Research & Technology Transfer

Alaska Department of Transportation & Public Facilities

Geotechnical Asset Management Plan

Technical Report

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

May 31, 2016

Prepared for:
Alaska Department of Transportation & Public Facilities
Statewide Research Office
3132 Channel Drive
Juneau, AK 99801-7898

Report STP000S(802)(A)

REPORT DOCUMENTATION PAGE

Form approved OMB No.

1. AGENCY USE ONLY (LEAVE BLANK)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
STP000S(802)	May 31, 2016	Final, 2013-2016

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Geotechnical Asset Management Plan Technical Report	Federal: STP000S(802) State: 80900
6. AUTHOR(S) Paul D. Thompson	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Paul D. Thompson 17035 NE 28th Place Bellevue, WA 98008	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) State of Alaska, Alaska Dept. of Transportation and Public Facilities Research and Technology Transfer 3132 Channel Drive Juneau, AK 99801-7898	10. SPONSORING/MONITORING AGENCY REPORT NUMBER STP000S(802)(A)

11. SUPPLENMENTARY NOTES

Research performed in cooperation with the Alaska Department of Transportation and Public Facilities and the US Department of Transportation, Federal Highway Administration.

12a. DISTRIBUTION / AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
No restrictions	

13. ABSTRACT (Maximum 200 words)

Geotechnical assets – which include rock and soil slopes, retaining walls, and material sites – support and protect the Department's pavements and bridges, and provide the material from which these assets are built. They are the front line of the Department's site-based risk management strategies, as they bear the brunt of natural hazards such as extreme weather, floods, and earthquakes. In terms of reconstruction cost they are more than three times as valuable as the Department's bridge inventory, and are a continuing focus of maintenance and preservation expenditures.

The Plan provides guidance for, and summarizes, the Department's management process for its geotechnical assets. This process ensures that the Department is continuously measuring its performance, and programming investments that are most cost-effective to improve performance. It is based on the principle that what gets measured gets done.

This Technical Report provides a detailed analysis of relevant performance objectives and measures; the inventory and current conditions of geotechnical assets; methods to compute and minimize life cycle cost; methods to manage risk; and the Department's financial plan and investment strategies for its geotechnical assets. The report provides the technical background for a continuing process to improve the Department's geotechnical risk management capability.

14- KEYWORDS :	15. NUMBER OF PAGES
Geotechnical Asset Management, GAM, Risk Management, Risk Analysis, Rock Slopes, Rockfall, Soil Slopes, Landslides, Embankments, Unstable, Debris Flows, Retaining Walls, Material Sources, Material Scarcity, Condition, Condition States, Condition Index, Resilience, Programmatic Cost Estimates, Deterioration, Life Cycle Cost Analysis	59
	16. PRICE CODE N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	N/A

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3

		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A
*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi

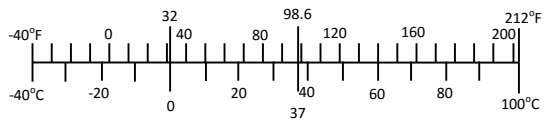

Table of contents

Foreword 6

Acknowledgements 7

1. Introduction and plan objectives 8
   1.1 How geotechnical assets affect transportation system performance 8
   1.2 Transportation Asset Management Plan 13
   1.3 Why Include Geotechnical Assets in a TAM Plan? 15
   1.4 Business process of Geotechnical Asset Management 16

2. Performance objectives and measures 19
   2.1 Alaska Administrative Code 19
   2.2 Alaska Statewide Policy Plan 20
   2.3 Federal performance goals 21
   2.4 Relating performance measures to actions 21
   2.5 Using condition as a measure of resilience 23
   2.6 Condition states and indexes 25

3. Inventory, conditions, and performance gaps 27
   3.1 Asset inventory requirements 27
   3.2 Inspection process 29
   3.3 Current status of inventory and condition 32

4. Life cycle cost 33
   4.1 Treatment selection and cost 35
   4.2 Deterioration 37
   4.3 Time value of money 39
   4.4 Computation of life cycle cost 40
   4.5 Return on investment 41

5. Risk management 43
   5.1 Likelihood of service disruption 43
   5.2 Safety consequences of service disruption 44
   5.3 Mobility consequences of service disruption 45
   5.4 Recovery costs 46
   5.5 Total project benefit 46
   5.6 Systemic risks 47

6. Financial plan and investment strategies 49

References 53

Foreword

This report is the product of Task E of the Geotechnical Asset Management Plan (GAM Plan) Development Project. It summarizes the research conducted over the course of the entire project, contributing to a formal Asset Management Plan for geotechnical assets, as well as the implementation of a geotechnical asset management process within the Alaska Department of Transportation and Public Facilities (DOT&PF).

While the report continues to follow the general outline laid out in Task B, it has benefited from many refinements of the GAM concept over the course of the study, and from the input of a great many practitioners in the field including parallel efforts in other states, especially Colorado, Washington, and Oregon, and the Federal Land Management Agencies.

A February 2015 Federal Highway Administration Notice of Proposed Rule-Making responding to 23 USC 119(e) sets out the requirement that each State Department of Transportation prepare a Transportation Asset Management Plan (TAM Plan) addressing at least pavements and bridges on the National Highway System. Because of the significance of geotechnical assets – in reconstruction value more than three times as large as the bridge inventory, and the most significant and costly aspect of the Department's risk management activities – the Department has moved to develop its GAM capability to the level where geotechnical assets can also be included in the TAM Plan.

As a result of this goal, the accompanying Task H GAM Plan Executive Summary is written at a level of detail suitable for inclusion in the State TAM Plan, either as an appendix, or as a set of sections that can be inserted into the TAM Plan outline. It is written for a relatively non-technical audience of interested stakeholders, similar to what would be anticipated for the pavement and bridge content.

Separate documents, also non-technical, have been prepared to summarize the GAM communication plan and implementation plan for Task F. The present Task E document provides the technical background for all three of the companion documents.

This study relies heavily upon two other current studies for geological data collection and geotechnical methodology development:

- The Landslide Technology GAM Methods Study developed condition state definitions and related field procedures; preservation actions and their costs and effectiveness; and deterioration models for geotechnical assets;
- The Shannon & Wilson GAM Risk Management Study developed resilience definitions and related field evaluation procedures; improvement actions with their costs and effectiveness; and a framework for risk management.

The contributions of these related works is gratefully acknowledged. Relevant results from these studies are summarized in the present report where needed.

Acknowledgements

The research reported herein was performed under Agreement 025-3-1-042 with the Alaska Department of Transportation and Public Facilities, with funding from the Federal Highway Administration of the US Department of Transportation.

Paul D. Thompson was the report author. Barry A. Benko, C.P.G. was the Alaska DOT&PF Project Manager at the time of publication. Earlier, David A. Stanley, C.E.G. initiated the project and served as its Project Manager.

Significant content summarized in this report was prepared under a companion project, Statewide Geotechnical Asset Management Program Development, whose authors were Darren L. Beckstrand, C.E.G., Barry A. Benko, C.P.G., Aine E. Mines, P.E., Lawrence A. Pierson, C.E.G., Paul D. Thompson, and Robert E. Kimmerling, P.E.

Additional information in this report was summarized from another companion project, Geotechnical Asset Risk Management, led by Mark Vessely of Shannon & Wilson Inc.

In the early stages of the project, technical assistance was received from an advisory panel composed of Dave Stanley, Barry Benko, and Steve Evans of Alaska Department of Transportation and Public Works, Scott Anderson and Khalid Mohamed of FHWA, Ty Ortiz of Colorado Department of Transportation, and Tom Badger of Washington State Department of Transportation.

The author wishes to thank all of these individuals for their generous time and thought in commenting on the various reports produced during the 3 ½ year study. Any errors remaining in the report are solely the responsibility of the author.

1. Introduction and plan objectives

Geotechnical assets – which include rock and soil slopes, embankments, retaining walls, and material sites – support and protect the Department's pavements and bridges, and provide the material from which these assets are built and maintained. They are the front line of the Department's site-based risk management strategies, as they bear the brunt of natural hazards such as extreme weather, floods, and earthquakes. In terms of reconstruction cost they are more than three times as valuable as the Department's bridge inventory, and are a continuing focus of maintenance and preservation expenditures.

1.1 How geotechnical assets affect transportation system performance

Geotechnical assets have an often "behind the scenes" role in the transportation system. The traveling public and their vehicles rarely notice or come into contact with these features unless there is a critical condition state or failure. The public may view them as natural features which never change except when Department workers modify them. Nonetheless there are reasons why the Department builds and maintains its slopes, embankments, retaining walls, and material sites.

Slopes (Exhibit 1) are modified or constructed, and maintained in order to properly align the road geometry, allowing for the necessary road grade, width, and speed. Slopes can deteriorate because of rock or soil types, weather effects such as erosion and ice wedging, plant and animal activity, and other reasons. Deterioration can lead to rockfall, landslides, and debris flows. Often slopes are modified or protected in order to reduce the likelihood of slope failures. Often the original construction of slopes did not consider the need for preservation; but as slopes age, preservation work becomes necessary in order to offset deterioration and ensure a long life.

Exhibit 1. Rock slope in fair condition, South Tongass Highway. Rocks occasionally reach the road and cause a safety hazard.

Embankments (Exhibit 2) are very much like slopes in their role of providing a stable geometry for the road. Deformation/movement of embankments may be caused by construction practices, consolidation of the subgrade or embankment materials, seasonal permafrost activity, seasonal freeze/thaw of groundwater, erosion, and loads applied by traffic. When an embankment deforms, the pavement deforms, and over time the pavement may fail or break up, thus creating a safety hazard and/or limiting mobility. The Department conducts surface preservation work to try to prevent or correct this deterioration, which improves the life of both the embankment and the pavement it supports, but there is little or no possibility of successful rehabilitation of the embankment soil or the subgrade short of complete reconstruction. Embankments are treated as a type of soil slope in the GAM analysis because of the similarities in materials, treatment options, and economics.

Exhibit 2. Soil slope in Poor condition, Tok Highway. Movement is relatively rapid, necessitating frequent maintenance to keep the road passable.

Retaining walls (Exhibit 3) are used both above and below roadways in situations where a necessary change in elevation would be too steep or unstable if unsupported, particularly where a slope failure might threaten significant impacts to the public or to environmental resources. There are many types of retaining walls, but all are constructed using man-made and natural materials that deteriorate with age, and which can be attacked by corrosive agents, water, freeze/thaw, chemical activity, and earth movement. The Department can attempt to discover this deterioration and correct it using preservation actions. When done consistently and effectively, preservation can ensure a very long life for these assets. If a retaining wall fails, often a considerable amount of material supported by the wall is involved, which can do catastrophic damage to a road or adjacent property.

Material sites (Exhibit 4) are locations where soil and/or rock can be obtained for nearby road construction or maintenance work. These materials are used to construct embankments, pavements, and drainage systems, and to repair damage to those assets. They may also be used as an ingredient in concrete for pavements, bridges, and retaining walls. Larger sizes are used as rip-rap, buttress rock, or rockery walls. State-owned or operated material sites reduce construction costs. Soil and crushed rock are heavy and bulky, therefore very expensive if they must be transported long distances. Proximity,

quality, and quantity are key properties which affect the value of these sites. Material sites deteriorate by being depleted or becoming uneconomical to operate. Each one has a limited quantity of economically usable material.

Exhibit 3. Retaining wall in Poor condition, Seward Highway. The wall is bowed outward, causing deformation of the guardrail and pavement.

Exhibit 4. Material site on the Parks Highway, a source of crushed stone for Alaska DOT&PF maintenance projects.

What these geotechnical assets all have in common is that they affect safety, mobility, and economic efficiency of the road network primarily by their failure or exhaustion. Exhibit 5 summarizes the hazards that are most likely to cause failure, and their consequences. Slopes, embankments, and retaining walls all need preservation work in order to reduce the likelihood of failure and prolong their useful lives. Properly timed preservation is often highly cost-effective because these assets are very expensive to reconstruct, and the impacts related to failure can be considerable.

Exhibit 5. Examples of hazards that can cause failure of geotechnical assets

Hazard	Effect on assets	Impact on transportation system
Severe deterioration	• Reduced strength of retaining walls and embankments • Increased likelihood of rockfall, slope failure, or embankment settlement	• Travel delay due to uneven or impassable road surface • Safety impact of rocks in roadway (Exhibit 6) or rough road surface • Increased maintenance and claims costs
Rockfall and landslides	• Consumption or damage to protective systems • Slope failure	• Travel delay due to road blockage • Safety impacts of debris on road • Recovery and claims costs
Earthquakes	• Partial or complete collapse of slopes and walls • Ground displacement	• Travel delay due to road surface collapse or debris in roadway • Safety impact of falling rock or debris in roadway • Recovery and claims costs
Floods, extreme rainfall events, tsunamis	• Washout of roadway embankment, debris flows	• Travel delay or excess user cost due to impassible road (Exhibit 7) • Recovery and claims costs
Freeze/thaw events	• Unstable permafrost under pavement • Detachment of rocks from slopes • Wall deformation or collapse from ice pressure	• Travel delay or safety reduction due to uneven or impassable road surface • Safety impact of debris in roadway • Increased pavement costs and claims
Unknown material quality or quantity	• Projects unable to obtain needed material at expected distance, quantity, and/or quality	• Increased project costs and claims

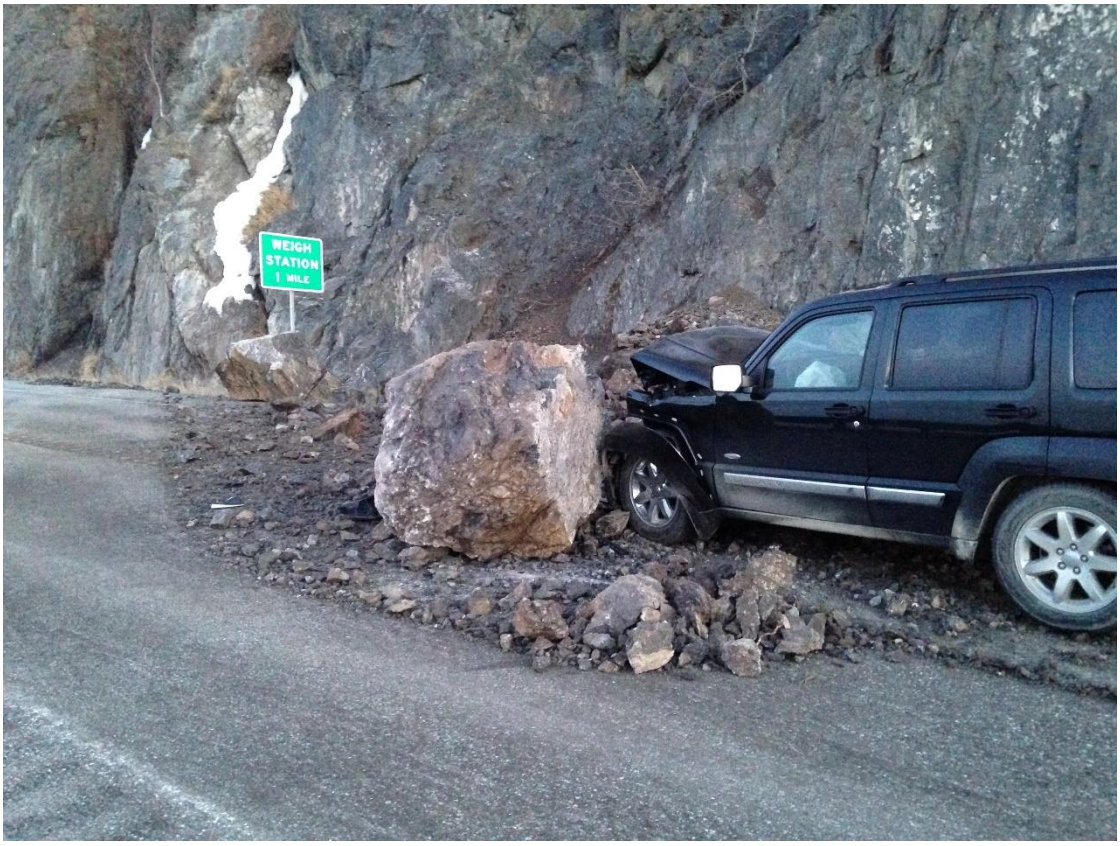

Exhibit 6. February 2015 rock slope failure on the Seward Highway

Exhibit 7. April 2015 washout of the Dalton Highway

1.2 Transportation Asset Management Plan

The Department is in the process of developing a Transportation Asset Management Plan (TAM Plan) to provide guidance over a ten-year timeframe on the development of preservation and replacement projects and programs for pavements and bridges. This is partly in response to the requirements of the federal Moving Ahead for Progress in the 21st Century Act (MAP-21), and partly an internal effort to make better use of data and engineering economic methods to improve the productivity of Department investments: to do more with less.

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

At the time of this writing, several state DOTs are gaining experience in the development of these Transportation Asset Management Plans. Nearly all of these states are including assets other than pavements and bridges, and many are including assets that are not on the National Highway System. For example, Georgia has released a draft plan which includes highway signs; Minnesota is including certain drainage culverts, stormwater tunnels, sign structures, and high-mast light poles; Ohio is including culverts; Nevada, New York, Texas, Louisiana, and Alabama also are developing plans with a broader scope than NHS pavements and bridges, some of them covering all roads on the state highway network. These agencies have found that the structure of a TAM Plan can readily accommodate these additional asset categories.

All of the basic components of asset management and TAM Plans have been codified in various standards documents in recent years (Exhibit 8). 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). AASHTO has built on this concept in great practical detail with the AASHTO Transportation Asset Management Guide, Volume 2: A Focus on Implementation (Gordon et al 2011).

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.

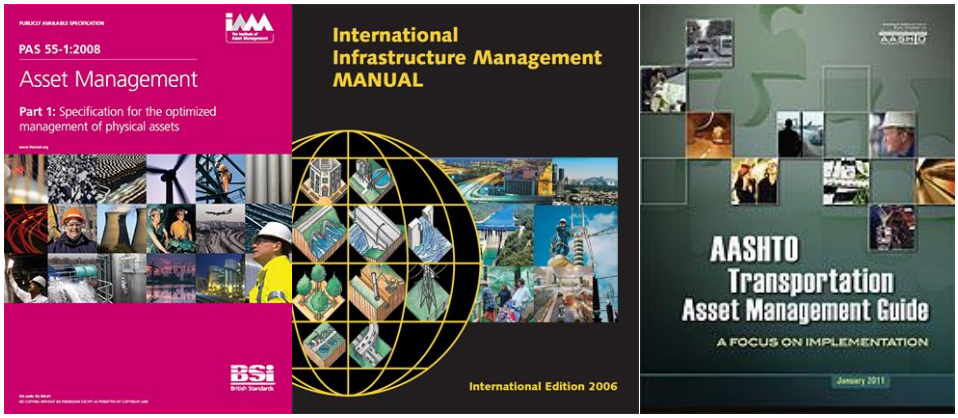

Exhibit 8. International asset management standards

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).

On 20 February 2015, FHWA published a Notice of Proposed Rule-Making (NPRM) to present its proposed regulations regarding the TAM Plan requirements (FHWA 2015b). The NPRM specifies in Section 515.009(f) that the TAM Plan shall cover at least a 10-year period, shall be made easily accessible to the public, and shall establish a set of investment strategies that improve or preserve condition and performance in support of the national goals in 23 USC 150(b).

The regulation explicitly links the TAM Plan to the Statewide Transportation Improvement Program (STIP), which is the primary vehicle for programming of transportation projects. Section 515.009(h) says "A State DOT should select such projects for inclusion in the STIP to support its efforts to achieve the goals" of the TAM Plan. In the commentary for Section 515.015, the NPRM suggests possible ways of explicitly tying STIP projects to the TAM Plan, including listing the projects in the TAM Plan itself, marking within the STIP those projects which are justified by the strategies in the TAM Plan, providing a list of such projects to FHWA under separate cover, or in a narrative within the STIP.

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

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

MAP-21 specifies that the TAM Plan shall be risk-based. The NPRM, Section 515.007(a)(3) elaborates that the TAM Plan must establish a process to identify the hazards affecting the movement of people and goods, assess the likelihood and consequences of adverse events, and evaluate and prioritize mitigation actions. Section 505.007(a)(2) specifies that the life cycle cost analysis is a quantitative

network-level analysis that considers current and desired condition levels, asset deterioration, effects of adverse events, and treatment options over the whole life of assets.

1.3 Why Include Geotechnical Assets in a TAM Plan?

The National Highway Performance Program (NHPP) was established in MAP-21 as the primary federal means of paying for infrastructure replacement and preservation. Funding can be used for "a project or part of a program of projects supporting progress toward the achievement of national performance goals for improving infrastructure condition, safety, mobility, or freight movement on the National Highway System" (23 USC 119(d)(1)(A)). Inclusion of geotechnical assets within the Transportation Asset Management Plan ties the construction and preservation of these assets to the national goals and ensures the eligible use of these funds under 23 USC 119(d)(2)(A), "Construction, reconstruction, resurfacing, restoration, rehabilitation, preservation, or operational improvement of segments of the National Highway System."

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

It is clear from the MAP-21 legislation and subsequent NPRM that the TAM Plan is intended to become a strategic document that guides and justifies a large portion of the STIP. By providing an objective, data-driven justification for the funding and selection of geotechnical investments, and by including these investments in the STIP process, incorporation of geotechnical assets within the TAM Plan gives this asset class a seat at the table in preservation strategy, funding allocation, and investment programming decisions (Stanley 2011).

The purpose of a GAM Plan is very similar to a TAM Plan. Therefore it would promote the eventual usefulness and understandability of the GAM Plan if it is written to be consistent with the requirements of a TAM Plan. It is also important that the GAM Plan satisfy a set of Department objectives which may or may not be the same as the federal MAP-21 objectives. From the Alaska perspective the GAM Plan objectives can be described as follows:

For stakeholders and customers (the public perspective):

- Define the types of geotechnical assets and explain how they contribute to cost-effective, safe, and reliable transportation service.
- Describe why preservation and risk mitigation are necessary for geotechnical assets, because of foreseeable impacts on mobility, safety, condition, and other performance concerns.
- Explain how the Department recognizes problems and measures success.
- Show the Department's 10-year objectives and the progress it is making toward them.
- Show that the public's investment is being used as efficiently as possible to achieve success.
- Be consistent and credible in how the Department grades itself.

For agency decision-makers (the technical perspective):

- Develop and apply a consistent, objective basis for selecting actions.

- Estimate costs and 10-year needs using available data.
- Invest at the right times to keep assets in service for as long as possible.
- Prioritize for long-term success (as explained to stakeholders).
- Determine 10-year network performance targets that are feasible with expected funding.
- Allocate limited funding toward the greatest reduction in risk and life cycle cost.

For both stakeholders and decision-makers:

- Improve the reliability of cost and performance forecasts.
- Provide a migration path so future research can improve the measures without re-defining them.
- Be compatible with pavement and bridge asset management, to facilitate long-term implementation.

The GAM Plan will be useful for multiple audiences. For outside stakeholders, the general public, and senior leaders the Executive Summary of the GAM Plan will communicate performance and decisions in a meaningful but non-technical manner. For professionals within the Department, the GAM Plan Technical Report will provide the necessary support for performance targets, budgets, and capital programs, showing how these investments relate to the Department's mission, goals, and objectives. For geotechnical and maintenance personnel, the GAM Plan provides the rationale and methods to guide routine decision-making regarding geotechnical assets, in pursuit of better transportation system performance. It also identifies additional or modified data collection practices to support the plan.

1.4 Business process of Geotechnical Asset Management

For long-term viability, it is important for the GAM Plan to be backed by business processes that can keep the plan up-to-date, and that can ensure that the objectives of the plan are accomplished. The Department already has a guidance document on TAM processes in general (Thompson 2013, Exhibit 9), covering:

- Legislation, codes and policies
- Organization and culture
- Asset inventories
- Inspection and monitoring
- Performance assessment
- Decision support capabilities

This document anticipates the subsequent federal TAM Plan requirements and contains a Work Plan for process implementation.

Alaska DOT&PF is a leader in applying these concepts to geotechnical assets, but precedents do exist in other agencies. For example, the Central Federal Lands Division of FHWA gave these issues 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 tool for managing transportation system risk, with the corridor as the unit of risk analysis (Verhoeven and Flintsch 2011, Anderson and Rivers 2013). 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).

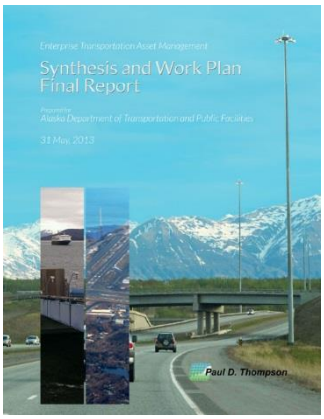

Exhibit 9. Alaska DOT&PF Enterprise Asset Management: Synthesis and Work Plan 2013 report

The Department's GAM process, described in Exhibit 10, ensures that the Department is continuously measuring its performance, and programming investments that are most cost-effective to improve performance. It is based on the principle that what gets measured gets done. Key features include:

- A clear relationship between GAM decisions and agency objectives. Performance measures are designed to provide an indication of how well each asset and project satisfies agency goals and policies (Stanley and Pierson 2011).
- Maintenance of an asset inventory listing all of the significant rock slopes, unstable soil slopes, retaining walls, and material sites.
- Periodic inspection of assets to update the inventory and performance measures. This information serves as the basis for project identification. Forecasting models estimate future changes in performance and future needs, providing an opportunity for the Department to anticipate and avoid or delay future costs.
- Consideration of program alternatives, to account for uncertainty in funding, costs, conditions, and hazards. Performance measures are used in the calculation of benefit/cost ratios to optimize performance under each scenario.
- Development of short-range and long-range plans, programs, and targets, culminating in updates to this GAM Plan and projects in the STIP.

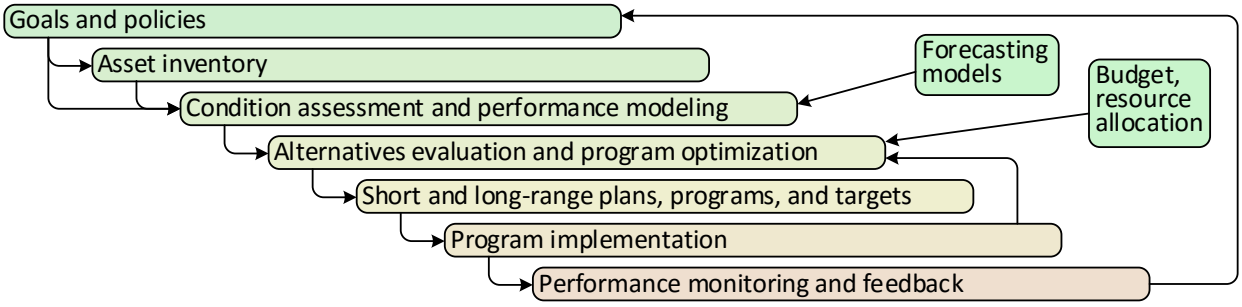

Exhibit 10. Geotechnical Asset Management (GAM) process

- As these optimized investments are delivered, their effectiveness is measured, to ensure that Department objectives are achieved and to further improve the forecasting and delivery capability.

In this way, the Department engages in a process of continuous improvement, using its ability to measure performance in order to identify ways of improving. All of the ingredients in the process work together to help the Department keep its long-term costs low and manage risk.

2. Performance objectives and measures

In the Alaska Statutes, AS 44.42.020 ("Powers and Duties" of the DOT&PF) sets out the responsibility to maintain transportation facilities in sub-section (a)(1) (also mentioned in AS 19.05.030); the duty to study existing facilities and to evaluate economic costs and environmental and social effects in (a)(2) and (3); the responsibility for facility program plans in (a)(10); and the emphasis on studying alternatives, which appears in several sections especially (a)(3) and (15).

AS 37.07.014 calls for "Results-Oriented Government." It describes a performance management framework that pre-dates MAP-21 but sounds much the same. Subsection (f) requires DOT&PF to:

- Allocate resources to achieve its mission and desired results.
- Express desired results in measurable terms (as performance targets).
- Ensure progress toward performance targets.
- Promote activities consistent with desired results that reduce future costs.
- Plan for the short and long term using consistent assumptions.
- Require accountability for results at all levels.

Although the term "asset management" is not used, this statute encompasses all of the key components of the business process discussed in Chapter 1. The requirement of accountability means that the Department is required to set measurable performance targets for the future, to communicate these objectives clearly to stakeholders, and attempt to achieve the targets (Cambridge et al 2010, TransTech 2003). AS 37.07.040 directs the state Office of Management and Budget to

> *(10) establish and administer a state agency program performance management system involving planning, performance budgeting, performance measurement, and program evaluation; the office shall ensure that information generated under this system is useful for managing and improving the efficiency and effectiveness of agency operations.*

This statute is the basis for the Department's Key Performance Indicators. No distinction is made in the statutes among geotechnical assets, pavements, and bridges.

2.1 Alaska Administrative Code

The Alaska Statutes do not specify the performance objectives or targets mandated in AS 37.07.014, leaving it to future action by the Legislature. However, the Alaska Administrative Code in 17 AAC 05.125 does provide a specific list of performance concerns:

> *(a) In the statewide transportation planning process, the department will consider goals and objectives that will further*
>
> > *(1) the economic vitality of the state;*
> >
> > *(2) the safety and security of users of the state's transportation system;*
> >
> > *(3) accessibility and mobility options available to people and for freight;*
> >
> > *(4) the integration and connectivity of various modes of the state's transportation system;*
> >
> > *(5) the preservation of existing transportation systems; and*

(6) any metropolitan area plan developed under 23 U.S.C. 134 and 49 U.S.C. 5303-5306.

(b) When formulating its goals and objectives in the statewide transportation plan, and the strategies to implement those goals and objectives, the department will consider the concerns of interested persons and minimize any adverse environmental, economic, or social impact of those goals and objectives upon any segment of the population.

2.2 Alaska Statewide Policy Plan

Several policies in Alaska's Statewide Policy Plan (Alaska DOT&PF 2008) relate to basic functions of transportation asset management, and, in most cases, do not distinguish geotechnical assets from any other infrastructure assets.

Policy 3: Apply the best management practices to preserve the existing transportation system.

Policy 4: Increase understanding of and communicate ADOT&PF's responsibilities for system preservation as the owner of highways, airports, harbors, and vessels.

Policy 5: Ensure the efficient management and operation of the transportation system.

Additional policies refer to specific aspects of performance to be managed, including cost-effectiveness, mobility (encompassing travel time, access, and reliability), safety, security (encompassing facility risk and emergency preparedness), energy efficiency, economic development, and other positive social attributes (environmental, social, economic, human health, local community concerns, and quality of life). Policy 14 is the most specific about decision support for asset management:

Policy 14: The statewide plan will provide the analytical framework from which ADOT&PF sets investment priorities.

- *We will monitor, forecast, and report transportation system performance through data-driven management systems.*
- *We will provide information for performance-based planning and budgeting.*
- *We will promote and work to improve coordination between public transportation and human services transportation.*
- *We will use best practice techniques and technology for involving the public in the transportation planning process.*

As the Statewide Policy Plan proceeds to describe strategies and actions, it sets a very positive direction for asset management while also demonstrating the limits of the Department's current capabilities. In strategy 1, the need is expressed for a system perspective:

Because our transportation system is a network of different modes of transportation, and within modes different facilities, we can make better use of funds by starting from a system-level perspective. This is especially important in a fiscally constrained environment because this level of analysis enables consideration of how best to provide the infrastructure to meet the state's diverse travel demands.

Action 1.1 starts to express one of the key institutional needs, in order for asset management to take root in the Department:

> *The plan distinguishes between routine maintenance, life cycle management, and system development. Going forward we will use planning analysis to support this decision making.*

With improved decision support tools, the Department should be able to quantify an optimal level of preservation and life cycle funding, sensitive to performance objectives. This information would enable decision makers to drive funding based on desired level of service, without appealing to historical funding levels that may no longer be relevant. Some of the early steps to accomplish this, are called for in the Statewide Policy Plan:

> *Action 2.2. Establish a core set of performance measures to monitor performance against plan goals.*
>
> *Action 2.6. Establish a level of service based approach to maintenance and operations planning and budgeting.*

The Statewide Policy Plan is currently under revision. The new version may contain additional content focused on transportation asset management.

2.3 Federal performance goals

MAP-21 specifies national performance goals that are much the same as those specified in the Alaska Administrative Code, as follows (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.*

2.4 Relating performance measures to actions

Many aspects of performance are beyond an agency's control, so it is important to focus performance measures on aspects of the agency objectives which can be influenced by Department actions. As a part of maximizing these system objectives, each asset makes its contribution by satisfying various criteria for its level of service:

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

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

Geotechnical assets affect transportation system performance primarily through the possibility of adverse events which cause service disruption, thereby decreasing network safety, mobility, and/or sustainability, and increasing life cycle costs. Disruptions to service are typically uncommon and unexpected, but costly when they occur. As a result, geotechnical asset performance is typically managed using the principles of risk management.

Through its maintenance forces and contractors, a transportation agency implements treatments that maintain or enhance the characteristics of its geotechnical assets which minimize the frequency of disruptions. These characteristics make up a property called resilience (Committees 2012, Hughes 2014). For geotechnical assets, resilience can be defined as follows:

> *… the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must* (Allenby and Fink 2005).
>
> *'Vulnerability' seems largely to imply an inability to cope and 'resilience' seems to broadly imply an ability to cope. They may be viewed as two ends of a spectrum (Levina and Tirpak 2006).*

"Internal and external change" can be interpreted in the context of geotechnical assets as changes caused within the asset itself (i.e. normal deterioration) and change caused by external forces (natural extreme events, such as floods and earthquakes). "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 geotechnical asset may be considered to have high resilience to the extent that it is sufficiently able to refrain from service disruptions caused by normal deterioration or by adverse events.

As an example of the application of resilience, a rock slope with "Good" resilience is performing in a manner completely consistent with new slopes that are constructed today, generally with no measurable movement and nearly all rockfall effectively separated from the traveled way. A slope with "Poor" resilience may have frequent incidents of rockfall in the roadway, or may be judged by a qualified inspector to be especially vulnerable to earthquakes. A rock slope that has Good resilience has the following characteristics:

- Is in good condition (minimal deterioration relative to a newly cut slope);
- Has appropriate catchment ditch and/or mitigation features;
- Lacks characteristics of geology and geometry that are associated with catchment ineffectiveness or slope collapse during expected (but uncommon) seismic or weather events.

A slope that is in good condition may nonetheless have characteristics (such as high steep slope, adverse discontinuities, extreme freeze/thaw, or proximity to the traveled way) that make catchment of large blocks difficult to ensure, that make the slope vulnerable to collapse, or that produce debris flows requiring constant maintenance. While slope condition can generally be improved through preservation activities (for example scaling, drainage work, or ditch cleaning), other factors influencing resilience generally require more expensive activities such as the addition of mitigation structures (fences, barriers), removal of a part of the slope, or relocation of the road.

2.5 Using condition as a measure of resilience

It is desired that the field assessment of geotechnical assets be an efficient way to gather the most essential information about the factors affecting the likelihood and consequence of disruption. Examples of the factors making up resilience, affecting the likelihood of disruption, include:

Material condition	Contributing properties
Raveling of rock or wall face	Ice and freeze/thaw
Disintegration of rock face or wall	Design criteria
Differential erosion	Geological character
Debris accumulation	Climate
Deformation of wall or soil slope	Drainage and hydrology
Water infiltration and accumulation	Presence of mitigation features
Loss of vegetation	Geometry and size of slope face or wall
Permafrost degradation	Permafrost quality
	Wall foundation

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 or components.

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 repairs or rehabilitation of a retaining wall (Fay et al 2012). In most cases, the most cost-effective agency response is the addition of a mitigation feature 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:

Improving wall drainage
Soil nailing or rock bolting
Addition of shotcrete, fences, drapes, and barriers
Construction of a retaining wall (where one did not previously exist)
Embankment reconstruction
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. They incorporate many of the same factors that many states use in their rockfall

hazard rating systems (Pack et al 2006, Turner and Schuster 2012), but in a form that is adapted to the needs of asset management. The primary variables that make up the assessment are:

Rock slopes	• 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.
Soil slopes	• Roadway displacement or slide deposit: assesses the direct effect on the roadway surface of earth movement, combining the effects of all relevant condition characteristics and mitigation features. • Length of affected roadway and roadway impedance: assesses the geometry of the site. • Movement history: assesses the combined effect of geological character, climate, hydrology, and permafrost.
Retaining walls	• Vertical and horizontal wall alignment: assesses one aspect of condition (deformation), combining the effects of drainage, geometry, and foundation. • Impacts to the roadway: assesses the effect of physical condition of the roadway as it relates to wall condition. • Critical component health: assess all aspects of wall condition other than deformation.
Material sites	• Proximity, quality, and quantity of materials for each maintenance station.

These factors are combined into a determination which is called the “GAM condition state.” While this is somewhat broader than the traditional definition of the term “condition,” it serves GAM purposes well:

- It is believed to be more efficient, and just as useful at this stage of development, to have just one set of service levels representing both condition and resilience, rather than assessing the two concerns separately.
- Material condition in the strict sense — damage, degradation, disintegration, or deformation of materials — is the primary factor causing changes in the condition state over time, but is not readily improved by the treatments most often available to the department. This differs from the situation with pavements and bridges.
- Conditions expressed in this way are believed to deteriorate over time in a manner that can be described and predicted by relatively simple probabilistic models. Such models can be validated and improved over time as historical data sets are accumulated.
- Agency treatment alternatives for preservation, risk mitigation, and reconstruction can improve the assets in a predictable way.
- The costs of these treatments can be predicted and together with routine maintenance, over time, comprise life cycle agency costs in the same manner as for bridges and pavements.

- The assessment of these condition states provides a reasonable basis for quantifying the likelihood of service disruption for risk analysis.

The decision to continue to call them condition states reflects the fact that condition is one of the most important concerns addressed, and that their use and interpretation in asset management is intended to be the same as bridge and pavement condition states.

2.6 Condition states and indexes

Alaska DOT&PF research on condition inspection of geotechnical assets has found that trained inspectors can readily distinguish five condition states in the field, and that this level of detail is useful for selection of appropriate actions, forecasting of deterioration, and estimation of costs. Chapter 3 provides an example of detailed definitions of the condition states.

Federal performance management regulations (FHWA 2015a) have specified that the tracking and target-setting for pavement and bridge condition required under MAP-21 must be expressed in three categories – good, fair, and poor. This is useful for purposes such as characterizing large groups of assets (as percent good or percent poor) and for plotting conditions on a color-coded map (Exhibit 11).

In order to serve all asset management purposes well, field inspections rate each asset in one of five possible condition states, which are then grouped into three categories for communication and target-setting. The three categories are as follows:

Good: Identified defects, if any, are minor and do not require corrective action. Asset performance and life cycle cost are not adversely impacted by condition.
Fair: Significant deterioration has been identified. Corrective action is feasible and would extend the service life and/or improve the performance of the asset.
Poor: Deterioration is advanced. Significant mitigation, repairs, rehabilitation, or reconstruction are needed to restore full functionality.

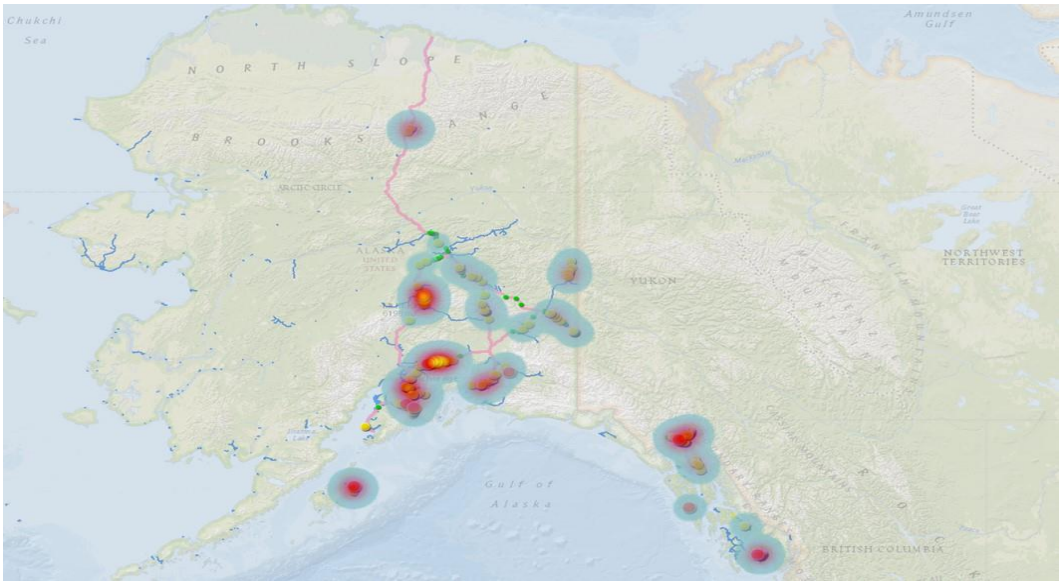

Exhibit 11. Example of color-coded map of rock slope conditions (source: Landslide Technology GAM Methods Study)

The inspection process described in the next chapter distinguishes two levels of fair and two levels of poor, so that there are five condition states in total.

There are certain purposes where condition states can be inconvenient, especially when plotting condition trends over time (Exhibit 12). This has always been an issue for pavements and bridges as well, and has led to the development of a condition index as a weighted average of condition states (Shepard and Johnson 2001, ASTM 2012).

Condition indexes assign a score of 100 to any asset in condition state 1 (Good), any group of assets where all are in Good condition, or a forecast of condition where there is a 100% probability of Good condition at some future time. At the opposite end of the spectrum, an asset in the worst condition state (state 5) receives a score of 0, as does any group or forecast where there is 100% frequency or probability of condition state 5. In between, each asset receives a score that is weighted by its size and each condition state is weighted by its frequency or probability. In the Alaska framework, the following condition state scores are used:

1 – Good	100
2 – High Fair	91
3 – Low Fair	73
4 – High Poor	19
5 – Low Poor	0

These weights were selected because they match criteria used in computing the condition states, as documented in the Landslide Technology GAM Methods Study. For rock slopes and retaining walls, size is measured in square feet. For soil slopes, size is measured in linear feet of affected roadway. For material sites, each maintenance station receives equal weight.

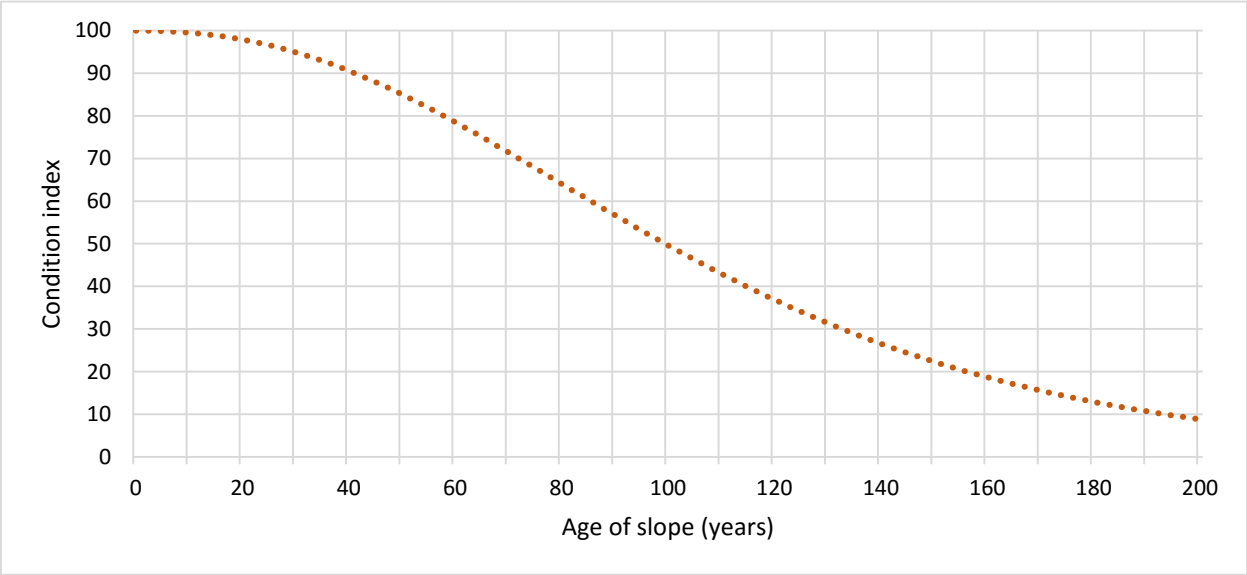

Exhibit 12. Example graph of rock slope condition over time

3. Inventory, conditions, and performance gaps

Alaska DOT&PF owns an estimated 67 million square feet of rock slopes with a nominal value of $3.9 billion, 1.3 million linear feet (measured along the road centerline) of soil slopes worth $14.4 billion, and 7.6 million square feet of earth retaining walls worth $0.7 billion. Together at $19 billion, these are more than three times the value of the state's bridge inventory based on current reconstruction costs.

The Department does not yet have a complete formal inventory database for geotechnical assets, but does have partial inventories, mainly held within its geographic information system (GIS). The companion Landslide Technology GAM Methods Study substantially expanded and improved the inventory, and established a condition rating benchmark for all of the asset classes considered in this plan.

3.1 Asset inventory requirements

Although the inventory is not yet complete, the Department GIS, augmented by the new data collection in the GAM Methods Study, has enough information to begin to support a GAM process. Several existing guidance documents prepared by the Department describe existing or desired data:

- Retaining Wall Inventory Procedures Manual
- Unstable Slope Management Program Rating Category Descriptions
- Criteria for Entering Sites into the DOT&PF USMP Database
- Material Site Inventory Methodology

The types of information generally required for complete support of transportation asset management are as follows:

- Clear identification according to a naming or numbering scheme, or in terms of position on the road network.
- Asset location, which typically includes latitude/longitude coordinates and route/milepoint.
- Type of asset, with enough detail to support future research on deterioration and costs. Generally this information includes a classification of the materials making up the asset.
- Size of asset, typically height, width, and length. Other geometric attributes which may be significant include slope angle, volume or mass of material, and depth below ground.
- Road network data, especially traffic volume, truck traffic, functional class, speed, sight distance, detour length, and detour speed.
- Economic data including reconstruction cost, maintenance cost, alternative mode cost (if the road is blocked and no detour exists), and recovery cost (to repair damage and restore service in the event of asset failure).
- Condition data, including the date of inspection and the condition state assessed by the inspector, with supporting data as documented in the separate Landslide Technology GAM Methods Study.
- Assessments of potential safety, mobility, and environmental impacts of adverse events, as discussed in the chapter on risk management.
- Work history data, including the date and type of maintenance, preservation, or reconstruction work performed.

One of the most mature descriptions 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.

NCHRP Project 20-07 developed a survey in 2008 which contacted all 50 states plus additional Canadian and municipal agencies to quantify the extent of retaining wall management programs (Brutus and Tauber 2009). It found eight agencies with inventory and inspection programs, many built as extensions of bridge management. The report covers much of the same ground as the NPS report but offers some additional insights into program design. Colorado evaluated the potential for a retaining wall management system in 2003 (Hearn 2003), and is currently taking steps to implement one.

Several survey and synthesis reports have been prepared which summarize the types of inventory and condition data gathered by transportation agencies for asset management:

- 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). A later study provided additional guidance in the form of a model inventory (Lefler et al 2010).
- 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 437 includes a survey of data items collected for mechanically-stabilized earth walls (Gerber 2012).
- 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 2008).

- The National Bridge Inventory Coding Guide (FHWA 1995) provides detailed requirements for collection and submittal of required bridge inventory and condition data items.

The information in these reports may be helpful in the future when modifying the agency's asset inventory, augmenting the Department's GIS, or developing a new database, to support routine geotechnical asset management.

3.2 Inspection process

Inspectors assess the risks faced by geotechnical assets based on visual conditions and the observation of mitigated and unmitigated hazards. A hands-on inspection is most accurate and precise for assessing risks and deciding on necessary actions. However, this type of inspection is more expensive and may not be necessary for all assets. More cursory inspections can be performed more quickly, but they gather less information and with less confidence. The lack of information in a less detailed inspection is itself a contributor to risk.

The Department is implementing a multi-level risk-based inspection process, as depicted in Exhibit 13. Each level includes a risk assessment, which is used in order to decide whether to go to the next level of inspection. Once an inspector is physically present at a site, it is usually economical to cover all assets near the site, and in some cases to escalate to the next level of inspection when the risk assessment warrants it.

In most cases the assessment of the likelihood of an extreme event, and the importance or risk sensitivity of each asset, can be performed in the office from existing data and maps on soils, hydrology, traffic, and functional classification. So the risk assessment at each level would use conservative assumptions about unknown aspects of asset condition. These assumptions can often be made less conservative after a field inspection, thus reducing risk.

As an example, soil slopes are selected for field inspection based on an assessment, made in the office, of whether any unstable soil slopes are likely to exist in a given area. Stable soil slopes are always considered to be in condition state 1 and are not assessed further. Only those believed to be in state 2 or below warrant a site visit.

The main reason to distinguish one condition state from another, is to make distinctions in the types of actions which may be feasible and appropriate. For geotechnical inspection, five condition states provide enough resolution for this assessment. Exhibit 14 shows an example of the condition state language for rock slopes. The companion Landslide Technology GAM Methods Study has documented all of the condition state definitions. The condition state language follows the same philosophy as is commonly used for bridges (MTO 2000, AASHTO 2013), in maintenance management (Zimmerman and Stivers 2007), and in rockfall hazard assessment (Nicholson 2004). Eventually, an inspection manual will be developed, either as a separate document or as an enhancement for the state's Geotechnical Procedures Manual (Alaska DOT&PF 2007), to specify the methods in even more detail.

Condition state 1 corresponds to Good condition in the definitions given earlier, for presentation purposes. Condition states 2 and 3 are Fair, and 4 and 5 are Poor. The relationship between condition states and actions is one of feasibility and not necessity. The suggested action might not be performed if funding is limited, if the effect on safety and mobility is minimal, if a threshold of cost-effectiveness is

not satisfied, or if site characteristics apart from condition (e.g. access, geological character, etc.) make the action infeasible.

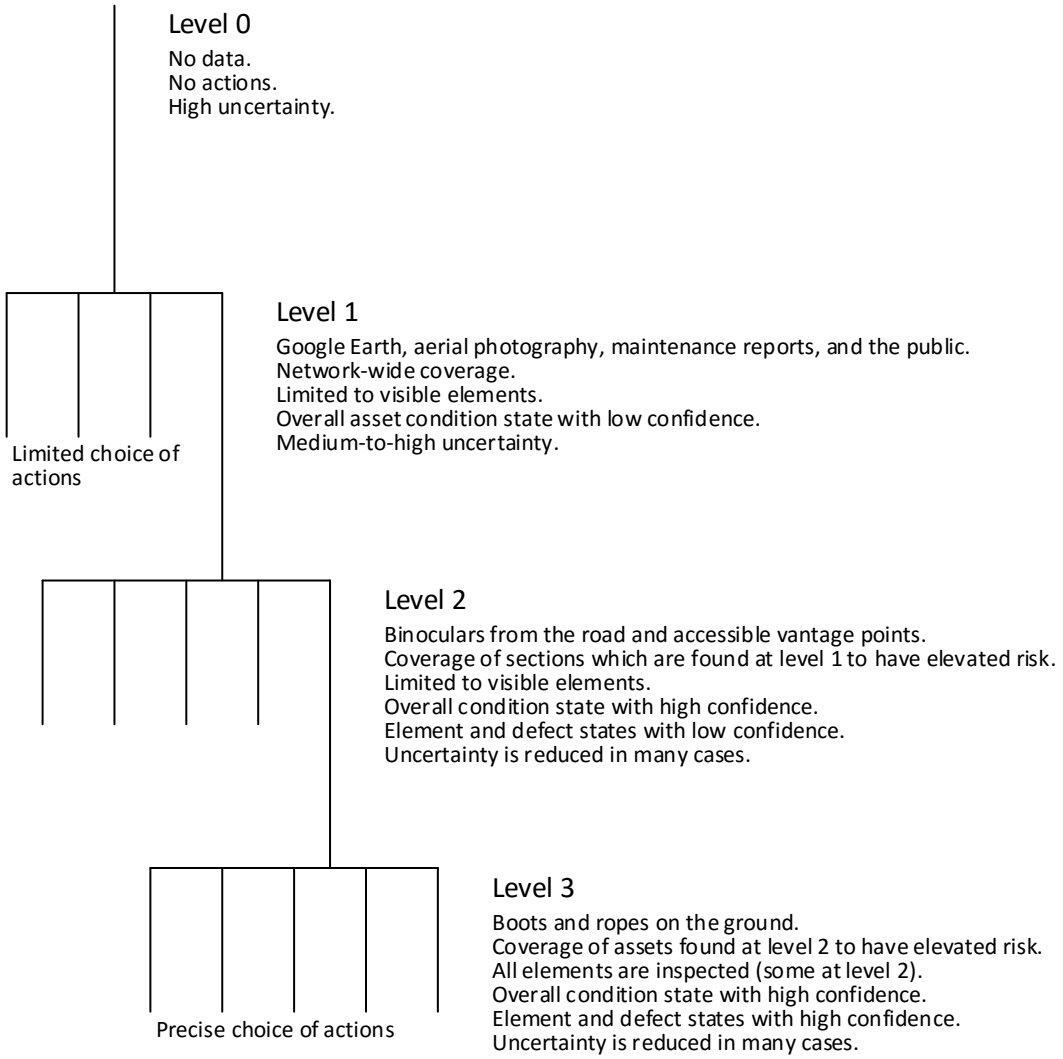

Exhibit 13. Risk-based multi-level inspection process

Exhibit 14. Example condition states – rock slopes

Condition State	Description
1. No action needed	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. Any mitigation measures present are in new or like new condition.
2. Review status at 5-year intervals	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 present are in generally good condition, with only surficial rust on devices or other minor apparent damage.
3. Inspect at semi-annual intervals. Consider mitigation efforts.	Rock slope produces many rockfalls with a rock occasionally reaching the road. Maintenance is generally a scheduled event and is required annually or semi-annually to maintain safety. Mitigation measures appear to have more significant corrosion or damaged minor elements. Preventative maintenance or replacement of minor components are warranted.
4. Inspect annually. Perform minor rehab and repair efforts.	Rock slope produces constant rockfall with rocks frequently reaching the road. Maintenance is required annually or more often to maintain ditch. Mitigation measures are generally ineffective due to significant damage to major components or deep apparent corrosion.
5. Perform major mitigation efforts	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. Nearly all mitigation measures are ineffectual either due to deferred maintenance, significant damage, or deep corrosion.

3.3 Current status of inventory and condition

Currently there is a complete inventory of material sites for the connected road network, but only a partial inventory of other asset classes. Exhibit 15 summarizes the current status, based on estimates prepared in the GAM Program Methods Study.

Exhibit 15. Status of inventory and condition inspections

Asset class	Statewide Count	Statewide Quantity	Units	Percent inspected
Rock slopes	2,672	66,545,610	sq.ft	36%
Unstable soil slopes	1,422	1,254,614	ln.ft	36%
Retaining walls	5,250	7,615,712	sq.ft	4%
Material sites	2,934	51	stations*	100%

* Maintenance station service areas

The estimated total statewide reconstruction value and conditions of these assets are summarized in Exhibit 16. It can be seen that soil slopes in Poor condition represent a significant liability for the state of Alaska, as these are the assets likely to produce the biggest expenditures in reconstruction costs over the coming years. It is also apparent that there is considerable potential for relatively inexpensive preservation activities on rock and soil slopes currently in Fair condition, to keep them out of the Poor category.

The conditions reported in Exhibit 16 are based on the inspections to-date, and may change as coverage increases. Because of uneven coverage so far among the three regions, it is premature to estimate asset value and condition by region. However, a goal is to be able to document and track region-level conditions in future GAM Plans.

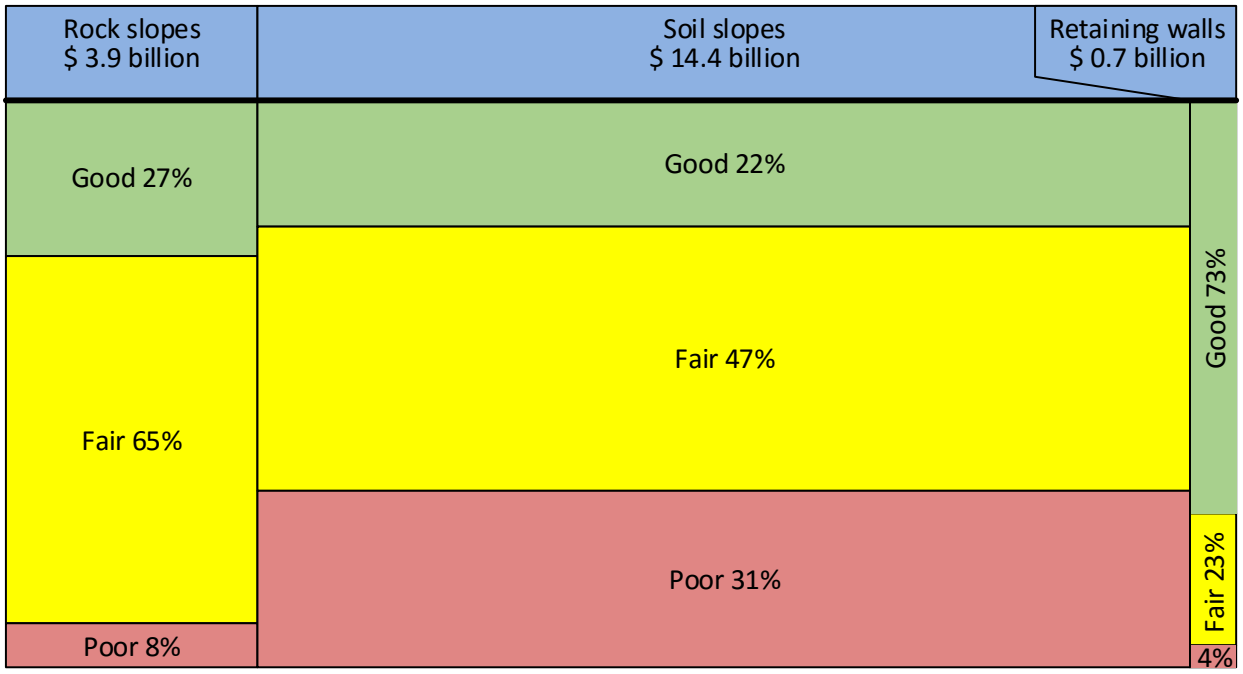

Exhibit 16. Geotechnical inventory and conditions (material sites to be added when available)

4. Life cycle cost

Over the course of its life, each slope and retaining wall undergoes deterioration because of age, weather, water and earth movement, freeze/thaw, and other factors. The effect of deterioration is to increase the likelihood of service disruptions, and to increase the frequency and cost of routine, reactive maintenance such as cleaning of catchment ditches and sealing of cracks. Occasionally it is necessary for the Department to intervene to counteract this deterioration. The kinds of actions the Department might take include:

- Routine maintenance, such as catchment ditch cleaning and crack sealing, occur potentially every year on a reactive basis. As condition declines, these activities are needed more frequently.
- Corrective action, which includes preservation and risk mitigation, is programmed work whose scope is determined by condition in the most recent inspection, and site characteristics. This category of work occurs infrequently, typically once every 20-65 years at a given site.
- Reconstruction may entail complete removal or reconstruction of the asset, or realignment of the road. This takes place at the end of the asset's service life.

Material sites also require occasional work, including exploration, expansion of access, opening of new sites, reclamation of exhausted areas, and stockpiling of materials transported from elsewhere.

Preservation and risk mitigation treatments for geotechnical assets have important inter-temporal tradeoffs analogous to preservation of pavements and bridges. In many cases a small timely investment in mitigation can extend the life of a slope or wall and postpone the day when a major reconstruction might be necessary. If such a treatment is feasible but is not accomplished in a timely way, further deterioration may render it infeasible or increase the rehabilitation cost substantially. Life cycle cost analysis informs these tradeoffs (FHWA 2002, Hawk 2003, Loehr et al 2004).

In the GAM life cycle cost analysis, all of these costs are expressed in dollars and combined in a framework where tradeoffs in scope and timing of work can be evaluated. Exhibit 18 shows the ingredients:

- A treatment model (green) forecasts the costs and effects of mitigation and preservation activities in each condition state. The amount of each treatment is guided by a treatment policy and constrained by available funding.
- A deterioration model (yellow) forecasts the change in condition from year to year when no treatment is applied, starting with current conditions from the most recent inspection. At the network level, conditions are expressed as the fraction of the inventory in each condition state. At the asset level, condition is expressed as the probability of each possible condition state. There is a cause-and-effect relationship between funding and policy on the one hand, and 10-year condition outcomes on the other hand. When funding is set at an expected or proposed level, the outcome is a fiscally-constrained condition target in the same sense as in the federal regulations (FHWA 2015a).
- The risk model (red) uses a site assessment of potential safety and mobility impacts, along with data on traffic and detour routes, as discussed in Chapter 5. The condition of each asset affects the likelihood of service disruptions, thus affecting the expected value of disruption costs.
- Risk costs are included in life cycle cost (blue) so that the appropriate balance between agency and user costs can be determined, and the total can be minimized. All costs are discounted, based on the year in which the costs are incurred, to reflect the time value of money. By comparing different

policy and funding alternatives, the Department can compute economic metrics such as life cycle social cost savings and return on investment.

The primary forecasting models (deterioration, treatment cost and effect, and disruption likelihood) are research-based. The best such models used in pavement and bridge management rely on many years of quality-assured data, which the Department does not yet have for geotechnical assets. As was the case for pavements and bridges, the Department will need to start with what research and data can be found, some from other agencies, along with the best available expert judgment. In a bootstrapping process it will gradually use these initial models to build a sustainable GAM program while at the same time maintaining good records of the conditions observed, treatments accomplished, and adverse events, so it can improve its forecasting models. In time it will be able to optimize its program, particularly able to optimize its policies on mitigation and preservation resource allocation, and its selection of projects, to minimize life cycle cost.

The analysis described here was conducted as a part of the Landslide Technology GAM Methods Study, using methods documented in the Final Report of that study.

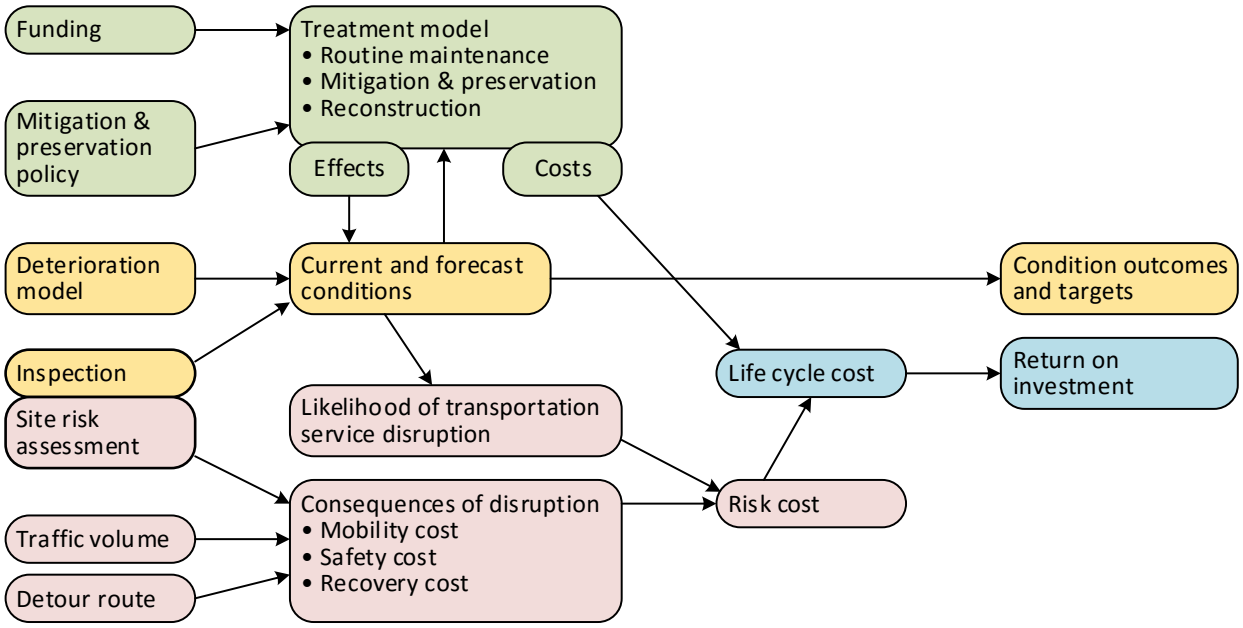

Exhibit 18. Analytical framework

4.1 Treatment selection and cost

For the analysis of corrective action and reconstruction, a single generic treatment was defined for each condition state, to represent the combined effect of all feasible mitigation and preservation activities that may be applicable to a given asset. Each generic treatment was associated with an improvement by an integral number of condition states. An analysis was performed to estimate a unit cost for each of these generic treatments. The details of this analysis vary by asset class:

- Rock slopes. A simple correlation of cost estimates with condition states was developed using data from the Rockfall Hazard Rating System performed for Montana. A significant part of Montana's implementation was an onsite conceptual mitigation design developed for the 100 highest-rated slopes in the state. This information was not readily available for Alaska, but Montana's geological conditions and rating methods are very similar. An overhead factor to account for engineering, mobilization, and traffic control was developed using project data provided by Washington State DOT.
- Soil slopes. Neither Alaska nor Montana DOT have a set of data for soil slopes comparable to what was used for rock slopes. However, Washington State DOT does have a suitable database. Moreover, Washington has many similar soil characteristics and problems (with the notable exception of permafrost), as well as condition data that can be aligned with Alaska's condition state definitions. A data set containing 89 condition ratings and conceptual mitigation designs was prepared in order to estimate the direct costs of mitigation, and 54 of these sites also had project data suitable for estimation of overhead costs. The designs include horizontal drains, tieback/soldier pile walls, buttress construction, debris flow fencing, stone columns, and bridge construction.
- Retaining walls. Metrics for retaining wall cost estimation were developed from Alaska DOT&PF bid tabulations, which primarily involved initial construction or reconstruction of these walls. A linear relationship with condition states was assumed.
- Material sites. A cost model was developed for development of new material sites and for excess haul costs to any point on the network that is not within five miles of a material site.

Exhibit 19 (a-d) summarizes the unit costs and application rates used in the life cycle cost analysis. Application rates indicate the fraction of sites, in a given condition state, receiving each treatment each year. A rate less than 1 indicates that a site may remain in the indicated condition state for more than a year before corrective action is taken, or that some sites never receive corrective action. A rate greater than 1 indicates that some sites receive more than one application in a year.

The application rates depend on the deterioration model discussed in the next section. They were determined by the same panel that developed the deterioration model, based on calculation of the rates required in order to sustain what the group believes is a stable long-range acceptable condition level, thereby offsetting the expected deterioration rates. The application rates actually used in the life cycle cost analysis may be less than these values if constrained by funding availability.

The rightmost column of each table is a calculation of the total cost that would be incurred this year, based on current conditions, if the indicated unit costs and application rates are applied.

For material sites, the indicated cost in Exhibit 19d is the estimated site development cost per mile of unserved road, if a new material site is developed within five miles of the road.

Exhibit 19a. Treatment unit costs and application rates for rock slopes

Treatment model	Percent acted upon each year, starting in each state					Unit cost	Total cost
	State 1	State 2	State 3	State 4	State 5	$/sq.ft	$k/year
Routine maintenance	0.00%	10.00%	100.00%	150.00%	1000.00%	0.26	5,427
Corrective action							
Improve by 1 state			1.00%	0.50%	5.00%	7.30	904
Improve by 2 states			4.00%	1.00%	1.00%	14.60	6,475
Improve by 3 states				5.00%	1.00%	21.90	5,658
Improve by 4 states					1.00%	29.20	0
Total percent improved	0.00%	0.00%	5.00%	6.50%	8.00%		13,036

Reconstruct/relocate $ 58.40/sq.ft

Exhibit 19b. Treatment unit costs and application rates for soil slopes

Treatment model	Percent acted upon each year, starting in each state					Unit cost	Total cost
	State 1	State 2	State 3	State 4	State 5	$/ln.ft	$k/year
Routine maintenance	0.00%	0.00%	10.00%	100.00%	1000.00%	10.00	16,316
Corrective action							
Improve by 1 state			0.50%		2.00%	2392.34	12,609
Improve by 2 states			0.50%	1.00%	5.00%	4784.68	56,550
Improve by 3 states				3.00%	5.00%	7177.02	103,095
Improve by 4 states					5.00%	9569.36	63,170
Total percent improved	0.00%	0.00%	1.00%	4.00%	17.00%		235,424

Reconstruct/relocate $ 11483.23/ln.ft

Exhibit 19c. Treatment unit costs and application rates for retaining walls

Treatment model	Percent acted upon each year, starting in each state					Unit cost	Total cost
	State 1	State 2	State 3	State 4	State 5	$/sq.ft	$k/year
Routine maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0	0
Corrective action							
Improve by 1 state		8.00%	4.00%	2.00%		23.42	3,082
Improve by 2 states				2.00%		46.84	275
Improve by 3 states				2.00%		70.26	413
Improve by 4 states					1.00%	93.68	0
Total percent improved	0.00%	8.00%	4.00%	6.00%	1.00%		3,771

Reconstruct/relocate $ 93.68/sq.ft

Exhibit 19d. Treatment unit costs and application rates for material sites

Condition state	Cost per mile	Application rate
1	0	0.000%
2	4,447	0.839%
3	3,123	2.031%
4	2,071	4.237%
5	2,020	5.809%

4.2 Deterioration

The simplest possible deterioration model using condition state data is a Markov model, which expresses deterioration rates as probabilities of transitions among the possible condition states each year. This type of model is used in nearly all bridge management systems, and in a few pavement management systems as well. For long-lived assets, a Markov model can be expressed as the vector of median transition times from each state to the next. The methods for developing and using these models are documented in NCHRP Report 713 (Thompson et al 2012). Exhibit 20 (a-d) shows the models that were developed for geotechnical assets using the methods described below.

Exhibit 20a. Markov deterioration model for rock slopes

Deterioration model	Markov model - starting condition state				
	State 1	State 2	State 3	State 4	State 5
Transition time (years)	38.3	32.5	21.2	13.7	--
Same-state probability	0.9821	0.9789	0.9678	0.9507	1.0000
Next-state probability	0.0179	0.0211	0.0322	0.0493	0.0000

Exhibit 20b. Markov deterioration model for soil slopes

Deterioration model	Markov model - starting condition state				
	State 1	State 2	State 3	State 4	State 5
Transition time (years)	55.0	23.1	12.6	7.6	--
Same-state probability	0.9875	0.9704	0.9465	0.9128	1.0000
Next-state probability	0.0125	0.0296	0.0535	0.0872	0.0000

Exhibit 20c. Markov deterioration model for retaining walls

Deterioration model	Markov model - starting condition state				
	State 1	State 2	State 3	State 4	State 5
Transition time (years)	25.2	20.8	8.3	7.2	--
Same-state probability	0.9729	0.9672	0.9199	0.9082	1.0000
Next-state probability	0.0271	0.0328	0.0801	0.0918	0.0000

Exhibit 20d. Markov deterioration model for material sites

Deterioration model	Markov model - starting condition state				
	State 1	State 2	State 3	State 4	State 5
Transition time (years)	16.4	13.9	16.6	18.0	--
Same-state probability	0.9587	0.9514	0.9592	0.9622	1.0000
Next-state probability	0.0413	0.0486	0.0408	0.0378	0.0000

In this table the transition time is the number of years that it takes for 50% of a representative population of assets to deteriorate from each condition state to the next-worse one; for example, from state 1 to state 2. The same-state probability is the statistical probability, in any one year, that a given asset will remain in the same condition state one year later. The next-state probability is then the probability that a given asset will deteriorate to the next-worse condition state. In the models used here, the sum of the same-state probability and next-state probability is always 1.0000.

The condition state data being collected for geotechnical assets are very similar to data sets that are maintained by most state DOTs for their bridge elements. These data sets are ideal for statistical

modeling of deterioration. Florida DOT has documented a complete example of the development of such models (Sobanjo and Thompson 2011). If the transition time is known or estimated, the same-state probability can be computed using the formula:

$$p_{jj} = 0.5^{(\frac{1}{t})}$$

Where j is the condition state (before and after 1 year)
t is the transition time in years

The forecast condition of the inventory in any given year is expressed as the fraction in each condition state. These fractions must sum to 1.0000 over the five condition states. For any given condition state, the fraction in that state after one year is computed by multiplying the current fraction in each state by the corresponding same-state and next-state probabilities. This calculation can be repeated as many times as needed in order to extend the forecast for additional years in the future.

Since the Department does not yet have the geotechnical asset condition history required in order to develop deterioration models using statistical methods, an expert judgment elicitation process was used instead. A panel of experts was asked a series of structured questions such as the following: "Suppose 100 rock slopes are currently in condition state 2. After how many years will 50 of the slopes reach state 3 or worse, if no action is taken?" Each panelist was asked to answer the questions independently from his or her own experience, then the results were tabulated and discussed. Panelists were then allowed to change their answers, which helped to improve the level of common understanding and consensus. For each question, the mean response was used as the transition time. Transition probabilities were then computed from this information as shown above.

Exhibit 21 (a-c) shows the combined effect of the deterioration and treatment models, expressed as a condition index where 100 is a new asset and 0 is the worst possible condition. This example reconstructs the asset when the probability of condition state 5 reaches 50%, and has periodic mid-life corrective actions. (The material site model does not have preservation and reconstruction actions.)

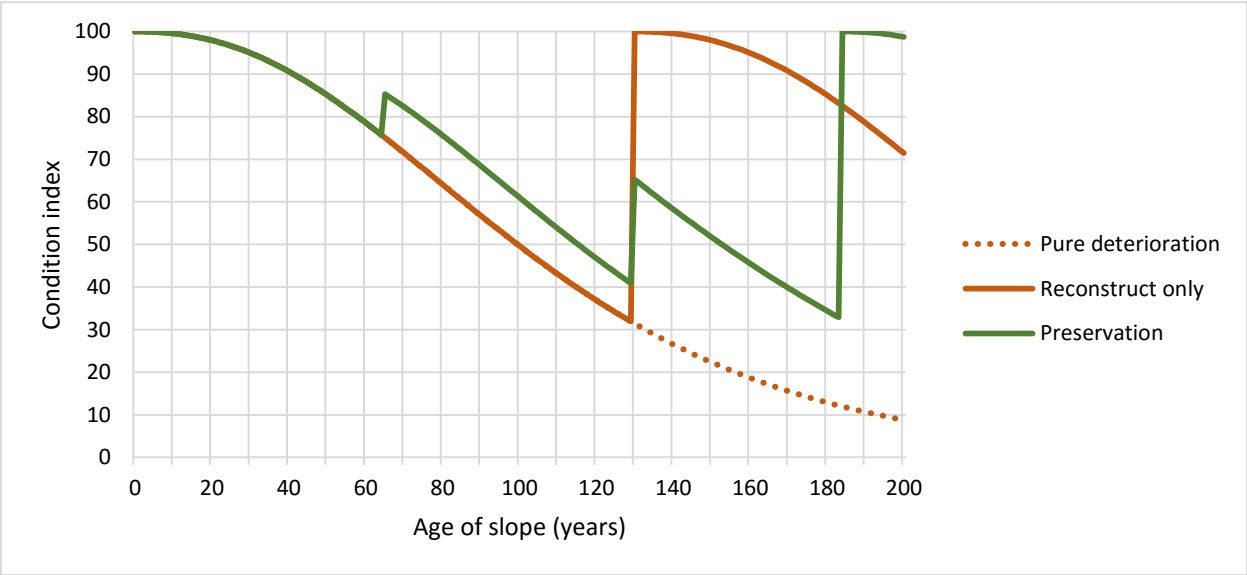

Exhibit 21a. Deterioration, reconstruction, and preservation for rock slopes

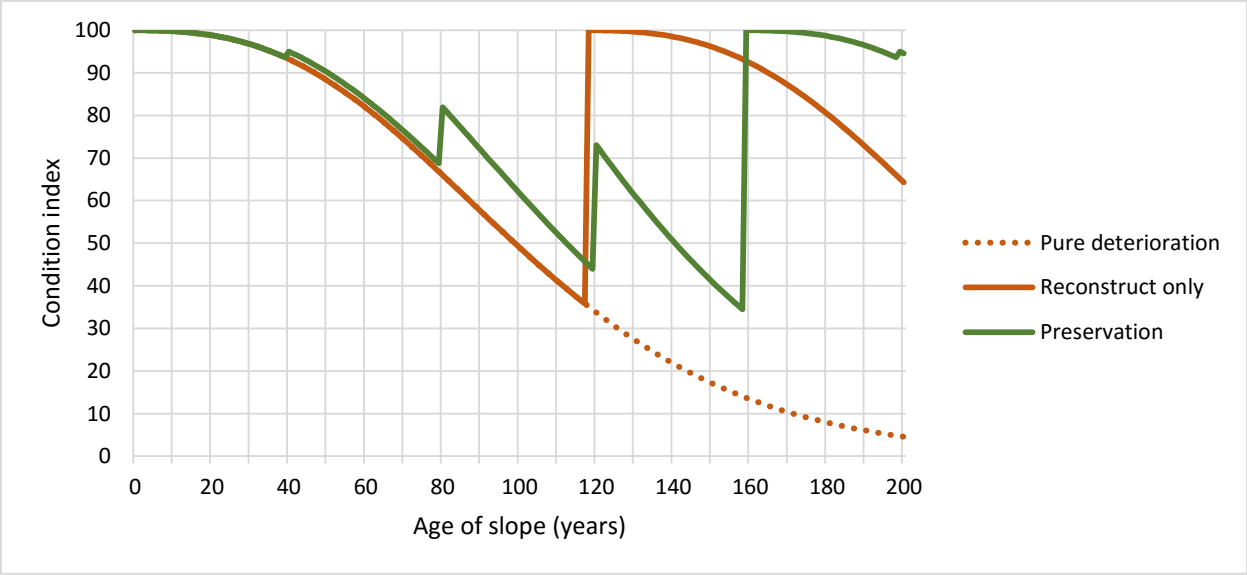

Exhibit 21b. Deterioration, reconstruction, and preservation for soil slopes

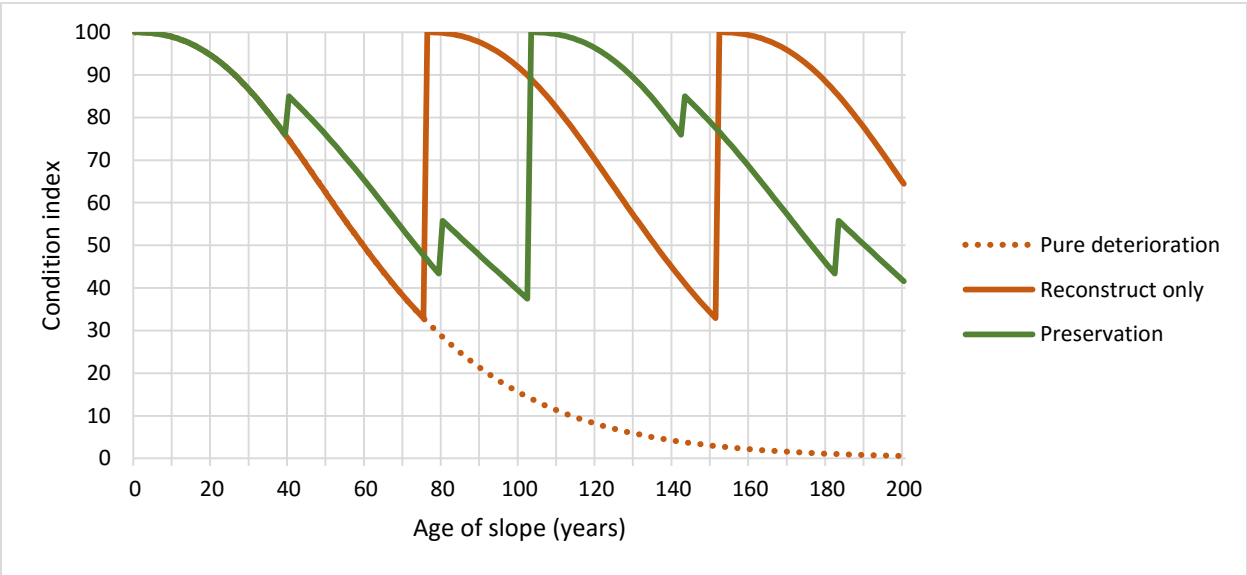

Exhibit 21c. Deterioration, reconstruction, and preservation for retaining walls

4.3 Time value of money

The key tradeoff in life cycle cost analysis is the ability to spend a small amount of money in the near future in order to postpone a much larger expenditure, as was shown above in Exhibits 21 with the postponement of reconstruction by the preservation strategy. Economists use a metric known as a discount rate to measure the benefit of postponing costs. If a 2% discount rate is used, for example, then the benefit of postponing a $1 million expenditure for one year is 2% of that amount, or $20,000. It would be worth spending up to $20,000 today in order to postpone that $1 million expenditure.

The concept of discount rate is essentially the same as the interest rate that many consumers pay on mortgage loans. By paying 4% interest each year on the outstanding balance, the homeowner is able to

postpone having to pay off the much larger principal amount, instead paying just a small fraction of it each month.

If a large expense can be postponed long enough, it might become nearly insignificant in near-term decision making, because the delay in having to pay the expense is valuable in itself. In life cycle cost analysis, if a cost can be delayed its magnitude is reduced, or discounted, according to the discount rate and the length of the delay. The present value of a future cost, known as the discount factor (*DF*), can be computed from the discount rate d and the number of years of delay t using

$$DF = \left(\frac{1}{1+d}\right)^t$$

So if the discount rate is 2%, delaying an expenditure of $1 million for 10 years reduces the value of that expenditure to $820,348 and delaying it for 100 years reduces it to $138,033.

NCHRP Report 483 (Hawk 2003) has a thorough discussion of how discount rates are determined. In short, they are determined by agency policy, which should be consistent across all types of assets and all investments of similar lifespan. A common source of guidance is The White House Office of Management and Budget (OMB) Circular A-94[1]. Typically inflation is omitted from life cycle cost analyses because this practice simplifies the computations. A riskless and inflationless cost of capital for long-lived investments may use 30-year US Treasury bonds for guidance, with a 2016 real interest rate of 1.5%[2]. Transportation agencies usually specify higher discount rates than this, in the 2-3 percent range, because of uncertainties in long-term future travel demand and infrastructure requirements.

Currently the GAM analysis is using a discount rate of 2.1 percent per year, which is within the typical range of state DOT TAM Plans. As of this writing, the Department has not yet selected a discount rate for its TAM Plan. An analysis period of 200 years is used because the corresponding discount factor of 1.57% reduces even the largest reconstruction costs to a point where they do not affect near-term decision making.

4.4 Computation of life cycle cost

Combining all the models discussed in this chapter, a life cycle cost model can be computed. This model follows an asset through its life cycle, simulating deterioration and appropriate actions to correct or limit deterioration, using a set of decision rules to select these hypothetical future actions. Future costs are discounted to reflect the value of delaying expenditures as long as possible. This type of analysis is very common in pavement and bridge management systems (Cambridge 2003).

In a typical program-level analysis, budget constraints are applied year by year. The highest priority projects are identified for the first year's budget, and then the remaining projects are delayed for consideration in the following year. If a project is delayed, there will be an increased risk of service disruption, and preservation work may become infeasible due to further deterioration. This might shorten the asset's lifespan. Therefore it is necessary to consider all of the forecast costs over the entire life of the asset in order to make a fair comparison between alternatives.

[1] http://www.whitehouse.gov/omb/circulars_a094/
[2] http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c/

The main components of the analysis are shown in Exhibit 18 above. The analysis starts with current asset condition, and forecasts events into the future. The first agency action in the sequence is the candidate project under evaluation. Remaining actions, further in the future, are projected. The year in which the work is under consideration is the "program year." The sequence of steps is as follows:

0. Start with the first year in which work is to be considered. This is the first "analysis year".
1. Forecast condition and resilience for the start of the analysis year, based on normal deterioration rates.
2. Estimate normal maintenance costs ($) and the likelihood (probability, %) and consequence ($) of adverse events for the analysis year. These methods are discussed with risk analysis in the next chapter.
3. If the analysis year is also the program year:
    a. then estimate the initial cost of the candidate project and forecast the condition immediately following completion of the project;
    b. otherwise evaluate a set of decision rules based on forecast condition, to determine whether any preservation actions are warranted. If so, estimate the initial cost of the warranted project and forecast the condition immediately following completion of the project. If not, carry forward the condition forecast from Step 1, and do not add any additional project cost.
4. Compute life cycle social cost as follows:
    a. Add maintenance cost and project cost (if any) to the product of likelihood × consequence of service disruption from the risk analysis.
    b. Multiply the result by the discount factor.
    c. Add the result to the accumulated life cycle social cost.
5. Return to step 1 for the next analysis year. Continue the year-by-year simulation until the end of the analysis period.

The result of the computation is life cycle social cost, which is the sum of life cycle agency cost and life cycle user cost. Many of the above computations have probabilistic inputs (such as the deterioration model) and therefore have economic results which are a statistical expected value computed over the range of possible inputs.

While some of these estimates are highly uncertain, the important thing is to use the best-available methods possible under the current state of understanding and data availability, and to use these methods consistently. No one expects forecasts made 200 years in advance to be precise. All that is expected is a reasonable, defensible, and consistent basis for setting priorities, compatible with methods used for pavements, bridges, and other transportation assets.

4.5 Return on investment

It is possible to compare life cycle costs between a worst-first reconstruction-only policy, and a policy featuring timely corrective action. This analysis was performed as a part of the Landslide Technology GAM Methods Study. For this purpose, the annual budget for both scenarios was set at a level that maintains current conditions over ten years. The following results were obtained:

Rock slopes. Annual funding of $12.18 million is sufficient to maintain the current statewide condition index of 85.2 after ten years. At this funding level, preservation and risk mitigation work make up 83% of

the budget, with reconstruction making up the rest. Compared to a strategy where no preservation work is done, the desired preservation investment reduces life cycle costs by 17%, a savings which is 138% of the preservation investment over the analysis period.

Soil slopes. Annual funding of $150.4 million is sufficient to maintain the current statewide condition index of 61.0 after ten years. At this funding level, preservation and risk mitigation work make up 33% of the budget, with reconstruction making up the rest. Compared to a strategy where no preservation work is done, the desired preservation investment reduces life cycle costs by 10%, a savings which is 29% of the preservation investment over the analysis period.

Retaining walls. Annual funding of $5.63 million is sufficient to maintain the current statewide condition index of 93.8 after ten years. At this funding level, preservation and risk mitigation work make up 72% of the budget, with reconstruction making up the rest. Compared to a strategy where no preservation work is done, the desired preservation investment reduces life cycle costs by 53%, a savings which is 15 times the preservation investment over the analysis period.

Material sites. Annual funding of $244,000 on new site development is sufficient to maintain current statewide average material availability, with 5% of maintenance stations in Good condition (optimal availability) and 57% Poor. The return on investment, primarily a savings in excess haul costs, is 882 percent.

The relatively low return-on-investment for preservation of soil slopes reflects a dearth of attractive technologies and methods for reducing deterioration. Because of their poor condition and large quantity, this is a very attractive area for future research.

These return-on-investment figures are calculated based on the entire inventory, including roads which may have very low traffic volume and/or short detour length. The portion of life cycle cost associated with mobility benefits is proportional to traffic volume and detour length, so the social cost savings and return-on-investment are higher than these averages for roads which have higher ADT and longer detours. The methods for considering safety and mobility benefits are discussed in the next chapter.

5. Risk management

Geotechnical assets impact transportation system performance primarily by means of the risk of service disruption. Therefore it is very common for geotechnical hazards to be addressed as part of an agency's risk management planning process (FHWA 2012, 2013a, 2013c). By their nature, adverse geotechnical events such as rockfall, debris flows, washouts, and landslides are uncommon and unpredictable at a given site, but total impacts are reasonably predictable on a statewide long-term basis. The business process is made more manageable and efficient by focusing on programmed corrective actions that the agency can take, in response to periodic inspections, to identify sites with the highest risk and then to work on reducing that risk.

In Alaska's GAM process, risk assessment consists of two parts:

- Likelihood of service disruption, a probability in percent, which depends on condition as assessed by a trained inspector.
- Consequence of service disruption, a summary in dollars of the safety, mobility, and recovery cost impacts that are likely to occur if there is a service disruption.

Risk is the product of likelihood times consequence. The overall framework for project evaluation and for monetizing impacts of decisions and hazards, closely follows the widely used methodology of AASHTO's Manual for User and Non-User Benefit Analysis for Highways, commonly known as the "Red Book" (AASHTO 2010). The first edition of the Red Book was published in 1960 (AASHO 1960), and has periodically been updated (AASHTO 1977, 2003, and 2010). Today these methods are standard features of pavement management systems such as HDM-4 (Zaniewski et al 1985, Lea 1995) and bridge management systems such as Pontis (Johnston et al 1994, Thompson et al 1999, Sobanjo and Thompson 2004). They contribute to federal estimates of road, bridge, and transit funding needs and economic benefits (FHWA 2005 and 2013d, commonly known as the biennial "C&P Report") and to post-event assessments of economic damage from geotechnical failures (HDR 2010). They are used in developing contractual incentives for early completion and to evaluate strategies to minimize work zone disruption (Mallela 2011). An NCHRP synthesis report (Markow 2012) discusses the widespread applications of these methods.

Since risk is expressed in dollars, it is easily incorporated into the life cycle cost model, making it possible to prioritize projects according to benefit/cost ratio in a manner consistent with pavement and bridge management (FHWA 2013b, Sobanjo and Thompson 2013, Mn/DOT 2013). Risk management can therefore become an integral part of the programming process for all preservation and reconstruction investments.

5.1 Likelihood of service disruption

In Alaska's GAM framework, the likelihood of service disruption is directly related to condition of a slope or retaining wall. The companion Shannon & Wilson GAM Risk Management Study has developed a simplified table to make this relationship explicit (Exhibit 22). These are a rough and general way of characterizing risk, which can be replaced by a more precise estimate if available on a site-specific basis. These estimates are meant to incorporate routine adverse events such as seasonal rockfall, as well as extreme events such as earthquakes and floods.

The companion Landslide Technology GAM Methods Study describes how site variables related to resilience contribute to the condition state of each asset, which in turn provides the rationale for assessments of likelihood of service disruption.

Exhibit 22. Likelihood of service disruption based on condition state

Rock slopes		
Condition State	Years between adverse events	Annual probability
1 – Good	25	4%
2 – Fair	10	10%
3 – Fair	5	18%
4 – Poor	1	63%
5 – Poor	0.5	86%

Soil slopes and embankments		
Condition State	Years between adverse events	Annual probability
1 – Good	50	2%
2 – Fair	10	10%
3 – Fair	2	39%
4 – Poor	1	63%
5 – Poor	0.5	86%

Retaining walls		
Condition State	Years between adverse events	Annual probability
1 – Good	75	1%
2 – Fair	25	4%
3 – Fair	10	10%
4 – Poor	5	18%
5 – Poor	1	63%

Material sites		
Condition State	Years between adverse events	Annual probability
1 – Good	100	1%
2 – Good	100	1%
3 – Good	100	1%
4 – Fair	10	10%
5 – Poor	1	63%

5.2 Safety consequences of service disruption

The GAM Risk Management Study defines Threat to Safety as an estimate made by an inspector of the number of vehicle crashes likely to be caused by a service disruption event. These can entail vehicles being struck by falling debris, vehicles striking debris that is already lying in the road, or vehicles that lose control or are damaged due to debris avoidance or pavement damage. For this analysis, these incidents are assumed to be single-vehicle crashes. The AASHTO Red Book has procedures and research-based metrics which take into account typical crash injury severity rates and property damage. The safety disruption cost is:

$$S\$ = AC \times ACC\$$$

Where AC is the estimated accident count
ACC$ is the average cost per crash ($43,525 in 2015$[3])

In the absence of a precise estimate, the Risk Management Study proposes a set of Threat to Safety ranges that might be more easily characterized by an inspector with knowledge of the site. The ranges are as follows, with representative midpoint values in parentheses:

- Low: No reported accidents or minimal severity of accidents (0);
- Medium low: Fewer than two accidents (1);
- Medium: Two to five accidents (3);

[3] AASHTO Red Book, page 5-24. This figure is an average over all vehicle classes and accident types. It excludes insurance reimbursement to avoid double-counting of costs. It is updated to 2015 dollars using the Consumer Price Index.

- High: More than five accidents, or severe injury/fatality accidents (6).

The Department has found it difficult to develop statistics on actual crash rates caused by geotechnical hazards, because of the difficulty in determining, for each accident report, whether rockfall, pavement damage, or other hazards were contributing factors. Improvements in accident reporting procedures have been recommended to help improve the quality of crash data in the future.

5.3 Mobility consequences of service disruption

The GAM Risk Management Study defines Threat to Mobility as an estimate of the likely duration of road closure caused by an adverse event. This is measured in hours, and may be estimated using the following ranges, with representative values in parentheses:

- Negligible: No closure or interference with traffic (0 hours);
- Minor: Less than one hour of closure (0.5 hours);
- Major: 1-24 hours of closure (12 hours);
- Critical: One to four days of closure (60 hours);
- Catastrophic: More than four days of closure (120 hours).

If Threat to Mobility is less than one hour, it can be assumed that travellers will wait for the road to be cleared, unless the detour route is faster. In this case, the impact of a service disruption will be a closure of up to an hour, for which a representative duration would be 30 minutes. The mobility disruption cost will then be:

$$M\$ = \frac{ADT}{48} \times 0.25 \ \times TT\$ \times VO$$

Where ADT/48 is the number of vehicles to arrive at the site in one half hour
0.25 is the average delay in hours per vehicle if vehicles arrive randomly over the half hour
TT$ is travel time cost, the value per hour of a vehicle occupant's time ($30.50 in 2015$[4])
VO is the average vehicle occupancy rate (1.3[5])

If the Threat to Mobility is greater than one hour, the impact is likely to be travellers using an alternate route, if one is available. In this case the mobility disruption cost is:

$$M\$ = ADT \times DD/24 \times (DL \times VOC\$ + DL/DS \times TT\$ \times VO)$$

Where ADT is the number of vehicles per day which normally use the route
DD is the duration of the disruption, in hours (Threat to Mobility)
DL is the detour length in miles
VOC$ is the average vehicle operating cost per mile ($0.207 in 2015$[6])
DS is the detour speed in mph

[4] AASHTO Red Book, page 5-4. This figure uses the average over all occupations, computed as an opportunity cost. It is updated to 2015 dollars using the Consumer Price Index.
[5] This value was suggested in the Red Book, but the Department Planning Office might have a different estimate.
[6] AASHTO Red Book, page 5-10. This is based on the "large car" column and includes fuel, oil, maintenance, and tires. It is updated to 2015 dollars using the Consumer Price Index.

TT$ is travel time cost, the value per hour of a vehicle occupant's time ($30.50 in 2015$)
VO is the average vehicle occupancy rate (1.3)

Detour length can be computed for most assets using the Department's geographic information system. For all other assets, the GAM Risk Management Study suggests ranges that can be assessed in the field, whose midpoints can be used in this computation. Detour speed should be assessed in the field, and if unknown, can be assumed to be the same as the roadway at the asset site.

In cases where the Threat to Mobility is greater than one hour and no detour route is available, the computation can assume a shift to a different mode. In this case mobility disruption cost is:

$$M\$ = ADT \times DD/24 \times VO \times AM\$$$

Where ADT is the number of vehicles per day which normally use the route
DD is the duration of the disruption, in hours (Threat to Mobility)
VO is the average vehicle occupancy rate (1.3)
AM$ is the alternate mode cost

The alternate mode cost can be assessed in the office using published marine or air fares, and is only needed for sites that lack a detour route.

5.4 Recovery costs

The GAM Risk Management Study provides ranges of recovery cost which can be assessed in the field, to reflect the cost of repairing damage and restoring service in case of an adverse event. The ranges and representative values are:

- Acceptable: Less than $10,000 ($5,000);
- Low: $10,000-$50,000 ($30,000);
- Minimal: $50,000-$100,000 ($75,000);
- Major: $100,000-$250,000 ($175,000);
- Catastrophic: More than $250,000 ($350,000).

5.5 Total project benefit

The total cost of a transportation service disruption is estimated as the sum of mobility cost, safety cost, and recovery cost:

$$Consequence = M\$ + S\$ + R\$$$

Finally, then, the total expected value risk cost component of life cycle social cost is:

$$Likelihood \times Consequence$$

Project benefits are estimated as the difference in life cycle cost between two alternatives:

- The candidate project in the program year under consideration;
- Do-nothing in the program year under consideration, followed by taking an appropriate action in the following year.

A project is economically attractive if the life cycle social cost of doing the work today is less than the life cycle cost of the do-nothing alternative, which may entail doing more expensive work, or incurring more severe user costs, in a future year.

Since project benefit is computed by arithmetic subtraction, it is conventional to omit from life cycle cost estimates any costs that are constant across all alternatives to be considered (for example, the consequences of a millennial earthquake, or user costs incurred on an unobstructed road).

Life cycle costs are usually roughly proportional to the size of the asset, as are initial costs. The ratio of these two costs, therefore, cancels the effect of asset size and focuses instead on project merits, making it a suitable metric for priority-setting. In a given program year, a list of candidate projects sorted by benefit/cost ratio provides the basis for achieving the highest possible benefit for any given investment of funds in that program year. It also directly indicates which additional investments would be next in line if more funding becomes available or if any projects higher on the list are delayed.

One of the pitfalls that has been identified in considering adverse events as contrasted with normal deterioration, is the proper recognition of phenomena such as rockfall and debris flows, which could fit into either category. By handling both using the same life cycle cost framework, it becomes unnecessary to make the distinction.

5.6 Systemic risks

In addition to site-specific risks, the GAM program also faces a number of systemic risks affecting the long-term ability to effectively manage these assets, achieve performance objectives, and ensure continuity of service of the state's highways. These include:

- Future land-use, particularly private landowner decisions that affect the stability of slopes or that place private assets in a position threatened by unstable slopes on State land.
- Staffing levels, particularly the availability of sufficient Department staff to update the inventory and condition survey, to execute GAM business processes, to update this GAM Plan, and to carry out preservation and mitigation work.
- Staff qualification and training, the ability of the Department to attract and retain geotechnical talent, and to keep them current with the state of the practice. This concern also includes succession planning as existing staff are promoted or retire over time.
- Inadequate information, a special concern at this early stage of GAM implementation, when the inventory is only partially complete. An incomplete or outdated inventory creates the potential that vulnerable sites are unknown, or that mitigation projects are not appropriately prioritized.
- Program uncertainty. Geotechnical projects have not had a dedicated program, so the level of funding available to be applied to preservation and mitigation is currently unknown. This plan will help in the effort to set an appropriate allocation, but there remains uncertainty as to whether the needed funding will be available.
- Market conditions. Material and labor costs have inherent vulnerability to inflation, transportation costs, and competing uses. The material site program, in particular, faces a risk of unavailability of new sites due to property ownership, licensing and permitting issues, real estate cost, access, and other factors. This can lead to escalation of Department-wide construction costs.

- Management support. All asset management business processes require positive senior management support in order to perpetuate the cultural changes and cooperation that are necessary. A thorough discussion of these issues can be found in Gordon et al (2011).
- Unpredictability of large-scale changes and extreme events, including climate change and major earthquakes. While GAM provides a means of prioritizing the most vulnerable sites, it can reduce but not eliminate the potential damage (Mote et al 2012, Connor and Harper, 2013).

GAM provides tools to help with many of these risk factors, as discussed throughout this document. Others are already well-known and are the subject of active management processes within the Department.

6. Financial plan and investment strategies

The GAM framework serves as a roadmap to make the GAM Plan implementable. It specifies the data to be collected, and the analyses necessary to relate data to actions and desired outcomes. It then specifies the means of presenting data, actions, and outcomes to various audiences. In order for the GAM framework to be compatible with, and participate in, the Department programming process, it needs to provide investment candidate cost and benefit information compatible with what is produced by pavement and bridge management. Exhibit 23 shows schematically how these systems fit together.

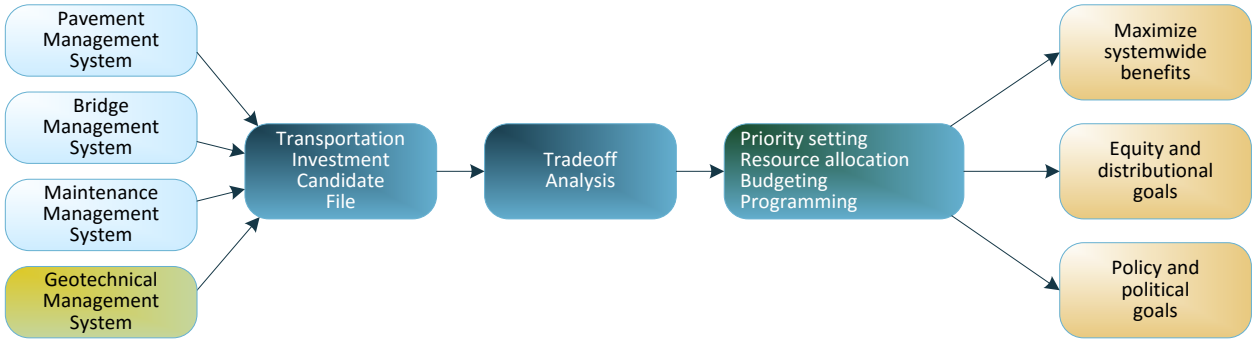

Exhibit 23. GAM contributes to agency-wide decision-making (adapted from Gordon et al 2011)

In Exhibit 23, the box labeled "Geotechnical Management System" is not a specialized software system like a PMS or BMS. It is merely a database of inventory and condition data, which already exists in the Department, and one or more spreadsheets to perform the necessary analysis. A prototype description of the Investment Candidate File is presented in Gordon et al (2011).

A key to integrating these dissimilar assets into a common tradeoff analysis is the use of economic benefit/cost analysis for priority-setting, using a consistent set of benefit and cost estimates, in dollars. The methods described in this GAM Plan are consistent with many of the pavement and bridge management systems in common use. The Department's BMS is already capable of producing this information, particularly when the Department implements the upgrades to the system currently under development by AASHTO. Its PMS will require some modification, similar to modifications that are already necessary for compliance with proposed federal regulations on Transportation Asset Management (FHWA 2015b). It will be necessary for the pavement management system to conduct a life cycle cost analysis and be able to prioritize projects to minimize life cycle costs, in a manner consistent with industry standards.

Currently the Department does not have capital accounts or maintenance activity codes specifically focused on geotechnical assets. Occasionally work activities can be reliably identified from existing activity codes combined with work descriptions and locations. Often, however, work on slopes and retaining walls is integral with pavement or drainage projects and not separately identified. As a result, the Department does not have formal budgets for this type of work, even though such work is often performed by maintenance crews and contractors. It will be important to address this situation as GAM implementation proceeds, especially in regard to corrective actions that the Department hopes to plan using GAM methods (Hearn et al 2010).

Even in the absence of well-defined fiscal scenarios, it is possible to use deterioration and cost models to estimate the medium range cost of maintaining assets in their current condition, and to assess the

condition outcomes if funding is higher or lower than this estimate. This information can be used to establish a geotechnical preservation and reconstruction budget, and to set corresponding condition targets for the 10-year timeframe.

This analysis has been performed as part of the GAM Program Methods study. The process is similar to what is described in the earlier chapter on life cycle cost analysis, with a year-by-year simulation of asset deterioration and maintenance at the network level. Over a period of ten years, the simulation produces an estimate of condition and costs of maintenance, preservation, and reconstruction. Preservation is given higher priority in this analysis because of its higher return on investment, but the overall program is constrained by budget scenarios. A range of funding scenarios was investigated for each asset class, to show how performance is affected by the allocation of resources.

Rock slopes (Exhibit 24). Annual funding of $12.18 million is sufficient to maintain the current statewide average condition index of 85.2 after ten years. At this level the ten-year performance targets for TAM Plan purposes would be 31% Good and 8% Poor. The total 10-year funding requirement, including 2.5% per year inflation, is $136 million.

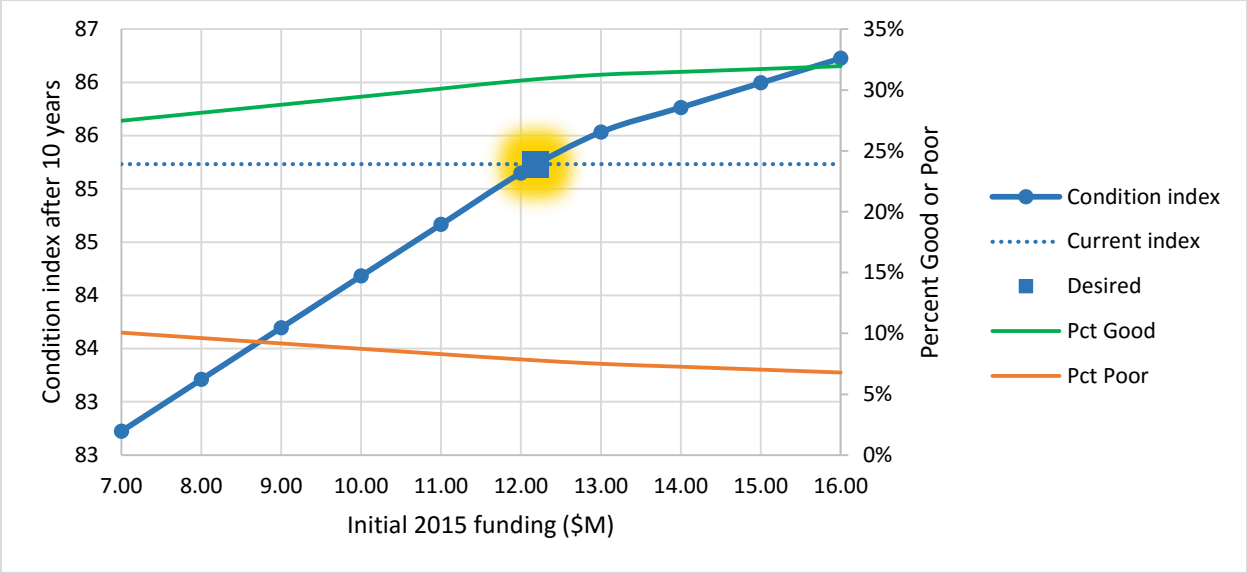

Exhibit 24. Condition vs funding for rock slopes

Soil slopes (Exhibit 25). Annual funding of $150.4 million is sufficient to maintain the current statewide average condition index of 61.0 after ten years. At this level the ten-year performance targets for TAM Plan purposes would be 27% Good and 34% Poor. The total 10-year funding requirement, including inflation, is $1.685 billion.

Retaining walls (Exhibit 26). Annual funding of $5.63 million is sufficient to maintain the current statewide average condition index of 93.8 after ten years. At this level the ten-year performance targets for TAM Plan purposes would be 71% Good and 3% Poor. The total 10-year funding requirement, including inflation, is $63 million.

Material sites (Exhibit 27). Annual funding of $244,000 on new site development is sufficient to maintain current statewide average material availability, with 5% of maintenance stations in Good

condition (optimal availability) and 57% Poor. The total 10-year funding requirement, including inflation, is $3 million.

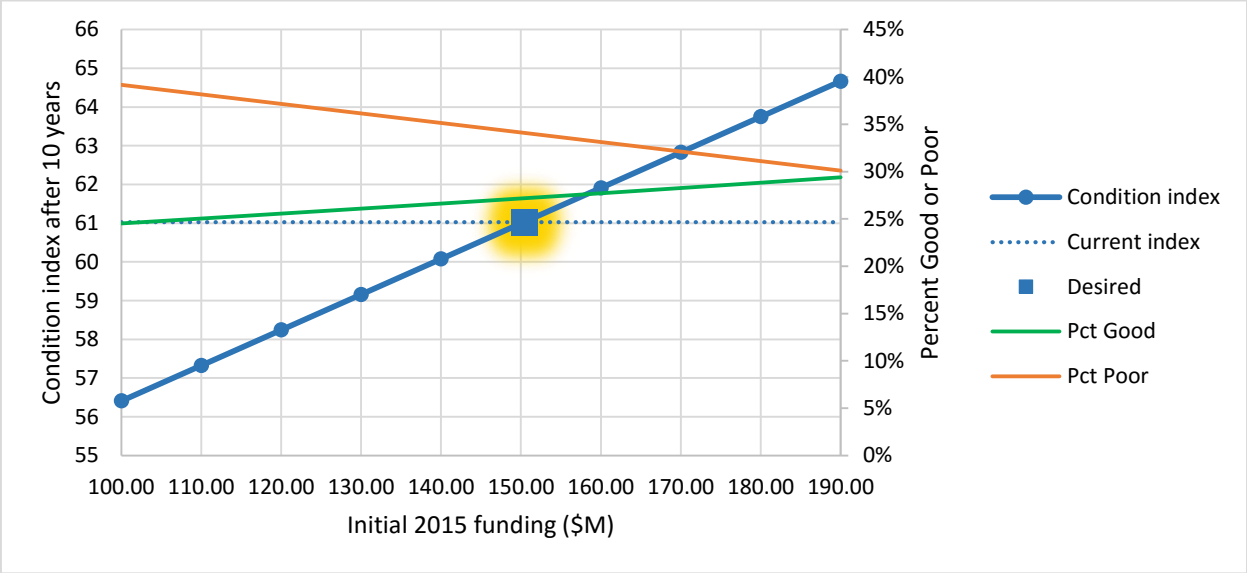

Exhibit 25. Condition vs funding for soil slopes

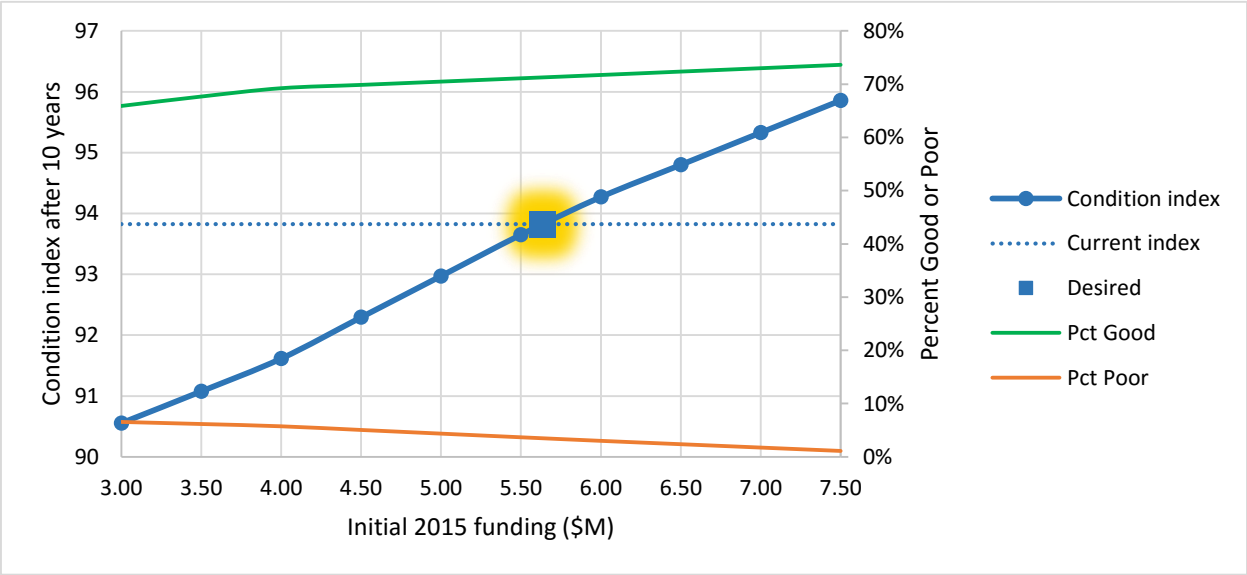

Exhibit 26. Condition vs funding for retaining walls

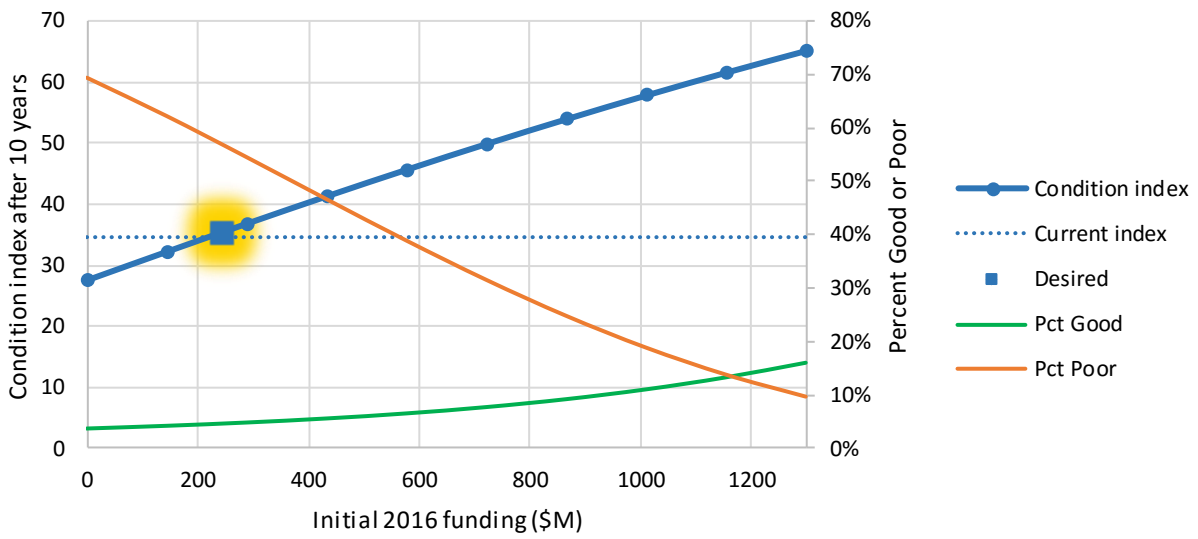

Exhibit 27. Condition vs funding for material sites

References

In the following citations a link is provided if the document is accessible online, or if it is only available for purchase or loan from a specialized source. Other works cited are available for purchase from general commercial sources or from the specific agency cited.

AASHO. Road User Benefit Analyses for Highway Improvements. American Association of State Highway Officials, 1960. (Superseded by AASHTO 1977)

AASHTO. A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements. American Association of State Highway and Transportation Officials, 1977. (Updated in 2003, then superseded by AASHTO 2010.)

AASHTO. User and Non-User Benefit Analysis for Highways. American Association of State Highway and Transportation Officials, 2010.
Available at https://bookstore.transportation.org/collection_detail.aspx?ID=65.

AASHTO. AASHTO Manual for Bridge Element Inspection. American Association of State Highway and Transportation Officials, 2013.
Available at https://bookstore.transportation.org/collection_detail.aspx?ID=129.

Alaska DOT&PF. Alaska Geotechnical Procedures Manual, 2007. Available at http://www.dot.alaska.gov/stwddes/desmaterials/mat_geology/assets/pdf/geotechman/geotechmanual_all_07.pdf.

Alaska DOT&PF. Let's Get Moving 2030: Alaska Statewide Long-Range Transportation Policy Plan. Alaska Department of Transportation and Public Facilities, 2008.
Available at http://www.dot.alaska.gov/stwdplng/areaplans/2030/assets/SWLRTPPfinal022908.pdf.

Allenby, Brad and Jonathan Fink. "Toward inherently secure and resilient societies." *Science* 309:5737, pp. 1034-1036. August 12, 2005.
Available at http://www.sciencemag.org/content/309/5737/1034.full.

Anderson, Scott A., Daniel Alzamora, and Matthew J. DeMarco. "Asset management systems for retaining walls." In GEO-velopment: The Role of Geological and Geotechnical Engineering in New and Redevelopment Projects. American Society of Civil Engineers Geotechnical Practice Publication No. 5., 2008.
Available at http://books.google.com/books?id=jOAYGiBP9OUC&lpg=PA164&vq=retaining%20wall&pg=PP1#v=snippet&q=retaining%20wall&f=false.

Anderson, Scott A., and Benjamin S. Rivers. "Corridor management: A means to elevate understanding of geotechnical impacts on system performance." Paper prepared for presentation at the Annual Meeting of the Transportation Research Board, 2013.
Available at http://docs.trb.org/prp/13-3018.pdf.

ASTM. Standard Test Method for Airport Pavement Condition Index Surveys. ASTM D5340-12, 2012.
Available at http://www.astm.org/Standards/D5340.htm.

Brutus, Olivier and Gil Tauber. Guide to Asset Management of Earth Retaining Structures. National Cooperative Highway Research Program Project 20-07 Task 259, Transportation Research Board of the National Academies, 2009.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/nchrp20-07(259)_FR.pdf.

BSI. Asset Management Part 1: Specification for the optimized management of physical assets. British Standards Institute, Publicly Available Specification 55-1 (PAS 55-1), 2008.
Available at http://shop.bsigroup.com/en/ProductDetail/?pid=000000000030171836.

BSI. Asset Management Part 2: Guidelines for the application of PAS 55-1. British Standards Institute, Publicly Available Specification 55-2 (PAS 55-2), 2008.
Available at http://shop.bsigroup.com/en/ProductDetail/?pid=000000000030187096.

Cambridge Systematics, Inc., Parsons Brinckerhoff Quade and Douglas Inc., Roy Jorgensen Associates Inc., and Paul D. Thompson, Transportation Asset Management Guide, American Association of State Highway and Transportation Officials, 2002.
Available at http://downloads.transportation.org/amguide.pdf.

Cambridge Systematics, Inc. Pontis 4.3 Technical Manual. American Association of State Highway and Transportation Officials, 2003.

Cambridge Systematics, Inc., Boston Strategies International, Inc., Gordon Proctor and Associates, and Michael J. Markow. Target-Setting Methods and Data Management to Support Performance-Based Resource Allocation by Transportation Agencies. National Cooperative Highway Research Program Report 666. Transportation Research Board of the National Academies, 2010.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_666.pdf.

Committee on Increasing National Resilience to Hazards and Disasters, and Committee on Science, Engineering, and Public Policy. Disaster Resilience: a National Imperative. Washington: The National Academies Press, 2012.
Available at http://www.nap.edu/download.php?record_id=13457.

Connor, Billy, and James Harper. “How vulnerable is Alaska’s transportation to climate change?” TRNews Volume 284, Jan-Feb 2013.
Available at http://ine.uaf.edu/wp-content/uploads/2013/03/TRN284_ConnorHarper_pp23-29.pdf.

CTC and Associates. Asset Management for Retaining Walls. Minnesota Department of Transportation Report TRS 1305, 2013.
Available at http://www.dot.state.mn.us/research/TRS/2013/TRS1305.pdf.

Czerniak, Robert. Collecting, Processing, and Integrating GPS data into GIS. National Cooperative Highway Research Program Synthesis 301. Transportation Research Board of the National Academies, 2002.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_301.pdf.

DeMarco, Matthew, David Keough, and Stephen Lewis. Retaining Wall Inventory and Assessment Program (WIP): National Park Service Procedures Manual. Federal Highway Administration Report FHWA-CFL/TD-10-003, 2010.
Available at

http://www.cflhd.gov/programs/techDevelopment/geotech/WIP/01_retaining_wall_inventory_condition_assessment_program.pdf.

Fay, Laura, Michelle Akin, and Xianming Shi. Cost-Effective and Sustainable Road Slope Stabilization and Erosion Control. National Cooperative Highway Research Program Synthesis 430, Transportation Research Board of the National Academies, 2012.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_430.pdf.

FHWA. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, US Federal Highway Administration report FHWA-PD-96-001, 1995.
Available at http://www.fhwa.dot.gov/bridge/mtguide.pdf.

FHWA. Life Cycle Cost Analysis Primer. US Federal Highway Administration, 2002.
Available at http://isddc.dot.gov/OLPFiles/FHWA/010621.pdf.

FHWA. Highway Economic Requirements System – State Version: Technical Report. US Federal Highway Administration, 2005.
Available at http://www.fhwa.dot.gov/asset/hersst/pubs/tech/TechnicalReport.pdf.

FHWA. Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities: Report 1. US Federal Highway Administration Report FHWA-HIF-12-035, 2012.
Available at http://www.fhwa.dot.gov/asset/pubs/hif12035.pdf.

FHWA. Risk-Based Transportation Asset Management: Managing Risks to Networks, Corridors, and Critical Structures: Report 4. US Federal Highway Administration Report FHWA-HIF-13-017, 2013a.
Available at http://www.fhwa.dot.gov/asset/pubs/hif13017.pdf.

FHWA. Economic Analysis Primer: Benefit-Cost Analysis. US Federal Highway Administration, 2013b.
Available at http://www.fhwa.dot.gov/infrastructure/asstmgmt/primer05.cfm.

FHWA. Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets: Report 5. US Federal Highway Administration Report FHWA-HIF-13-018, 2013c.
Available at http://www.fhwa.dot.gov/asset/pubs/hif13018.pdf.

FHWA. Status of the Nation's Highways, Bridges, and Transit: Conditions and Performance: Report to Congress. US Federal Highway Administration, 2013d. (Updated biennially.) Available at file:///C:/~~Type/Asset%20Mgmt/Report%20to%20the%20Congress%20on%20Conditions%20and%20Performance%20cp2013.pdf.

FHWA. Notice of Proposed Rule-Making on National Performance Management Measures. Federal Register 80:2, Pages 386-393. Federal Highway Administration. January 5, 2015.
Available at http://www.gpo.gov/fdsys/pkg/FR-2015-01-05/pdf/FR-2015-01-05.pdf.

FHWA. Notice of Proposed Rule-Making on Transportation Asset Management Plans. Federal Register 80:34, Page 9232 and 9236. Federal Highway Administration. February 20, 2015.
Available at http://www.gpo.gov/fdsys/pkg/FR-2015-02-20/pdf/2015-03167.pdf.

Flintsch, Gerardo W., and J.W. Bryant Jr. Asset Management Data Collection for Supporting Decision Processes. Federal Highway Administration 2006.
Available at http://www.fhwa.dot.gov/asset/dataintegration/if08018/assetmgmt_web.pdf.

GASB. Basic Financial Statements — and Management's Discussion and Analysis — for State and Local Governments. Government Accounting Standards Board Statement 34. http://www.gasb.org, 1999.

Gerber, Travis M. Assessing the Long-Term Performance of Mechanically-Stabilized Earth Walls. National Cooperative Highway Research Program Synthesis 437, Transportation Research Board of the National Academies, 2012.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_437.pdf.

Gordon, Mark, George Jason Smith, Paul D. Thompson, Hyun-A Park, Frances Harrison, and Brett Elston. AASHTO Transportation Asset Management Guide, Volume 2: A Focus on Implementation. American Association of State Highway and Transportation Officials. Prepared under NCHRP Project 08-69, 2011.
Available at https://bookstore.transportation.org/item_details.aspx?id=1757.

Hawk, Hugh. Bridge Life Cycle Cost Analysis. National Cooperative Highway Research Program Report 483, Transportation Research Board of the National Academies, 2003.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_483a.pdf.

HDR. Economic Impact of Rockslides in Tennessee and North Carolina. Appalachian Regional Commission, 2010.
Available at http://www.arc.gov/assets/research_reports/EconomicImpactofRockslidesinTNandNC.pdf.

Hearn, George. Feasibility of a Management System for Retaining Walls and Sound Barriers. Prepared for the Colorado Department of Transportation, Report CDOT-DTD-R-2003-8, 2003.
Available at http://ttap.colostate.edu/downloads/library/CDOT/CDOT-DTD-R-2003-8.pdf.

Hearn, George, Paul D. Thompson, Walter Mystkowski, and William Hyman. Framework for a National Database System for Maintenance Actions on Highway Bridges. National Cooperative Highway Research Program Report 668, Transportation Research Board of the National Academies, 2010.
Available at http://www.trb.org/Main/Blurbs/164203.aspx.

Hensing, David J., and Shahed Rowshan. Roadway Safety Hardware Asset Management Systems Case Studies. Report FHWA-HRT-05-073. Federal Highway Administration, 2005.
Available at http://www.fhwa.dot.gov/publications/research/safety/05073/index.cfm.

Hughes, J.F. and K. Healy. Measuring the resilience of transport infrastructure. New Zealand Transport Agency research report 546. 2014.
Available at http://www.nzta.govt.nz/resources/research/reports/546/docs/546.pdf.

Johnston, David W., C. Chen, and Imad Abed-Al-Rahim. Developing User Costs for Bridge Management Systems. Transportation Research Circular 423, Transportation Research Board of the National Academies, 1994.
Available at http://pubsindex.trb.org/view.aspx?id=382196.

Kim, Y. Richard, Joseph E. Hummer, Mohammed Gabr, David Johnston, B. Shane Underwood, Daniel J. Findley, and Christopher M. Cunningham. Asset Management Inventory and Data Collection: Final Report. North Carolina Department of Transportation Report FHWA/NC/2008-15, 2009.
Available at http://www.ncdot.gov/doh/preconstruct/tpb/research/download/2008-15finalreport.pdf.

Lea. Modeling Road User Effects in HDM-4. International Study of Highway Development and Management Tools (ISOHDM). Prepared for Asian Development Bank by N.D. Lea International Ltd. 1995.
Available at http://www.lpcb.org/index.php/component/docman/doc_view/468-1995-modelling-road-user-and-environmental-effects-in-hdm-4?Itemid=32.

Lefler, Nancy, Forrest Council, David Harkey, Daniel Carter, Hugh McGee, and Michael Daul. Model Inventory of Roadway Elements – MIRE, Version 1.0. US Federal Highway Administration Report FHWA-SA-10-018, 2010.
Available at http://www.mireinfo.org/.

Levina, Ellina and Dennis Tirpak. Adaptation to change: Key terms. Organization for Economic Cooperation and Development. Report JT03208563, 2006.
Available at http://www.oecd.org/env/cc/36736773.pdf.

Loehr, J. Eric, Kristen Sanford Bernhardt, and Daniel R. Huaco. Decision Support for Slope Construction and Repair Activities: An Asset Management Building Block. Missouri Department of Transportation Report RDT 04-006, 2004.
Available at http://library.modot.mo.gov/RDT/reports/Ri00014/RDT04006.pdf.

Mallela, Jagannath, and Suri Sadasivam. Work Zone Road User Costs: Concepts and Applications. US Federal Highway Administration Report FHWA-HOP-12-005, 2011.
Available at http://ops.fhwa.dot.gov/wz/resources/publications/fhwahop12005/fhwahop12005.pdf.

Markow, Michael J., Managing Selected Transportation Assets: Signals, Lighting, Signs, Pavement Markings, Culverts, and Sidewalks, National Cooperative Highway Research Program Synthesis 371, Transportation Research Board of the National Academies, 2007.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_371.pdf.

Markow, Michael J. Engineering Economic Analysis Practices for Highway Investment. National Cooperative Highway Research Program Synthesis 424, Transportation Research Board of the National Academies, 2012.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_424.pdf.

Mn/DOT. Benefit/Cost Analysis for Transportation Projects, 2013.
Available at http://www.dot.state.mn.us/planning/program/benefitcost.html.

Mote, Phil, Jason Ideker, Miguel Figliozzi, Ming Lee, and John McArthur. Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska. Washington State Department of Transportation, Report OTREC-RR-12-01, WA-RD 772.1, 2012.
Available at http://www.wsdot.wa.gov/research/reports/fullreports/772.1.pdf.

MTO. Ontario Structure Inspection Manual (OSIM). Ontario Ministry of Transportation, 2000.
Available at http://www.mto.gov.on.ca/english/bridges/frequently-asked-questions.shtml#nine.

NAMS Steering Group. International Infrastructure Management Manual (IIMM). National Asset Management Steering Committee, New Zealand, 2006.
Available at http://www.nams.org.nz/digitiseshop/prod-67/2011-International-Infrastructure-Management-Manual.htm.

Nicholson, D.T. "Hazard assessment for progressive, weathering-related breakdown of excavated rock slopes." Quarterly Journal of Engineering Geology and Hydrogeology, Volume 37, 2004.
Available at http://trid.trb.org/view.aspx?id=749481.

Ogle, Jennifer H. Technologies for Improving Safety Data. National Cooperative Highway Research Program Synthesis 367, Transportation Research Board of the National Academies, 2007.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_367.pdf.

Pack, Robert T., Ken Boie, Stoney Mather, and Jamie Farrell. UDOT Rockfall Hazard Rating System: Final Report and User's Manual. Utah Department of Transportation Report UT-06.07, 2006.
Available at http://www.udot.utah.gov/main/uconowner.gf?n=7863418259216350.

Proctor, Gordon, Hyun-A Park, Shobna Varma, and Frances Harrison. Beyond the Short-Term: Transportation Asset Management for Long-Term Sustainability, Accountability, and Performance. US Federal Highway Administration Report FHWA-IF-10-009, 2010.
Available at http://www.fhwa.dot.gov/asset/10009/tam_topr806.pdf.

Shepard, Richard W., & Michael Johnson. "California Bridge Health Index: A Diagnostic Tool to Maximize Bridge Longevity, Investment". *TR News* 215, 2001.
Available at: http://onlinepubs.trb.org/Onlinepubs/trnews/trnews215full.pdf.

Sobanjo, John O., and Paul D. Thompson. Development of Agency Maintenance, Repair, and Rehabilitation (MR&R) Cost Data for Florida's Bridge Management System: Final Report. Florida Department of Transportation Contract BB-879, 2001.
Available at http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_MNT/FDOT_BB879_rpt.pdf.

Sobanjo, John O., and Paul D. Thompson. Project Planning Models for Florida's Bridge Management System: Final Report. Florida Department of Transportation Contract BC 352-9, 2004.
Available at http://www.dot.state.fl.us/research-center/completed_proj/summary_mnt/fdot_bc352_09rpt.pdf.

Sobanjo, John O., and Paul D. Thompson. Development of Risk Models for Florida's Bridge Management System: Final Report. Florida Department of Transportation Contract BDK83 977-11, 2013.
Available at http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_MNT/FDOT-BDK83-977-11-rpt.pdf.

Stanley, David A. "Asset management in a world of dirt." TR News 277, Nov-Dec 2011.
Available at http://www.fhwa.dot.gov/asset/pubs/trn277.pdf.

Stanley, David A. and Lawrence A. Pierson. "Geotechnical asset management performance measures for an unstable slope management program." Sixty-second Highway Geology Symposium, 2011.
Available at http://www.highwaygeologysymposium.org/uploads/pastmeetings/62_hgs.pdf.

Task Force 45. AASHTO-AGC-ARTBA Joint Committee Asset Management Data Collection Guide: Task Force 45 Report. American Association of State Highway and Transportation Officials publication TF-45-1, 2006.
Available at https://bookstore.transportation.org/item_details.aspx?ID=389.

Thompson, Paul D., Fazil T. Najafi, Roberto Soares, and Hong Jae Choung. Florida DOT Pontis User Cost Study: Final Report. Florida Department of Transportation, 1999.
Available at http://www.pdth.com/images/fdotuser.pdf.

Thompson, Paul D., Kevin M. Ford, Mohammad H.R. Arman, Samuel Labi, Kumares Sinha, and Arun Shirolé. Estimating Life Expectancies of Highway Assets. National Cooperative Highway Research Program Report 713, Transportation Research Board of the National Academies, 2012.
Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_713v1.pdf.

Thompson, Paul D. Enterprise Transportation Asset Management: Synthesis and Work Plan, Final Report. Prepared for the Alaska Department of Transportation and Public Facilities, 2013.
Available at
http://www.dot.state.ak.us/stwddes/asset_mgmt/assets/enterprise_tam_workplan_final.pdf.

TransTech Management, Inc. Strategic Performance Measures for State Departments of Transportation: Final Report. National Cooperative Highway Research Program Project 20-24(20), Transportation Research Board of the National Academies, 2003.
Available at http://downloads.transportation.org/HCE-1.pdf.

Turner, A. Keith, and Robert L. Schuster, editors. Rockfall Characterization and Control. Transportation Research Board of the National Academies, 2012.
Available at http://www.trb.org/Main/Blurbs/167065.aspx.

Verhoeven, Jack and Gerardo Flintsch. "Generalized framework for developing a corridor-level infrastructure health index." Paper submitted for presentation at the 2011 Transportation Research Board Annual Meeting, 2011.
Available at http://docs.trb.org/prp/11-3281.pdf.

Vessely, Mark. Geotechnical Asset Management: Implementation Concepts and Strategies. Federal Highway Administration Report FHWA-CFL/TD-13-003, 2013.
Available at
http://www.cflhd.gov/programs/techDevelopment/geotech/GAM/documents/GeotechnicalAssetManagementImplementationConceptsAndStrategies.pdf.

WSDOT. WSDOT's Unstable Slope Management Program. Brochure, 2010.
Available at http://www.wsdot.wa.gov/NR/rdonlyres/7D456546-705F-4591-AC5B-7E0D87D15543/78408/UnstableSlopeFinaFolioWEBSMALL.pdf.

Zaniewski, John P., Gary E. Elkins, and Patrick R. Flanagan. An Algorithm for User Cost Calculations in a Pavement Management System. Proceedings of the First North American Pavement Management Conference, Toronto, 1985.
Available at http://www.pavementmanagement.org/ICMPfiles/1985025.pdf.

Zimmerman, Kathryn, and Marshall Stivers. A Model Guide for Condition Assessment Systems: Final Report. National Cooperative Highway Research Program Project 20-07, Task 206. Transportation Research Board of the National Academies, 2007.
Available at http://maintenance.transportation.org/Documents/Final%20Report%2020-07%20Task%20206-2.pdf.