# ALBERTA TRANSPORTATION GEOTECHNICAL ASSET MANAGEMENT (GAM) FRAMEWORK DEVELOPMENT, GAM PLANNER APPLICATION AND PILOT STUDY

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## Abstract

Tetra Tech Canada Inc. was retained by Alberta Transportation (AT) to assist in the development of a risk-based Geotechnical Asset Management (GAM) framework and pilot study, with the vision of transforming AT’s current Geohazard Risk Management Program (GRMP) into a GAM program. The main objectives of the study were to develop a GAM framework for managing selected geotechnical assets located along the Provincial highway system, and to develop a spreadsheet tool for implementing this framework to a pilot-scale inventory of 27 geotechnical assets. The intent of the GAM framework development was to enhance AT’s ability to effectively prioritize, measure, and manage life-cycle investments in assets such as slopes, embankments, retaining walls and subgrades, based on performance expectations and risk tolerance. The GAM Framework Development and Pilot Study was undertaken in a manner consistent with the methodology and recommendations of NCHRP Report 903: Geotechnical Asset Management for Transportation Agencies (2019), which includes a supporting computational tool implemented in Microsoft Excel, that was customized as part of the project. The tool includes economic analyses based on annual monetized risk and life-cycle costs over a 50-year time period, through monetizing the asset-specific costs and benefits associated with the recommended treatment, applied in the optimal year. A collaborative and highly-interactive approach was essential to the project delivery, with AT’s Geotechnical Asset Management Specialist involved as one of the key team members during all stages of the project. The customized “GAM Planner” application provides an integrated solution for collecting, storing, and managing information on Alberta’s geotechnical highways assets, in one Excel-based application which can be used for capital planning and the prioritization of rehabilitation projects on an annual basis. The GAM Planner was modified from the original NCHRP tool, to reflect AT's agency-specific requirements regarding inventory, treatments, inspection requirements, site-specific user cost model, risk-based life cycle plan, incorporation of monetized risk, site-specific traffic, site-specific detour length, provincial highway classification, field inspection report, and other additional enhancements.

# 1.0 INTRODUCTION

Transportation Asset Management (TAM) is a strategic and systematic process focused on business and engineering practices for allocating resources to assets throughout their lifecycles (AASHTO, 2020). In simple terms, asset management is the process of making decisions about the use and care of infrastructure, to deliver services in a way that considers current and future needs, manages risks and opportunities, and makes the best use of resources (Alberta Municipal Affairs, 2015).

The management of bridge and pavement assets has for many years garnered significant attention by transportation agencies, while the management of geotechnical assets such as retaining walls, slopes, embankments, and subgrades has received lesser attention. Traditionally, geotechnical assets have often been viewed as an unpredictable liability to transportation operations, with unforeseen failures causing traffic disruptions, delays, damage to other infrastructure, and safety impacts. Geotechnical (earth) assets are, however, vital to the successful operation of transportation systems and present an opportunity for agency owners and operators to realize economic benefits through proactive, risk-based management of these assets. Implementing asset management principles commonly allows agencies to shift from reacting to failures as they occur, to proactively and systematically prioritizing work, maintaining assets in acceptable condition, and identifying cost-effective treatments to prolong life (NCHRP, 2019).

Tetra Tech Canada Inc. (Tetra Tech) was retained by Alberta Transportation (AT) to provide engineering consulting services in support of transforming AT's current Geohazard Risk Management Program (GRMP) into a Geotechnical Asset Management (GAM) program. The objectives of the GAM Framework Development and Pilot Study consisted of 1) Developing a GAM Framework for managing current and future geotechnical assets located along the Provincial highway system, based on risk and life cycle cost considerations; and 2) Applying this Framework to a pilot-scale inventory of 27 geotechnical assets identified by AT. Tetra Tech and AT’s geotechnical specialists (collectively referred to as "the Project Team") carried out all phases in cooperation. The collaborative approach ensured that the project deliverables were customized to AT’s existing work flows and agency-specific needs, and that both parties were equally invested in the success of the innovative outcomes.

# 2.0 BACKGROUND

AT’s strategic mandate is to support the province’s economic, social and environmental success by building and maintaining a safe and efficient transportation system. As part of this mandate, AT owns and maintains the geotechnical assets which are located within the provincial highway right-of-way, and which may impact areas inside and outside the right-of-way. These assets include natural and constructed soil and rock slopes, earth embankments, and geotechnical structures such as retaining walls. Geohazards, such as landslides, erosion sites, and problematic subgrade locations, are also considered to be geotechnical assets in the sense that future capital expenditures are required to maintain or repair these sites.

AT’s current GRMP was established in 1999 and consists of an inventory of approximately 500 documented geohazard sites. Of these, approximately 250 are active sites which pose ongoing risks to the safe and efficient operation of Alberta’s highways. The remaining sites represent geotechnical features which are currently inactive or have been repaired. Unstable soil slopes and embankments make up approximately 75% of the active GRMP inventory, with unstable subgrades, retaining walls and rock slopes comprising the remaining 25%.

AT and their geotechnical consultants conduct recurring field inspections and instrumentation monitoring at the active sites in the GRMP inventory. Based on the findings of the field inspections, each site is assigned a relative Risk Level (RL) rating, to assist in prioritizing candidate mitigation projects for capital repairs. While the GRMP risk level rating system provides a relative ranking of sites for remediation, it does not facilitate cross-asset comparisons with other capital projects competing for funding, nor strategic decision making based on benefit-cost ratios, monetization of risk, life-cycle deterioration modelling, or forecasting of future needs.

The intent of the GAM framework development is to build upon AT's existing GRMP, applying an asset management lens to effectively prioritize, measure, and manage life-cycle investments in natural and constructed GAs such as slopes, embankments, retaining walls and subgrades, based on performance expectations and risk tolerance. This process requires a knowledge of the age, condition, and deterioration rates of the assets, and the ability to undertake analyses related to life cycle costs, cost-benefit objectives, risk management, and investment strategies at the site level and the inventory level. One of the key objectives outlined in AT's 2022-25 Business Plan is the use of asset management principles to support strategic decision-making for implementing capital maintenance investments, which are expected to amount to approximately $600M in 2022-23 (Government of Alberta, 2022). In support of this objective, AT's Technical Standards Branch has recently drafted the Department's first TAM Plan, which includes pavements, bridges, and geotechnical assets.

## 3.0 LITERATURE REVIEW

Processes for managing risks to linear infrastructure posed by geohazards are relatively well established within the engineering community and have been used by AT since 1999 (see, for example, Tappenden and Skirrow (2020), and Vessely et al. (2019). GAM takes these geohazard risk management processes a step further by: including constructed geotechnical assets in addition to natural hazards in the inventory, developing deterioration models specific to geotechnical assets, applying these models with unit cost estimates to forecast future risk levels and funding needs, and estimating the optimal timing and benefit-cost ratio of interventions (see for example Anderson et al. (2017), NCHRP (2012), and Thompson (2017)).

Since 2012, TAM has been mandated in the US through the US Federal authorization, *Moving Ahead for Progress in the 21st Century Act* (MAP-21), and its current successor, the *Fixing America's Surface Transportation Act* (FAST Act). In order to qualify for Federal funding, all US State Departments of Transportation (DOT) are required to submit risk-based Asset Management Plans for bridges and pavements on the National Highway System. They are also encouraged (though not required) to prepare AMP's for ancillary assets located within the highway right-of-way, including geotechnical assets. To support the inclusion of geotechnical assets in an agency's TAM plan, NCHRP Report 903 provides a research overview (NCHRP, 2019), implementation manual (NCHRP, 2019) and an Excel-based "GAM Planner" tool for agencies seeking to establish GAM programs.

The Colorado Department of Transportation (CDOT) has also recently implemented a TAM Plan that incorporates geotechnical assets and geohazards (Anderson, Vessely, & Ortiz, 2017). CDOT classifies retaining walls as geotechnical assets, and inspects the visible elements of the walls based on the National Bridge Inventory (NBI) ratings. Slopes, embankments and subgrades are managed together as geohazards, considering threat likelihood as an annual probability of failure, and monetized consequences to highway mobility, maintenance and safety. The total risk is expressed in dollars to facilitate project prioritization, and to demonstrate a favourable benefit-cost ratio for certain proactive interventions (Anderson, Vessely, & Ortiz, 2017).

The Ohio Department of Transportation (ODOT) has an asset management system that includes approximately 18,000 inventoried geohazards (landslides, rock fall sites and abandoned underground mines) in a publicly-accessible geographic information system (GIS) online platform (Ohio Department of Transportation, 2022). Relative risk "tiers" (on a scale of 1-4) are used to determine the frequency of re-inspection, and the priority for repair. Repaired sites are not retired from the inventory, but are included as assets with expected future maintenance and rehabilitation/replacement needs (Merklin, 2020).

In 2017, the Alaska Department of Transportation & Public Facilities (Alaska DOT) published a comprehensive GAM Plan for slopes, embankments, retaining walls and material (borrow) sites, with simple Markov deterioration models to aid in management and needs forecasting for geotechnical assets (Thompson, 2017). Simultaneously, another multi-year research was carried out to develop the risk assessment framework for the Alaska DOT, which included an overview of risk-based geotechnical asset management studies. The work included identifying geotechnical risks based on performance objectives, incorporation of risk into the GAM Program, and risk management using benefit-cost and life cycle investment analyses (Vessely M. , 2017). Numerous other jurisdictions and infrastructure owners in the United States and Canada have risk-based management systems in place for specific earth assets, such as retaining wall management systems or rock fall hazard management systems.

Outside of North America, asset management practices across a wide portfolio of assets, including geotechnical assets, are well-established elsewhere. In the United Kingdom, for example, embankments and slopes have been included in risk-based asset management programs for Network Rail and the U.K. Highways Agency since the 1990's (Power et al. (2016), Arup (2010)). Together, these two agencies manage nearly 250,000 slopes and embankments using asset management principles (Vessely, Newton, & Anderson, 2019).

In 2019, the U.S. NCHRP published Report 903: Geotechnical Asset Management for Transportation Agencies, including Vol. 1: Research Overview (NCHRP, 2019), and Vol. 2: Implementation Manual (NCHRP, 2019). The Implementation Manual and accompanying spreadsheet tool (GAM Planner), are considered to represent the State-of-the-Art in the emerging field of geotechnical asset management, and hence were used as the basis for AT's GAM Framework Development and Pilot Study.

## 4.0 METHODOLOGY

The NCHRP Implementation Manual (2019) outlines a clear process to assist agencies in getting started with risk-based GAM, utilizing performance objectives related to asset condition, safety and mobility. While the Implementation Manual provides a straight-forward and simple basis for agencies to begin GAM, the purpose of AT's GAM Pilot Study was to take the NCHRP framework and supporting spreadsheet tool, and to customize it to AT's specific needs and existing work flows, while leveraging the asset inventory and condition information already contained within AT's existing GRMP. The generalized workflow, as outlined in NCHRP (2019), consists of maintaining a comprehensive asset inventory with up-to-date condition measurements, utilizing analytical tools to forecast changes in condition or performance over time, and investment analyses to estimate treatment costs and effectiveness, allowing one to communicate meaningful results and improve their processes over time.

In laying out the Terms of Reference for the GAM Pilot Study in alignment with the NCHRP recommendations, AT decided to focus the study on the specific tasks described in Figure 1.

Tetra Tech proposed the incorporation of **risk monetization** be explored as part of assessing geotechnical asset performance. Monetizing the consequences of adverse performance of a geotechnical asset would allow for quantifying the benefits of investments in geotechnical assets, and the consequences of inaction, while also facilitating comparison across multiple portfolios (e.g., comparing the benefits of investing in a geotechnical asset repair, compared to a highway rehabilitation, for example).

| Defining and Locating Assets | Current Condition | Assess Performance | Investment Analysis | Communicate Results |
|---|---|---|---|---|
| • Recommended a taxonomy that can be applied for consistent classification of AT's existing inventory of geohazard sites / geotechnical assets. | • Modify AT's GRMP Risk Level rating system into a risk-based GAM rating system applicable to the full range of geotechnical assets, incorporating measures of asset condition and consequences to highway safety and efficiency. | • Develop a supporting field inspection form for consistent and repeatable asset condition inspections. | • At the site level, recommend deterioration models and unit treatment costs, for forecasting future asset condition and associated funding requirements.<br>• At the inventory level, develop decision making tools for prioritizing candidate projects based on risk and investment criteria. | • Conduct field inspections at approximately 25 GRMP sites with AT staff, to populate a pilot-scale inventory of GAs.<br>• Implement the tools in an Excel workbook, based on the NCHRP GAM Planner, to demonstrate the utility of GAM at the pilot scale (25 sites). |

**Figure 1: GAM Framework Development and Pilot Study Tasks**

Tetra Tech's overall approach for the GAM framework development and pilot-scale implementation is summarized in the process flow chart below. The flow chart shows the sequence and interdependency of components in the framework. The developed framework is reported in the Geotechnical Asset Management Framework Development report (Waseem, Fung, Reggin, St. Michel, & MacEoin, 2021). The results of pilot-scale implementation in the GAM Planner are presented in Pilot Scale Implementation report (Waseem & Reggin, 2021).

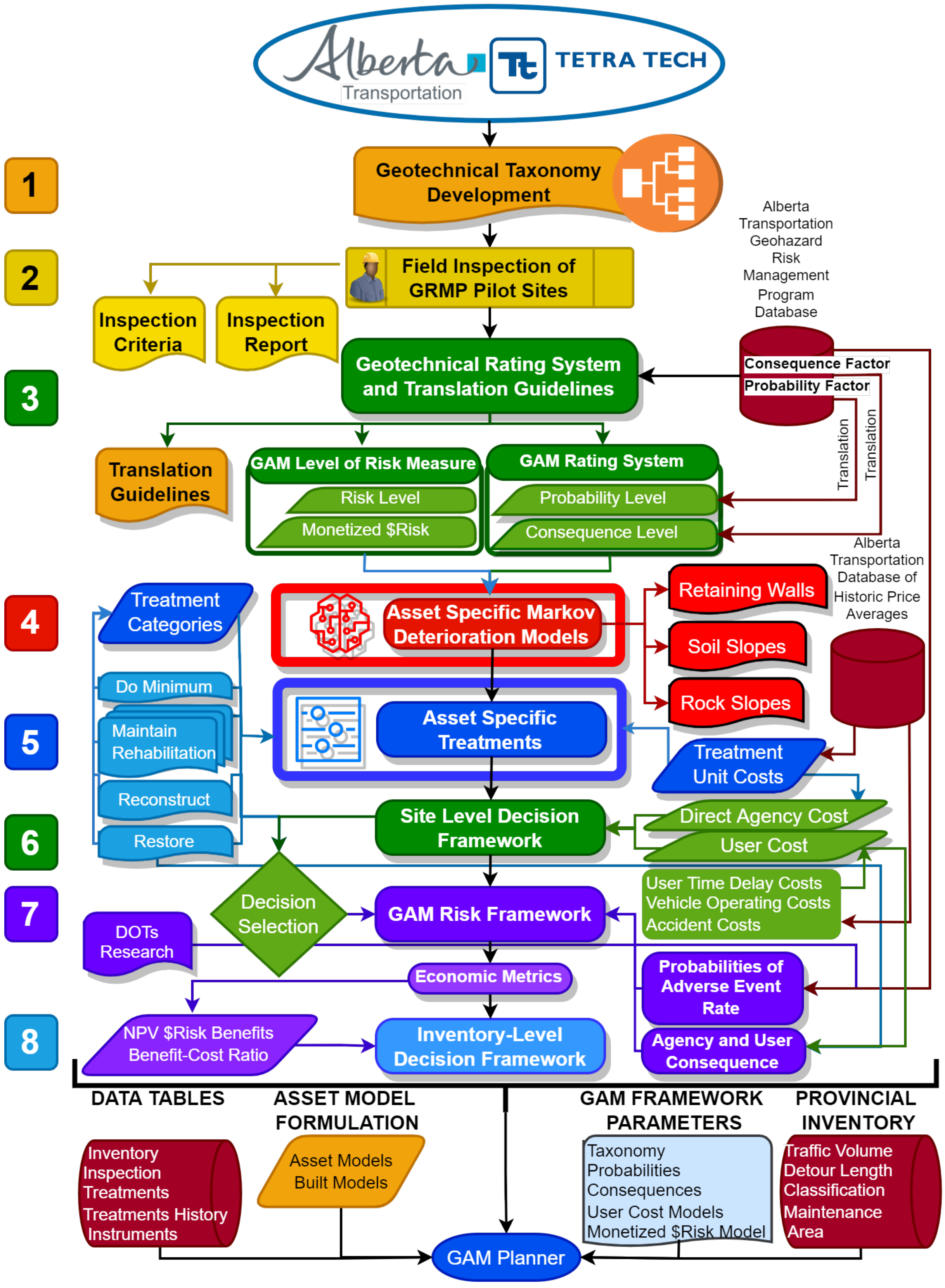


Figure 2: GAM Framework Development Process Flowchart

# 5.0 GEOTECHNICAL ASSETS TAXONOMY DEVELOPMENT

A taxonomy's main objective is to provide a proper classification that facilitates effective asset management and facilitates communications between geologists, engineers in different disciplines, and transportation asset management (Anderson, Schaefer, & Nichols, 2016). The first step in the GAM Framework development was to research and develop appropriate nomenclature for classifying geotechnical assets, for application to AT's inventory of constructed earth assets and natural geohazards. This taxonomy would form the basis for categorizing different types of geotechnical assets, and applying appropriate performance measures, unit costs, and deterioration models.

Geotechnical assets can be defined as physical, independent assets that are present within the highway right-of-way, which contribute to the safe and efficient operation of the transportation corridor (Anderson, Schaefer, & Nichols, 2016).

Anderson, Schaefer & Nicols. (2016) proposed a taxonomy that organizes geotechnical assets into four broad categories: i) slopes, ii) embankments, iii) retaining walls, and iv) subgrades. They suggested that the four categories of geotechnical assets can be further described by their primary material composition, e.g., soil, rock, debris or modified (for slopes).

In considering AT's existing inventory of geotechnical sites, the project team agreed to build the classification schema around Anderson et al.'s (2016) taxonomy, with the additional distinction of 'natural' vs. 'constructed' assets, followed by material composition, and then adding a 'behavior type' classification, as shown in Figure 3. The purpose of the different behaviour type categories was to distinguish between differences in expected deterioration rates between assets. For example, a 'modified' earth embankment would include a highway embankment where spaced H-pile reinforcement has been driven vertically into the embankment to reduce lateral spreading/highway cracking, of which AT has many examples. The expected performance and deterioration of a highway embankment that has been 'modified' in this way would be different from an embankment which has simply been constructed of compacted lifts of engineered fill, in the typical manner of highway construction.

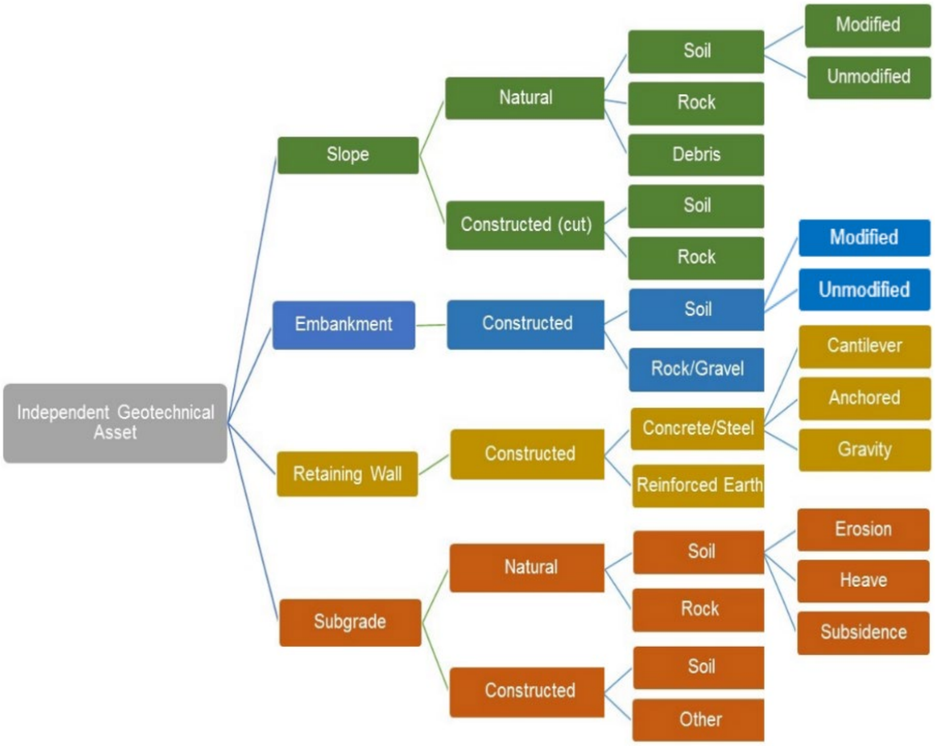


**Figure 3: Proposed Taxonomy of Geotechnical Assets, based upon (Anderson, Schaefer, & Nichols, 2016)**

# 6.0 ASSET CONDITION AND PERFORMANCE ASSESSMENT

## 6.1 GAM Risk Framework

Risk is defined by as the effect of uncertainty on objectives and is expressed in terms of the likelihood of occurrence of an asset failure (or adverse event), and the consequence of damage given such an event. The United States Army Corps of Engineers (USACE, 2011) guide to risk and reliability based engineering for civil structures uses the same generally-accepted definition of risk, as the product of the probability of an adverse event and the economic consequences of the event (Equation 1). The USACE methodology applies the concept of monetizing the consequences of unsatisfactory performance, placing a financial value on such things as loss of use.

$$\$Risk \ = \ P(Adverese\ Event\ Occurrence)\ x\ Monetized\ Consequence \qquad (1)$$

Where:
$P(Adverse\ Event\ Occurrence\ )$ is the probability of adverse event occurrence.
$Monetized\ Consequence$ is the monetary value of the loss in terms of direct cost to owner and indirect cost to the road users as a result of the adverse event.

For risk-based GAM, the condition assessment of the asset is used as a proxy for the likelihood of adverse performance, and the associated consequences are expressed in terms of impacts to the safety and efficiency of the highway. While AT’s existing GRMP Risk Level rating system provides a relative prioritization of sites for capital invention, the risk levels are qualitative in nature; the risk level does not expressly relate the geotechnical asset performance to highway safety and efficiency, nor allow for quantification of the likelihood of adverse performance and monetization of the associated user and owner consequences. The NCHRP GAM Implementation Manual (2019) also provides a qualitative assessment of asset condition and performance consequences. In order to achieve the goal of monetizing the risk associated with the failure (or adverse performance) of a geotechnical asset, the project team developed a customized risk-based rating system, in alignment with the USACE approach. The GAM Risk Rating System describes the annualized probability of adverse performance (based upon the current condition of the geotechnical asset), and the associated consequences to the safety and mobility of the highway (in terms of owner and user costs incurred, based on the magnitude and duration of the associated service disruption).

## 6.2 Probability Rating (Condition State)

The Probability Rating for the asset is defined by the current condition (Excellent to Very Poor), as a proxy for the likelihood of failure or adverse performance in any given year. Field description and characteristics for each asset type and condition rating were developed, and are presented in the report (Waseem, Fung, Reggin, St. Michel, & MacEoin, 2021).

Table 1 presents the condition states, and corresponding estimated mean time between adverse events (in years). An adverse event can be defined as an occurrence from a geotechnical asset that impacts the system's performance (Vessely M. , 2017). This could include isolated and sudden disruptions such as a rockfall reaching the road or debris flow into the ROW, or cumulative impacts arising from ongoing processes such as extremely-slow moving slope failure or deterioration of retaining wall reinforcement. The mean time between adverse events were adapted from AKDOT (Vessely M. , 2017), and modified based on the asset type and condition state, using expert judgement and experience.

The annualized adverse event rate (AAER) can then be calculated from the estimated mean time between adverse events, using the equation below (Vessely M. , 2017). Annualized Adverse Event Rate is the estimated probability that an adverse event will occur during a full year of use, expressed as a percentage.

$$AAER = 1 - e^{-\frac{1}{t}} \tag{2}$$

Where:

$AAER =$ Annualized Adverse Event Rate

$t =$ mean time between adverse events (in years)

### Table 1: Condition States and Annualized Adverse Event Rates

| Asset Type | Condition States | Excellent (1) | Good (2) | Fair (3) | Poor (4) | Very Poor (5) |
|---|---|---|---|---|---|---|
| **Slope (Soil) or Embankment** | Years between adverse events | 50.0 | 30.0 | 7.5 | 3.0 | 0.8 |
| | Annualized adverse event rate | 2% | 3% | 12% | 28% | 74% |
| **Slope (Rock)** | Years between adverse events | 25.0 | 17.5 | 7.5 | 3.0 | 0.8 |
| | Annualized adverse event rate | 4% | 6% | 12% | 28% | 74% |
| **Retaining Wall** | Years between adverse events | 75.0 | 50.0 | 15.0 | 3.0 | 0.8 |
| | Annualized adverse event rate | 1% | 2% | 6% | 28% | 74% |
| **Subgrade** | Years between adverse events | 50.0 | 30.0 | 7.5 | 3.0 | 0.8 |
| | Annualized adverse event rate | 2% | 3% | 12% | 28% | 74% |

As an asset ages, the asset condition deteriorates over time. As a result, the frequency of traffic disruptions may increase. The annualized adverse event rate, therefore, increases with as the asset condition deteriorates. The AAER shown in Table 1 are incorporated into the customized GAM Planner for AT's use. The probabilities of failure, or adverse event rates, can be calibrated to actual performance as data on maintenance work frequencies and event tracking are compiled. Future climate change impacts could also potentially be incorporated into future versions of the deterioration models.

## 6.3 Consequence Rating

The Consequence Rating for the asset is defined by the potential impacts of adverse performance on highway safety, efficiency (indirect costs to the user), and direct costs to the owner (maintenance, rehabilitation and reconstruction). The five Consequence States that were developed are: Negligible, Minor, Moderate, Major, and Critical, as shown in Table 2. The purpose of the consequence rating scale was to facilitate the monetization of the impacts to the highway associated with the adverse performance of a geotechnical asset. Therefore, the categories focus on categorizing the number of traffic lanes that would likely be affected, the duration of delay, or, for an event rendering the full highway impassable, the duration of the detour. So, for example, will the impacts of a rock fall from a deteriorating cut slope be limited to the accumulation of debris within the ditch ('Negligible'), or will it result in the temporary closure of one lane in a multi-lane highway ('Moderate')? In order to monetize the consequences, as shown in Table 2, assumptions are required as to the duration of each consequence, based on how long the delay or detour would remain in place until maintenance actions, or engineering design and construction, could be completed.

### Table 2: GAM Rating System Consequence States, Consequence Factors and Impact Type

| Consequence State | Impact Severity | Description | Impact |
|---|---|---|---|
| Negligible | No Impact | Disruption confined to the shoulder or right-of-way; unlikely to impact traffic flow. | Speed restrictions or single lane closure for up to 1 day. |
| Minor | Shoulder (Minor Delay) | Disruption would require maintenance work; majority of traffic lanes would remain open during repair. | Speed restrictions or single lane closure for up to 1 week. |

| | | | |
|---|---|---|---|
| Moderate | One Lane (Moderate Delay) | Disruption would require rehabilitation, resulting in delays for extended duration. | Speed restrictions or single lane closure for up to 6 months (during engineering design and construction). |
| Major | One Direction (Major Delay) | Disruption would require rehabilitation or reconstruction, resulting in alternating traffic for extended duration. | Alternating traffic for up to 6 months (during engineering design and construction). |
| Critical | Both Directions (Detour) | Disruption would render road impassible, resulting in detour for extended duration, while reconstruction takes place. | Full road closure with traffic detour for up to 6 months (during engineering design and construction). |

### 6.3.1 Monetized Consequences

The consequences shown in Table 2 can be monetized based on the user and owner costs associated with each scenario.

The direct owner costs of a highway service disruption consist of the cost for restoring the asset, with an increase to account for the higher costs for design and construction on an emergency basis compared to planned work. The owner costs for each consequence scenario are determined by the GAM Planner tool, based on the asset type, condition, and unit price averages.

The indirect user costs of a highway service disruption can be calculated based on the specific consequence scenario. The user costs depend on type of disruption (work zone delay or detour), detour length, number of days to mitigate failure consequence, traffic volume, and percentage commercial traffic. Depending on the type of disruption (‘Negligible’ to ‘Critical’), the user costs may consist of time delay costs, incremental vehicle operating costs, and an incremental increase in accident costs determined by the length of the detour. Time delay costs are the opportunity costs incurred due to additional time spent completing a journey because of a work zone delay or detour. Consistent with AT’s bridge management system, a value of $20/hr was assigned to user time costs for passenger vehicles, and $38/hr to user time costs for commercial vehicles. User time costs will be incurred in all consequence scenarios as a result of reduced speed through the work zone (Negligible/Minor/Moderate consequence scenarios), queuing time for alternating traffic (Major consequence scenario), or additional time required to take a longer detour route (Critical consequence scenario). In determining the vehicle operating costs (VOC’s) associated with each consequence scenario (as a result of speed reductions or detour length), a unit cost of $0.35/km was used for passenger vehicles, and $0.60/km for commercial vehicles. The VOC’s were calculated using site-specific information on the traffic volume and composition (percent commercial traffic compared to passenger vehicles). Based on Provincial statistics for the number of vehicle accidents per highway kilometre, an incremental accident cost was also considered for the ‘Critical’ (detour) consequence scenario. Accident costs are valued at $3M per fatality accident, $100,000 per injury accident, and $10,000 per property damage accident.

The total user costs associated with each of the five consequence scenarios are calculated in the customized GAM Planner tool, and a detailed description of the calculations is included in Tetra Tech’s report (Waseem, Fung, Reggin, St. Michel, & MacEoin, 2021).

## 7.0 ASSET-SPECIFIC DETERIORATION MODELS

Beyond the current asset condition or risk level rating, an important component of asset management is the application of deterioration models. These models allow for forecasting the performance of the asset inventory into future years, facilitating capital budget planning and cost-benefit analyses of intervention options. While adverse geotechnical events may be perceived as uncommon and unpredictable at the local scale, total needs and impacts can be reasonably predicted on an aggregated regional basis, using deterioration models that are specific to geotechnical assets.

The simplest deterioration model using condition state data is a Markov model, which expresses deterioration rates as probabilities of transitions between the possible condition states each year (Thompson, 2017). Markov deterioration models are used in the GAM Planner tool to simulate the change in condition of an asset over time. Markov deterioration models are frequently used in bridge management systems, and also in some pavement management systems as well.

NCHRP (2012) documents the development of Markov deterioration models specifically for geotechnical assets. Table 3 below summarizes the deterioration models developed by the Alaska Department of Transportation for soil slopes, rock slopes, and retaining walls, based primarily on expert elicitation (Thompson, 2017). The models are predicated on an asset condition or risk rating scale which ranges from State 1 ("Very Good", no action needed) to State 5 ("Very Poor", major mitigation required). The transition time shown in Table 3 is the estimated 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; 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.

**Table 3: Markov Deterioration Models for Different Geotechnical Assets (Thompson, 2017)**

| Asset Type | Condition States | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Soil Slopes | Same-state probability | 98.7% | 97.0% | 94.6% | 91.3% | 100.0% |
| | Next-state probability | 1.3% | 3.0% | 5.4% | 8.7% | 0.0% |
| | Median Years to Deteriorate (Years) | 55 | 23.1 | 12.6 | 7.6 | |
| Rock Slopes | Same-state probability | 98.2% | 97.9% | 96.8% | 95.1% | 100.0% |
| | Next-state probability | 1.8% | 2.1% | 3.2% | 4.9% | 0.0% |
| | Median Years to Deteriorate (Years) | 38.3 | 32.5 | 21.2 | 13.7 | |
| Retaining Walls | Same-state probability | 97.3% | 96.7% | 92.0% | 90.8% | 100.0% |
| | Next-state probability | 2.7% | 3.3% | 8.0% | 9.2% | 0.0% |
| | Median Years to Deteriorate (Years) | 25.2 | 20.8 | 8.3 | 7.2 | |

If the transition time is known or estimated, the same-state probability, *pjj*, can be computed using Equation 3 (Thompson, 2017):

$$p_{jj} = 0.5^{\frac{1}{t}} \tag{3}$$

Where:

$j$ is the condition state (before and after 1 year)

$t$ is the transition time in years

$p_{jj}$ is the same state probability one year later in state $j$

This calculation can be repeated as many times as desired in order to extend the inventory condition forecast into the future (Thompson, 2017). The simplified Markov models presented in Table 3 limit the transition of an asset in any given year from one state to the next worse one, and are dependent only on the type and current condition of the asset.

In the GAM Planner tool, the Markov deterioration models are used to calculate transition probability between states in asset-specific matrix for the 25 combinations of probability and consequences states. Asset-specific treatments are recommended by the GAM Planner for each condition state, based on the methodology provided in the NCHRP GAM Implementation Manual (NCHRP, 2019). The treatment with the highest calculated benefit in each condition state is selected as the recommended treatment.

In addition to the deterioration models proposed by Thompson (2017), the NCHRP (2019) study also presents additional Markov deterioration models for soil and rock slopes, embankments, subgrades, and retaining walls. These models were also included in the customized GAM Planner tool for AT’s use.

The NCHRP Markov deterioration models are slightly different than Thompson’s (2017), in that an independent failure probability is included for all condition states. So in addition to transitioning to the next worse state, there is a small probability included in the model of sudden asset failure ($p_{jf}$). The next state probability is therefore computed using the following formula (Equation 4):

$$p_{jk} = 1 - p_{jj} - p_{jf} \tag{4}$$

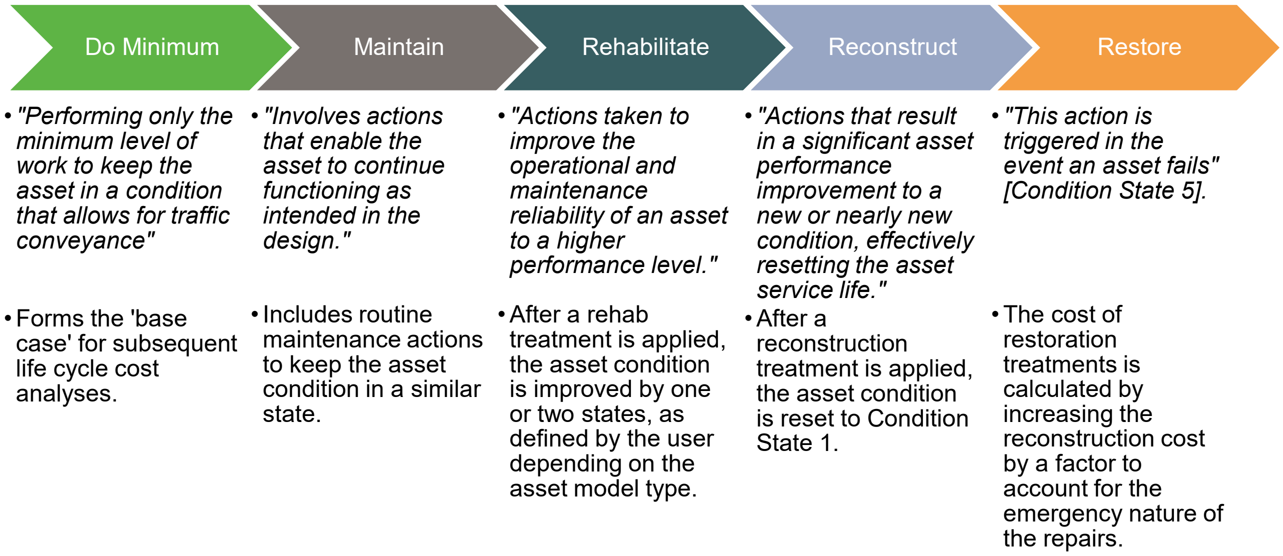
Where:
$p_{jf}$ is the probability in one year of failure in state $j$

In future, it is proposed that as part of AT’s ongoing GAM program development, the Markov deterioration models be calibrated against the Province’s growing inventory of slopes, embankments, retaining walls and subgrades. As asset-specific condition data is collected over time as part of the GAM program, these models can be refined in an evidence-informed manner. One such example is the Florida DOT's development of Markov deterioration models using historical condition state data (Florida State University, 2001).

# 8.0 ASSET TREATMENTS AND UNIT COSTS

## 8.1 Treatment Categories

The GAM Framework consists of five categories of treatments: Do Minimum, Maintain, Rehabilitate (Rehab), Reconstruct (renew), and Restore, which are available for selection in the GAM Planner tool. The team developed several treatments in each category, based on the AT's geotechnical asset management practices and past experience. Unit prices for the different treatments were then assigned by Tetra Tech using Alberta’s unit price averages. The GAM Implementation Manual (NCHRP, 2019) defines the different treatment categories as shown in Figure 4.



| Do Minimum | Maintain | Rehabilitate | Reconstruct | Restore |
|---|---|---|---|---|
| • *"Performing only the minimum level of work to keep the asset in a condition that allows for traffic conveyance"* | • *"Involves actions that enable the asset to continue functioning as intended in the design."* | • *"Actions taken to improve the operational and maintenance reliability of an asset to a higher performance level."* | • *"Actions that result in a significant asset performance improvement to a new or nearly new condition, effectively resetting the asset service life."* | • *"This action is triggered in the event an asset fails" [Condition State 5].* |
| • Forms the 'base case' for subsequent life cycle cost analyses. | • Includes routine maintenance actions to keep the asset condition in a similar state. | • After a rehab treatment is applied, the asset condition is improved by one or two states, as defined by the user depending on the asset model type. | • After a reconstruction treatment is applied, the asset condition is reset to Condition State 1. | • The cost of restoration treatments is calculated by increasing the reconstruction cost by a factor to account for the emergency nature of the repairs. |

**Figure 4: Description of Treatment Categories (from NCHRP 2019).**

The GAM Rating system consists of five probability/condition states and five consequence states; hence an asset can exist in a total of 25 states. The set of treatments (Do Minimum, Maintain, Rehab, Reconstruct, and Restore) that can be performed in each state can be adjusted in the customized GAM Planner tool to include or exclude a treatment option from a condition state. For example, the rehabilitation treatment option can only be applied once the asset reaches “Fair” condition or worse. Similarly, if the asset is in “Very Poor” condition, a Do-Minimum treatment is only considered feasible when the asset consequence Level is Negligible, and is not an available option if the Consequence Level is any greater than Negligible.

## 8.2 Treatment Unit Costs

Asset specific treatment unit costs were input into the GAM Planner tool for each of the treatment categories (Do Minimum, Maintain, Rehab, and Reconstruct). The available treatments in each category were classified by asset type (i.e. embankments, retaining wall, slope, and subgrade), and material composition (debris, rock, soil, soil / rock / other, stabilized earth / steel / concrete). The base construction costs for each treatment were developed utilizing the AT's database of unit price averages for recent highway, bridge and water management construction tenders (August 1, 2015 – November 30, 2020). For treatments where a comparable cost in AT's database was not available (e.g. barriers, vertical inclusions/piles, soil nails/anchors, highway realignment), Tetra Tech estimated unit costs by reviewing other similar construction projects/tenders. For pile walls constructed to stabilize landslides, high-level construction costs were estimated based on published case studies for Alberta (Abdelaziz, Proudfoot, & Skirrow, 2011)

For each geotechnical treatment, engineering costs and additional construction lump sum costs were estimated by applying markup factors to the base construction costs. In addition, a 20% contingency was applied to the estimated unit rate to account for potential unknowns during construction, to arriving at the “total project cost” estimated unit rates. Table 4 lists all treatments for independent geotechnical assets where unit costs were developed. The unit costs are then applied within the GAM Planner tool, based on the specified length of highway affected.

### Table 4: Treatments for Embankment, Retaining Wall, Slope, and Subgrade Assets

| Asset Type | Do Minimum | Maintain | Rehab | Reconstruct |
|---|---|---|---|---|
| Embankment<br>(Soil / Rock / Others) | ▪ Install Signage<br>▪ Pavement Patch<br>▪ Inspection | ▪ Minor Regrading<br>▪ Monitoring System<br>▪ Pavement Patch / Restoration<br>▪ Restore Site Drainage | ▪ Flatten slope<br>▪ Soil replacement<br>▪ Vegetation / Hydroseeding<br>▪ Drainage System | ▪ Ground Improvement<br>▪ Lightweight Fill<br>▪ MSE Wall<br>▪ Realign highway<br>▪ Structural inclusions<br>▪ Toe berm |
| Retaining Wall<br>(Stabilized Earth / Steel / Concrete) | ▪ Install signage<br>▪ Inspection<br>▪ Monitoring system | ▪ Monitoring systems<br>▪ Occasional element replacement<br>▪ Replace / Improve deteriorated wall facing | ▪ Buttress<br>▪ Install anchors | ▪ Ground improvement<br>▪ New Wall<br>▪ Realign highway<br>▪ Structural inclusions |
| Slope | ▪ Install signage<br>▪ Remove debris from road | ▪ Remove debris<br>▪ Replace damaged infrastructure - guardrail, culverts<br>▪ Mesh Fence | ▪ Debris Basins<br>▪ Deflection Berms | ▪ Realign highway |
| Slope (Rock) | ▪ Install signage<br>▪ Remove Rocks<br>▪ Replace / reset damaged fences and railings | ▪ Remove rock<br>▪ Mesh Fence | ▪ Barriers<br>▪ Catchment Ditches<br>▪ Mesh Draping | ▪ Flatten Slope<br>▪ Realign Highway<br>▪ Rock Bolts / Rock Anchors |

| Asset Type | Do Minimum | Maintain | Rehab | Reconstruct |
|---|---|---|---|---|
| | ▪ Inspection | | | |
| Slope (Soil) | ▪ Install signage<br>▪ Remove Soils<br>▪ Replace damaged infrastructure<br>▪ Inspection | ▪ Minor regrading<br>▪ Monitoring system<br>▪ Replace damaged infrastructure - guardrail, signage<br>▪ Restore site drainage<br>▪ Remove Soils from road | ▪ Barriers<br>▪ Flatten slope<br>▪ Vegetation – Hydroseeding<br>▪ Drainage System | ▪ Ground improvement<br>▪ Realign highway<br>▪ Soil nails / anchors<br>▪ Structural inclusions<br>▪ Toe berm |
| Subgrade<br>(Soil / Rock / Others) | ▪ Install signage<br>▪ Pavement restoration<br>▪ Inspection | ▪ Minor riprap repair<br>▪ Pavement restoration | ▪ Regrade ditch<br>▪ Riprap erosion protection (Rehab)<br>▪ Soil replacement<br>▪ Surcharge fill | ▪ Horizontal inclusions<br>▪ Lightweight fill<br>▪ Riprap erosion protection (Reconstruct)<br>▪ Vertical inclusions – piles |

## 8.3 Optimizing Treatment Type and Timing

In quantifying the forecast life cycle costs for the geotechnical assets as they deteriorate over time, the GAM Planner tool automatically selects the treatment category to be applied in any given year (Do Minimum, Maintain, Rehabilitate, Reconstruct, Restore). This is achieved by formulating a linear program which can be solved to determine what actions, if taken, will minimize the asset costs over time. This model is built into the NCHRP GAM Planner tool using the Solver function in Excel. The basic inputs to the model are:

- Set of defined condition states for the asset;
- Set of treatments that can be performed in each state, including a "Do Minimum" treatment (base case);
- Treatment costs and effects;
- Treatment effects are described through a matrix detailing the improvement in condition state, given a specific treatment is performed. The deterioration of the asset is described through the Markov deterioration model and the effects of the "Do Minimum" treatment.
- Discount rate for present-value calculations (4%).

As described in the NCHRP (2019) Implementation Manual, *"The GAM model is a condition-based model that recommends the optimal treatment* to *perform for each of a number of discrete condition states to minimize life-cycle costs of maintaining the* asset. *This approach has been applied previously to a number of asset types, as described in TCRP Report 157: State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit* (TCRP, 2012)."

In order to determine the optimal course of treatment, the model compares the benefits of intervening in any given year against the base case (Do Minimum). As described in the NCHRP (2019) Implementation Manual, the benefit of performing a treatment is the savings that will result from performing the action relative to deferring the work for one decision period (one year). If this difference is non-zero, it will be more cost effective to perform the action than to defer the work. The priority of performing a treatment can be calculated by dividing this benefit by the cost of the treatment. The GAM planner recommends treatments in each of the ten analyzed years based on the GAM Model Formulation.

The asset model is formulated as a linear program and solved using the Excel Solver function; random numbers from 0 to 1 are generated for each asset and year, for use with the Markov deterioration models to simulate changes in condition over time. For example, if the deterioration transition probability for the current state is 5%, the asset is modeled as deteriorating to the next worse condition is the random number generated is between 0 and 0.05. When the treatment actions are applied, the model improves the condition of the asset by the specified number of states.

# 9.0 RISK-BASED ECONOMIC ANALYSIS

## 9.1 50-Year Life Cycle Benefit-Cost Ratio

The prioritization of asset treatment decisions based on life cycle cost and/or investment benefits is fundamental to a functional GAM Framework deployment. An agency's capital budget is often insufficient to implement all recommended treatments at the optimal time, and the asset manager is tasked with prioritizing interventions based on justifiable criteria, such as economic measures.

As part of the customization of the NCHRP (2019) GAM Planner tool, Tetra Tech added a module for calculating the monetized risks and benefits of interventions over a 50-year analysis period. The risk-based economic analysis considered costs and benefits in risk reduction of the recommended treatment to both AT and highway users.

The benefits in the economic analysis are the reduction annualized monetized risk, over the 50 year time period, resulting from implementing the recommended treatment, compared to the “Do Minimum” base case (Equation 5). The "Do Minimum" base case assumes the asset will be left as is and will not be regularly maintained or upgraded over its useful life, and only a minimum level of action will be undertaken on an as-required basis to keep the traffic moving at the asset location. The benefits are incurred over a future period, while most recommended treatment costs are incurred upfront and in the present. All costs are computed in terms of present value (PV) using a discount rate of 4%.

$$BENEFITS = \sum(\$Risk\ for\ \text{"}Do\ Minimum\text{"}\ Strategy) - \sum(\$Risk\ for\ Recomended\ Treatment) \qquad (5)$$

The customized GAM Planner tool calculates the economic metrics for informing risk-based project prioritization decisions, including the monetized benefits of risk reduction achieved by the recommended treatment over a 50-year time period (PV $Benefits in Reduced $Risk), compared to the present value cost (PV Cost) of the recommended treatment (BCR). If the BCR is above one, the strategy is considered cost-effective. When comparing candidate projects, the option with the higher BCR is the more cost-effective one.

The costs considered in the calculation of BCR include direct costs to the agency (the capital cost to AT arising out of repairing/replacing the asset) as well as indirect costs to road users (vehicle operation costs, delay/detour costs, accident costs, as described in Section 6.3.1). The cost of the initial intervention is the capital cost of the recommended treatment. Subsequent downstream costs are expressed in terms of monetized risk.

The benefit-cost ratio was assessed in terms of the following indices:

- **Recommended Treatment PV Cost**: The Present Value Cost is the discounted total expenditures by the Agency in terms of the treatment (strategy) cost during the considered analysis period of 50 years. When comparing similar alternate strategies at an inventory level, the lowest NPV cost strategy is considered the most cost-effective one.
- **Present Value $Risk:** The Present Value $Risk is the discounted total monetary risk of the asset over its life-cycle, due to the probability of unsatisfactory performance and the associated consequences. The Present Value $Risk is calculated for the base case (Do Minimum) treatment

and for the recommended treatment over the analysis period, as **“**Do Minimum PV $Risk”, and “Recommended Treatment PV $Risk”, respectively.

- **Present Value $Benefits in Reduced Risk:** The PV $Benefits in Reduced Risk is the discounted reduction in $Risk due to site-level treatment recommendation compared to the Do Minimum strategy over 50 years.
- **PV $Benefits in Reduced Risk over PV Cost Ratio (BCR):** The numeric ratio expresses the PV $Benefits (in Reduced Risk) of the strategy relative to PV Cost. The strategy with the highest PV $Benefits over PV Cost Ratio is the most cost-effective when comparing alternatives.

The comparison of the BCR indicates the option that maximizes the net benefit. As such, BCR is frequently used to prioritize candidate projects when funding restrictions apply. The 50-year Benefit Cost Ratio was computed in the customized GAM Planner tool for comparison among the twenty five pilot study sites.

# 10.0 PILOT STUDY RESULTS AND RECOMMENDATIONS

## 10.1 Pilot Study Sites

AT selected twenty-seven geotechnical assets from their inventory for inclusion in the Pilot Study, representing a variety of natural and constructed slopes, embankments, retaining walls and subgrades. The twenty-seven assets are located at various sites north-west of Edmonton, Alberta, as shown in Figure 5. The Project Team performed field inspections at ten of the pilot study sites, and desktop review of existing information for the remaining 17 assets. The information collected was utilized to develop a pilot-scale inventory of assets, with location information, probability and consequence ratings, and asset type information (slope, retaining wall, embankment, subgrade). The field visits were used to establish the field inspection criteria and template field inspection forms for facilitating future GAM implementation.

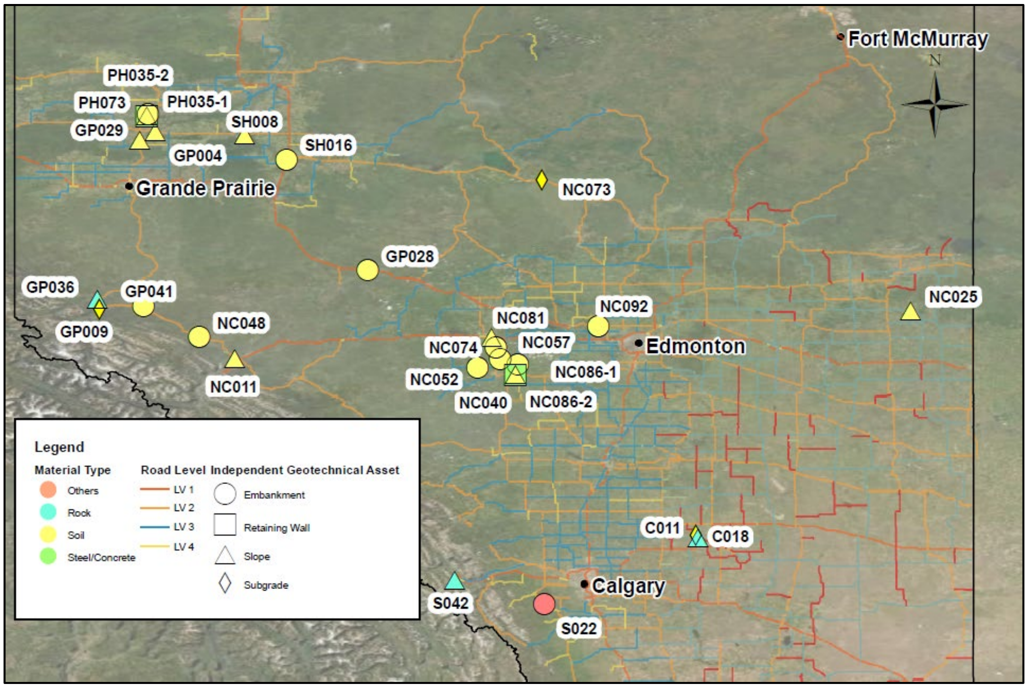


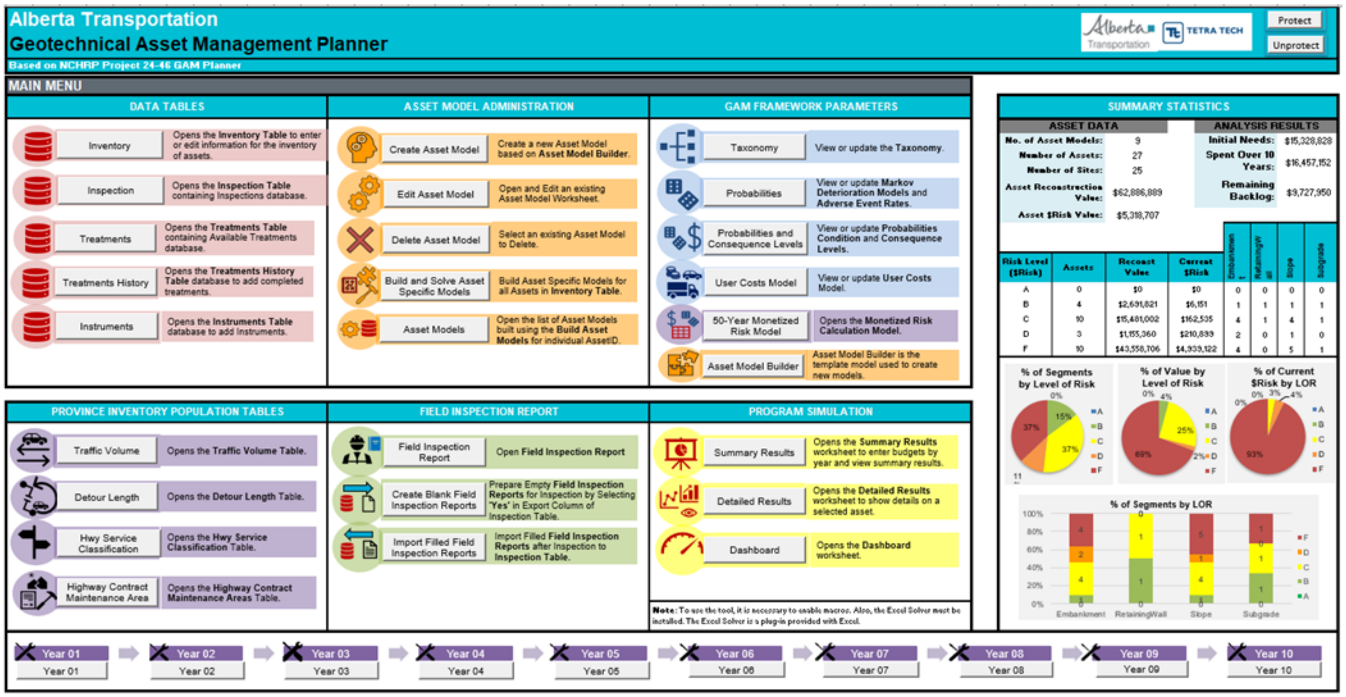
**Figure 5: Location Map of the 25 Pilot Study Sites (27 Assets)**

The Field Level Assessment parameters were developed to include inspection criteria such as Site Location information, Highway Service Classification and Traffic Volume information, Asset Type, Condition and Consequence information, Instrumentation, Current Restrictions/Controls in Place, Site Plans and Photos, etc. A template field inspection report was prepared in Excel, based on the above criteria, and incorporated into the GAM Planner tool.

## 10.2 Customized GAM Planner Interface

The existing NCHRP Project 24-46 Excel-based GAM Planner was used as the foundation for developing the advanced GAM Planner for the AT. The Excel-based GAM Planner tool provides a solution to model assets using a Markov Decision Process to create a life cycle plan for the geotechnical assets. The GAM Planner was modified to reflect the AT's Framework requirements regarding inventory, treatments, inspection requirements, user cost model, risk-based life cycle plan, incorporation of monetized Risk, corridor-specific traffic volumes, detour lengths, provincial highway service classification, field inspection report, and many additional enhancements. A manual for the use of GAM Planner was developed for documentation and training purposes provided in the report (Waseem, Fung, Reggin, St. Michel, & MacEoin, 2021).

As part of the Pilot Study, AT selected twenty-seven geotechnical assets from their existing GRMP inventory, to be entered into the GAM Planner application. The locations of the pilot study sites are shown in Figure 5. The sites were chosen to represent a range of geotechnical assets (soil and rock slopes, embankments, retaining walls and subgrade issues), in a variety of locations and varying states of condition/deterioration. The user interface for the GAM Planner tool which Tetra Tech customized based on NCHRP (2019) is shown in Figure 6 below.



DATA TABLES

| | |
|---|---|
| Inventory | Opens the **Inventory Table** to enter or edit information for the inventory of assets. |
| Inspection | Opens the **Inspection Table** containing Inspections database. |
| Treatments | Opens the **Treatments Table** containing Available Treatments database. |
| Treatments History | Opens the **Treatments History Table** database to add completed treatments. |
| Instruments | Opens the **Instruments Table** database to add Instruments. |

ASSET MODEL ADMINISTRATION

| | |
|---|---|
| Create Asset Model | Create a new Asset Model based on **Asset Model Builder**. |
| Edit Asset Model | Open and Edit an existing Asset Model Worksheet. |
| Delete Asset Model | Select an existing Asset Model to Delete. |
| Build and Solve Asset Specific Models | Build Asset Specific Models for all Assets in **Inventory Table**. |
| Asset Models | Open the list of Asset Models built using the **Build Asset Models** for individual AssetID. |

GAM FRAMEWORK PARAMETERS

| | |
|---|---|
| Taxonomy | View or update the Taxonomy. |
| Probabilities | View or update Markov Deterioration Models and Adverse Event Rates. |
| Probabilities and Consequence Levels | View or update Probabilities Condition and Consequence Levels. |
| User Costs Model | View or update User Costs Model. |
| 50-Year Monetized Risk Model | Opens the **Monetized Risk Calculation Model**. |
| Asset Model Builder | Asset Model Builder is the template model used to create new models. |

PROVINCE INVENTORY POPULATION TABLES

| | |
|---|---|
| Traffic Volume | Opens the **Traffic Volume Table**. |
| Detour Length | Opens the **Detour Length Table**. |
| Hwy Service Classification | Opens the **Hwy Service Classification Table**. |
| Highway Contract Maintenance Area | Opens the **Highway Contract Maintenance Areas Table**. |

FIELD INSPECTION REPORT

| | |
|---|---|
| Field Inspection Report | Open **Field Inspection Report** |
| Create Blank Field Inspection Reports | Prepare Empty **Field Inspection Reports** for Inspection by Selecting 'Yes' in Export Column of Inspection Table. |
| Import Filled Field Inspection Reports | Import Filled **Field Inspection Reports** after Inspection to **Inspection Table**. |

PROGRAM SIMULATION

| | |
|---|---|
| Summary Results | Opens the **Summary Results** worksheet to enter budgets by year and view summary results. |
| Detailed Results | Opens the **Detailed Results** worksheet to show details on a selected asset. |
| Dashboard | Opens the **Dashboard** worksheet. |

**Note:** To use the tool, it is necessary to enable macros. Also, the Excel Solver must be installed. The Excel Solver is a plug-in provided with Excel.

SUMMARY STATISTICS

ASSET DATA

| | |
|---|---|
| No. of Asset Models: | 9 |
| Number of Assets: | 27 |
| Number of Sites: | 25 |
| Asset Reconstruction Value: | $62,886,889 |
| Asset $Risk Value: | $5,318,707 |

ANALYSIS RESULTS

| | |
|---|---|
| Initial Needs: | $15,328,828 |
| Spent Over 10 Years: | $16,457,152 |
| Remaining Backlog: | $9,727,950 |

| Risk Level ($Risk) | Assets | Recount Value | Current $Risk | Embankment | RetainingWall | Slope | Subgrade |
|---|---|---|---|---|---|---|---|
| A | 0 | $0 | $0 | 0 | 0 | 0 | 0 |
| B | 4 | $2,691,821 | $6,151 | 1 | 1 | 1 | 1 |
| C | 10 | $15,481,002 | $162,535 | 4 | 1 | 4 | 1 |
| D | 3 | $1,155,360 | $210,899 | 2 | 0 | 1 | 0 |
| F | 10 | $43,558,706 | $4,939,122 | 4 | 0 | 5 | 1 |

Figure 6: Customized GAM Planner Tool Interface

## 10.3 Prioritizing Candidate Projects

The risk-based economic analysis of the asset's recommended treatment was carried out for a 50-Year analysis period using the GAM Risk Framework. The risk-based economic analysis provides economic metrics such as current monetized risk and Do Minimum treatment 50-Year monetized risk for assets in terms of the asset condition and safety and mobility consequences. The **PV $Benefits in Reduced Risk over PV Cost Ratio (BCR)** of the recommended major treatments is used to prioritize the Inventory from highest to lowest BCR.

Table 5 shows the risk-based economic metrics of GAM for the twenty-seven analyzed assets, generated by the GAM Planner tool. The BCR results provide good differentiation between the various candidate sites, ranging from a high BCR of 98 to a low BCR of 1. The table values are conditionally colored from red to green, where red is the highest priority and green are the lowest priority. The results of the prioritization analysis within the GAM Planner tool can be utilized by AT's asset manager, in conjunction with the agency's organizational objectives, financial constraints, and risk tolerance, to arrive at a justifiable list of prioritized investments in geotechnical assets.

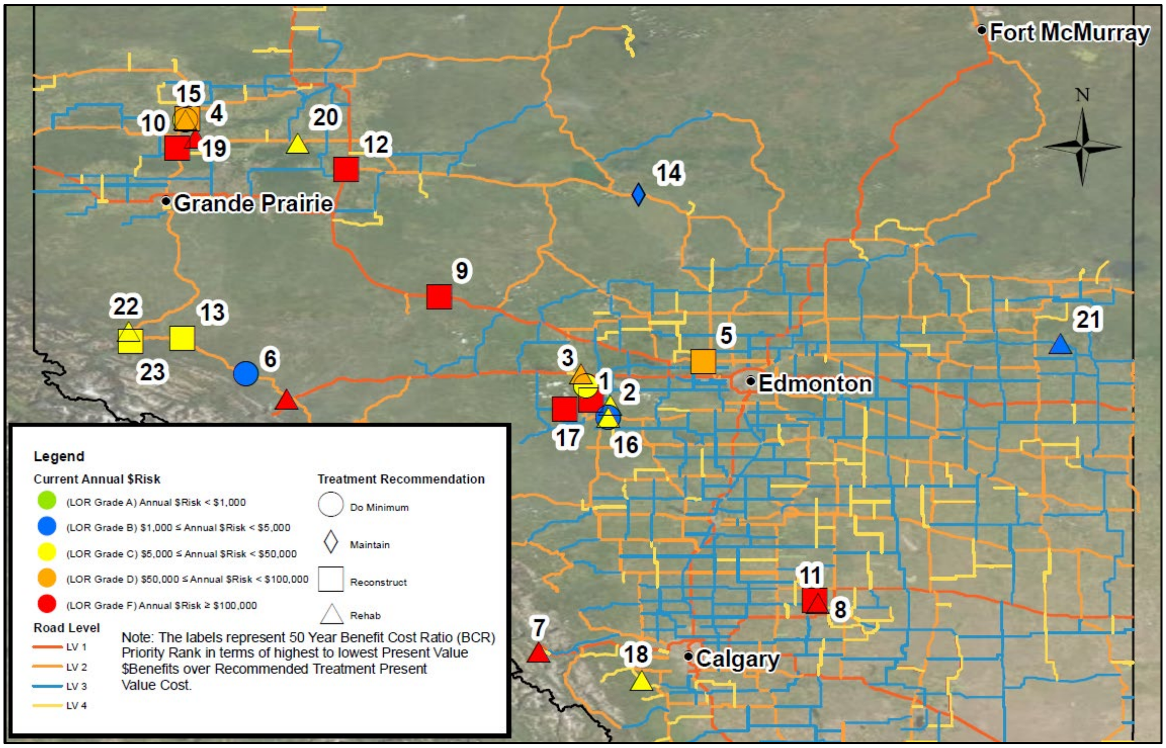
### Table 5: Risk-Based Economic Metrics in GAM Planner Tool

| Asset ID | Unique Asset's Primary Issue | Independent Geotechnical Asset | Recom Treatment PV Cost [i] | Do Minimum PV $Risk (Year 01 to Year 50) [ii] | Recom Treatment PV $Risk (Year 01 to Year 50) [iii] | PV $Benefits in Reduced $Risk [iv] | PV $Benefits over Recom Treatment PV Cost [v] | 50-Year BCR Priority Rank [vi] |
|---|---|---|---|---|---|---|---|---|
| C011 | Erosion | Subgrade | **$690,192** | **$8,712,998** | **$14,053** | **$8,698,945** | **13** | **11** |
| C018 | Rock slope (cut) | Slope | **$526,332** | **$14,641,023** | **$5,583,887** | **$9,057,137** | **17** | **8** |
| GP004 | Soil slope (valley wall) | Slope | **$551,776** | **$15,828,557** | **$2,415,386** | **$13,413,172** | **24** | **4** |
| GP009 | Earth embankment with bio-engineering; creek erosion at toe. | Embankment | **$345,484** | **$3,483,166** | **$44,115** | **$3,439,051** | **10** | **13** |
| GP028 | Earth embankment with dewatering pumps | Embankment | **$767,711** | **$11,124,754** | **$181,671** | **$10,943,083** | **14** | **9** |
| GP029 | Soil slope (valley wall) | Slope | **$1,353,425** | **$18,864,558** | **$211,609** | **$18,652,949** | **14** | **10** |
| GP036 | Rock slope (backslope cut) | Slope | **$351,766** | **$655,229** | **$178,316** | **$476,913** | **1** | **22** |
| GP041 | Ditch erosion | Subgrade | **$1,234,549** | **$976,291** | **$61,148** | **$915,143** | **1** | **23** |
| NC011 | Soil slope (downslope of road, fill/valley wall) with river erosion at the toe. | Slope | **$979,230** | **$30,460,361** | **$11,078,392** | **$19,381,970** | **20** | **6** |
| NC025 | Soil slope with buried concrete pile wall | Slope | **$82,892** | **$157,451** | **$23,384** | **$134,068** | **2** | **21** |
| NC040 | Earth embankment | Embankment | **$179,700** | **$622,120** | **$92,393** | **$529,727** | **3** | **17** |
| NC048 | Earth embankment with toe berm and wick drains | Embankment | [vii] | **$185,021** |  |  |  |  |
| NC052 | Earth embankment with horizontal drains | Embankment | **$395,745** | **$38,903,213** | **$30,671** | **$38,872,542** | **98** | **1** |
| NC057 | Earth embankment on soft subgrade; artesian groundwater conditions. | Embankment | **$666,058** | **$3,208,768** | **$16,737** | **$3,192,031** | **5** | **16** |
| NC073 | Frost heave | Subgrade | **$12,788** | **$129,282** | **$5,255** | **$124,027** | **10** | **14** |
| NC074 | Earth embankment with H-Pile reinforcement | Embankment |  | **$179,063** |  |  |  |  |
| NC081 | Soil slope (natural) | Slope | **$78,298** | **$3,817,252** | **$1,178,683** | **$2,638,569** | **34** | **3** |
| NC086-1 | Steel sheet pile cantilever retaining wall | Retaining Wall |  | **$103,905** |  |  |  |  |
| NC086-2 | Landslide downslope of sheet pile wall | Slope | **$36,096** | **$3,162,185** | **$355,437** | **$2,806,748** | **78** | **2** |
| NC092 | Earth embankment over bridge-size culvert | Embankment | **$128,051** | **$2,950,109** | **$5,560** | **$2,944,549** | **23** | **5** |

| Asset ID | Unique Asset's Primary Issue | Independent Geotechnical Asset | Recom Treatment PV Cost [i] | Do Minimum PV $Risk (Year 01 to Year 50) [ii] | Recom Treatment PV $Risk (Year 01 to Year 50) [iii] | PV $Benefits in Reduced $Risk [iv] | PV $Benefits over Recom Treatment PV Cost [v] | 50-Year BCR Priority Rank [vi] |
|---|---|---|---|---|---|---|---|---|
| PH035-1 | Concrete pile wall with tie backs | Retaining Wall | | **$219,971** | | | | |
| PH035-2 | Landslide downslope of pile wall | Slope | **$257,119** | **$502,979** | **$23,449** | **$479,530** | **2** | **19** |
| PH073 | Earth embankment over culvert | Embankment | **$426,960** | **$4,067,132** | **$18,015** | **$4,049,117** | **9** | **15** |
| S022 | Earth embankment with Cematrix light-weight fill | Embankment | **$125,925** | **$277,478** | **$13,956** | **$263,522** | **2** | **18** |
| S042 | Rock slope | Slope | **$1,077,930** | **$26,765,681** | **$7,284,088** | **$19,481,593** | **18** | **7** |
| SH008 | Soil slope (cut) | Slope | **$276,306** | **$713,024** | **$220,166** | **$492,858** | **2** | **20** |
| SH016 | Earth embankment (bridge head slope) with stone columns | Embankment | **$831,619** | **$8,823,264** | **$189,220** | **$8,634,045** | **10** | **12** |

[i] **Recom Treatment PV Cost:** As defined in Section 9.1.
[ii] **Do Minimum PV $Risk (Year 01 to Year 50):** As defined in Section 9.1.
[iii] **Recom Treatment PV $Risk (Year 01 to Year 50):** As defined in Section 9.1.
[iv] **PV $Benefits in Reduced $Risk:** As defined in Section 9.1.
[v] **PV $Benefits over Recom Treatment PV Cost:** As defined in Section 9.1.
[vi] **50-Year BCR Priority Rank:** BCR Priority Rank for **PV $Benefits over Recom Treatment PV Cost** from highest value to lowest value in the inventory.
[vii] Empty cells in the Table shows that the recommended treatment was "Do Minimum" for the assets.

Figure 7 shows the BCR Priority Rank of 27 GA as shown in Table 5. The points are color coded in accordance with the current annual monetized risk and LOR Grade category. The shape of points represents the recommended treatment for the GA.



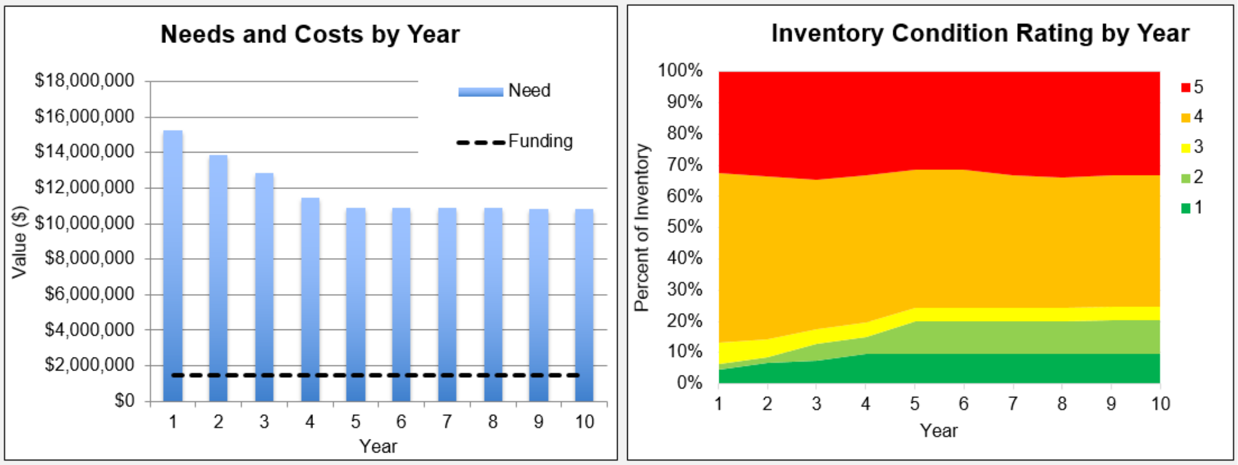
Note: The labels represent 50 Year Benefit Cost Ratio (BCR) Priority Rank in terms of highest to lowest Present Value $Benefits over Recommended Treatment Present Value Cost.

**Figure 7: BCR Priority Rank of GA, LOR Grade and Treatment Recommendation**

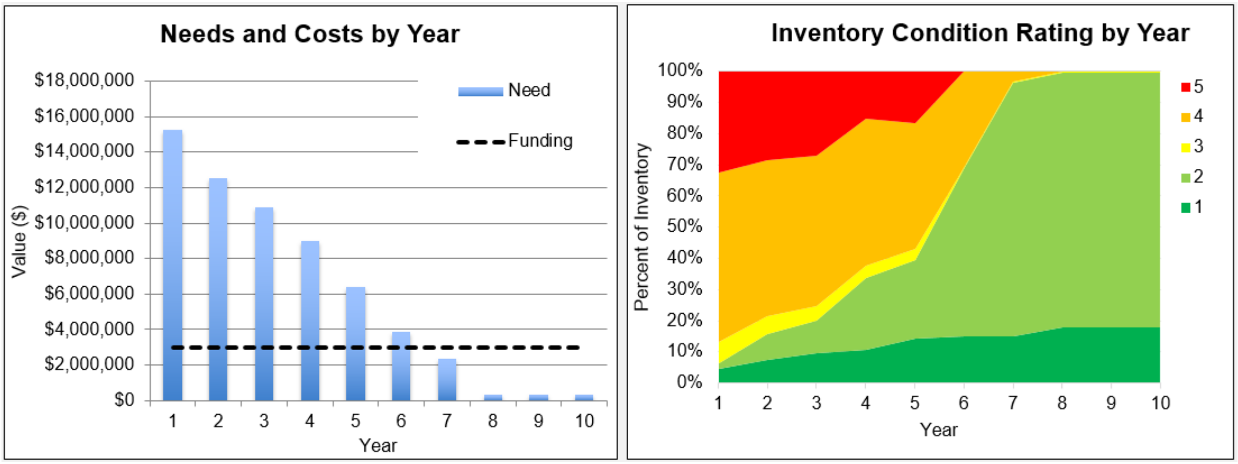
## 10.4 Analyzing Program Investment Levels

The GAM Planner tool can be used to provide an inventory level picture of how different funding scenarios would impact the future needs and condition of the portfolio.

The transportation agency requires a minimum investment level for their asset portfolio in order to maintain the desired level of network performance or level of service. The network's performance improves or deteriorates as the investment levels increase or decrease. The performance of the network can be measured using condition rating indices such as the Condition Ratings for the assets in the inventory, or the current annualized monetized risk for all assets in the inventory. In the GAM Planner tool, the annual capital need is the agency expenditure required to undertake the least life-cycle cost recommendations by year. Note that actual agency expenditures may exceed this amount as a result of budgetary constraints leading to escalating “Do Minimum” and/or failure costs for unfunded/deferred needs. The GAM Planner analysis provides the opportunity to propose investment strategies for a portfolio of assets, and to demonstrate that overall life-cycle costs are likely to increase if sufficient funds are not applied to maintain the assets in a state of good repair.



*(a) $1.5M Annual Funding*



*(b) $3.0 M Annual Funding*

**Figure 8: Forecast Pilot-Scale Inventory Condition with different Annual Funding Levels over a 10-Year Period: (a) $ 1.5M Annual Funding; (b) $ 3.0M Annual Funding**

The results of an example investment analysis for the 25 sites contained in the Pilot Study is shown in Figure 8 as screen captures from the GAM Planner tool. In Figure 8 (a), an annual capital budget of $1.5 Million is applied to the asset inventory, and the forecast condition of the assets over the next ten years, as determined by the GAM Planner tool using the Markov deterioration models, is as shown. It can be observed that an annual budget of $1.5 Million would be adequate to essentially maintain, but not improve, the expected condition (approximately 30% “Very Poor”) of the assets in the inventory over the next 10 years. In Figure 8 (b), an annual budget of $ 3.0 Million is applied to the asset inventory, and the results demonstrate that this funding level would be expected to substantially improve the condition of the assets in the inventory over the next 10 years, effectively addressing all “Very Poor” and “Poor” condition sites.

## 11.0 NEXT STEPS

Next steps for AT will be to begin implementing the GAM probability and consequence inspection rating criteria and the monetized risk concept to their full inventory of active geotechnical assets (250 sites); this will be undertaken over several years, beginning at select sites during the annual inspections in 2022. The Department has recently completed their Transportation Asset Management Plan for pavements, bridges and geotechnical assets, and is committed to providing the executive team with an annual update in the form of a ‘State of the Assets’ report. It is expected that future deployment of the GAM Planner tool to the full inventory of geotechnical assets, enabling the application of the deterioration models to forecast future inventory condition and funding needs, will facilitate better communication with decision-makers on the benefits of investing in our geotechnical assets. The AT is also exploring the modernization of their current data management system, to a GIS-centric cloud-based platform, that would facilitate improved data collection, interpretation, visualization and management. In alignment with the initiative, this year, the AT will also be trialling the development of mobile field inspection forms using GIS-based field data collection.

Future work could include calibration and verification of the Markov deterioration models using site-specific inspection findings and maintenance records. Further refining and validating the unit treatment costs for different asset types can also be undertaken. Consideration may also be given to adding a module for vulnerability assessment due to climate change or extreme weather events.

Tetra Tech has found that the developed methodology can assist several other agencies in managing geotechnical assets inventory overall risk at state, provincial and municipal levels. Similarly, the developed method can also be used in different fields to manage budgets and prioritize treatment for flood dikes, railway embankments, railway industry assets, mining industry assets, etc. Tetra Tech can also incorporate the climate change vulnerability of the assets to provide financially justified adaptation recommendations for agencies with limited capital budgets.

# 12.0 REFERENCES

AASHTO. (2020). *AASHTO Transportation Asset Management Guide: A Focus on Implementation.* Washington: American Association of State Highway and Transportation Officials.

Abdelaziz, T. S., Proudfoot, D. W., & Skirrow, R. (2011). Stabilization of Alberta Highway Landslides using Pile Walls. *Canadian Geotechnical Conference.* Toronto.

Alberta Municipal Affairs. (2015). *Getting started : Toolkit User Guide. Quick Start Tools and Templates for Building an Asset Management Program.* Edmonton: Municipal Affairs.

Anderson, S. A., Schaefer, V. R., & Nichols, S. C. (2016). Taxonomy for Geotechnical Assets, Elements, and Features. *Transportation Research Board 95th Annual Meeting: Compendium of Papers* (pp. 16-5659). Washington, D.C.: Transportation Research Board of the National Academies. Retrieved from https://trid.trb.org/view/1394094

Anderson, S. A., Vessely, M. J., & Ortiz, T. (2017). Communication and Management of Geotechnical Risks to Transportation Performance Objectives. *Geo-Risk 2017: Geotechnical Risk Assessment and Management* (pp. 279-290). Denver: Amercian Society of Civil Engineers.

Arup. (2010). *A Risk-Based Framework for Geotechnical Asset Management. Phase 2 Report.* United Kingdom Highways Agency.

Florida State University. (2001). *Developement of Agency Maintenance, Repair & Rehabilitation (MR&R) Cost Data For Florida's Bridge Management System.* Department of Civil Engineering. Tallahassee: Florida Department of Transportation. Retrieved from https://trid.trb.org/view/690539

Government of Alberta. (2022). *2022-25 Transportation Business Plan.* Retrieved from https://open.alberta.ca/dataset/9d234882-5822-4e06-8e08-b00faa488647/resource/6300efaa-3546-4c70-8e74-f4d7f0e75639/download/trans-transportation-business-plan-2022-25.pdf

Merklin, C. (2020). *AASHTO TAM Webinar 43: Geotechnical Assets and TAM.* Retrieved from https://www.tam-portal.com/?s=tam+webinar+43&submit=Search

NCHRP. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* National Cooperative Highway Research Program, Transportation Research Board, National Research Council. NCHRP.

NCHRP. (2012). *Estimating Life Expectancies of Highway Assets, Volume 1: Guidebook.* National Academies of Sciences, Engineering, and Medicine, National Cooperative Highway Research Program. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/22782

NCHRP. (2012). *Estimating Life Expectancies of Highway Assets: Volume 2: Final Report.* National Academies of Sciences, Engineering, and Medicine, National Cooperative Highway Research Program. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/22783

NCHRP. (2019). *Geotechnical Asset Management for Transportation Agencies Volume 1: Research Overview.* National Academies of Sciences, Transportation Research Board. Washington: National Cooperative Highway Research Program.

NCHRP. (2019). *Geotechnical Asset Management for Transportation Agencies, Volume 2: Implementation Manual.* National Academies of Sciences, Engineering, and Medicine, National Cooperative Highway Research Program. Washington, DC: The National Academies Press. Retrieved from https://doi.org/10.17226/25364

Ohio Department of Transportation. (2022, 04 21). Retrieved from Transportation Information Mapping System (TIMS): https://gis.dot.state.oh.us/tims/Map/Geotechnical

Power, C., Mian, J., Spink, T., Abott, S., & Edwards, M. (2016). Development of an Evidence-Based Geotechnical Asset Management Policy for Network Rail, Great Britain. *Advances in Transportation Geotechnics 3: The 3rd International Conference on Geotechnics (ICTG 2016)*, (pp. 726-733). Portugal.

Tappenden, K., & Skirrow, R. (2020). Vision for Geotechnical Asset Management at Alberta Transportation. *Canadian Geotechnical Conference (GeoVirtual)* (p. 10). Canadian Geotechnical Society.

TCRP. (2012). *State of Good Repair: Priortizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit.* Washington: Transportation Research Board. Retrieved from http://www.trb.org/Publications/Blurbs/167637.aspx

Thompson, P. D. (2017). *Geotechnical Asset Management Plan.* Juneau, AK: Alaska Department of Transportation & Public Facilities.

USACE. (2011). *Risk and Reliability Engineering for Major Rehabilitation Studies.* Washington: US Army Corps of Engineers Engineering and Design.

Vessely, M. (2017). *Risk Based Framework for Geotechnical Asset Management.* Juneau: State of Alaska, Alaska Dept. of Transportation and Public Facilities, Research and Technology Transfer.

Vessely, M., Newton, S., & Anderson, S. (2019). Evidence for the Value of Risk-Based Lige-Cycle Management for Geohazards and Geotechnical Assets. *Proceedings of the 70th Highway Geology Symposium.* Portland.

Waseem, A., & Reggin, A. (2021). *Geotechnical Asset Management Pilot Study Report.* Vancouver: Tetra Tech Canada Inc.

Waseem, A., Fung, G., Reggin, A., St. Michel, G., & MacEoin, S. (2021). *Geotechnical Asset Management Framework Development.* Transportation Practice. Vancouver: Tetra Tech Canada Inc.