APPENDIX A: LITERATURE REVIEW

Overview

The purpose of this literature review was to collect and synthesize information from national and international sources on topics related to best practices, assessment, risk and risk-based management, life-cycle costs and investment, and cross-asset interaction and decision support. The review of literature continued through the project as new information becames available. This appendix summarizes key findings from the literature review as described in Chapter 2 of the Interim Report. Accordingly, this review focuses on subject matter that the research team believed would be beneficial towards development of the implementation manual. Certain simple resources detailing fundamental financial principles were excluded from this review but helped shape the initial chapters of the guidebook. Appendix A to the Interim Report (available on request from TRB staff) contains descriptions of all the literature reviewed by the project team at the time of the Interim Report.

Key Findings

For domestic transportation agencies, GAM is mostly a voluntary activity developed and implemented at the geotechnical subject matter expert (SME) operational level. As such, there is a wide range of practices based on operational level perspectives and often with only minimal input or consideration of the tactical and strategic levels of an organization. Well-documented financial and investment decisions based on GAM planning are limited within domestic transportation agencies; however, other domestic infrastructure sectors such as water resources and utilities, and select international transportation agencies provide valuable examples of GAM practices that have been successfully implemented throughout the asset management cycle and at all levels of an organization.

The synthesis literature review outcomes that can help implement GAM for a domestic transportation agency are discussed below.

Best Practices

- <u>Practices outside U.S. DOTs:</u> There are developed and implemented asset management plans for multiple types of ancillary assets classes that include some form of geotechnical assets. International examples exist for transportation infrastructure in New Zealand, Australia, Canada, United Kingdom (UK), Switzerland, and Sweden, among others. Reviewed literature from sources in New Zealand, Australia, and Canada indicated implementation also extends into the utility and municipal sectors. Within the United States, the Army Corps of Engineers (USACE) appears to have a successful asset management process for water infrastructure, of which geotechnical assets are incorporated, although not specifically identified in such terms (e.g., geotechnical asset management). With respect to the USACE, multiple criteria are considered in decision processes and the cumulative risk exposure is estimated.

- GAM drivers: For the international and non-DOT practice examples mentioned above, plans can be directed towards managing the asset value and/or managing the asset performance. Further, the plans are primarily based on strategic goals (top down) and often have a basis in legislative requirements or directives. As a result, plans appear to be adapted to each agency and there is not a singular template. While there is not singular template, there is guidance towards different levels of plan complexity with examples ranging from two levels (defined as simple and complex) to five levels of detail. Also, there are references towards an implementation advantage of initiating plans early and with known deficiencies and then using continuous improvement rather than developing a comprehensive plan prior to implementation.
- Business Case for GAM: Based on information contained in the transportation literature, plans appear to be most developed when there is a financial incentive and potentially an outside financial interest (private partner), with legislative direction also providing a strong catalyst for successful implementation. The criticality of an asset is discussed in some plans and may be helpful at directing the outcome towards certain direction, such as political or social influences.
- Levels of Complexity and Maturity: Where asset management is successfully implemented, there are examples of data management systems that are adapted for different levels of plan complexity. There are conflicting conclusions about software to support data and asset management with the USACE relying on spreadsheets due to a wide adoption ability and user familiarity; while the International Infrastructure Management Manual (IIMM) indicates a preference towards specific proprietary software that supports asset management.
- Return on Investment: There are examples of a financial benefit for GAM based on documented savings that range from 3 to 38 percent cost reduction over a longer-term budget cycle. In terms of general asset management, the international literature indicates there can still be implementation challenges or resistance even when there is favorable business case.
- Life Cycle Management: The best practices reviewed in the literature rely on decision-making processes that consider the asset life cycle, often in a financial context that evaluates a return on investment or some type of trade off analysis. The best practice examples also use some form of life-cycle measurement of asset performance, which is suggested as a key step towards successful implementation (e.g., what gets measured, gets managed). To facilitate this life-cycle process, there are examples of formally separating staff roles for asset management and planning from the day to day operational work, rather than combining into positions that cover both operations and planning. However, these agencies also indicate an emphasis towards a culture of asset

management across all work areas which suggests that the separated roles are still mutually aligned towards asset management concepts.

- Staff Capacity: Where discussed in the literature, competency and workload capacity are indicated to be major barriers to implementation. As a result, training and contractor support are identified as means to enable implementation.

Assessment

- Geotechnical Assets are defined as physical and independent assets that are within the right-of-way and an integral part of a transportation corridor (Anderson et al. 2016) and can be considered as one of four types: slope, embankment, subgrade and earth retaining structure. The classes of independent geotechnical assets, geotechnical elements and geotechnical features are distinguished from one another and from other physical and non-physical geotechnical assets by the way in which their life cycles can be managed.
- There are several assessment methods from other asset types that could be adapted to geotechnical assets detailed below. Separately, a GAM taxonomy has been proposed by Federal Highway Administration (FHWA) as a starting point to enhance communication between parties working on GAM.
- Retaining walls and soil and rock slopes are the geotechnical assets for which the most effort has been expended towards assessment. Rock slopes have a well-developed inventory scheme with several states having adopted some version of rock slope rating systems. The concepts from the establish rock slope inventory processes also have been expanded to include soil slopes in select cases. Detailed inventory methodologies also have been developed for retaining structures (Brutus & Tauber 2009; FHWA 2005; CDOT 2016). The inventory collection and maintenance in the existing slope and retaining wall examples are generally labor intensive.
- Condition indices and service life evaluations are developed for a limited number of cases and are most often for either earth retaining structures or slopes, with rock slopes being most common. Of the different systems reviewed, there is not a straightforward connection to TAM processes related to risk, life-cycle costs and investment, or cross-asset decision support.
- Deterioration curves discussed in the literature have tended to be only conceptual or hypothetical. Network Rail in the United Kingdom has developed different deterioration mechanisms for soil and rock slopes, and assigns different qualitative rates of deterioration for each mechanism (slow, rapid, instantaneous) for earthworks that are greater than 100 years old (Network Rail 2017). However, there are very few instances of deterioration curves having been developed for specific geotechnical assets.
- Nondestructive tests and evaluation methods have been applied to several geotechnical assets at the individual asset level. While there is promise in these methods, their

application is not mainstream for technologies such as light detection and ranging (LIDAR), interferometric synthetic aperture radar (InSAR), ground penetrating radar, insitu moisture measurement, or corrosion measurement and tracking.

Risk and Risk Management

- Throughout the infrastructure asset management literature, risk was defined as the product of the probability of an event occurring and the consequences of that event. Specific methods for implementing this definition varied.
- Risk can refer to events beyond strictly "failure" events typically considered in engineering design. Sources of risk encountered in the review of literature include
    - For USACE's dam program, four sources of risk are considered: annual probability of failure, life safety risk, economic risk, and environment and other non-monetary risk.
    - AASHTO defines four major types of risks: operational, physical failure, external agency impacts, and natural hazards.
    - For Network Rail in the UK, the GAM risk source includes safety and performance.

  The risk cube concept presented by Anderson (2016) is an effective way to consider multi-objective risks and communicate them to stakeholders.
- For geotechnical assets, physical failure (due to deterioration, overloading, etc.) and geologic or natural hazard events (e.g., rockfall, landslides due to extreme weather events) are primary sources of risk.
- The concept of tolerable risk has received significant attention from transportation agencies in the transition to reliability-based design. The concept is also important in the context of TAM as agencies begin to develop risk-based TAM systems. Many infrastructure agencies across the globe have tackled the issue of tolerable risk, which has philosophical, moral, economic, and legal implications.
    - As discussed in USACE's Dam Safety Regulation (2014), establishing tolerable risk levels requires balancing equity and efficiency. USACE establishes a tolerable risk limit for dams that serves as a maximum value "except under extreme circumstances." Once the risk level for a dam has satisfied the tolerable limit, the risk is to be lowered to values as low as reasonably practical (ALARP). For USACE, determination of ALARP is based on consideration of the risk level with respect to tolerable limits, the cost effectiveness of risk reduction measures, compliance with agency guidelines, and societal concerns.

  - The World Road Association (PIARC 2012) reported that public risk tolerance depends on consequence magnitude, with less tolerance for events that are "grouped in time and space" than for events that are random.
  - PIARC (2012) also reported public risk tolerance is as much as 1,000 times greater for voluntary risks (e.g., smoking) compared to involuntary risks (e.g., food additives).
- Several sources referred to three levels of asset management: time-based, condition-based, and risk-based. Condition-based asset management was considered an intermediate system along the way to truly risk-based asset management.
- Network-level risk management efforts have been considered across infrastructure sectors, and are generally motivated by an assumption that risk-based decision making will either increase system reliability without necessarily increasing costs or reduce costs without necessarily reducing system reliability. The benefits of risk management are seen as especially favorable in light of aging infrastructure and emerging infrastructure threats (e.g., extreme weather events). However, implementing network-level risk management is challenging for technical and organizational reasons. Technical challenges primarily stem from the definition of risk; defining event probabilities and consequences is difficult, especially for low-probability, high-consequence events. Organizational challenges include difficulties collecting data across large networks, difficulties implementing risk management for agency decision processes that occur over different time scales, and agency inertia.
- Vick (2017) described how agency complacency can spoil implementation of risk-based methods by a process of "normalization of deviance" wherein a pattern of unsatisfactory performance leads to the acceptance of greater risks than intended. Vick concludes diligence in risk management should be embedded throughout an agency's culture to avoid the normalization of deviance.
- The state of practice with respect to risk management varies by infrastructure sector. Several significant examples are summarized below. Additional examples are documented in Appendix A.
  - <u>Highways</u>: Several U.S. and international agencies have developed slope and/or rockfall management systems that are at least nominally risk-based. Most of the systems assign rankings based on quantitative scores based on qualitative factors that address the probability of failure and the consequences of failure.
  - <u>Railways</u>: Great Britain's Network Rail has implemented a risk-based asset management system for all earthworks 3-m high or taller. Risk scores are based on visual site inspection data as well as geologic and other "desk study"

parameters. The algorithm for determining scores was recently updated so that scores better reflect observed failures (Power et al. 2016). Scores are considered with a network-level decision tool that considers life-cycle costs.

  - Water resources: The U.S. Army Corps of Engineers' Dam Safety Regulation establishes procedures that are "risk-informed, not risk-based." All dams are assigned a Dam Safety Action Classification (DSAC) score from 1 (very high urgency) to 5 (normal) based on risk assessment procedures documented in the regulation. Interim Risk Reduction Measure (IRRM) plans are required for all DSAC 1, 2, and 3 dams. As established in the regulation, funding for the IRRM plans is prioritized by risk, although exceptions are allowed.
  - Power Transmission: GARPUR ("Generally Accepted Reliability Principal with Uncertainty modelling and through probabilistic Risk assessment") is a collaborative effort by 20 industry and university partners to develop a smart grid for Europe's electrical power transmission system. Part of the effort involves moving from a deterministic ("N−1") approach to a true risk assessment. The GARPUR project has resulted in research that addresses the technical challenges of implementing network-level risk management. The research includes work that shows a reliability approach has lower overall costs compared to a deterministic approach with the same probability of failure (Karagnelos and Wehenkel 2016) as well as development of a computational method for identifying optimal maintenance strategies with lower costs compared to conventional (e.g., "oldest-first," "cyclic," etc.) strategies (Dalal et al. 2016).
  - Natural Hazards Protection (Multiple Sectors): Switzerland formed the National Platform for Natural Hazards (PLANAT) in 1997. The PLANAT mandate includes coordination among various sectors impacted by natural hazards, improving public awareness, and strategic efforts, including development of "an optimized allocation of financial resources by reducing risk" (Bründl et al. 2009). The Swiss government has deployed an online tool, EconoMe, for evaluating risk reduction projects. Use of the tool by practitioners is required for all project costing more than 1 million CHF (appox. $1M). The tool is based on quantitative risk calculations and quantitative cost-benefit analysis, the results of which must be favorable for funded projects.

- Academic research includes promising developments for risk-based TAM. Three prominent examples are summarized briefly below; additional details and additional examples are presented in Appendix A of the Interim Report.

  - Govindasamy et al. (2017) developed a comprehensive, quantitative risk-based asset management protocol for levee systems. The protocol involves assessment of probability of failure based on previous performance data and then updating the probability of failure for incoming field inspection data using Bayesian methods. The protocol could be generalized to other infrastructure systems.
  - Bush et al. (2011) proposed a three-tiered system for bridge asset management, where the level of condition data collection and analysis varies by tier. Tiers are assigned based on risk and criticality.
  - Cheng and Hoang (2013) developed a machine learning method to perform network-level analyses of slope stability. The machine correctly predicted stability or instability for 38 of 40 test slopes.
- Climate change poses new risk considerations for GAM, increasing the likelihood of natural hazards in some areas, decreasing the likelihood in other areas, and creating additional uncertainty regarding potential consequences. The literature is sparse and exploratory in this regard, though there has been theoretical effort to incorporate resilience (defined as “continuous performance under changing conditions” in this context) into GAM.

Life-Cycle Costs and Investment

- There are limited examples of life-cycle and investment analysis in support of GAM for domestic transportation infrastructure. Further, there are few examples of data that could validate assumptions about life cycle costs for geotechnical assets, which could be a future research need.
- Life cycle analysis periods of greater than 30 years are recommended in the IIMM. In the UK, Network Rail presents a whole life concept of 100 years in support of investment analysis.
- References to life-cycle analysis and investment decisions appear to be limited in the domestic transportation literature, likely due to the common practice or annual budgeting.
- Degradation of geotechnical assets can be influenced by different factors such as (1) natural or material characteristics (2) natural versus constructed features, (3) weather and climate, or (4) other external contributors to the deterioration or failure such as operation and maintenance practices.
- Economic literature on the value of transportation, including travel time analysis, value of travel time savings (VTTS), value of travel time reliability (VTTR), statistical value of life, hedonic analysis, and environmental impact are variables that can be considered for incorporation for the financial and investment process for geotechnical assets.

- There can be difference in geotechnical asset expected performance and lifecycle versus those of traditional assets such as pavement and bridges. The identification of natural hazard risk factors should be included in lifecycle planning. Risks that are comprehensive, recordable and transparent can lead to development of life-cycle degradation curves in addition to natural hazard impacts toward the probable lifecycle of an asset. Other risk factors such as financial, administrative, legal liability, insurance, and operational impacts should be considered as part of the financial responsibility. The following excerpts have been taken from FHWA's Risk-based Transportation Asset Management Reports (Report 1: Risk-based TAM: Evaluating Threats, Capitalizing on Opportunities)
  - Once risk and risk management are described, it is apparent they are not new to U.S. transportation officials. Agencies have for many decades used risk-based approaches even if they have not described them as such. U.S. transportation agencies invest more resources into maintaining high volume, high-risk roadways than they do in low-volume, low-risk ones. Bridge engineers invest more resources into inspecting and monitoring high-risk bridges than they do with low-risk ones. High-risk assets such as traffic signal controllers receive far more attention than do low-risk assets such as isolated maintenance sheds. Safety analysts scour statewide crash data to identify high-risk locations for safety improvements. the identification of risk and the mitigation of it permeate U.S. transportation practices.
  - The International Organization for Standardization (ISO) risk management standard makes a similar point that the hallmark of a mature organization today is that its risk management is comprehensive, recordable and transparent.
  - The IIMM describes risk management as a visible, core business driver and not an isolated function. As such, risk management is incorporated into the life-cycle and investment steps.
  - In England, Treasury Department guidance says, "Government will be open and transparent about its understanding of the nature of risks to the public and about the process it is following in handling them. Government will make available its assessments of risks that affect the public, how it has reached its decisions, and how it will handle the risk." The English Highways agency says risk management is a high-profile component of good stewardship of assets along with other formal and recordable processes such as life-cycle costing, long-term strategies, and performance monitoring.

Cross Asset and Decision Support

- Cross-asset resource allocation has been of intense interest in recent years for transportation authorities and the literature is focused on the education and implementation of existing methodologies such as multiple-objective decision analysis

(MODA) and mathematical optimization technics (linear programming, computational optimization, etc.).

- NCHRP Report 806: *Guide to Cross-Asset Resource Allocation and the Impact on Transportation System Performance* points out that investment tradeoff analysis among state DOTs is most commonly made between bridges and pavements, where goals and objectives are more readily defined. To apply decision science at the program level in determining appropriate investments, agencies must assign relative importance of asset performance metrics. Without clearly defined metrics for geotechnical assets, implementation planning will need include reporting means that allow those asset categories to compete for investment against bridges and pavements.
- The same report discusses the importance of modeling performance impact at the project level when justifying investment. For geotechnical programs, project selection can benefit from considerations not just which projects to select, but what kind of treatment is optimal for both the individual asset and the system as well. Bridge, pavement, and safety performance areas have long been modeled in well-recognized software solutions, helping demonstrate benefit for an individual project. Slopes and embankment project benefits may be easy to explain, but are not as frequently articulated in terms of improved performance.
- AASHTO's Defining Cross-Asset Decision Making distinguishes cross-asset tradeoffs from cross-asset decision making as the difference between "perceived utility" and "measured or quantified utility." If a "utility function" is "the preference expressed given the expected risk and reward," investments in GAM may logically provide a high utility function. "If a department will pay more to prevent one crash than it would pay to reduce one mile of poor pavement, it demonstrates a higher utility for the crash reduction." The challenge of GAM, therefore, is to comparably express the utility function of improvements to the assets in order to establish relative benefits of investment.
- While the prior sources focus on project-level and program-level allocation of resources, Boadi et al. (2017) examines corridor-level analysis in *Goal-Oriented Analysis of Transportation System Performance: A Corridor-Level Study of Georgia's State Routes*. Multiple Criteria Decision Methods (MCDM) would, in theory, enable stakeholders within a region to develop a "corridor health analysis framework," comparing "core performance" of safety, mobility, and accessibility to "wider performance" such as economic development. Few studies exist to help guide GAM practitioners in determining the impact to the corridor of geotechnical investment in terms of these performance areas.

- Whether managing life cycles, demonstrating return on investment, or trading off across asset categories, the discussion of risk is prevalent throughout GAM. Spielhofer et al (2016), in *Cross-asset risk assessment (X-ARA) on network level*, state that a procedure for the aggregation of risks from pavements, drainage, geotechnical and other assets onto network level is critical in project selection and scoping. “X-ARA will enable a road administration to execute a risk-based assessment and comparison of different maintenance strategies on network level, and then ‘overlay’ the effects of broad influencing factors to assess ‘what if’ outcomes.”
- Similarly, Anderson (2016) introduced a “risk cube” for communicating “multiobjective” risks based on asset type, risk source, and performance goal. The cube was developed for GAM, but could be applied to TAM or even more generally.
- At the geotechnical program level, project selection can benefit from considerations not just which projects to select, but what kind of treatment (e.g., design) is optimal for both the individual asset and the system as well.
- The domestic TAM practice appears to have a lesser role from legislation and regulation for asset management practices when compared to countries such as Australia, New Zealand, UK.

APPENDIX B: CASE STUDY INTERVIEW OUTLINE

NCHRP 24-46 Implementation Manual for Geotechnical Asset Management

Case Study Interview Outline

SME Specific Introduction:

The National Cooperative Highway Research Program is developing an Implementation Manual for Geotechnical Asset Management for Transportation Agencies (NCHRP 24-46) in partnership with geotechnical firm Shannon & Wilson, transportation management consultants Spy Pond Partners, the University of Missouri, and Iowa State University. The study calls for state DOT participants to share their experiences, barriers to implementation, and best practices in GAM. For this study, geotechnical assets consist of features such as unstable soil and rock slopes (landslides, rockfall), embankments, or subgrades.

1. Executive Action Area
    a. Does the DOT/agency dedicate resources to geotechnical asset management (e.g., retaining walls, slopes, embankments, drainage basins, etc.)?
    b. Does it have the capability to fund geotechnical asset management if not supported by FHWA or another external source?
    c. Does your agency experience impacts from adverse events or deterioration associated with geotechnical assets?
        i. Type of impact: Cost/safety/mobility/other?
        ii. Degree of impact
        iii. Frequency of impact
    d. Can maintenance and engineering program expenses be reported based on asset groups?
    e. How are impacts from off-ROW assets addressed (e.g., an adjacent retaining wall impacting the ROW or a rock/debris that originates off-ROW)?
2. Planning Action Area
    a. Does the TAM plan consider geotechnical assets?
    b. How is the risk across asset groups evaluated?
    c. Does the agency measure direct impacts from events related to geotechnical assets (e.g., damage to highway, clean-up costs, damage to personal property, injuries, etc.)?
    d. Does the agency measure indirect impacts from these events (e.g., economic loss, vehicle delays, etc.)?
    e. How does source of funding factor into the trade-off analysis (e.g., FHWA or FEMA emergency funds, agency contingencies, programed design budgets)?
3. Geotechnical Action Area
    a. Are there inventory or condition data for any of the geotechnical assets? If so, what percentage? What are the tools used for data collection.
    b. Is the geotechnical program required to report on the performance of any geotechnical assets? If so, what are the performance metrics and how are they assessed?

c. Does your agency differentiate the management of geotechnical assets based on whether the source area is on or off ROW?
d. Have you been trained in the concepts and implementation of any type of transportation asset management? Are you familiar with the performance measures for your agency?
e. How does the geotechnical program assess risk? Subjectively/qualitatively/quantitatively?
f. Does the agency conduct proactive geotechnical measures or are activities related to rockslides and other geotechnical events mostly reactive?
g. Are the geotechnical staff trained and able to perform risk assessment?
h. Do you consider transportation asset management concepts in design?
   (e.g., life-cycle cost, design features to support inspection, different design standards based on performance/risk [even if it would be below AASHTO guidance])
i. Are maintenance/repair costs tracked?
j. What are the impacts geotechnical assets have outside of the department geotechnical group? Are they measured?
   i. Type of impact: Cost/safety/mobility/other?
   ii. Degree of impact
   iii. Frequency of impact
k. Are there examples of successful proactive project work on a geotechnical asset, such as repair or rehabilitation, that you believe prevented a future adverse event?

General:

4. What can/would enable GAM implementation
5. What are the barriers to GAM implementation