Rockfall Hazard Process Assessment
State of Montana, Project No. 15-3059V

Task 1 Report
Literature Search and Information Technology Review
ROCKFALL HAZARD PROCESS ASSESSMENT

TASK 1 REPORT

STATE OF THE PRACTICE
LITERATURE SEARCH AND
INFORMATION TECHNOLOGY

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Prepared by:

Landslide Technology
10250 SW Greenburg Road, Suite 111
Portland, OR 97223

In partnership with:

Paul D. Thompson
17035 NE 28th Place
Bellevue, WA 98008

DA Stanley Consulting
1109 Woodstock Way #201B
Bellingham, WA 98226

Geographic Communication Systems
115 South 4th Street West
Missoula, MT 59801
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Executive Summary

This document is the deliverable for Task 1 of the Montana Department of Transportation (MDT) research project “Rockfall Hazard Rating Process Assessment” (Project No. 15-3059V). The purpose of the review is to provide a synthesis of current knowledge and state of the practice of existing and newly developing systems for rockfall hazard management and their application in transportation asset management programs. MDT’s objective for the project is to obtain an evaluation of the existing rockfall hazard rating process and recommend updates as necessary for a more effective asset management system for their rock slopes. The updates are intended to be used as a planning device to provide guidance to MDT on selection and advancement of rockfall mitigation projects. This guidance is developed for use by MDT geotechnical staff as decision support tools to advance appropriate projects to the design and construction phases, either on a District or Statewide level.

The previous rockfall management project implemented the nationally and internationally utilized Rockfall Hazard Rating System (RHRS), with only minor adjustments to the climate categories. Implementing the RHRS consisted of visiting 2,653 rockfall sites; and performing detailed ratings, where 13 criteria are evaluated, at 869 of those sites. Of these detailed rating sites, a cutoff score of 350 points (of a total possible score of 1,100 points) was established to define highest-hazard, or ‘A’-rated sites. This resulted in a total of 368 A-rated sites on the evaluated MDT highway system (Figure 1).

Based on this literature review, the most widely used rockfall ranking and management systems in North America are variations or modifications of the Rockfall Hazard Rating System, developed in 1993 (FHWA Publication No. FHWA SA-93-057). Other similar hazards rating systems, such as those for landslides, use a similar exponential scoring system as found in the RHRS (Liang, 2007). The DOTs of New York, Ohio, Utah, Washington, Alaska, Tennessee, and Missouri are all examples of agencies that along with MDT have utilized RHRS-based systems for ranking and evaluating rock slopes. In a 2008...
survey (TRB, 2012), 25 U.S. State or Canadian Provincial transportation agencies utilize a management system to track rock slope data and most of these (88%) are based on the RHRS. Most of these agencies have made modifications to the RHRS to meet departmental goals and objectives, such as Montana’s relatively minor modification for climatic criteria.

There have been two primary modifications of the RHRS in recent years. The first comes from the province of Ontario, Canada. In their Ontario Rockfall Hazard Rating System (RHRON), the rating categories are subdivided and grouped into four Factors to approximate 1) magnitude, 2) instability, 3) reach, and 4) consequences. Each of these categories are evaluated on a 0 (good) to 9 (bad) scale. This system uses categories from the RHRS and adds additional lab testing or estimations to further assess certain rock characteristics. Concepts in the RHRON system may be applicable to MDT’s goals of identifying slopes with possible rockfall concerns in the short-term future and assist with ways to prioritize those sites.

The second set of modifications are the result of ongoing research into developing concepts of geotechnical asset management (GAM) by the Alaska Department of Transportation. The purpose of this research project is to develop a comprehensive plan to manage geotechnical assets, focused on rock slopes, unstable soil slopes and embankments, retaining walls, and material sources. The research includes development of a GAM Plan, inventorying assets, developing rating systems, conducting field ratings, developing condition states, deterioration curves, programmatic cost estimations, and modelling funding scenarios on maintaining these assets. The nearly completed project will be a comprehensive asset management program for geotechnical assets compatible with Alaska’s Transportation Asset Management (TAM) plan. This project has demonstrated how to adjust RHRS-like inventory and rating programs into TAM-compatible systems based on condition states, which can be utilized for deterioration modeling and life cycle cost analyses to support efficient and cost-effective management.

The advent of readily available and inexpensive GPS-capable mobile computing platforms in the past five years has made inventory, mapping, and analysis more accessible to geotechnical personnel and planners. Utilizing these platforms would modernize the IT interface and make the use of the data less challenging and more intuitive, therefore increasing its use at more technical and managerial levels within MDT.

Major developments in the field of laser scanning and photogrammetry have occurred or become more widespread in the last 10 years. The use of aerial and ground-based laser scanning have made landform interpretation and monitoring much more accessible and accurate. Advancements in photogrammetry now make it possible to remotely measure rock joint orientations for engineering analysis, zoom in with greater detail for visual inspections, and generation of detailed surface models for change detection and volume calculations for quantitative analysis of rockfall activity.

The maturation of rockfall hazard management programs through alignment with asset management systems has been partially driven by the 2012 Moving Ahead for Progress in the 21st Century Act (MAP-21) and partially by increasing agency awareness of advances in management and technology. Through these advances, the process to inventory and assess slope condition and risks will be much improved. A modernized rockfall management system should meet the goals of MTD’s developing asset management program and improve safety, mobility and efficiency for the road system. The MAP-21 law requires a streamlined and performance-based and risk-based transportation program for bridges and pavements but also encourages similar management practices for other types of transportation assets. The goals of this current project align with both the objectives of federal mandates and with MDT’s goals and objectives.
1 Introduction

As transportation agencies modernize their infrastructure data collection and usage, they increasingly look for ways to improve the integration of data and analysis into routine decision making. This effort is intended to maximize the value of the data, to clarify what data items are needed and for what purpose, to establish expectations for quality and timeliness, and in the end, to help agencies make well-informed decisions. Transportation Asset Management (TAM) is the framework commonly used by state Departments of Transportation (DOTs) for these initiatives.

The Task 1 Report provides a background synthesis of existing and newly developing systems of rockfall hazard assessment, field data collection techniques, and a literature review of TAM and its application to rock slopes. Using rockfall data in an asset management program is a new concept, and therefore relies to some extent on studies that are underway and not yet published, as well as literature focused on asset classes other than rock slopes. Development of new concepts in this area is advancing rapidly, pushed by federal initiatives, increased concern about changed site conditions related to climate, and a growing realization that cost-effective management based on performance and risk management is needed to meet agency goals and objectives such as safety, mobility and efficiency. Agencies realize they must do more with less given the increasing intensity of road network usage and lower funding levels for added capacity, network redundancy and preservation of current service levels and asset condition.

In looking to the TAM literature for guidance, several important questions should be addressed:

- In what ways do rock slopes affect the performance of the transportation network?
- What properties of rock slopes change over time, causing changes in road network performance?
- What information is necessary, and can be gathered economically, to sufficiently understand and manage these effects?
- What actions can the agency take, with regard to a given rock slope, to maximize adjacent roadway performance and minimize cost over the long term?
- How can rock slope investments compete for limited funding in the same increasingly rigorous processes now being adopted for pavements and bridges?
- What is the right total level of investment in rock slopes to maximize road network performance, given fiscal constraints?
- How can stakeholders gain understanding and confidence in allocating money for the preservation and improvement of rock slopes?

For all classes of transportation assets, these questions have always been seen as highly relevant, but may have been dismissed as unanswerable except by professional judgment. Today, however, transportation agencies have the capability — in fact, are required by law — to give quantitative answers based on quality data, at least for pavements and bridges.

A major lesson learned from pavement and bridge management, and one now being learned for geotechnical assets, is that these questions are not as intractable as they may have appeared. This literature review will describe how the problem has been organized and attacked from several disciplines to construct the necessary standards, processes, and tools, which are now being applied to the management of rock slopes.
2 Rock slope inventories

One of the most established examples of a geotechnical asset inventory was developed for retaining walls in National Parks (DeMarco et al. 2010, Anderson et al. 2008). The Wall Inventory Program described in this manual addresses the full range of program design considerations, including inventory data fields, inspection interval, training, and field procedures. It has substantial sections devoted to the classification and qualification of geotechnical features. For example, consider Figure 2, depicting a structure consisting of placed stone on a constructed slope, with a face angle of 50 degrees. Is this a retaining wall? An embankment? A protected slope? Does it belong in the inventory at all?

Figure 2: Geotechnical feature with ambiguous classification

The criteria for making this determination could consider any of the following:

- Does the feature impact transportation system performance, such as by presenting a failure or rockfall risk? Does a slope have to be unstable in order to be included? “Unstable” by what criteria?
- Is the feature man-made (as contrasted with naturally-occurring slopes in the vicinity of a road)?
- Is the feature wholly or partially on agency-owned or publicly-owned land?
- Is the feature historic, monumental, or culturally significant?
- Does the feature require maintenance or programmed work to ensure transportation system performance?
- Is the feature already part of a bridge or other asset managed separately (a determination made in order to avoid counting the same feature in two different inventories)?
- Does the feature satisfy geometric criteria for inclusion in the program as a whole, or in a specific asset category? Such criteria might include maximum height of the structure above lower ground, maximum change in ground level, length of the feature or structure, face angle, distance from a transportation facility (lane line, bikeway, sidewalk, parking lot, etc.), and configuration of tiered walls.
• What structure types and materials are included? What usage is included above and below the feature? For example, are culvert headwalls, protected abutment slopes, and bridge wingwalls included (if not already in the bridge inventory)? Are river banks (protected or unprotected) included as embankments or as slopes (stable or unstable)?
• Are buried or partially-buried assets included, and what inferences, if any, should be made about buried assets which affect the inclusion or classification of geotechnical features?
• It is also necessary to determine the physical boundaries of the inventory asset. For example, a rock slope is 1000 feet long, but most of it appears to be stabilized by slope angle and vegetation. However, two 100-foot sections are chutes with rockfall in evidence. Is this two short slopes, or one long slope?
• Can a structure of uniform design and material be divided into two or more asset classes, for example part retaining wall and part protected slope? How is the transition between the two parts determined?

Slope characteristics are routinely modified by maintenance crew activities or small construction projects. It may be difficult to ensure that the asset inventory is kept up-to-date with such changes. If the geometric criteria are set too low, or if the inspection interval is too long, or if inventory inclusion criteria are affected too much by natural events or inspector judgment, this can cause significant concerns about inventory accuracy. These factors are also directly related to ongoing inspection costs.

Fortunately for MDT, these criteria were largely determined during the 2005 Rockfall Hazard Rating System program implementation. The included rock slopes were delineated as follows:

• All rock slopes that were excavated as part of road construction were included for evaluation.
• Natural outcrops within ROW were included; those outside ROW, unless judged as highly active with the ability to affect the roadway, were excluded.
• Rock slopes with no ability or history of providing rocks on the road were excluded from the database as “C” slopes, rock slopes with a low hazard were included as “B” slopes, and those with a high hazard were included as “A” slopes and received a detailed evaluation. Scores from the detailed evaluation were then used as a cutoff (350 points) between “B” and “A” slopes.
• Long slopes were subdivided by either topographic depressions within the slope (e.g. gullies), geologic characteristics (jointed hard rock versus soft rock subject to rapid differential erosion), or rock slope condition and mitigation approach (basic roadside barrier versus on slope mitigation measures).

2.1 Other inventory resources
Several survey and synthesis reports have been prepared which summarize the types of inventory and condition data gathered by transportation agencies. Few of these reports address geotechnical assets at a useful level of detail for the present study, but many have useful ideas and insights that can be adapted. These reports include the following:

• FHWA has published a guide for asset management data collection, presenting the results of a survey of the states. It provides a broad overview (but not much detail) on data collection methods and data uses related to management systems for pavements, bridges, highway safety, traffic congestion, public transportation facilities and equipment, intermodal transportation facilities and systems, and maintenance (Flintsch and Bryant 2006).
• The 2006 AASHTO Asset Management Data Collection Guide provides data dictionaries for drainage, roadside, pavement and traffic assets; guidance on data collection frequencies;
describes data collection equipment options; provides an overview of data processing, storage and analysis procedures; and discusses data integration considerations. It has a short section on slopes which focuses on slope dimensions and erosion (Task Force 45, 2006).

- NCHRP Synthesis 371 provides detail on current practices for maintenance of performance and service life information for signals, lighting, signs, pavement markings, culverts and sidewalks. It is based on a survey of 35 transportation agencies as well as an extensive literature review (Markow 2007).
- NCHRP Synthesis 301 presents a methodology for collecting Global Positioning System data and integrating it into geographic information systems (Czerniak 2002).
- A 2005 FHWA report on Roadway Safety Hardware Asset Management Systems presents case studies of road feature inventories. This report includes detailed information on inventory and condition assessment methods and frequencies for selected agencies, as well as the results of a broader survey (Hensing and Rowshan 2005).
- NCHRP Synthesis 367 focuses on the management of crash data, and also includes a review of methods and technologies for collecting roadway inventory data (Ogle 2007).
- Minnesota DOT has a compendium of useful resources for management of retaining walls (CTC 2013).
- North Carolina’s Asset Management Inventory process includes a treatment of embankments, slopes, and earth retaining walls (Kim et al 2009).
- The National Bridge Inventory Coding Guide (FHWA 1995) provides detailed requirements for collection and submittal of required bridge inventory and condition data items.

2.2 Other agency RHRS rockfall inventories

As part of project planning and scoping in the Alaska program, the University of Alaska at Fairbanks reviewed nine rockfall programs (Huang & Darrow, 2009). This study found these programs drew heavily on the Rockfall Hazard Rating System (RHRS) assessment categories developed in the late 1980s, but they often expanded on, altered, or replaced the initial RHRS evaluation categories to cover unstable soil slopes or to meet specific geographic or department needs, as was done in Montana. In general, the surveyed inventory programs utilized a two-stage implementation, with preliminary ratings followed by more detailed evaluations. The unstable slopes management systems surveyed and evaluated in the Phase 1 study included:

- Oregon DOT-I, 1985; an RHRS system developed to assess rock slopes across the state.
- Oregon DOT-II, 2001; a new rating system applicable to rock slopes, landslides, and debris flows, unlike the rock slope-specific 1985 program.
- Ohio DOT, 2007; a Geologic Hazards Management System (GHMS) designed to manage landslides across the state, as well as potential hazards posed by abandoned mines, karst, and shoreline erosion.
- New York DOT, 1988 and 1993; a Federal Highways Administration (FHWA) – based system for evaluating rockfall sites across the state.
- Utah DOT, 2001; a multi-phase rockfall rating system, with the rockfall hazard inventory in Phase I followed by rockfall hazard rating for select sites in Phase II. Applied Oregon DOT-I in Phase I and drew from Oregon DOT-I, Oregon DOT-II, and New York DOT to develop suitable parameters in Phase II.
- Washington DOT, 1993; a matrix-based rating system designed to rate rock slopes, landslides, erosion, and settlement.
- Tennessee DOT, 2000; a two-phase rockfall hazard rating system, using the standard RHRS in Phase I, and a detailed RHRS rating system slightly altered to meet state-specific needs.
- Missouri DOT, 2004; a two-phase rating system which organized parameters into “risk of failure” and “consequence of failure” categories, instead of the “hazard” and “risk” categories used by other DOTs.
- British Columbia Ministry of Transportation, 2000; adopted the RHRS system developed in Oregon DOT-I, but converted units to metric and Transportation of Canada (TAC) standards.

A study was undertaken in 2008 to ascertain the current state of the practice in the use of rock slope management systems within the United States and Canada. They survey result in responses in from 50 agencies (8 Canadian, 42 US). Forty-two of these respondents indicated that rockfall issues pose some level of safety concern or maintenance burden, with 36% indicating high hazards, 40% medium hazards, and 24% low hazards. Of these, approximately half of those indicating high or medium rockfall hazards exist undertake a systematic rock slope rating or ranking process, including Montana. This survey indicates that Montana is among the leading agencies in North America systematically assessing their rock slopes.

2.3 Recently Developed System - RHRON

The primary development in approach to evaluating and inventorying rockfall sites in the past 10 years, besides their integration into TAM plans, has been the development of a rockfall hazard rating system by the Canadian province of Ontario, called RHRON (Ontario Rockfall Hazard Rating System) (Franklin et al, 2013). This system, loosely based on the Oregon DOT-I RHRS, was developed to determine four primary factors, rated good (numeric score of 0) to bad (9):

F1 – Magnitude “How much rock might come down?”
F2 – Instability “How soon is it likely to come down?”
F3 – Reach “What are the chances of rock reaching the roadway and how much of it will be blocked?”
F4 – Consequence “How severe will be the consequences?”

Following a preliminary evaluation focused largely on the angle from the edge of pavement to the highest potentially unstable rock (termed Crest angle), those meeting “Class A” criteria (Figure 3) are the subject to a detailed rating evaluation. This crest angle evaluation effectively quantifies the relationship between slope height, slope angle, and ditch width, but neglects to account for flatter slopes resulting in additional horizontal velocity or for launch features reducing ditch effectiveness.

Figure 3: RHRON Classification Scheme.
The detailed evaluation evaluates 20 different criteria that include those found in MDT’s RHRS as well as additional categories that evaluate rock strength criteria and judgement-based estimates of the largest potential rockfall volume and a total of potential rockfall volume. Various combinations of these categories are then combined to determine the F1 through F4 criteria outlined above. A flow chart of RHRON criteria is shown in Figure 4.

The criteria that may be of the most interest to MDT is the approach to F1, Magnitude and F3, Reach. Factor 1 offers an approach to estimating the quantity of material subject to failure while components of F3 evaluates the likelihood of the material reaching the roadway. These factors may be extracted from MDT’s existing RHRS with some definition modification. Coupled with possible Functional Classification cutoff, traffic volume thresholds, life-cycle cost analyses, and risk models, a variety of prioritization approaches could be formulated.

2.4 Recently Developed System – AKDOT Unstable Slope Management Program
The Alaska Department of Transportation and Public Facilities (AKDOT) has undertaken extensive research in the development and implementation of the nation’s first-ever comprehensive Geotechnical Asset Management (GAM) system that is compatible with TAM systems and approaches for assessment of condition, risk, programmatic cost estimations, deterioration, and life cycle cost estimation for rock slopes, unstable soil slopes and embankments, and retaining walls. For condition assessment, the condition of rock slopes has been evaluated based on two primary criteria; rockfall activity and ditch effectiveness. Other RHRS factors, such as geologic characteristic, height, decision sight distance, etc. are measured and recorded to generate an RHRS-like exponential score, but only select few conditions are used to evaluate condition.

Ditch effectiveness, as a measurement of slope condition, is the ability of the roadside ditch, including any improvements and slope defects, to restrict rockfall from entering the roadway. This includes both improvements to the ditch and slope and also defects in the ditch or on the slope, such as launch features and full ditches, which increase the ability for rocks to reach the roadway. Geologic characteristics that affect the rockfall activity, such as high differential erosion rates or continuously oriented adverse jointing, that are evaluated in other categories are accounted for in the activity category. This is also similar to the RHRON Crest angle evaluation criteria, but also accounts for irregularities, defects, and improvements that may be in place.

The evaluation of both criteria are compared to descriptions contained in the RHRS and are combined to form a Condition Index (0-100, failed to new condition), Condition States (1-5), and Good/Fair/Poor groupings. These scoring criteria are not exponential like the RHRS and also are reversed for indication of good (high numbers) to poor (low numbers), but are consistent with standard approaches to slope degradation modelling and other TAM criterial. However, these can all be calculated from the exponential scoring criteria and definitions utilized in the RHRS. As discussed earlier, this approach permits for the utilization of expert judgement in the field to evaluate ditch effectiveness in light of existing launch features, narrow ditches, and the improvements from rockfall mitigation measures such as draped mesh, attenuator fences, and concrete barriers. Improvements to reduce the rockfall activity, such as rock bolts, cable lashing, and pinned mesh, will improve the rockfall activity scores and result in condition improvements from decreased activity levels.
Figure 4: Flowchart for individual components of the four RHRON factors.
Table 1: Rock Slope Condition States from AKDOT (2015).

<table>
<thead>
<tr>
<th>Condition State, Condition Index and Action Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Good (80-100) No action needed</td>
<td>Rock slope produces little to no rockfall and no history of rock reaching the road. Little to no maintenance needs to be performed due to rockfall activity. Mitigation measures, if present, are in new or like new condition.</td>
</tr>
<tr>
<td>2 – Fair (60-79.99) Review status at 5-year intervals</td>
<td>Rock slope produces occasional rockfall with a rock rarely reaching the road. Some maintenance needs to be performed due to rockfall activity to maintain safety. Mitigation measures, if present, are in generally good condition, with only surficial rust or minor apparent damage.</td>
</tr>
<tr>
<td>3 – Fair (40-59.99) Inspect at bi-annual intervals. Consider mitigation efforts.</td>
<td>Rock slope produces many rockfalls with a rock occasionally reaching the road. Maintenance is required bi-annually or annually to maintain safety. Mitigation measures, if present, appear to have more significant corrosion or damaged minor elements. Preventative maintenance or replacement of minor mitigation components is warranted.</td>
</tr>
<tr>
<td>4 – Poor (20-39.99) Inspect annually. Perform major rehab and repair efforts.</td>
<td>Rock slope produces constant rockfall with rocks frequently reaching the road. Maintenance is required annually or more often to maintain ditch. Mitigation measures, if present, are generally ineffective due to significant damage to major components or deep apparent corrosion.</td>
</tr>
<tr>
<td>5 – Poor (0-19.99) Perform major mitigation or reconstruction efforts</td>
<td>Rock slope produces constant rockfall and nearly all rockfall reaches the road. Virtually no rockfall catchment exists. Maintenance is cleaning rock off the site regularly, possibly daily during poor weather. If present, nearly all mitigation measures are ineffectual either due to deferred maintenance, significant damage, or deep corrosion.</td>
</tr>
</tbody>
</table>

The AKDOT GAM program is utilizing the State’s ArcGIS online accounts for the presentation and distribution of rating data and exhibition of poor asset condition (Figure 5). Eventually, MDT’s RHRS could be based on a similar platform, as discussed below. If additional geotechnical assets, such as landslides and retaining walls are eventually added to MDT’s Asset Management system, tabbed maps can be added to the interface.

MDT has the critical elements of rock slope condition already collected and assessed through the RHRS. Due to the variable nature and the judgement involved with assessing rockfall potential, hazard, and activity, the larger variety of elements to evaluate as illustrated in the bridge examples above are not typically required for rock slopes.

Figure 5: AKDOT ArcGIS.com interface with all geotechnical assets available from one internet portal.
3 MDT’s existing digital rockfall inventory management system

MDT has existing IT infrastructure and an Oracle system in place for storage and review of RHRS information. This system, however, would not be considered a “modern” IT implementation and is not entirely user friendly or widely used by staff.

The system consists of an Oracle instance in MDT’s enterprise database system along with an Oracle Forms application for end users. Oracle Forms is a Java based interactive “screens” platform for application development to interface with an Oracle database. It is primarily intended as data entry or basic query/review application environment. It is not a true “Rich Application Interface” that can provide users with ease of use or design features, such as streamlined mapping and geographic queries that users have come to expect in the Google era. An example search screen for the existing application is shown on Figure 6.

![Figure 6: Search Screen from the existing Oracle application.](image)

Beyond the “old school” nature of the platform and accessibility, the current application provides only a few functional abilities: create new record, search, and view existing record(s). The application does not provide a functional ability to “update” existing records nor maintain any sort of “version history”. The end result is that the system is simply an inventory and “snapshot” of the original assessment information. The search mechanisms are also cumbersome to use. The application provides only basic lookup based on record identifiers (e.g. section number) that are not commonly known to end users. Spatial searches and other detail attribute searches are not available.
Another detraction to the system is that RHRS information cannot be displayed visually in conjunction with map features and other related media (pictures, video, reports, etc.). GIS integration is done ad-hoc, manually using commercial off-the-shelf (COTS) applications e.g. ArcGIS for Desktop by advanced analyst users. Even in this use scenario, there is no automated connectivity between the GIS features and the RHRS information.

3.1 Future Systems Recommendation

Leveraging the current RHRS information database environment, a modern information system and end user application environment can be constructed to meet staff needs for everyday information access and upkeep as well as provide dashboard-type overviews for program and business managers and potentially real-time connections with field data collection. This enhancement to the system can be achieved with a combination of existing vendor platforms e.g. ArcGIS.com, COTS sub products, and refined workflows. Custom application development of the “templates” provided by ArcGIS.com would be required to achieve some specialized functional abilities but the scope of work would be considerably less than a full scale custom application development project.

Integration with COTS field products like ArcGIS Collector would allow for off-line data use for staff working disconnected in the field and real-time data entry. Data accuracy and lineage would be improved, which in turn would provide staff with better information with respect to rockfall hazards.

Using GIS map services hosted with the State of Montana and ArcGIS.com, the following example web template application shows “click-to-access” functionality with integrated links to images and data:

![Mock-up of potential future MDT rockfall web-based GIS interface.](image)
4 Data Collection Techniques

In the past decade, there has been a number of developments in the availability and use of technological advancements in consumer mobile computing platforms and in remote sensing techniques. Advances and techniques relevant for rock slope hazard monitoring and assessment are summarized below.

4.1 Field GIS and Mobile Computing

Previously, powerful computers capable of high resolution imaging and display, retrieving data from remote servers, and capable of geolocation were very high-end products and were not generally available to the public. With the advent and mass-adoption of smart phones and portable, cellular-capable tablets, the ability to collect and store data in user-friendly, affordable devices across multiple platforms and operating systems has become more realistic and cost-effective (Figure 8).

While third party or Open Source solutions are available, the most comprehensive platform that leverages new-generation devices and operating systems is ESRI. Coupled with ArcGIS online accounts, collecting GIS data utilizing Android or Apple iOS devices are possible via ESRI’s Collector Application. This permits the mobile collection of data using affordable, easily replaceable devices and automated data backup onto remote servers either via a cellular network or offline data collection with nightly backup on a wireless network. The data is immediately available through ArcGIS.com online maps or Windows-based desktop computers with ArcMAP.

Landslide Technology has found these systems to sometimes be error-prone and have problems uploading data collected offline on a nightly basis, though these issues may have been the fault of configuration errors outside our control. With proper configuration and training, these mobile devices and applications have the promise to collect accurate field data with a high degree of confidence, ease-of-use, and reliability.

Figure 8: ESRI’s Collector Application on Android, iOS, with Windows-based ArcMAP exhibiting field data.
4.2 LiDAR and Laser Scanning

LiDAR is an acronym that stands for light detection and ranging. LiDAR has become increasingly common for landform interpretation for geological, geotechnical, habitat, biologic assessments and many other uses. Laser light pulses are emitted and return times of each pulse are recorded, permitting the delineation of vegetation (first pulse return) to those on the ground (last pulse return). Through data processing to generate a point cloud of the last pulse returns, a vegetation-free, bare earth model can be generated and mapped for detailed geomorphic surface interpretation. This technology is used from a variety of platforms.

A drawback of all laser techniques is that it is a line-of-sight method from a single point. Features not within view of the scanner cannot be measured, potentially omitting significant features from measurement. For aerial LiDAR, rock slope overhangs are undetected. For terrestrial laser scanning, features out of view or ‘around the corner’ from steep features are not seen or measured. Mobile LiDAR exhibits similar drawbacks.

4.2.1 Aerial LiDAR

This method of Aerial LiDAR Scanning (ALS) data acquisition has been the most common and useful for geotechnical and geologic professionals over the past 10 to 15 years. The bare earth models have permitted a wide variety of landform interpretation, particularly for landslide identification and delineation. A recent example of this functionality has been utilized following the Oso, Washington landslide disaster in 2014 (Figure 9) (Haugerud, R.A, 2014).

Figure 9: Landslide Interpretation following the 2014 Oso landslide.

Recently, MDT has utilized LiDAR on the D3 rockfall mitigation project on Interstate 15 between Helena and Great Falls. These detailed maps permitted detailed rockfall modeling and plans preparation. For
purposes of rockfall hazard assessment, aerial LiDAR would provide detailed surface maps that may illustrate significant features that could contribute to rockfall, such as wide tension cracks, presence of large boulders, orientations of exposed, large structural planes, etc. Smaller features and those obscured by dense vegetation are typically masked and could only be identified by a detailed ground reconnaissance. Multiple, repeat LiDAR surveys can be used for surface change detection where significant block movement between surveys may be identified by subtracting the two surfaces from one another and identifying resulting anomalies. While this has been performed for landslide detection (for example, Burns et. al., 2010), this technique for has not been used for detection for the type of rockfall common to highway rock cuts.

Due to the steep nature of most rock cuts, downward facing instruments and the resulting low point density on rock cut faces, it is doubtful that ALS would prove to have the point density required for accurate change detection for rock slope monitoring, except where the slope angle is sufficiently flat. Where this method could prove useful is change detection in rockfall containment ditches that may go uncleared for a prolonged period, such as the highly active slopes ascending to Lookout Pass on I-90. Past studies that have focused on using ALS for rock slope monitoring has been on large, mountain-scale rockslides, reinforcing that the ALS approach to small-scale rock slope movements and change detection is still tenuous on steep rock cuts (Jaboyedoff et al, 2012).

4.2.2 Terrestrial Laser Scanning

Ground-based terrestrial laser scanning (TLS) has been used to obtain highly detailed surface maps of rock cuts for monitoring on a variety of research and practical projects (Jaboyedoff et al, 2012). In this application, the laser scanning devices is set-up and georeferenced via a control survey much like a traditional theodolite. After set-up, a ‘window’ where the detailed survey is to take place is programmed into the robotic scanner and scanning begins. The subsequent point cloud is then manipulated back in the office for referencing and correction. Other analyses, such as discontinuity identification, classification, and measurement can also then take place. Multiple surveys can be compared and used for detection of movement (Figure 10).

![Figure 10: TLS surface comparisons used for deformation detection (Abellan et al., 2010).](image)

These scans have been subsequently used for detection and measurement of discontinuities using a variety of computational techniques (Jaboyedoff et al, 2012). TLS has been used in Montana on the US 2 Badrock Canyon Monitoring project near Columbia Falls between 2006 and 2011 before being discontinued. These scans (Figure 11) were used to monitor for small changes in the rock blocks on the slope at certain locations. In these instances, the change detected in the blocks were smaller than the
accuracy of the instrument and/or control survey. This project demonstrated that TLS has promise for monitoring rock cut faces, but that the technique of surface comparison rather than comparison of only specific points on the slope would be a better application of TLS techniques.

Figure 11: TLS survey on US 2 in Badrock Canyon. Numbered points indicate control point locations.

4.2.3 Mobile Laser Scanning
Similar to TLS, mobile laser scanning (MLS) utilizes a laser scanner, but instead of mounted on a tripod, it is mounted on a moving vehicle to rapidly obtain feature data visible from the roadway. This method relies on inertial GNSS/GPS referencing techniques and either real-time or post-processing for correct georeferencing of the point clouds. This technique has been used in pilot programs for unstable slope monitoring on the Parks Highway near Denali National Park, Alaska with promising early results for change detection on scree slopes (Figure 12). The Federal Highway Administration has sponsored a NCHRP report proposing guidelines for both TLS and MLS data collection on US Highways. (Olsen et al., 2013).

Like the TLS scanning techniques, MLS suffers from a degradation in point density the further the scanner is from the feature. Note that in Figure 12 the upper portions of these slopes are not well covered, so rockfall from these upper sources cannot be monitoring with this technique. Similar limited topographic data extent for geotechnical use has been observed in pilot projects for the Idaho Transportation Department. However, the use for managing short to moderate (<100 feet) height rock cut
slopes, which are generally within full view from the roadway with light vegetation, is a promising data collection tool for comparative surveys to serve as an unbiased method for rockfall activity measurement.

Figure 12: MLS scanning on the Parks Highway, Alaska with an aerial oblique photo from an alternate vantage point. Note the MLS data is limited to the approximately bottom third to half of this very tall slope.
4.3 Photogrammetric Techniques

Use of photogrammetric techniques for monitoring rock slopes and other geotechnical assets have recently been receiving additional attention for both highly detailed digital photographs and the ability for point cloud creation with the use of digital single lens reflex (DLSR) cameras and specialized software.

4.3.1 Gigapixel Photography

Digital cameras have simplified obtaining photographic records of rock slopes and other geotechnical features for long-term record keeping of condition and visual detection of changes. However, even most consumer digital cameras are within the 12 to 24 megapixel range. Having images easily enlarged on a computer screen versus using a loupe or magnifying glass on a film print offers a significant improvement. However, even with these new techniques, geologists and geotechnical engineers still find that they are often struggling to see change on the face of a rock slope. For these instances, obtaining a large number of photos and stitching them together using freely available tools offers the level of detail often sought after.

To create the panorama, the user first obtains a large number of photos (10 to 100 photos are typical depending on the distance to the feature and its size), ideally from one position. A DSLR with a moderate or long fixed focal length telephoto lens on a DLSR camera is ideal, though most cameras at a moderate zoom also produce acceptable results. Hardware to automate photograph acquisition are available, though not required. Next, the user then loads the individual files comprising the panorama into a software program\(^1\) capable of creating, editing, and uploading the composite image. The image can then be used in the future as a precondition inspection record in the event of a significant rockfall or as visual record to replace minor site visits.

An example of a 630 megapixel photo composite from a Landslide Technology project in Alaska and the detail available from a maximized zoom are below and on the internet\(^2\) is shown in (Figure 13).

4.3.2 Structural Geology Photogrammetry

The use of stereophoto pairs has long been a fundamental aspect of geologic work. The collection and use of digital stereo pairs for mapping and measuring geologic structures has recently become more accessible. The advantages of these programs (Sirovision, BlastMetrix, 3DM Analyst) are that they provide for acquisition of geological discontinuity data on slopes that are dangerous and/or difficult to access while leaving the roadway open to traffic. Other methods to collect this information require the geologist to be physically present to place a geologic compass on the discontinuity and would require either rope methods or lifts to access the slope, typically requiring full or partial road closures.

These software packages, initially formulated for the mining industry, utilize images captured by DSLRs to create three dimensional surfaces using proprietary image analysis algorithms. The surfaces are then georeferenced to either local, project, or global coordinate systems to determine distances, spacing, and orientations of critical discontinuities. These measurements can then be utilized for stereonet generation and engineering analyses. For rockfall hazard assessments, these techniques are best suited for focused study on a subset of high hazard, hard rock slopes that exhibit discontinuity-controlled (e.g. Type 1 RHRS slopes) rockfall mechanisms.

\(^1\) Image Composite Editor (http://research.microsoft.com/en-us/um/redmond/projects/ice/) with Photosynth.net (http://photosynth.net/) website (free) and Gigapan (http://www.gigapan.com/) (not free) are two options.

\(^2\) https://photosynth.net/view.aspx?cid=160416b8-0d0a-475a-ac60-4e72284c5cd8
These techniques have been used for various rockfall mitigation projects for MDT on Interstates 15 and 90 in the past two years. The data has been shown to provide accurate and useful information for rockfall hazard assessment and design purposes. Sample images from the Sirovision software package from the D3 rockfall mitigation project on I-15 near the Prickly Pear Canyon entrance at Sieben is shown in Figure 14. This is a composite of 16 photos (8 stereo pairs) taken from the opposite side of the highway. An internet video demonstrating the process and use of Sirovision on the D3 project is located at http://landslidetechnology.com/rockfall-3D-Photogrammetry.htm.
The point clouds generated can also be imported into other point cloud manipulation programs for comparisons and change analysis. This technique was used on the I-90 MP 6.5 project in 2014 to approximate change in the slope configuration before and after failed wedge excavation (Figure 15).

Figure 14: Sirovision-produced structural geology imagery. Photographic surface model above with the point cloud of the same region shown below.
Figure 15: Surface comparison before and after slope excavation at the I-90 MP 6.5 rockfall mitigation project. Blue indicates where the most excavation took place.
4.3.3 Photogrammetric Surface Generation

A relatively new methodology for rapidly collecting and assessing hazardous rock and soil slopes above highways has been the release of professional-grade photogrammetric software. These newer software packages are intended for a wider user base (survey, cultural, Hollywood visual effects, etc.), thus making software more affordable with associated online user groups also available.

Agisoft’s PhotoScan photogrammetric software has recently been used to monitor rockfall activity above rail and transportation corridors in Canada and for a pilot program for the Colorado Department of Transportation (Lato et al., 2015). This software permits the rapid creation of surface models from photos collected via aerial oblique photos or from the ground surface. Photos collected from a helicopter with its doors removed offers the most rapid data collection technique while still producing reliable and accurate results. Using this method, an entire corridor (such as I-90 near Lookout Pass) can be photographed from a helicopter in an afternoon with corresponding surface models generated and georeferenced soon thereafter. Figure 16 illustrates the surface model generated at the Parks Highway site in Alaska.

Figure 16: Parks Highway PhotoScan surface model. Blue squares indicate helicopter positions. This low density surface consists of 1.6 million points and 323,000 TIN faces.

Repeated surveys can be used to detect changes resulting from rockfall activity or mass movement. Landslide Technology recently tested the technique for AKDOT by comparing a 2011 ALS LiDAR surface to the surface model generated by PhotoScan. Following a georeferencing process in another software package (CloudCompare), the surfaces were compared with absolute differences shown in Figure 17. This comparison revealed potential landslide movement generating rockfall activity from the weak rocks present on the slope as well as more active rockfall chutes on the southern (right) edge of the slope. Note the debris accumulation indicated in ditch, signifying a concentration of rockfall activity.

These datasets illustrate a key advantage of this photogrammetric technique; the nearly normal incidence angle of the photograph to the slope face results in an even point density that stays consistent to the top of
the slope. This preserves details that would otherwise be lost from road-based survey techniques and also permits observation of overhangs that would not be seen from ALS techniques.

On a recent field visit to the US 2 Badrock Canyon site, photos were collected from the roadside and importation into PhotoScan was tested for suitability. Ninety-three (93) separate photographs were needed to create the surface model (Figure 18). A low density cloud resulted in 2.27 million points along a 450-foot section of roadway. To focus on a smaller area within the same rock cut, a smaller set of 12 photographs was used to create a high point density surface. This subset resulted in 18.35 million points over approximately a 25x40-foot area, or approximately 18,000 points per square foot in this model.
4.4 Data Collection Summary and Recommendations

The techniques and approaches summarized above illustrate recent methodology developments in field data collection and rockfall hazard assessment and management techniques. These methods were not available in 2005 and can now be utilized to better leverage available technologies. At this early stage, potential recommendations to better assess rockfall hazard include:

- Development of a mobile GIS-based data collection platform, potentially using ESRI’s Collector Application.
- Collection of gigapixel photo mosaics at the top 50 sites and/or the top 5 corridors where topographic and vegetation conditions allow.
- Pilot program in a high-hazard corridor (I-90, MP 0 to 30, for example) for collection of two data sets in fall and spring for helicopter-based photographs for monitoring and change detection.
- Collection and processing of Sirovision photogrammetry at key discontinuity-controlled rockfall sites for kinematic and stability analyses, where appropriate.
- Use of existing base-earth ALS data for terrain mapping and map generation.
- TLS or MLS scanning by in-house survey crews for change detection for short hazardous slopes.
5 Transportation 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).

For certain major asset classes such as pavements and bridges, the techniques of TAM are codified in law (23 USC 119, FHWA 2015) and in various standards documents (Thompson and Hyman 1992, GASB 1999, Cambridge et al 2002, NAMS 2006, BSI 2008, Gordon et al 2011). Mature data collection processes are in place for these asset classes, with relatively advanced models and information systems (Cambridge 2003, Hawk 2003, Sobanjo and Thompson 2011 and 2013).

5.1 Relevance of the asset management concept

It is important at the outset to explain why the concept of “asset management” is relevant to rock slopes. Transportation assets such as pavements, bridges, and slopes are not usually bought and sold in a competitive market as may be the case for real estate, buildings, equipment, financial securities, and other common assets (Stanley 2011). Additionally, rock slopes usually do not directly carry traffic in the way that pavements and bridges do. On the other hand, rock slopes are constructed for a purpose, and are expensive to build:

- Roads often must be constructed on or near very large natural slopes whose stability is essential for the road’s continued function. Often slopes are modified or protected in order to reduce the likelihood of slope failures.
- Slopes are constructed and maintained in order to flatten and straighten the road geometry, allowing for the desired road grade, width, and speed. They provide value to the public, which justifies the cost of construction.
- Slopes can deteriorate because of rock or soil types, weather effects such as erosion and ice wedging, plant and animal activity, and for other reasons. Slope deterioration can lead to rockfall and other hazards such as landslides and debris flows which may impact or block the roadway and impede traffic.
- To maintain the function of the roadway, agencies incur maintenance costs to clear rockfall deposits, repair damage caused by rockfall, and protect the public from hazards.
- As slopes age, capital preservation work becomes necessary in order to offset deterioration, reduce maintenance costs and service disruptions, and ensure a long life.

In short, rock slopes are very much like any other constructed facility in that they require periodic maintenance and reinvestment in order to maintain the function for which they were originally built. It is in this sense that the same concepts and tools that are becoming universal for pavements and bridges are also important for rock slopes.

5.2 Basis for quantifying performance and project benefits

Agencies measure their performance in a variety of ways for a variety of purposes. These can include measures of resource inputs (e.g. hours of labor, cubic yards of material, hours of equipment usage, dollars of outside services); work outputs (e.g. lane-miles paved, tons of rock removed, linear feet of ditch cleaned); productivity (e.g. tons of rock per crew member, equipment availability in percent of hours, or haul miles per day); and customer satisfaction (e.g. percent of respondents who approve) (Poister 1997, OECD 2001, Transtech 2003, Hyman 2004).
For asset management, agencies define performance in terms of outcomes (Cambridge 2006, Anderson and Rivers 2013). The specific outcomes derive from statements of the agency mission, goals, and objectives, which are then reduced to measurable quantities for various analytical and communication purposes.

At the national level, a set of goals have been defined by the Congress in 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.

Congestion reduction, system reliability, and freight movement are often considered together as “mobility.”

In Montana, the MDT Strategic Business Plan (MDT 2004) summarizes the Department’s major goals, which are resolved into policies and actions in Tranplan21, the Department’s Long-Range Transportation Plan (Cambridge 2008). Among the major goals in the Strategic Business Plan are:

- Ensure investment decisions consider policy directions, customer input, available resources, system performance, and funding levels.

- Enhance traveler mobility by providing a safe and efficient multimodal transportation system that supports Montana’s economy and is sensitive to the environment.

- Reduce fatal and injury crash rates.

- Continuously strive to improve the effectiveness and efficiency of operations and processes.

- Consistently communicate standards, guidelines, policies, and expectations throughout MDT.

A transportation asset management process structures a series of activities, data, and tools which provide a reasonable and consistent way to quantify these performance objectives, to assess how well the
objectives are being met at a given time for a single asset or an entire network; to track performance over time; to estimate the ability of specific projects to improve performance, and to compare the relative merits and priorities of investments across all asset classes in the entire inventory (Gordon et al 2011).

5.3 The federal TAM process and its applicability to rock slopes
From the preceding section it can be seen that the federal and state goals and objectives are very much in alignment for asset management purposes. Under the Moving Ahead for Progress in the 21st Century (MAP-21) Act, state DOTs are required to describe and quantify their strategies, targets, and progress in pursuing these goals by means of performance measures and the Risk-Based Transportation Asset Management Plan (TAM Plan). Although only National Highway System (NHS) pavements and bridges are required to be covered by the TAM Plan, 23 USC 119(e)(3) encourages States to include all infrastructure assets within the right-of-way corridor. Coverage of non-NHS roads is also encouraged.

In response to MAP-21, the Federal Highway Administration has drafted a set of rules for performance measurement and for Risk-Based Transportation Asset Management Plans (FHWA 2015a and 2015b). This proposed rule clarifies that the analyses mandated within the TAM Plan should be risk-based, meaning that they should account for the strategies and costs of managing risks to the performance of the transportation system, including any aspects of performance listed in 23 USC 150(b).

Rock slopes are a class of assets that affect the safety, mobility, and efficiency of Department operations and processes by means of the risk and occurrence of rockfall. MDT routinely expends scarce resources to clear fallen rocks from roads, to recover from rock-vehicle collisions, to scale loose rock before it falls, and to install and maintain mitigation measures such as catchment ditches, barriers, drapes, and fences. The ultimate purpose of these activities is to satisfy Department goals for safety, mobility, and efficiency.

With the aid of a comprehensive inventory, condition assessment, and system-wide cost estimations of rock slopes, MDT will eventually be able to perform the same types of analysis for these assets as it already does for pavements and bridges, and as required for assets included within the TAM Plan:

- It will be able to use its condition and work history data to develop forecasting models for deterioration and costs;
- It will be able to compute reasonable estimates of life cycle cost taking into account near-term and long-term forecasts of maintenance and capital costs, and to promote efficiency by minimizing these costs;
- It will be able to quantify safety and mobility impacts of rockfall using research-based methods.
- It will be able to compute the return on investment of preservation work. In asset management for pavements and bridges it is not uncommon for preservation work to have a return on investment of 50%\(^3\), which would mean that each investment of $1 will save $1.50 in life cycle costs, limited by the availability of feasible preservation projects. This return is increased to 100% or more when safety and mobility benefits are also included.
- It will be able to perform a fiscally-constrained investment analysis for the TAM Plan, satisfying all the federal requirements by incorporating funding uncertainty, and enabling the development of reasonable performance targets and expectations to fit any given funding level.

All of these are necessary conditions for the inclusion of rock slopes in the TAM Plan, according to the proposed federal rule. They all are also needed for inclusion in MDT’s Performance Programming

\(^3\) This was documented by one of the authors in TAM Plan development projects now underway in Ohio, Nevada, and Texas.
Process (P3, MDT 2012). These capabilities are all dependent on a consistent, objective assessment of rock slope condition.

By tying the enhanced rock slope rating system to the federal TAM Plan process, MDT will satisfy the immediate goals of identifying current needs, and will position itself to achieve the longer-range goals of the TAM Plan and the P3 process. Since MAP-21 and subsequent regulations are consistent with, and strengthen, the existing Montana P3 process, applying the federal process to rock slopes will give these assets a “seat at the table” in resource allocation decisions.

5.4 General TAM guidance and examples

All of the basic components of asset management have been codified in various standards documents in recent years (Figure 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).

The IIMM introduces a concept of self-assessment and gap analysis, to help agencies 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); and 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.
These same principles are widely used in the private sector, often taking the form of performance management frameworks such as the Balanced Scorecard and Six Sigma (Proctor et al 2010, Gordon et al 2011).

This way of improving the organization and technology in tandem was recognized in the software industry long ago, and resulted in the Capability Maturity Model (Paulk, 1994). The AASHTO Guide applied this to transportation asset management by defining a maturity scale and using it to group capabilities that typically are developed together and have strong interdependencies.

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, and requires the TAM Plan “to include strategies leading to a program of projects that would make progress toward achievement of the targets.”

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. 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).

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6 Performance assessment and communication
Rock slopes affect transportation system performance primarily through the risk of rockfall to users and the possibility of service disruption, 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 to the agency and to road users when they occur. As a result, asset management processes rely on the principles of risk management.

6.1 Risk assessment
There are many different kinds of risk in a transportation system (PIARC 2012b, FHWA 2012), so it is important to be clear on the types of risk that are significant to the management of rock slope assets. Specifically, the risk is the possibility that transportation service on a link of the network will be disrupted (blocked or severely impeded) by an unexpected failure, such as the fall of debris onto a roadway. By nature the hazardous event is unpredictable at any given site, and uncommon across the inventory. Yet road segments are disrupted one or more times every year by such events somewhere in the state, leading to substantial economic losses to the public, as well as injuries and property damage.

The nature of the hazards can vary, but all state DOTs have risk concerns and need risk management strategies. To support this need, AASHTO has published a Guide to Highway Vulnerability Assessment (SAIC 2002) and a series of technical guides to help implement a risk management plan (SAIC and PB 2009).

When a geotechnical asset fails, the consequence may be a local interruption of service at the failure site. Often it is more than this: failure of one link may mean failure of the entire corridor, with more widespread economic consequences. For precise analysis it is helpful to define some more specific concepts to increase understanding and provide a basis for risk-based asset management (Seville and Metcalfe 2005, Sobanjo and Thompson 2013):

- **Likelihood** of hazard. Slope failures are typically triggered by natural events, such as earthquakes, floods, ground saturation, groundwater movement, freeze/thaw, or general instability. These events are inherently uncontrollable. Another approach is to quantify the total number of failures for a given category of feature over a historical time period, then divide by the number of features in the category and number of years in the historical record (Sobanjo and Thompson 2013). Categories could be defined by geological character, water, or other characteristics for which data are available. Change in precipitation patterns may necessitate an analysis of changes in potential trigger processes over time (Mote et al 2012, Connor and Harper 2013).

- **Direct consequence** of hazard. A geotechnical hazard event is recognized if it causes damage requiring an agency response. This damage may be to the geotechnical asset itself, and may also encompass surrounding features, including a road or other transportation facility. It may also damage the property of others, or may cause personal injury. All of these consequences may be represented by costs in a risk computation. Alternatively, some risk assessment procedures use a scoring procedure (basically, a utility function) to represent the costs of a failure (Thompson et al 2012a). Agencies can often limit the consequences of a hazard event by making geotechnical assets and other nearby assets less vulnerable, or more resilient.

- **Impact** of hazard. If a hazard event occurs and causes damage to a road or other transportation facility, there may be social, environmental, and economic impacts that extend far beyond the geotechnical asset itself (Koorrey and Mitchell 2000, HDR 2010, PIARC 2000, PIARC 2012a). Traffic may be forced to take a longer route, or use a different mode of travel, for an extended period of time while the facility is repaired. Road users then incur costs for travel time, vehicle...
operating costs, and fares. Added traffic on detour routes may cause congestion on those routes, with further inconvenience. Businesses may be disrupted; some may even fail due to changes in traffic patterns. In the longer term, businesses may not want to locate in areas they perceive to be vulnerable, thus depressing economic conditions and/or property values.

Some authors group the direct consequences and the impacts together and merely call them “consequences” (SAIC 2002). However, the further separation is useful in transportation risk management because the impacts are often very substantial, and because the methods of estimating them are different from the methods used for direct consequences. Also, the agency has some amount of long-term control of consequences by means of risk mitigation or replacement actions, while impacts are largely out of the agency’s control.

A concern is sometimes expressed that gathering of risk-related data could potentially have liability consequences, in that it might increase the agency’s responsibility with regard to risk management. Of course, the purpose of gathering the data is to improve risk management, so this observation only reinforces the need to follow through to put the data to work for its intended purpose (Hillier 2012).

The components of risk are often analyzed using probabilistic models (Taylor et al 2001). One of the key assessments to be made is the probability that a slope failure will damage or block a road. This is what then drives the large economic impacts of a geotechnical asset failure (Koorkey and Mitchell 2000).

Risk is usually considered to be a quantity computed as likelihood × (direct consequences + impacts) (Seville and Metcalfe 2005). The process of estimating this risk is called risk assessment. The agency usually tries to minimize risk by hardening assets to make them more resilient. Often it is possible to reduce the likelihood of a hazard, for example by improving slope condition. Risk reduction actions may be costly, and they compete for funding with other project needs. It is necessary to prioritize and schedule these activities just like all other types of projects. This process is part of risk management.

6.2 Resilience as a measure of risk

Asset management procedures and tools are just as relevant to risk as to any other type of performance, so it is considered best practice to integrate risk management into asset management, using a measure of risk as a performance measure (Gordon et al 2011, Cambridge 2011). Since performance measures are usually quantities of desirable attributes under the agency’s control, it is becoming common for agencies to focus on asset resilience as the performance measure (Thompson et al 2012a). Risk assessment activities record data related to asset resilience, and actions are taken to increase resilience.

Resilience then is any attribute, or combination of attributes, which help an asset resist damage in the face of an internal or external hazard (FHWA 2013b). In a field risk assessment process, trained personnel make note of the resilience attributes of each asset (NYSDOT 2013). This information is used in a risk computation, which then participates in asset management decision support capabilities. When communicating with the public, the term “resilience” (rather than its inverse, vulnerability) focuses attention on the positive outcomes of actions that the agency can control, and for which it can be accountable. In general, resilience is defined as follows:

_The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events_ (Committees, 2012).

There are, in fact, a great many definitions of resilience in the literature, especially in areas associated with climate change adaptation (Hughes and Healy 2014, Levina and Tirpak 2006). One that is especially focused on engineering systems is:
... 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).

“Internal and external change” can be interpreted in the context of rock slopes 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 slope may be considered to have high resilience to the extent that it is sufficiently able to refrain from causing service disruptions due to normal deterioration or adverse events.

A risk management framework defines scenarios of undesirable service disruption events such as rocks on the roadway blocking traffic. An analysis attempts to predict the likelihood of each scenario as a probability, and the consequence of the scenario as a social cost. Resilience is the combination of asset characteristics which affect the likelihood of adverse events.

As an example, a rock slope that has good resilience has the following characteristics:

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

A slope that would otherwise be in good condition may nonetheless have characteristics (such as high steep slope, adverse jointing, extreme freeze/thaw, or proximity to the traveled way) that make catchment of large blocks difficult to ensure, that make the slope vulnerable to rockslides, or that produce debris requiring constant maintenance. When addressed with appropriate rockfall reduction and/or catchment measures, the potentially adverse characteristics can be mitigated to improve both Condition and Resilience.

For most purposes in asset management, measures of condition focus purely on processes that damage, degrade, disintegrate, or deform the materials making up the facility (FHWA 2015a, AASHTO 2013). As agencies develop streamlined processes for rock slope management, they often expand the concept of “condition” to include resilience, facilitating a more direct linkage between asset deterioration and the probability of transportation service disruption. In Alaska, for example, the following properties of a rock slope are considered in the definition of condition index and condition state:

<table>
<thead>
<tr>
<th>Material condition</th>
<th>Contributing properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raveling of rock or wall face</td>
<td>Ice and freeze/thaw</td>
</tr>
<tr>
<td>Disintegration of rock face or wall</td>
<td>Design criteria</td>
</tr>
<tr>
<td>Differential erosion</td>
<td>Geological character</td>
</tr>
<tr>
<td>Debris accumulation</td>
<td>Climate</td>
</tr>
<tr>
<td>Water infiltration and accumulation</td>
<td>Drainage and hydrology</td>
</tr>
<tr>
<td>Loss of vegetation tied to rockfall activity</td>
<td>Presence of mitigation features</td>
</tr>
<tr>
<td>Root wedging and wind jacking from trees</td>
<td>Geometry and size of slope face</td>
</tr>
</tbody>
</table>

The items in the left half of the above list are the same types of material damage, degradation, disintegration, and deformation that make up the concept of condition in pavement and bridge management. These describe processes that can deteriorate over time. The items on the right are typically
corrected, if at all, only by adding, removing, or relocating significant assets. These properties in both columns make up much of the RHRS system, variations of which are in use by approximately half of the states (Pierson 1993, Turner and Schuster 2012).

There are only a few classic preservation treatments available to a transportation agency to reverse some of the condition defects: for example, scaling of a rock slope or correction of drainage. In most cases, the most cost-effective agency response is the addition of a mitigation measure(s) or protective system, which does not necessarily correct the material defects but merely slows further deterioration or ameliorates the effect on road users. Such treatments include:

- Rock bolting
- Addition of shotcrete, fences, drapes, and barriers
- Construction of a retaining wall (where one did not previously exist)
- Embankment reconstruction and realignment of the road

In order to develop a relatively simple yet actionable assessment process, the Alaska GAM research studies have adopted a relatively simple set of composite measures which depend on, and summarize, all of the causal factors listed above, and which can be considered to directly affect the likelihood of service disruption. The primary variables that make up the assessment are:

- Ditch (or catchment) effectiveness: assesses how often falling rocks reach the roadway, combining the effects of all design, mitigation, and geometry concerns.
- Rockfall activity: assesses how active the slope is in producing falling rocks, combining the effects of all condition characteristics, geological character, climate, and hydrology

This expanded definition is believed to be usable in all of the same contexts where a pure condition state measure is used for other asset classes: ability to forecast deterioration using relatively simple models; identification of appropriate treatment alternatives; estimation of reasonable costs and effects of treatments; quantifying the likelihood of service disruption; and communicating current network performance, past trends, and future targets in the form of maps, trendlines, and other graphics.

6.3 Communicating performance

Effective performance 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). Some good examples of simple context and message in the communication of asset performance can readily be found online:

- Michigan
- Minnesota
- Oregon (Figure 21)
- Utah
- Wisconsin

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5 http://www.michigan.gov/midashboard/0,4624,7-256-59297---,00.html
7 http://www.oregon.gov/ODOT/CS/PERFORMANCE/docs/2012dashboard.swf
8 http://performance.utah.gov/agencies/udot.shtml
9 http://www.dot.wisconsin.gov/about/performance/docs/scorecard.pdf
Figure 21: Example performance dashboard from Oregon DOT
7 Decision support tools

A major goal of improved asset management is the ability to optimize decision making to maximize performance with limited funding. In order to optimize performance, decision makers need the ability to generate reasonable program alternatives, for a corridor or for the state as a whole, and evaluate their likely cost and performance outcomes. Effective asset management, like effective risk management, means taking cost-effective action before a problem becomes a crisis. It entails strategic, proactive policies and programs (Cambridge 2002). Information technology support, featuring predictive models, is necessary in order to adopt a reliable perspective about future outcomes (Keen and Scott Morton 1978).

Proactive asset management decision making addresses important questions on the minds of decision makers and stakeholders (Thompson 2013):

- If funding is cut, how much performance would be sacrificed?
- How much would it cost to keep performance from declining further?
- How much would it cost to improve performance to a desired level?
- Can we get more life out of our assets, and how best to do this?
- What policies would minimize life cycle costs?
- Is a given preventive maintenance program worth the expense, in terms of reducing life cycle costs?
- What is the best long-term preservation program for a given asset, in terms of the scope and timing of future interventions?

For geotechnical risk management it is impossible to know what geotechnical failures might happen in the future, yet it is possible and prudent to identify the weakest links in the network and find cost-effective ways to make them less vulnerable. Any reasonable, objective system for quantifying future risk is valuable for setting priorities and maximizing systemwide resilience. As the science of risk analysis advances, proactive decision making becomes more effective, and the frequency of catastrophic network failures should decline (Seville and Metcalfe 2005).

The same effect should be expected for any other aspect of transportation performance. Forecasting of performance allows resources to be focused on the assets whose performance can most efficiently be improved. The result should be a long-term improvement in systemwide performance. This approach has been clearly demonstrated in the traffic safety field, for example 10.

A Transportation Asset Management Plan (TAM Plan) is a forward-looking document that makes statements about expected future performance and describes how the Department intends to manage future performance (Lindquist and Wendt 2012). The decision support tools required for an ongoing transportation asset management process (Thompson 2013) are the same tools that are required for ongoing maintenance of the TAM Plan. Geotechnical Asset Management will ultimately be a part of TAM, so it will need to be able to feed into the Department’s Enterprise Asset Management processes, tools, and plans. The key tools are:

An investment candidate file, which identifies each potential investment and summarizes its cost, resource requirements, and effects on transportation system performance (Gordon et al 2011, Figure 22). It is most often prepared as an Excel spreadsheet file, which is simple, flexible, and entails minimal

system development costs. If the Department develops an enterprise investment candidate file covering all significant asset classes, the geotechnical version could use the same format, making it relatively simple to move geotechnical work candidates into the statewide programming process and STIP.

**Forecasting models**, especially deterioration models for rock slopes. Similar to the situation with bridges, precise deterministic forecasts are unlikely to be feasible, but probabilistic forecasts should be possible once a routine inspection process is in place (Thompson et al 2012b, Sobanjo and Thompson 2011, Flikweert et al 2009, PIARC 1997). In advance of data availability, an expert judgment elicitation process can generate models suitable for preliminary analysis (Cambridge 2003).

**Risk analysis models.** For the risk analysis, models of the likelihood of geotechnical hazards will be needed, as well as some parameters for estimating consequences and impacts (Sobanjo and Thompson 2013). In recent work underway in Alaska and Colorado, ranges of adverse event return periods have been estimated by panels of experts, with the intention of gathering data for later statistical analysis of actual event frequencies. In some agencies, typical return periods are built into the category definitions used in the rockfall hazard rating system (Turner and Schuster 2012).

It is common to employ user cost models to quantify the road user impacts of service disruptions. User cost models have been an important part of pavement and bridge management systems since the 1980s (Zaniewski et al 1985, Johnston et al 1994, Thompson et al 1999). They are also widely used in work zone design (Mallela and Sadasivam 2011, NJDOT 2001), comparison of project alternatives (Markow 2012, Mn/DOT 2013) and regulatory processes (Kragh, 1986), and are well supported by published economic data (FHWA 2013a). A standard methodology for this analysis can be found in the AASHTO Red Book (AASHTO 2010). A similar methodology has also been extended to address sustainability concerns (Litman 1996 and 2012, Matthews et al 2001).

**A process to generate project alternatives.** The Department already has capabilities to generate near-term geotechnical projects, but for proactive asset management it will need an additional capability to sketch possible future projects, based on performance forecasts, for an intermediate term, typically 10 years. The focus is on programmed preventive actions (to respond to deterioration) and risk mitigation projects (to increase asset resilience). This work entails making a list of action categories that respond to performance defects or risk mitigation opportunities. For each action, a decision rule then is needed in order to decide when the action is appropriate, using the data available (Loehr et al 2004). To a great extent this will be determined by the capabilities of Department forces and contractors. However, this may be an opportunity to start expanding local capabilities, including work order contracts for local contractors, and in the area of preventive activities (Fay et al 2012, WSDOT 2012b).

**Forecasting of project outcomes.** Models will be needed to forecast the costs and effectiveness of future geotechnical actions, in terms of the selected geotechnical performance measures. Initially these can be developed by summarizing current design practices. Eventually, inspection data and work accomplishment records should enable statistical models to be developed (Hearn et al 2010, Sobanjo and Thompson 2001). Landslide Technology has already performed this type of analysis on Montana projects in work performed for Alaska DOT (not yet published).

**Life cycle cost models.** Once the preceding tools are in place, even preliminary judgment-based models, the Department will be in a position to conduct a life cycle cost analysis (FHWA 2002, Hawk 2003, Walls and Smith 1998). This type of analysis helps to evaluate inter-temporal tradeoffs: sometimes it is better to make a small investment in prevention on a large number of assets now, rather than wait for a much larger disaster on one unpredictable site later on. Life cycle cost analysis helps to identify the most cost-effective candidates for preventive work. If performance measures and the risk analysis are converted to
dollar terms, as discussed in the previous sections, then a net present value analysis can be used as the basis for comparing alternatives. If some aspects of performance are left in a non-economic format, then utility theory can be used to accomplish the same purpose (Patidar et al 2007).

**Tradeoff analysis.** A tradeoff analysis tool in its simplest form sorts a group of investment candidates according to benefit/cost ratio, and then selects the highest-priority candidates that fit within a budget constraint. It then uses the forecasting models to estimate performance measures for the following year, where it repeats the process for the remaining candidates valid for that year. It continues with these steps year-by-year to the end of a program horizon, usually about 10 years.

Where the tradeoff comes in, is that the analyst can vary the budget constraint to see how this affects the performance outcomes. Generally more money yields better performance. The analyst can also change the weight given to different types of performance or different parts of the network, to see how increasing performance in one area causes decreases in other areas, if total funding remains the same.

There is an extensive literature on more elaborate procedures to optimize performance. One slightly more sophisticated model, the incremental benefit/cost (IBC) technique, handles multiple investment alternatives for each asset and automatically downscopes some of the alternatives when funding is tight (Shahin et al 1985). More than 20 years after the IBC method was first used in asset management, a review and benchmarking analysis in 2007 found that it still offers a practical balance of responsiveness, reliability, and optimality (Patidar et al 2007).

Several suitable tradeoff analysis tools have been developed and could be adapted for routine asset management (Cambridge et al 2005, Patidar et al 2007, Sobanjo and Thompson 2007). The tradeoff mechanism itself is simple enough that many agencies will simply develop their own tools using an Excel spreadsheet.
<table>
<thead>
<tr>
<th>Type of Information</th>
<th>Data Items</th>
<th>Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identification</strong></td>
<td>Project or work order ID</td>
<td>Unique project identifiers</td>
<td>Support project development workflow.</td>
</tr>
<tr>
<td></td>
<td>Responsibility (organization or unit)</td>
<td>Interface with related monitoring systems.</td>
<td>Support project development workflow.</td>
</tr>
<tr>
<td></td>
<td>Geographic location</td>
<td>List assets and policy concerns.</td>
<td>Support the direct justification of projects.</td>
</tr>
<tr>
<td></td>
<td>Jurisdiction</td>
<td>Describe work to be performed and build up cost estimate.</td>
<td>Document the direct justification of projects.</td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>Includes action warrants, level of service standards, damage, defects.</td>
<td>Includes action warrants, level of service standards, damage, defects.</td>
</tr>
<tr>
<td></td>
<td>Utilization</td>
<td>Includes any type of activity within the asset's functional or service scope.</td>
<td>Includes any type of activity within the asset's functional or service scope.</td>
</tr>
<tr>
<td><strong>Assets</strong></td>
<td>For each activity driver: cost object</td>
<td>Threshold level for performance measure or deficiency.</td>
<td>Includes threshold level for performance measure or deficiency.</td>
</tr>
<tr>
<td></td>
<td>Performance measure of deficiency</td>
<td>Actual level for performance measure or deficiency.</td>
<td>Includes actual level for performance measure or deficiency.</td>
</tr>
<tr>
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<td>Classification of activity.</td>
<td>Includes classification of activity.</td>
</tr>
<tr>
<td></td>
<td>Quantity (of output)</td>
<td>Cost (of output)</td>
<td>Includes cost (of output).</td>
</tr>
<tr>
<td><strong>Activities</strong></td>
<td>For each activity: cost object</td>
<td>Classification of cost object.</td>
<td>Includes classification of cost object.</td>
</tr>
<tr>
<td></td>
<td>Performance measure</td>
<td>Classification of performance measure.</td>
<td>Includes classification of performance measure.</td>
</tr>
<tr>
<td></td>
<td>Quantity (of input)</td>
<td>Cost (of input)</td>
<td>Includes cost (of input).</td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td>For each resource: contract pay item</td>
<td>Classification of contract pay item.</td>
<td>Includes classification of contract pay item.</td>
</tr>
<tr>
<td></td>
<td>Classification</td>
<td>Classification of contract pay item.</td>
<td>Includes classification of contract pay item.</td>
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<tr>
<td></td>
<td>Cost</td>
<td>Includes cost.</td>
<td>Includes cost.</td>
</tr>
<tr>
<td><strong>Forecast Outcomes</strong></td>
<td>Forecast change in performance measure</td>
<td>Effect of advancement or delay.</td>
<td>Includes effect of advancement or delay.</td>
</tr>
<tr>
<td></td>
<td>Forecast change in performance measure</td>
<td>Effect of funding.</td>
<td>Includes effect of funding.</td>
</tr>
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<td></td>
<td>Forecast change in performance measure</td>
<td>Forecast improvement.</td>
<td>Includes forecast improvement.</td>
</tr>
<tr>
<td><strong>Project Inter-Relationships</strong></td>
<td>Projects that must be completed first</td>
<td>Total and incremental benefit, total and incremental benefit/cost ratio.</td>
<td>Includes total and incremental benefit, total and incremental benefit/cost ratio.</td>
</tr>
<tr>
<td></td>
<td>Projects that can be programmed together</td>
<td>Priority setting and funding criteria.</td>
<td>Includes priority setting and funding criteria.</td>
</tr>
<tr>
<td><strong>Evaluation</strong></td>
<td>Total and incremental cost</td>
<td>Total and incremental benefit/cost ratio.</td>
<td>Includes total and incremental benefit/cost ratio.</td>
</tr>
</tbody>
</table>
8 References

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