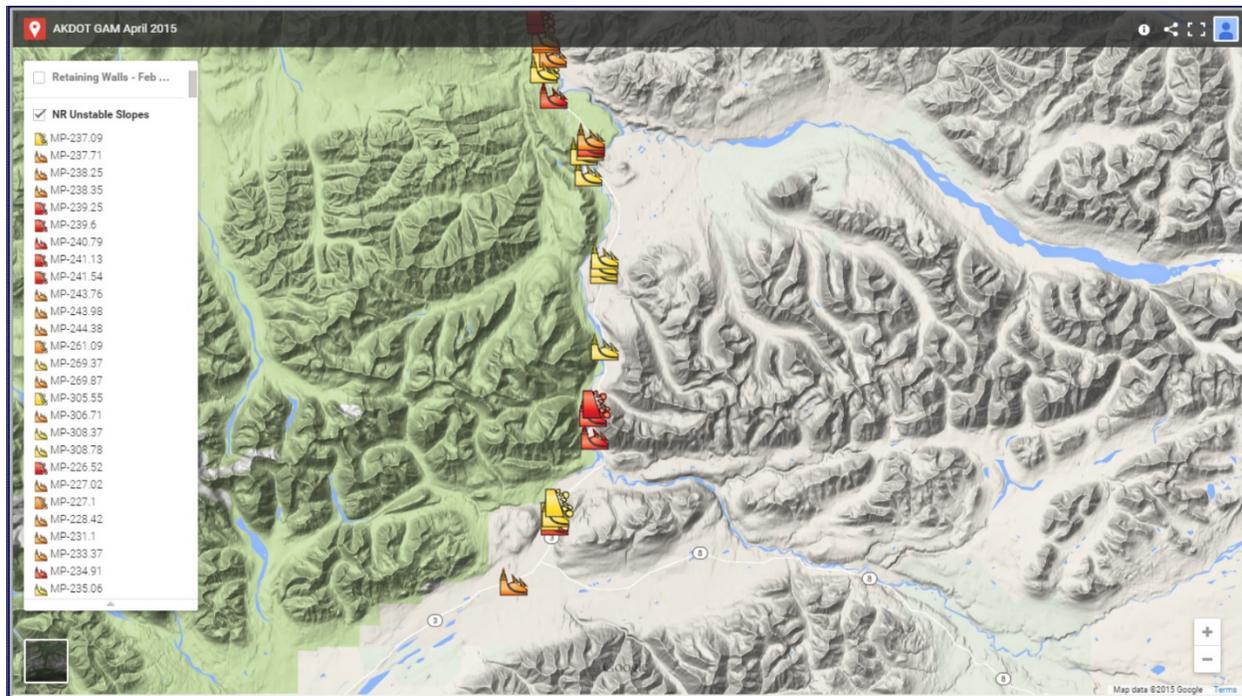


Figure C-4. Example map of geotechnical assets (Alaska DOT&PF)

C.2.2 Life Cycle Cost Models

The initial costs and maintenance costs of rockfall fence systems are an integral part of the life cycle cost of a slope, which in turn is a part of the cost of a road section. Important tradeoffs exist among these costs. For example:

- The cost of rockfall protection may be reduced by cutting a slope further from the road.
- Changing the alignment of a road may affect the cost of slope cutting and rockfall protection.
- Installation of rockfall protection may reduce the cost of periodic scaling, but may also increase the cost of debris removal and infrastructure maintenance.
- Installation or maintenance of rockfall fence systems may reduce the amount of debris entering a catchment ditch or roadway, thus reducing the cost of debris removal and incident response.
- Maintenance of rockfall fence systems may reduce or delay the cost of replacing the units.

A Transportation Asset Management Plan (TAM Plan) should include tools for understanding the cost tradeoffs quantitatively. A computation of life cycle cost includes the following ingredients:

- A model to forecast the deterioration of asset condition over time;
- A set of models to relate future condition to future actions, their costs, and their effects;

- A discount rate for costs that are expected to occur in the future, reflecting the time value of money.

With these tools, the agency can generate alternative futures for each asset, and evaluate their costs and performance. Asset management decisions are then based on the consideration of these alternatives in the context of funding constraints.

C.2.2.1 Deterioration models

A deterioration model is a statistical method to forecast future condition, based on current condition, age, and other variables. For asset management applications, the model should consider the “do-nothing” case when no action is taken, and should also be able to show how future conditions would differ for each of the agency actions under consideration.

As agencies begin to implement asset management for geotechnical assets, it is possible to develop a set of deterioration models using an expert judgment elicitation process. Such models will be rough at first, so they should be replaced later by statistical models once enough inspection data are available (Sobanjo and Thompson 2011).

The simplest possible deterioration model using element and condition state data is a Markov model, which expresses deterioration rates as probabilities of transitions among the possible condition states each year. For long-lived assets, a Markov model can be expressed as the vector of median transition times from each state to the next. The methods for developing and using these models are documented in NCHRP Report 713 (Thompson et al 2012). Figure C-5 shows an example of a deterioration model for condition states.

In this type of analysis, the replacement interval is determined by the probability of the worst condition state, and risk considerations. Often a 50% probability is used, but a lower probability is appropriate when larger volumes of traffic are exposed to the potential of falling rock or other risks. Maintenance actions are identified in response to the intermediate states. These can extend the service life. In this example, the 50% Severe level is reached in 71 years (between the highlighted cells in Figure C-5).

C.2.2.2 Treatment Options

At a given time, the condition state of an asset determines the range of maintenance and preservation treatments that are feasible. For example:

- In Good to Excellent condition, a rockfall fence system typically does not require any maintenance intervention with the possible exception of occasional cleaning of a catchment ditch.
- In Fair condition, the inspection frequency might be increased, and ditch cleaning might be more frequent. A few minor repairs might be indicated.
- In Poor to Critical condition, inspection and ditch cleaning frequency is further increased, and the agency may start to incur significant costs for rock removal from the road. Major repairs or rehabilitation may be indicated.

In typical asset management decision making, the consideration of treatments may be limited by level of service standards, which usually vary according to the functional class and/or traffic volume of the road. For example, Fair condition may be tolerated on low-volume local roads but not on interstate highways. In that case, the local road would not be considered for action unless it deteriorates further to Poor condition.

Each of these treatments has a cost and an effectiveness. Unit costs would be based on the gross dimensions of the slope, such as height and length. When establishing an asset management program, a way to develop these costs is to select a small number of representative slopes and develop a project cost estimate for them. The project cost should include all indirect costs such as mobilization, traffic control, engineering, demolition, and land acquisition. Sum the project costs over the whole set of representative slopes, then divide by the total gross area of the slopes, to arrive at a unit cost. This unit cost might be

very imprecise when applied to an individual project, but should provide a reasonable estimate of network-wide total costs for asset management purposes.

The effectiveness of a treatment is an estimate of the condition state following the treatment. This might be expressed probabilistically, for example “Good in 50% of cases, and Fair in 50% of cases.” This is determined from expert judgment. Over time if the agency is diligent about recording the actual maintenance and preservation work that is done, the database of work accomplishments can be mined to determine actual costs and effectiveness to improve the models.

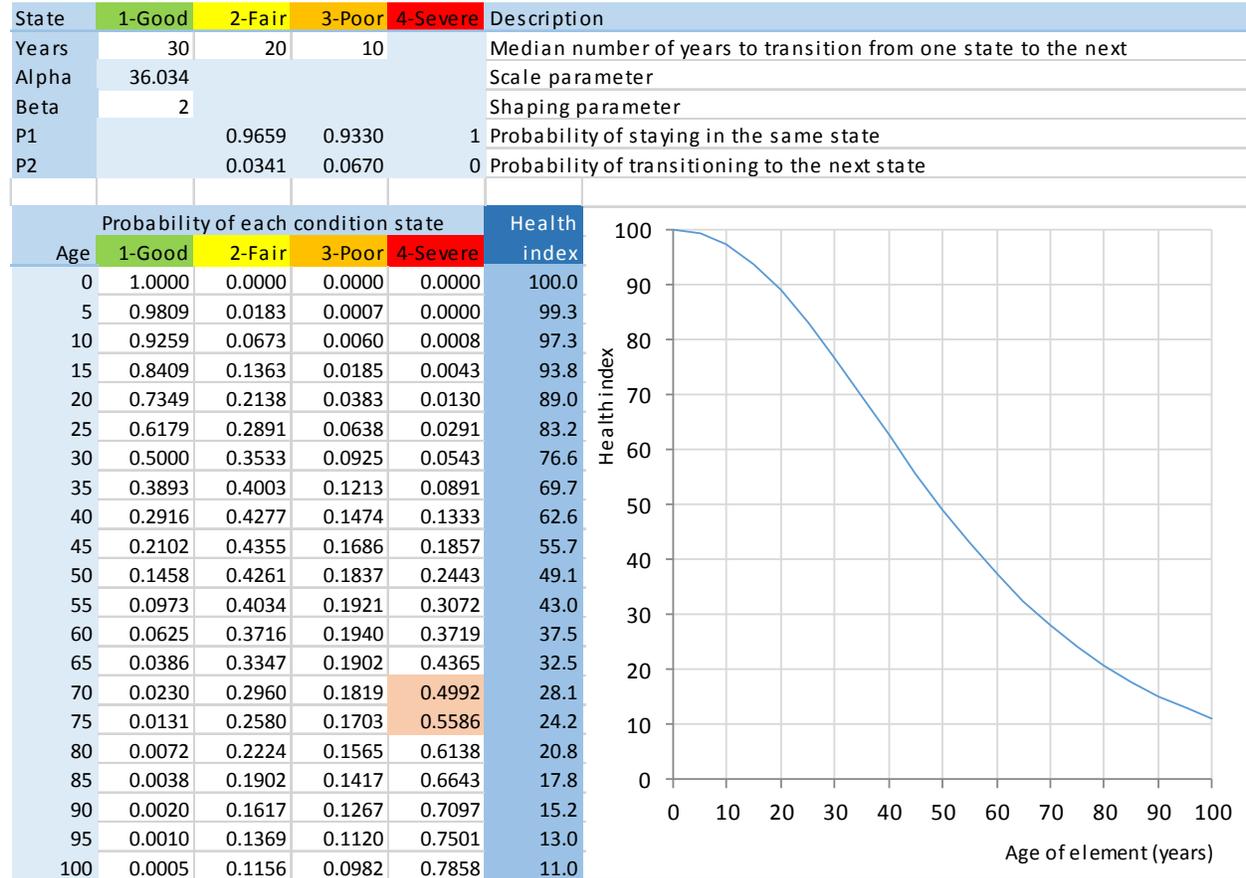


Figure C-5. Example deterioration model

C.2.2.3 Time Value of Money

A key consideration in life cycle cost analysis is the time value of money. Decision makers always prefer to postpone costs for as long as possible, because then they can use their cash for more pressing needs. However, if postponing an expenditure allows further deterioration which causes the cost to increase, the decision maker might instead decide to prevent the cost increase by making the investment today. This tradeoff is described using a discount rate.

In asset management, the key tradeoff is typically preservation vs replacement. If an asset is well-maintained and preserved, that maintenance work means incurring a near-term cost. This cost might be justified if it gains a sufficient extension of the lifespan of the asset, postponing the necessary cost of replacement.

NCHRP Report 483 (Hawk 2003) has a thorough discussion of how life cycle costs are calculated and how discount factors are determined. In short, they are determined by agency policy, which should be

consistent across all types of assets and all investments of similar lifespan. A common source of guidance is OMB Circular A-94 . Typically inflation is omitted from life cycle cost analyses because this practice simplifies the computations. A riskless and inflationless cost of capital for long-lived investments may use 30-year US Treasury bonds for guidance, with a real interest rate of 1.4%. Given uncertainties in the funding environment for infrastructure preservation and investment, many agencies use a higher discount rate to reflect non-zero risk, with 2-3% being very common.

C.2.3 Risk Analysis

In transportation asset management applications, risk is typically defined as the product of likelihood and consequence of service disruptions. A service disruption is an unexpected event that reduces network performance in terms of mobility, safety, sustainability, or costs. The likelihood of disruption depends on slope resilience, as discussed above, which in turn depends on the existence and condition of rockfall fence systems. The consequence of disruption is some measure of lost mobility, safety, or sustainability.

It is difficult to separate the risk associated with rockfall fence systems from the more general risk associated with a rock slope. As a result, it may be simplest, and provide the most complete picture, if the condition and/or resilience of the rock slope is also assessed. Rockfall fence system presence and condition might then influence the assessment of resilience of the rock slope. Many of the variables that are described in Rockfall Hazard Rating Systems (Pierson 2012) can be used in defining rock slope resilience. Alaska DOT&PF is in the process of defining a slope assessment process that is especially intended for this purpose.

Generally the steps in a risk analysis for asset management follow a common pattern (Sobanjo and Thompson 2013):

Step 1. Define one or more scenarios for a service disruption event. An example might be a rockfall incident that blocks half of a road for a period of 4 hours.

Step 2. Develop estimates for the typical return period of each scenario as a function of slope resilience and/or rockfall fence system condition. These are usually a matter of judgment unless the agency has gathered incident data. For example:

Condition	Return period (years)
Good to Excellent	10
Fair	5
Poor to Critical	1

These return periods can be converted into annual probabilities. For example, a return period of 10 years implies a probability of 10% each year. The return period might depend on slope characteristics other than condition, such as geological character or climate.

Step 3. Develop estimates of the consequence of the disruption scenario. It is simplest to express these as a dollar value using the methods in AASHTO’s Manual on User and Non-User Benefit Analysis for Highways (the “Red Book”, AASHTO 2010). Components of this estimate are:

- Safety – Each slope might be characterized according to its accident potential, as is done in Rockfall Hazard Rating Systems. Then the Red Book can provide an estimate of cost per accident. Most accidents are property-damage-only, but a small fraction are injury or fatal crashes. The Red Book compiles the results of extensive research in this area.
- Mobility – Each slope is characterized by traffic volume and detour distance, both of which are typically available in an agency’s geographic information system or bridge management system. The Red Book provides standard estimates of time and distance-based road user costs.
- Environmental and recovery costs – Each slope is characterized by a hypothetical or historical range of costs that might be incurred to clean up after the disruption event.

It is possible to perform an analysis of disruption consequences without expressing the result in dollars. However, the Red Book methods and similar user cost models are widely used in pavement and bridge

management, so using those methods helps to ensure consistency across asset classes and helps to maintain the objectivity of the analysis. Dollar-denominated risk costs are also much easier to combine with life cycle cost analysis, making it much simpler to consider cost and risk together in decision making.

Step 4. Assess the likelihood and consequence of disruption at each site for each scenario. Multiply likelihood by consequence, and sum the products over all scenarios considered.

Step 5. Incorporate the resulting dollar amount into the life cycle cost analysis described in the preceding section, using appropriate discounting for each year in which costs are incurred by the agency and by road users.

In risk analysis it is important for decision makers to be comfortable with the fact that extreme events are unusual, are never typical, and by nature cannot be predicted. The risk analysis is not intended to be a precise estimate of costs; rather, it is meant to provide a consistent basis for classifying corridor risks and for setting mitigation priorities. This basis is grounded in engineering and economic research and can be improved over time as more research is completed. Consistency is more important than precision in this analysis.

C.2.4 Project Evaluation and Prioritization

The process of finding suitable sequences of actions, determining whether they achieve and sustain a desired level of performance, and minimizing their cost, requires a capability to generate and evaluate alternative projects and life cycle activity profiles for an asset. If a road section is viewed as an asset to be managed, then rockfall fence system installation and maintenance could play a role in one or more alternative life cycle activity profiles for the road.

If a slope adjacent to a road section is subject to an unacceptable rockfall hazard, a rockfall fence system installation may be one of the alternatives to be considered in order to mitigate the hazard. If a rockfall fence system is already in place but is not performing at an acceptable level of service, some of the alternatives to be considered may entail repairing the system, or removing the rockfall fence system and taking some other action instead (for example, cutting back the slope, installing a barrier, or realigning the road). If an agency undertakes a comprehensive assessment of right-of-way safety and risk, rockfall protection would be one consideration along with all other applicable geotechnical and hydraulic elements.

The definition and evaluation of project alternatives in asset management entails multiple steps (Sobanjo and Thompson 2011):

- Identifying treatments which are feasible at the present time given current conditions and performance.
- Grouping these treatments into scoping approaches, such as reconstruction, rehabilitation, repair, and routine maintenance. The grouping is based on practical concerns such as the inter-relationship of treatments, the costs and impacts of work zone traffic disruption, and economies of scale.
- Estimating the costs and temporary loss of performance during the construction period.
- Forecasting the future conditions and performance after the project is completed.
- Making reasonable forecasts of future actions that will be necessary during the analysis period, as a result of the forecast future conditions and future traffic.

Each of the alternatives defined in this way is a life cycle activity profile (Figure C-6), delivering a level of performance and a life cycle cost that are predictable using the asset management tools discussed here. One of the alternatives may deliver the best combination of costs and performance, and may be considered to be the optimal alternative for the road section of interest. However, given resource constraints it may also be necessary to consider less expensive alternatives, including the possibility of doing nothing this year and instead selecting the alternative that is optimal next year.

The analysis of alternative investments is always a comparison among two or more alternative life cycle activity profiles. Usually the “base case” or default alternative is to do nothing this year and repeat the analysis next year instead. This may entail little or no commitment of resources in the current year. By definition, the base case has zero benefit.

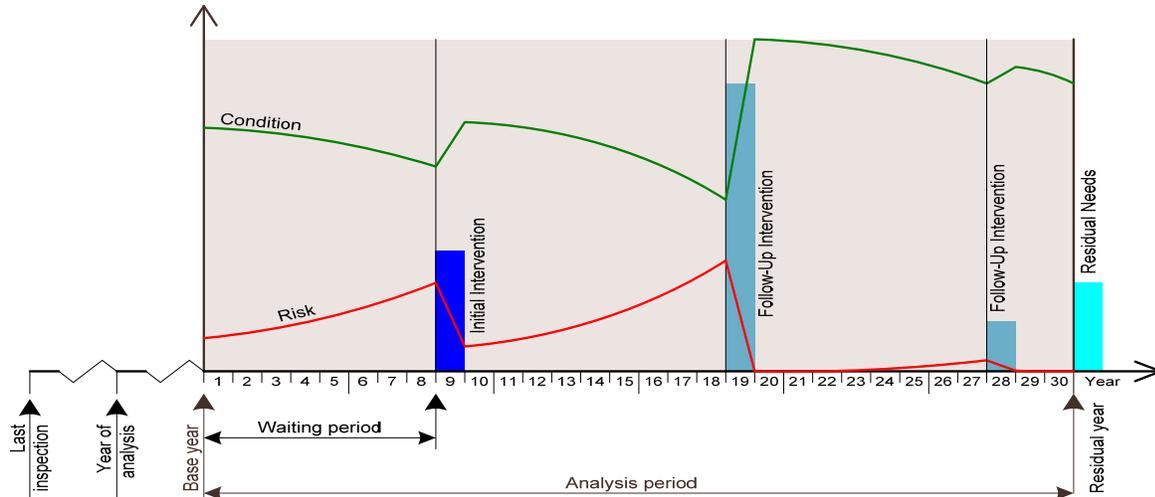


Figure C-6. Example life cycle activity profile

If more money becomes available, then an inexpensive alternative may become feasible, which has higher cost than the do-nothing alternative, but also has higher performance. If risk is analyzed as a cost, as in the preceding section, then the higher-performing alternative may have lower life cycle costs. The difference in life cycle cost between this alternative and the base case is its benefit.

In transportation asset management applications, projects are prioritized by the benefit/cost ratio. This ensures that the maximum benefit is gained for each dollar spent (Gordon et al 2011).

C.2.5 Network Level Analysis

The methods presented in the preceding sections for defining alternatives, combining multiple objectives, and benefit/cost analysis, all contribute to horizontal communication across the agency. They translate the specialized concerns of geology and engineering into a more generic language of system performance and economics, which can be understood across a wider range of disciplines. Pavement and bridge management systems have similar tools which convert their specialized concerns into the same generic framework (Thompson and Hyman 1992). This makes it possible to analyze investment alternatives across all types of assets, to evaluate the tradeoffs across asset classes and to define and evaluate corridor-level and program-level projects and strategies.

C.2.5.1 Role of Tradeoff Analysis

As shown in Figure C-7, the network level potentially considers all asset classes and encompasses business processes of priority setting, resource allocation, budgeting, and programming. The linkage among all the different asset classes is achieved through a generic list of investment candidates, which is analyzed, mapped, sorted, and prioritized using the tools of information technology. Resource constraints determine which investment candidates can be selected. Forecast outcomes from the selected projects are then aggregated into an estimate of network level performance, and the costs of the selected projects are summarized into resource allocations. Managerial decision making and stakeholder consultation then

determine a final program tailored to maximize system wide performance while meeting equity and policy goals.

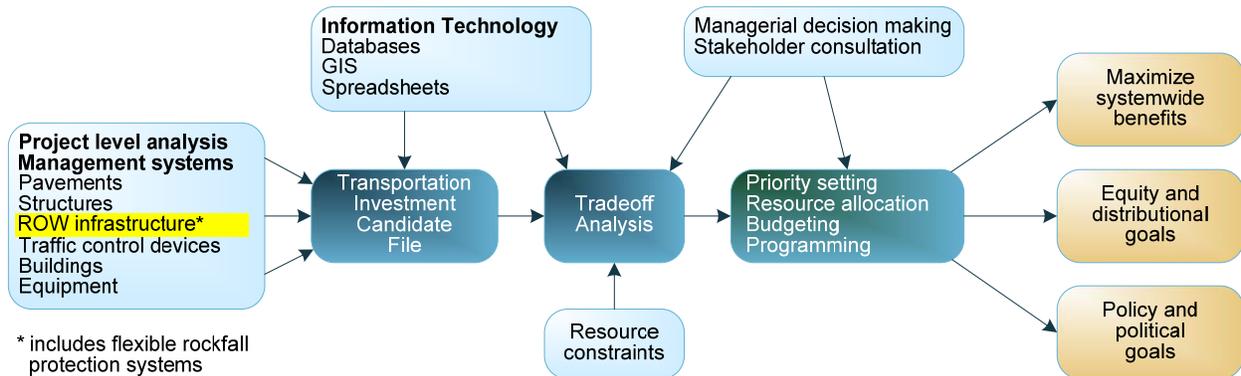


Figure C-7. Network level analysis (adapted from Gordon et al 2011)

While the methods described here are able to boil asset management decisions down into dollars and cents, policy makers often have preferences that are not economic in nature, or may differ in how they value the various aspects of performance. They may want to give extra weight to safety, for example, or may want to emphasize certain corridors for economic development. If the costs and benefits of projects are expressed in a uniform way, analysts can change the relative weights they assign to different types of benefits, which in turn may change the benefit/cost prioritization of projects. Allocating more money to one part of a program takes that money away from other parts. It is valuable to be able to see how such decisions affect overall performance of all parts of the network.

C.2.5.2 Investment Candidate File

The investment candidate file is the key ingredient that ties together the management systems for pavements, bridges, geotechnical assets, and all other asset classes. It presents a common geographic and performance framework for recognizing the inter-relationships among asset classes, for prioritizing dissimilar investments in a consistent manner, and for supporting a programming and budgeting process which fully considers geotechnical needs. The file can form the direct basis of the agency’s transportation asset management plan by serving as the source of tables and graphs supporting the life cycle management plan, development of performance targets, and description of investment strategies.

Figure C-8 summarizes the contents of the investment candidate file. Usually all of the data in the file are compiled from other systems such as management systems, asset inventories, and geographic information systems. The records in the file are projects or other programmable activities which affect asset performance and cost in a measurable way. The file should include any projects that are proposed for funding within the agency’s multi-year programming horizon, usually 10 years. Many of the projects may be tentative, based on forecasts of future conditions rather than current conditions. Where applicable, reasonable project alternatives should be included.

The system for tradeoff analysis associated with the investment candidate file should be capable of over-programming, so it can estimate performance outcomes under hypothetical budgets and costs that are higher or lower than expected.

Type of information	Data items	Description	Purpose
Identification	Project or work order ID Responsibility (organization or unit) Means of execution (contract, in-house, etc.) Desired/planned year Planning/delivery/workflow status	Identifiers here would feed into project tracking or enterprise resource planning systems where applicable.	Uniquely identify projects. Interface with related information systems. Support project development workflow.
Assets	For each cost object: Identification Geographic location Jurisdiction Value Utilization	List the assets and/or policy concerns that are affected by the action.	Support mapping and reporting by geography and jurisdiction. Provide planned work status to asset management systems. Provide asset weighting in the computation of benefits.
Activity Drivers	For each activity driver: Performance measure or deficiency Threshold level Actual level	Includes action warrants, level of service standards, vulnerability conditions, damage, or defects. Existing or forecast.	Document the direct justification of projects.
Activities	For each activity: Classification Quantity (of output) Cost	Includes any type of activity within the scope of asset management: capital, maintenance, preservation, functional improvement, expansion, etc. Also includes engineering, mobilization, traffic control.	Describe the work to be performed and build up the cost estimate.
Resources	For each resource: Classification Quantity (of input) Cost	Includes labor, materials, equipment, or contract pay items.	Interface with resource management to forecast staffing, stockpiles, and other resource needs.
Forecast Outcomes	For each performance measure: Forecast change in performance Scaled change in performance Effect of advancement or delay	Includes measures of condition, life cycle cost, user cost, mobility, safety, reliability, comfort/convenience, externalities, risk, etc.	Forecast the performance resulting from the work, and compare with performance targets. Support performance based management.
Project Inter-Relationships	Projects that must be completed first Projects that can't be programmed together Projects that must be programmed together Projects that are mutually exclusive	Constraints on the scheduling and funding of work.	Ensure that traffic control plans are valid, that projects are compatible, and costs are fully recognized.
Evaluation	Total and incremental cost Total and incremental benefit Total and incremental benefit/cost ratio	Priority setting and budgeting criteria.	Set priorities, manage funding limitations.

Figure C-8. Contents of the investment candidate file (Gordon et al 2011)

C.3 Integrating Rockfall Fence Systems into the TAM Plan and STIP

Transportation asset management plans (TAM Plans) have long been a valuable communication and implementation tool in numerous countries, especially New Zealand, Australia, and the United Kingdom. They were introduced to the United States in the 2011 AASHTO Guide for Transportation Asset Management (Gordon et al 2011), and became mandatory under federal law in 2012 with enactment of the Moving Ahead for Progress in the 21st Century Act (MAP-21).

On 20 February 2015, FHWA published a Notice of Proposed Rule-Making (NPRM) to present its proposed regulations regarding the TAM Plan requirements (FHWA 2015b). The NPRM specifies that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and requires (Section 515.009(f)):

An asset management plan shall establish and discuss a set of investment strategies leading to a program of projects that would

- (1) Achieve and sustain a desired state of good repair over the life cycle of the assets,*
- (2) Improve or preserve the condition of the assets and the performance of the NHS relating to physical assets,*
- (3) Make progress toward achievement of the State targets for asset condition and performance of the NHS in accordance with 23 U.S.C. 150(d), and*
- (4) Support progress toward the achievement of the national goals identified in 23 U.S.C. 150(b).*

The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects. Section 515.009(h) says “A State DOT should select such projects for inclusion in the STIP to support its efforts to achieve the

goals in paragraphs (f)(1) through (4) of this section.” In the commentary for Section 515.015, the NPRM suggests possible ways of explicitly tying STIP projects to the TAM Plan, including listing the projects in the TAM Plan itself, marking within the STIP those projects which are justified by the strategies in the TAM Plan, providing a list of such projects to FHWA under separate cover, or in a narrative within the STIP.

Section 515.009(d) lists the minimum content of the TAM Plan:

1. TAM objectives, aligned with agency mission;
2. Performance measures and targets;
3. Summary of asset inventory and condition;
4. Performance gap identification;
5. Life cycle cost analysis;
6. Risk management analysis;
7. Financial plan;
8. Investment strategies.

MAP-21 requires that TAM Plans address all pavements and bridges on the National Highway System. Under 23 USC 119(e)(3), states are encouraged “to include all infrastructure assets within the right-of-way corridor”. In the NPRM, Section 515.009(c) specifies, “If a State DOT decides to include other such assets on the NHS in its asset management plan, or to include assets on other public roads, the State DOT shall evaluate and manage those assets consistent with the provisions of this part.” This means that any such assets must satisfy the same requirements as are spelled out for pavements and bridges, including the linkage to the STIP and the minimum TAM Plan contents.

MAP-21 specifies that the TAM Plan shall be risk-based. The most prominent implication of this requirement is spelled out in the NPRM, Section 515.007(a)(3):

A State DOT shall establish a process for developing a risk management plan. This process shall, at a minimum, produce the following information:

(i) Identification of risks that can affect the NHS condition and effectiveness as they relate to the safe and efficient movement of people and goods, including risks associated with current and future environmental conditions, such as extreme weather events, climate change, seismic activity, and risks related to recurring damage and costs as identified through the evaluation carried out under § 515.019;

(ii) An assessment of the identified risks to assets and the highway system included in the plan in terms of the likelihood of their occurrence and their impact and consequence if they do occur;

(iii) An evaluation and prioritization of the identified risks;

(iv) A mitigation plan for addressing the top priority risks;

(v) An approach for monitoring the top priority risks; and

(vi) A summary of the evaluations carried out under § 515.019 that discusses, as a minimum, the results relating to the State’s existing pavements and bridges on the NHS, and any other pavement or bridge included in the asset management plan at the option of the State DOT.

This language makes reference to Section 515.019, which addresses facilities which are repeatedly damaged by natural disasters and catastrophic failures. But it makes clear that it is not limited to extreme events, but is intended to include all risks to safe and efficient movement of people and goods. The processes, data, and tools discussed in this Appendix for best-practice asset management clearly address the risk management planning requirements of Section 515.007(a)(3) as they pertain to geotechnical assets.

C.3.1 Why Include Geotechnical Assets in the TAM Plan?

The National Highway Performance Program (NHPP) was established in MAP-21 as the primary federal means of paying for infrastructure replacement and preservation. Funding can be used for “a

project or part of a program of projects supporting progress toward the achievement of national performance goals for improving infrastructure condition, safety, mobility, or freight movement on the National Highway System” (23 USC 119(d)(1)(A)). Inclusion of geotechnical assets within the Transportation Asset Management Plan ties the construction and preservation of these assets to the national goals and ensures the eligible use of these funds under 23 USC 119(d)(2)(A), “Construction, reconstruction, resurfacing, restoration, rehabilitation, preservation, or operational improvement of segments of the National Highway System.”

In addition, 23 USC 119(d)(2)(K) allows the use of NHPP funds for “Development and implementation of a State asset management plan for the National Highway System in accordance with this section, including data collection, maintenance, and integration and the cost associated with obtaining, updating, and licensing software and equipment required for risk-based asset management and performance-based management.”

It is clear from the MAP-21 legislation and subsequent NPRM that the TAM Plan is intended to become a strategic document that guides and justifies a large portion of the projects that make up the STIP. Geotechnical assets may play a prominent role in the required risk management analysis in Section 515.007(a)(3).

This Appendix has shown that rockfall fence systems, and geotechnical assets in general, can be managed using the same conventions as pavements and bridges, using simple and widely-accepted tools, provided that the agency makes a necessary investment in creating an inventory and keeping the condition assessment up-to-date. MAP-21 allows federal funds to be used in making this investment. By providing an objective, data-driven justification for the funding and selection of geotechnical investments, and by including these investments in the STIP process, incorporation of geotechnical assets within the TAM Plan gives this asset class a seat at the table in preservation strategy, funding allocation, and investment programming decisions.

C.3.2 Objectives, Performance Measures, and Targets

MAP-21 lists seven national goals in 23 USC 150(b): safety, infrastructure condition, congestion reduction, system reliability, freight movement and economic vitality, environmental sustainability, and reduced project delivery delays. Most state DOTs have mission statements, strategic plans, state laws, or administrative codes which specify a similar list of goals. The TAM Plan should specify the objectives that it is designed to serve, which should include the federal, state, and agency-specific goals.

MAP-21 and subsequent rule-making (FHWA 2015a) provided specifications for condition-related objectives, but left it to the states to describe within the TAM Plan how other national goals are to be satisfied under the proposed 23 CFR 515.009(f)(4). One way to do this is to monetize the objectives as social costs using standard methods such as the AASHTO Red Book (AASHTO 2010), and then use social costs in computing project benefits and benefit/cost ratios as described earlier in this Appendix. This type of analysis is already built into most pavement and bridge management systems, and is also used in the preparation of federal reports of performance and investment requirements at the national level (FHWA 2013). The methods are simple, consistent, widely understood, and can be relied upon to support progress toward the analyzed objectives as long as sufficient funding is available.

For geotechnical assets, condition or its close cousin, resilience, provide a basic consistent measure that is compatible with the percent Good and percent Poor measures required for pavement and bridge management. The effect of rockfall fence systems and other geotechnical assets on the remaining national goals is by means of the risk of service disruption. The likelihood and consequence of disruption can be analyzed as described earlier in this Appendix, making it possible to monetize these objectives as a part of project benefits, in the same way as is commonly done for pavements and bridges.

Using resilience-based condition states as described here, agencies can establish levels of service, perform periodic assessments of needs, track performance over time, map the locations of poor

performance, and establish targets for desired network performance. These constitute the basic tools necessary for performance management.

If geotechnical assets are included in the TAM Plan, its first edition should include aspirational targets for resilience, based on agency policy or judgment. In subsequent editions the Plan can rely on the targets developed in the previous edition's investment analysis, as described below.

C.3.3 Inventory, Condition, and Gap Identification

A complete assessment of geotechnical assets in most states would include rock slopes, soil slopes, retaining walls, and possibly embankments. All states are already required to include culverts of at least 20 feet in span in their TAM Plans, and some states are including smaller culverts as well. Culvert condition and embankment resilience are often closely linked. Rockfall fence systems may be considered as a separate asset class, or might be an element of the rock slope asset class. This would affect how the inventory and condition are communicated, but would not necessarily affect the analysis process or results.

The TAM Plan should describe the geotechnical or rockfall fence system inventory by type and quantity and summarize current conditions and/or resilience. Eventually, after more than one cycle of inspections are completed, the Plan can show condition trends in a manner similar to the bridge condition graph in Figure C-3 above. Current conditions must be compared with pre-existing targets to identify performance gaps and assess the level of progress toward resilience goals.

C.3.4 Life Cycle Cost and Risk Analysis

The TAM Plan should describe how the agency intervenes in the life cycle of each asset to prolong its life and minimize costs in the long term. It should describe how its life cycle cost analysis relates to the national goals, if at all, and should describe the practices it uses in order to minimize life cycle costs.

If rockfall fence system assets are analyzed as described in this Appendix, risk management is an integral part of the life cycle cost analysis, and risk mitigation is an integral part of asset preservation. The TAM Plan should describe how the agency has implemented this capability, and how it affects decision making. For compliance with the NPRM emphasis on national goals, the TAM Plan should describe how rock slope and rockfall fence system preservation and risk mitigation projects contribute to network safety, reliability, environmental sustainability, and cost minimization.

The risk management plan should discuss the potential for extreme events such as earthquakes, hurricanes, and floods, and may include estimates of the likelihood of such events within the quantitative risk analysis. In some cases it may be appropriate to include geotechnical assets within the assessment of facilities repeatedly damaged by natural disasters and catastrophic failures under proposed 23 CFR 505.019.

One way of showing the cost minimization benefits of a strong preservation function is to compare the typical life cycle conditions under current practices, under ideal practices, and under a system where no preservation work is done. Figure C-9 shows an example from one-state's TAM Plan (not yet published) which is based on the agency's typical bridge deterioration rates and treatments. The green line in the graph shows how the typical bridge replacement cycle is extended by the use of a preservation policy. This same analysis can also quantify the return on investment of preservation and risk mitigation work.

The TAM Plan should discuss the strengths and weaknesses of current geotechnical asset management capabilities, as the document offers an opportunity to build a case for further development. If the agency does not yet have a fully mature preservation or risk mitigation capability for rock slopes and rockfall fence systems, the TAM Plan should describe the agency's plans to make improvements. Even a mature capability is subject to periodic evaluation and continuous improvement (Gordon et al 2011).

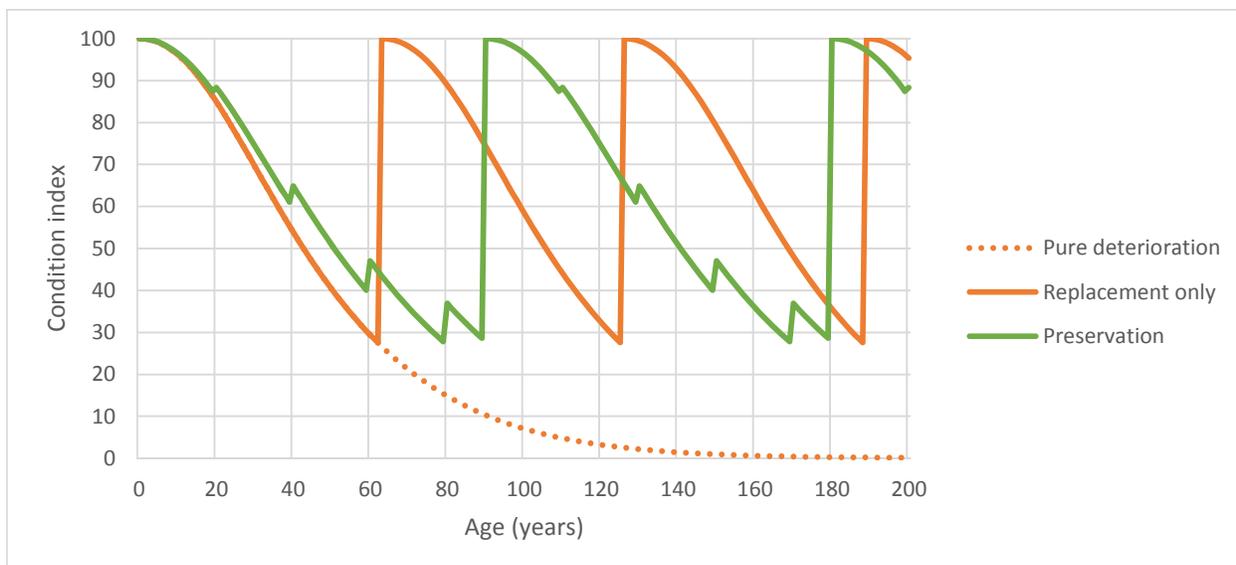


Figure C-9. Example graph of life cycle bridge conditions

C.3.5 Financial Plan and Investment Strategies

Agency commitments related to capacity, system performance, and work output depend on scenarios of funding availability. Most state DOTs rely heavily on federal funding for capital investment and on state funding for maintenance. Both funding sources may be uncertain and may be subject to annual political decision making or economic uncertainties. Many agencies have viewed the predictability of funding, especially at the state level, to be a strategic priority and have taken steps to work with policy makers to improve fiscal stability, such as by implementing more diversified revenue sources.

These same concerns apply within the agency with regard to geotechnical assets. A desired outcome of geotechnical asset management is the establishment of more predictable and sustainable funding allocation policies, which may serve to allocate risk more uniformly across all asset classes, to ensure that geotechnical assets are preserved to minimize life cycle cost, to enable long-range investments in improved agency capabilities, and to encourage improved contractor capabilities.

The TAM Plan should include estimates of expected funding, in total and for each asset class. Capital and maintenance funding should be included from all sources. Since uncertainty always exists, a set or range of reasonable alternative fiscal scenarios should be prepared. The analytical process described earlier in this Appendix can be used to estimate the 10-year performance to be expected from each fiscal scenario. Policy makers would use this information in order to determine a reasonable and equitable allocation of funding to rockfall fence systems and other asset classes.

If a continuous range of fiscal scenarios is developed, the analysis can produce a graph of funding vs performance. Figure C-10 shows an example, from a state which is in the process of developing its TAM Plan for rock slopes. The percent Good and Poor on the vertical axis can be interpreted as the maximum and minimum values of a condition target that is reasonably achievable at each possible funding level. This is the recommended procedure for establishing fiscally-constrained condition targets.

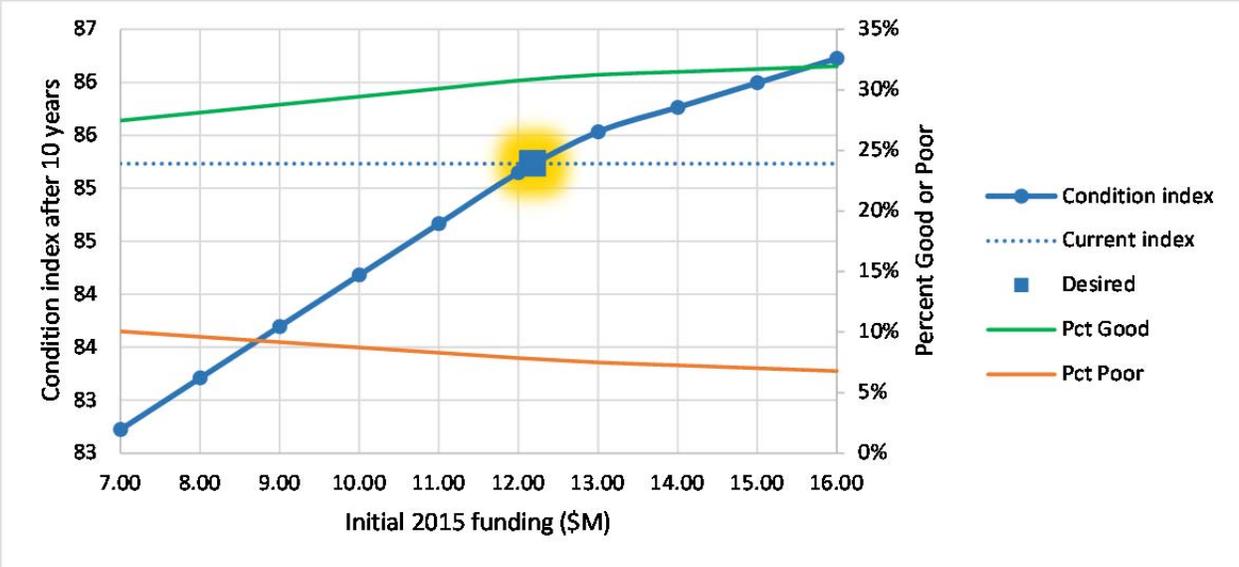


Figure C-10. Example graph of funding vs performance

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