Development of a Geotechnical Asset Management Collection and Rating Program for Missouri Department of Transportation

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16. Abstract

The Missouri DOT research team, led by Landslide Technology, developed a prototype Geotechnical Asset Management (GAM) program through close collaboration with MoDOT geotechnical engineers and MoDOT's IT group. The team adjusted published and commonly accepted categories from state and federal GAM inventory and rating approaches to match conditions specific to Missouri. The GAM program compiles condition and risk assessment for six asset types: engineered embankments, retaining walls, rock slopes, soil slopes, subsidence, and subgrade. Subsidence and subgrade improvements were successfully incorporated into Missouri's GAM program despite not being previously incorporated into an other DOT's GAM inventory. The risk assessment rating developed for this project allows DOTs to approximate risk in the absence of site-specific maintenance or accident records. Data is collected via ESRI's Survey123 Application before being scraped and processed in MoDOT's TMS system, where it is added to other department datasets. The application was field-tested on National Highway System (NHS) routes in the Northwest and Northeast Districts in October 2022.

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LANDSLIDE TECHNOLOGY
A DIVISION OF CORNFORTH CONSULTANTS

DEVELOPMENT OF A GEOTECHNICAL ASSET MANAGEMENT COLLECTION AND RATING PROGRAM FOR MISSOURI DEPARTMENT OF TRANSPORTATION

NORTHWEST AND NORTHEAST DISTRICTS, MISSOURI

MoDOT Project Number TR202007

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ABSTRACT

The Missouri DOT research team, led by Landslide Technology, developed a prototype Geotechnical Asset Management (GAM) program through close collaboration with MoDOT geotechnical engineers and MoDOT's IT group. The team adjusted published and commonly accepted categories from state and federal GAM inventory and rating approaches to match conditions specific to Missouri. The GAM program compiles condition and risk assessment for six asset types: engineered embankments, retaining walls, rock slopes, soil slopes, subsidence, and subgrade. Subsidence and subgrade improvements were successfully incorporated into Missouri's GAM program despite not being previously incorporated into another DOT's GAM inventory. The risk assessment rating developed for this project allows DOTs to approximate risk in the absence of site-specific maintenance or accident records. Data is collected via ESRI's Survey123 Application before being scraped and processed in MoDOT's TMS system, where it is added to other department datasets. The application was field-tested on National Highway System (NHS) routes in the Northwest and Northeast Districts in October 2022.

EXECUTIVE SUMMARY

This report documents research conducted as part of MoDOT research project 202007, *Geotechnical Asset Management (GAM) Collection and Rating Program.* The research objective was to develop a program to identify, inventory, and assess six geotechnical asset types: engineered embankments, retaining walls, rock slopes, soil slopes, subgrades/ground improvements, and subsidence. Assessments included determination of asset condition and a relative risk assessment. Asset locations were collected in the field and delivered in a format compatible with Geographical Information System (GIS) programs. Field testing took place on National Highway System (NHS) routes in the Northwest and Northeast Districts, and MoDOT plans to expand the program statewide after completing the research project.

The research program was originally scoped to include development of a mobile application. LT proposed and started the research project utilizing MoDOT's existing ESRI capabilities to collect, process, and store the GAM data. While the project was underway, the technical committee and the MoDOT IT group collaborated to develop a mobile application that integrates with the department's existing Transportation Management System (TMS). Using ESRI's Survey123 framework, LT created a survey program for MoDOT to publish through their ESRI Portal space. The TMS group also developed the programing required to extract data collected in the field from ESRI's cloud-based servers and incorporate it into the TMS database. LT and the MoDOT IT group collaborated to complete the mobile application and QC data imported from the field in an iterative process. The work completed by MoDOT's IT group is not discussed in detail in this research report. Figure ES-1 summarizes the inventory work completed in this research project.

Figure ES-1: Summary of statistics from the MoDOT Geotechnical Asset Management (GAM) Research Project

The methodology for assessing the six geotechnical asset types draws heavily on previously published rating methods, adjusted and expanded where necessary to describe conditions in Missouri. This allows MoDOT to combine their data with that collected by other agencies and develop asset life cycles, condition – risk correlations, unit maintenance/mitigation costs, and other components of a mature GAM Program while MoDOT is still in the early stages of inventory and assessment. As in other GAM programs, the inventory process is completed by an experienced engineering geologist or geotechnical engineer during a 20-minute site visit. The site visit should incorporate data collected from other sources, such as maintenance input on the frequency of movement at an unstable soil slope.

For each of the geotechnical asset types, the fields in the inventory Survey123 application are split into two groups: general information and detailed rating categories. The general information fields collected background information on the asset type, location, and any previous work performed. The research team developed 20 general information fields within the Survey123 application, but not all fields are required for any one asset. The detailed rating categories collected information directly related to the hazard associated with a given asset and the consequence of failure. Hazard categories described the condition of the slope and are quantitatively associated with event likelihood. Consequence categories incorporating roadway usage and geometry are qualitatively associated with the impact of failure. Each detailed rating category was scored from 0 to 100, with 100 being the best score, and 0 the worst. A total of 23 detailed rating fields are included in the Survey123 application, but again, only 8 to 12 fields are populated, depending on the asset type.

Using subsets of the detailed rating categories for each asset, the research team calculated and assigned an asset condition and level of risk to each inventoried asset. Asset condition is expressed in a variety of methods, including numerically and with ‘Good’/ ‘Fair’/ ‘Poor’ descriptors that have a broader appeal. Numerical asset scores range from 0 to 100, with 0 being the worst and 100 being the best. A map of the location and condition of assets inventoried during the field program is presented in Figure ES-2.

The research team also used subsets of the detailed rating categories to calculate an approximate Level of Risk for each asset. This level of risk is qualitative, because long-term data on the frequency and impact of asset failures is not currently available. The ability to compile and share this data is the impetus for this research program. Like asset condition, Level of Risk is scored from 0 to 100, with 0 being the highest risk sites and 100 being the lowest risk. The score is a combination of both asset condition and relative consequence. The research team determined that of the detailed rating categories available, traffic volume, roadway width, and sight distance could be combined to best estimate the relative consequence of a failure on roadway users. Level of Risk was calculated numerically and assigned ‘Low’/ ‘Moderate’/ ‘High’ descriptors that are more easily communicated and understood. The results of the risk matrix for the geotechnical assets supporting NHS routes in the North and Northeast districts are shown in Figure ES-3.

Using the results of the field work, the research team also developed a set of sample decision support tools intended to be a starting point for management of geotechnical assets. The team also developed a set of considerations and recommendations for project expansion and maintenance of the Survey123 application, since the existing Survey123 application requires interaction with software managed by MoDOT (TMS) and software managed by others (ArcGIS Online/ESRI).

This program represents MoDOT’s initial foray into GAM. Statewide inventory and condition assessments, proven within this program to be viable, will allow MoDOT to reap the benefits and operational cost savings of proactive management of their geotechnical assets.

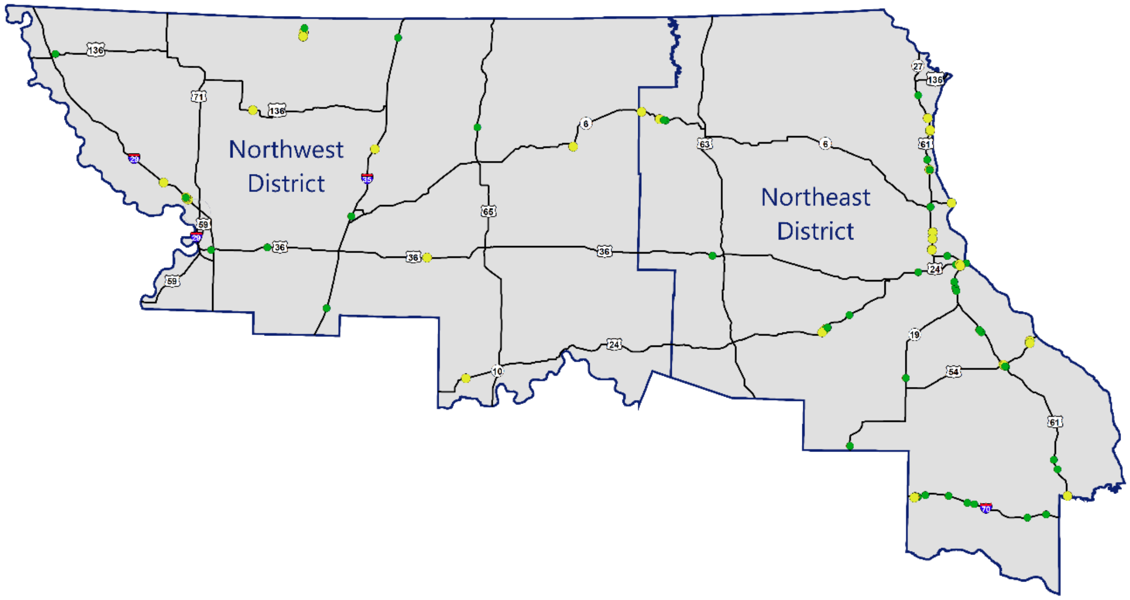

Figure ES-2: Map showing inventoried asset along NHS routes. All inventoried assets were in either Good (green) or Fair (yellow) condition.

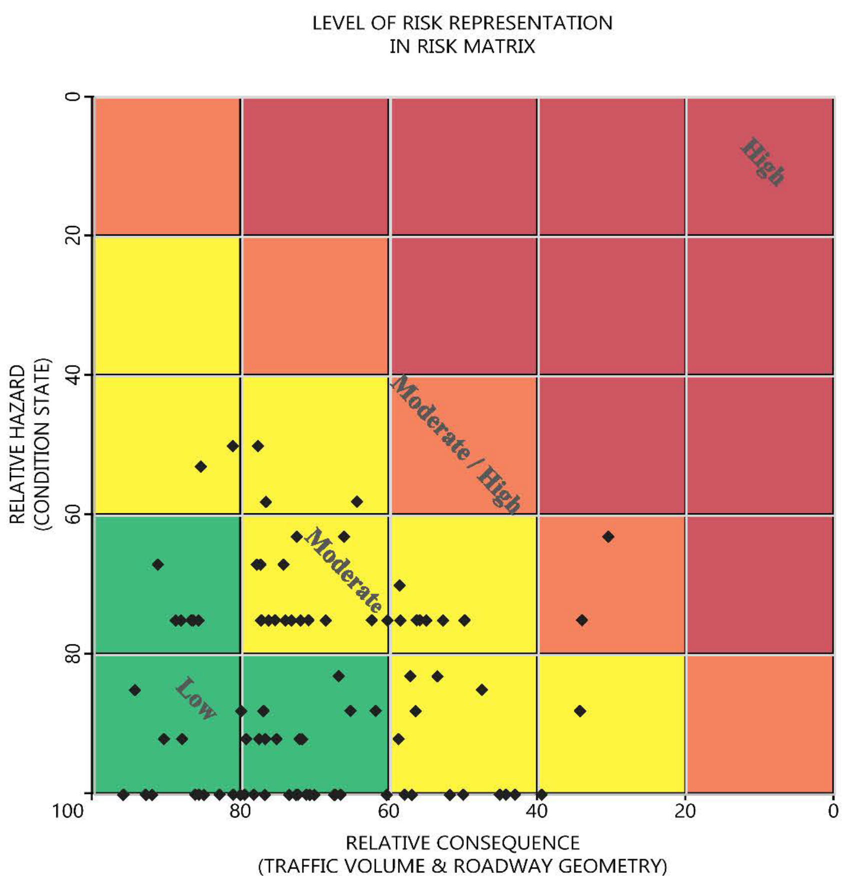

Figure ES-3: Level of Risk Matrix populated with Northwest and Northeast District geotechnical assets on NHS routes

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1 INTRODUCTION

Transportation Asset Management (TAM) is a strategic and systematic process of maintaining and managing infrastructure assets throughout their life cycle, focusing on business and engineering practices for resource allocation and utilization. It uses data and analysis to improve decision making, with the objective of providing the required level of service in the most cost-effective manner. All state Departments of Transportation (DOT's) were obligated to develop TAM plans for their National Highway System (NHS) routes by 2019 as a condition of federal funding. These TAM plans must include pavements and bridges, but DOTs are also "encouraged to include all infrastructure assets within the highway right-of-way" (Federal Highway Administration, 2022).

State and federal agencies have recognized the significance of geotechnical assets in the performance of transportation networks. The Rockfall Hazard Rating System (RHRS), developed by Oregon DOT to inventory and assess rock slopes throughout the state, was implemented in 1992, well before development started on ODOT's current TAM plan. Likewise, the Missouri Department of Transportation (MoDOT) has been internally tracking landslide and sinkhole locations for many years. Geotechnical assets were not included in the original push for better management of transportation assets despite these initial, promising steps. In the last 15 years, some states, including Alaska, Montana, Washington, Oregon, Washington, Tennessee and Colorado, have begun formally applying asset management principles to their geotechnical assets, particularly soil slopes, rock slopes, and retaining walls (Anderson & Rivers, 2013; WSDOT, 2010; ODOT, 2011; Anderson, Vessely, & Ortiz, 2017; Beckstrand, et al., 2017; Beckstrand, et al., 2017).

The objective of this research program is to facilitate geotechnical asset management of MoDOT's engineered embankments, retaining walls, rock slopes, sinkholes, soil slopes, and subgrades so that the failures and disruptive liabilities in the state's transportation system can be reduced. A rating and inventory methodology was developed for all six asset types, along with a mobile device application that can be used in the field. The survey application is published within Survey123, an existing ESRI platform, to take advantage of MoDOT's existing software licensing. The final survey is maintained by MoDOT's IT group, which also developed a process to pull data from the ESRI servers into MoDOT's Transportation Management Systems (TMS) space. This allows the GAM assets to easily be incorporated into the planning and project analyses completed by other groups. The current Survey123 application was field tested by inventorying and assessing geotechnical assets on NHS routes in the Northeast and Northwest regions. Successful field testing in these regions makes it possible for MoDOT personnel to expand the inventory and assessment processes to other regions and route types. Completing this inventory and assessment work will enable MoDOT to collect the maintenance, degradation, and life-cycle costs to support a full-fledged GAM program within the department's TAM plan structure.

2 PREVIOUS INVENTORY AND RATING EFFORTS IN MISSOURI

MoDOT has gradually implemented inventory and rating efforts, focusing on different asset types over time, like other DOTs nationwide. Early efforts were typically limited by the ability to collect data in the field and transfer it to an active database that could be easily updated over time. Each inventory and rating effort also focused on only one or two geotechnical assets, and long-term asset management was not a formal goal for any of the projects.

The earliest inventory and rating effort funded by MoDOT that was identified during the review for this project was the Missouri Rockfall Hazard Rating System (MORPH RS). This research project was completed in 2004. Researchers at the University of Missouri – Rolla (now Missouri University of Science and Technology), modified existing rockfall hazard rating systems to reflect conditions in Missouri. They also recognized the value of grouping rating categories to approximate hazard separately from risk. The 2004 MORPH RS system relied on a dashboard-mounted camcorder to collect rock slope video that was then analyzed in the office before making a separate site visit to rock slopes above a predefined threshold. MORPH RS was never implemented beyond the research program test cases, or expanded in a programmatic fashion (i.e., to all NHS routes, or within a given district) (Maerz & Youssef, 2004).

In 2012, geotechnical engineers in the department tried to fund a research project that would inventory landslides statewide. It was not possible to integrate external data collection with internal data management at that time, and the project transitioned to a guidebook on landslide repair and slope stabilization (Shannon and Wilson, 2012).

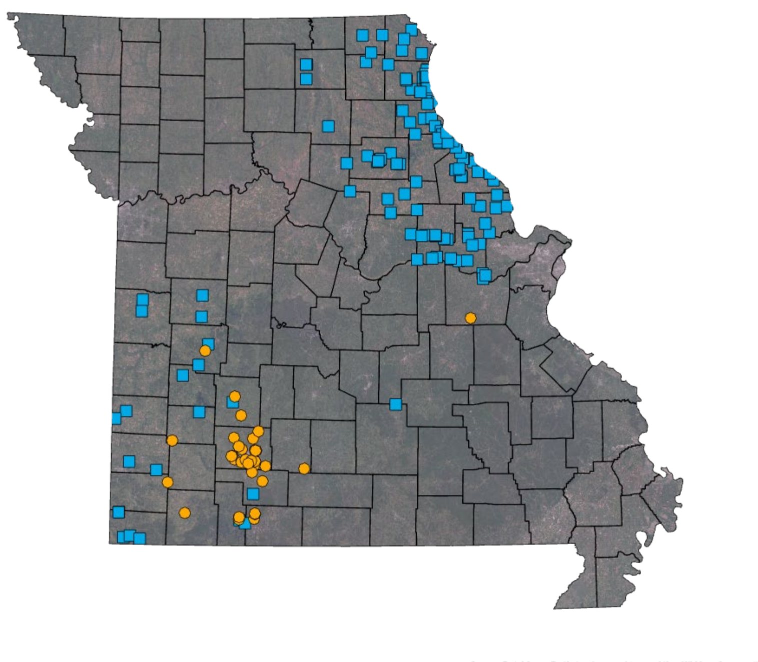


Figure 2-1: MoDOT Northeast and Southwest kmz data sets for landslides (blue) and sinkholes (gold) as of 2019.

MoDOT engineers in the Northeast and Southwest regions developed ad-hoc databases for landslides and sinkholes that had impacted MoDOT following the 2012 work. These databases were hosted in compressed Keyhole Markup Language (.kmz) files created within Google Earth, which allowed asset locations to be easily plotted in GIS environments or opened in a smart phone or tablet through the Google Earth application. Each slide was assigned an ID based on county. Popups for each entry included a brief description of the asset location, type of remediation, and date of remediation, if any. The popups in the Northeast district landslide database also included a link to a folder in the MoDOT SharePoint server that contained photos, drawings, and similar information. A map of these datasets is shown in Figure 2-1 above. These datasets represented a pure inventory, with no rating of individual assets, but were an invaluable first step in MoDOT's GAM program. The kmzs could be updated by district engineers and geologists adding. However, the kmz datasets could not be easily incorporated into the department's TMS structure. This made it more difficult for the district-level engineers and geologists collecting the data to share their results with department planners for use in budget forecasting or project prioritization. Landslides and sinkhole condition also was not assessed. Recognizing the limitations of the kmz datasets, the district engineers and geologists sought funding for a research project to develop a formal geotechnical asset management program for MoDOT that could be integrated into the department's TAM plan in the future.

3 GEOTECHNICAL ASSETS INVENTORIED

The geotechnical assets targeted for inclusion into MoDOT's GAM program are engineered embankments, retaining walls, rock slopes, soil slopes, subgrades/ground improvements, and subsidence (sinkholes/abandoned underground mines). The definition of these asset types was adapted from the NCHRP GAM Implementation Manual, with input from MoDOT personnel on select asset classes (National Acadamies of Science, Engineering, and Medicine, 2019).

The detailed condition and risk assessment of these assets uses a combination of scores from dropdown lists, scores calculated within the app using information from additional dropdowns, and internally calculated ratings to generate both an asset condition and a level of risk category. The information fields and rating categories are described in the following section. This section provides a brief description of the geotechnical assets inventoried followed by the acceptance criteria for including them into the database.

3.1 Engineered Embankments

Embankments are constructed earth fills of soil or rock that may also include reinforcing materials such as geogrids. The NCHRP GAM Implementation Manual suggests that a threshold height of 10 feet be used when accepting an embankment into the program. For the MoDOT project, the team elected make 5 feet the threshold height. A roadway damaging embankment whose degradation is not being caused by a different geotechnical asset (i.e., deformation due to failure of subgrade improvement, landslide movement, etc.) is accepted for inclusion in the GAM inventory. It is also recommended that all embankments constructed with reinforcement material in the future be added to the GAM inventory, so that the life cycle of these reinforcements can be tracked over the coming decades. Slope failures in embankments are considered landslides by MoDOT and are inventoried as such in the MoDOT GAM program for the sake of consistency.

Figure 3-1: Example of an embankment inventoried in the MoDOT GAM program.

3.2 Retaining Walls

Retaining walls are engineered structures that hold back the natural slope or placed fill in order to support the roadway or prevent an adjacent feature from impacting the roadway. The current design guidance is that retaining walls have a minimum vertical face inclination of 70 degrees. Less steep faces should be classified as engineered embankments and assessed in that category. The current recommended threshold for inclusion in a GAM program is a minimum wall height of 4 feet (National Academies of Science, Engineering and Medicine , 2019). This threshold height was adopted for the MoDOT GAM Program. Walls associated with bridges are already inventoried and assessed by MoDOT's bridge group and are therefore excluded from the GAM inventory. A reference shapefile of bridge-associated retaining walls was provided by MoDOT and referenced during the field work for this research project. An example of a retaining wall inventoried in the program is shown in Figure 3-2.

Figure 3-2: Example of a retaining wall inventoried in the GAM program.

3.3 Rock Slopes

Rock slopes may be either an excavated cut slope or a naturally occurring geologic outcrop capable of producing rockfall that may impact the roadway. The NCHRP GAM Implementation Manual recommended using a 10 ft rock cut height as the threshold for inventory and assessment. For implementation in Missouri, the team also added a threshold that the rock slope be taller than the adjacent ditch is wide, so that there is a realistic possibility for rock fall to reach the paved roadway. A rock slope that was inventoried and found to be in Fair condition is shown in Figure 3-3. An example of a rock slope that did not meet the inventory threshold is shown in Figure 3-4.

Figure 3-3: Rock slope near Louisiana, Missouri that received a detailed rating in the MoDOT GAM application.

Figure 3-4: Example of a rock slope that was not inventoried in the GAM application because the slope height was less than the ditch width.

3.4 Soil Slopes

Soil slopes, like rock slopes, can be either a naturally occurring adjacent feature or a cut soil slope. They can also be failures in embankment side slopes that have the same mechanism as landslides occurring in native soils and impacting the roadway. An example of a slope failure in the

Northwest District is shown in Figure 3-5. There is no threshold height for this asset. If a slope failure is impacting the roadway or associated features, such as drainage, then the slide should be inventoried and assessed. Cut soil slopes may include a mixture of soil and rock. In that case, the material controlling failure type should be used to determine which category the asset belongs in.

In the Northeast District, MoDOT has proactively addressed multiple landslides in cut slopes and embankment side slopes. These mitigated slides were inventoried and assessed, so that the Department can track mitigation performance and life cycle over time. A mitigated slide in an embankment side slope is shown in Figure 3-6.

Figure 3-5: Soil slope failure assessed and inventoried in the GAM program. Note ground cracks immediately left of the inspecting geologist.

Figure 3-6: Example of a successfully mitigated soil slope failure inventoried in the GAM application.

3.5 Subgrades / Ground Improvements

Subgrade assets are improvements completed below the paved surface during construction that have a life cycle. This can include drains, deep compaction, soil improvement, or other techniques summarized in Section 4.1.8. The type of improvement completed is typically invisible during field ratings. This asset category is created in preparation for tracking subgrade / ground improvement installations during future projects. This facilitates the department's ability to track performance and degradation of these assets over their life cycle.

No subgrade assets were inventoried during the 2022 field ratings for this project.

3.6 Subsidence

Much of Southern Missouri is underlain by limestone topography (karst). Scattered abandoned mining regions also are present statewide. Subsidence associated with both subsurface types has been a persistent issue for MoDOT. The NCRHP GAM Implementation Manual combines subsidence with subgrade improvement since mitigation work is typically below-ground. MoDOT wanted to track these assets separately because this type of geotechnical hazard is pervasive throughout Missouri.

Subsidence occurring within MoDOT ROW is typically backfilled immediately. If it is not possible to inventory a sinkhole in the GAM program before it is backfilled, then the mitigated feature should be added to the inventory. An example is shown in Figure 3-7. New sinkholes are more likely to develop in areas of previous subsidence.

Figure 3-7: Pair of photographs of a sinkhole near the Hwy 24 bridge at Quincy showing 2010 conditions (left) and post-mitigation conditions in 2022 (right).

4 ASSET INFORMATION FIELDS AND RATING CATEGORIES

The engineer or geologist performing the ratings collects general information about the asset type and more detailed information to develop a condition state rating for each inventoried and rated geotechnical asset. General site information may contribute to other calculations in the detailed ratings, but do not inherently determine asset condition. The general site information can be used for filtering the data set, or for future research on mitigation costs, asset life cycle, etc. Not all the detailed rating categories are used to develop asset condition state. For example, wall height does not directly impact wall condition, but it would factor into the cost of a conceptual mitigation cost estimate.

The following tables outline the site information and measurements to be collected and the asset-specific rating categories for each asset class. As these tables make clear, there is signification overlap between the data collected for six asset types. The table also includes the source of the data. Because the Survey123 data is "scraped" into MoDOT's TMS system, the research team leveraged the strength of MoDOT's TMS system to append some data after the survey is collected. To "scrape" data from the ESRI servers, the IT team downloaded a JSON file containing all the information in the Survey123 dataset, then processed it with internally developed scripts in MoDOT's TMS environment. The data on the ESRI server was then deleted, so that data was not duplicated in subsequent "scrapes."

Data appended in TMS after data is scraped from the ESRI servers is data that cannot easily be collected in the field by the rater, like annual average traffic volumes. Appended data and other calculations not necessary for asset condition state are all completed in TMS. Calculations performed in the Survey123 application and within TMS are also noted in the following tables.

Table 4-1: General Site Information for Geotechnical Assets

Field Alias	Asset Type						Data Source	Entry Type
	Rock	Soil Slope	Retaining Wall	Subsidence	Engineered Embankment	Subgrade		
AADT	X	X	X	X	X	X	TMS	Appended from TMS
Asset Length	X	X	X	X	X	X	Survey123	Manual
Axial Length		X					Survey123	Manual
Bare Erodible Slope	X	X					Survey123	Dropdown
Block Size/Vol	X						Survey123	Manual
Constructed of Known Degradable Material?					X		Survey123	Dropdown
Embankment Engineering Type					X		Survey123	Dropdown
Embankment Height					X		Survey123	Manual
Embankment Side Slope					X		Survey123	Manual

Field Alias	Asset Type						Data Source	Entry Type
	Rock	Soil Slope	Retaining Wall	Subsidence	Engineered Embankment	Subgrade		
Improvement Class						X	Survey123	Dropdown
Improvement Thickness						X	Survey123	Manual
Improvement Type						X	Survey123	Dropdown
Landslide Location		X					Survey123	Dropdown
Landslide Movement Type		X					Survey123	Dropdown
Length of Roadway Affected	X	X	X	X	X	X	Survey123	Drawn on embedded map
Mitigated?	X	X		X	X	X	Survey123	Dropdown
Mitigation Effective?	X	X		X	X	X	Survey123	Dropdown
Mitigation Type	X	X		X	X	X	Survey123	Dropdown
Project Number			X		X	X	Survey123	Manual
Repair Effective?			X				Survey123	Dropdown
Repair Type?			X				Survey123	Dropdown
Repaired?			X				Survey123	Dropdown
Roadway Width	X	X	X	X	X	X	Survey123	Manual
Rockfall Type	X						Survey123	Dropdown
Side of Roadway	X	X	X	X			Survey123	Dropdown
Sight Distance	X	X	X	X	X	X	Survey123	Manual
Slope Height	X						Survey123	Manual
Speed Limit	X	X	X	X	X	X	Survey123	Manual
Subsidence Location				X			Survey123	Dropdown
Subsidence Type				X			Survey123	Dropdown
Wall Height			X				Survey123	Manual
Wall Type			X				Survey123	Dropdown
Width of Roadway Affected				X			Survey123	Manual
Within Known Mine/Cave Area?				X			Survey123	Dropdown
Year Asset Constructed	X	X	X	X	X	X	Survey123	Manual
Year Mitigation Constructed? (If known)	X	X		X	X	X	Survey123	Manual
Year of Repair?			X				Survey123	Manual

Table 4-2: Detailed rating categories for Geotechnical Assets

Field Alias	Asset Type: Rock	Soil Slope	Retaining Wall	Subsidence	Engineered Embankment	Subgrade	Calculation Location	Entry Type
AADT Score	X	X	X	X	X	X	TMS	Calculated
Average Vehicle Risk Score	X	X	X	X	X	X	TMS	Calculated
Block Size Score	X						TMS	Calculated
Case 1 – Rock Friction Score	X						Survey123	Dropdown
Case 1 – Structural Condition Score	X						Survey123	Dropdown
Case 2 – Difference in Erosion Rates Score	X						Survey123	Dropdown
Case 2 – Structural Condition Score	X						Survey123	Dropdown
Ditch Effectiveness Score	X						Survey123	Dropdown
Drainage Score – Engineered Embankments					X		Survey123	Dropdown
Drainage Score – Subgrades						X	Survey123	Dropdown
Drainage Score - Subsidence				X			Survey123	Dropdown
Event Volume Score	X						Survey123	Calculated
Failure Extents		X			X	X	Survey123	Dropdown
Height Score – Embankments					X	X	TMS	Calculated
Height Score – Retaining Walls			X				TMS	Calculated
Height Score - Slopes	X	X					TMS	Calculated
Length of Roadway Affected Score	X	X	X	X	X	X	TMS	Calculated
Movement History Score		X					Survey123	Dropdown
Observable Critical Components Score			X				Survey123	Dropdown
Percent Decision Sight Distance Score	X	X	X	X	X	X	TMS	Calculated
Roadway Damage Score – Subgrades						X	Survey123	Dropdown
Roadway Deformation Score			X				Survey123	Dropdown
Roadway Displacement / Slide Deposit		X					Survey123	Dropdown
Roadway Impedance Score – Subsidence				X			Survey123	Dropdown

Field Alias	Asset Type: Rock	Soil Slope	Retaining Wall	Subsidence	Engineered Embankment	Subgrade	Calculation Location	Entry Type
Roadway Settlement Score – Engineered Embankments					X		Survey123	Dropdown
Roadway Width Score	X	X	X	X	X	X	TMS	Calculated
Rockfall Activity Score	X						Survey123	Dropdown
Settlement Rate Score – Subsidence				X			Survey123	Dropdown
Settlement Rate Score – Embankments					X	X	Survey123	Dropdown
Slope Drainage Score	X	X					Survey123	Dropdown
Wall Alignment Score			X				Survey123	Dropdown
Wall Drainage Score			X				Survey123	Dropdown

4.1 Geotechnical Asset General Information Fields

This section compiles the general information fields in alphabetical order. Each entry includes a summary of what type of data is collected, including any dropdown options in the Survey123 app. Data collected in these fields do not directly impact the scores in the rating categories described in the following subsection. However, they provide information that is useful from a geotechnical engineering perspective and provide ways to filter/group inventoried assets. This can help identify potential relationships over time, for example, a retaining wall type that performs particularly well.

4.1.1 Asset Type

Assets Collected For:

- All

In this field, the user selects the type of asset being rated. The selection in this field filters the remaining questions in the Survey123 application, so that the rater is only prompted to collect relevant data in the rest of the survey.

Table 4-3: Dropdown Entry Options – Asset Type

Asset Type
Engineered Embankment
Ground Improvements
Rock Slope
Retaining Wall
Soil Slope
Subsidence

4.1.2 Bare Erodible Slope

Assets Collected For:

- Rock Slope
- Soil Slope

Bare erodible slopes, typically related to shale or loess deposits, are extremely difficult to vegetate. They are weak, generally unstable, and a perennial maintenance issue or roadway hazard for MoDOT. Including this information in the final application was identified as a Department Need by the Technical Committee. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-4: Dropdown Entry Option – Bare Erodible Slope

Bare Erodible Slope
Yes
No

4.1.3 Constructed of Known Degradable Material?

Assets Collected For:

- Embankment

MoDOT is aware that embankments and subgrades in parts of the state, particularly in the southeast corner, have a higher likelihood of being constructed from degradable material. Sharkey clay was raised as a particular concern by the technical committee. Earthworks composed of degradable material have an increased risk of future poor performance, and to the extent possible, MoDOT intends to proactively track these locations within their geotechnical asset management database. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-5: Dropdown Entry Option – Degradable Material

Constructed of Known Degradable Material?
Yes
No

4.1.4 Engineered Embankment Type

Assets Collected For:

- Embankment

This field provides more information on the type of engineered embankment. Over time, it can be paired with embankment condition to provide more information on the life span of different engineered embankment types, options that work particularly well (or particularly poorly) in different regions, etc. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-6: Dropdown Options – Engineered Embankment Types

Engineered Embankment Type
Geosynthetic
Rock Fill
Lightweight Fill - Foam
Lightweight Fill - Haydite
Recycled Materials - Tires, etc.
Chemical Stabilization - Cement
Chemical Stabilization - Lime
Reinforced Soil Side Slopes
Unreinforced Fill

4.1.5 Embankment Side Slope

Assets Collected For:

- Embankment

Steeper slopes are generally at a higher risk for slumping and other stability issues. This field collects some basic additional information on the constructed embankment's side slopes. It is entered in degrees. The slope angle should be measured in the field. The Survey123 app also includes a reference table (reproduced below) that converts between common horizontal to vertical slopes and their angle in degrees. This table is intended as a helpful gut-check for the field rater. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-7: Copy of reference table provided in the Survey 123 app for embankment side slope angles

H:V	Degrees
1H:1V	45
1.5H:1V	33.7
2H:1V	26.6
2.5H:1V	21.8
3H:1V	18.4

4.1.6 Improvement Class (Subgrade/Ground Improvement)

Assets Collected For:

- Ground Improvement

Following discussion with the Technical Committee, subgrade and ground improvements were combined into a single asset class for rating purposes. Poor performance of both asset types will present in very similar ways on the roadway surface. The field collects information on which of the improvement types was used at this location. Correctly populating this field requires knowledge of how the project was constructed, because it will not be obvious in the field. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-8: Dropdown Options – Improvement Class

Improvement Class
Subgrade
Ground Improvement

4.1.7 Improvement Thickness

Assets Collected For:

- Ground Improvement

In this field, the user manually enters the thickness of ground improvement in inches. Like Improvement Class, correctly populating this field requires knowledge of how the project was constructed since it will not be observable in the field. This field is intended to enable the Department to track performance of different improvement thicknesses over time, with the long-term goal of more cost-effective project planning. This category is for use in filtering the geotechnical asset dataset. It is not scored.

4.1.8 Improvement Type

Assets Collected For:

- Ground Improvement

The field collects more information about the type of improvement used at this site and requires pre-existing knowledge about the project. Over time, it is intended to help MoDOT identify which improvement types are most effective under different conditions. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-9: Dropdown Options – Improvement Type

Improvement Type
Vertical Drains
Deep Compaction
Aggregate Columns
Column-supported Embankments
Deep Soil Mixing
Mass Soil Mixing
Grouting
Reinforced Soil
Stabilized Soil Subgrade

4.1.9 Landslide Location

Assets Collected For:

- Soil Slope

This field collects more information about location of an unstable soil slope relative to the roadway. Depending on location, landslides will impact the road in different ways, and may also require different mitigation options. For example, a buttress that could easily be constructed to mitigate a slide below the roadway may not be a feasible option for a slide moving in a slope above the road. In the long-term, MoDOT may be able to determine if maintenance and mitigation costs are significantly different for different slide locations, which would lead to better budget forecasting. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-10: Dropdown Options – Landslide Location

Landslide Location
Above
Below
Across

4.1.10 Landslide Movement Type

Assets Collected For:

- Soil Slope

This field collects more information about the type of slope instability observed at a site. When combined with information from other fields, it is intended to help the Department identify correlations between landslide types and maintenance costs, determine the most cost-effective mitigation types for different landslide types, etc. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-11: Dropdown Options – Landslide Movement Types

Landslide Movement Type
Translational Slide
Rotational Slide
Debris Flow
Slump
Erosional Failure

4.1.11 Mitigation and Repair Entry Options

Assets Collected For:

- All

The section describes a set of three fields: has the asset been mitigated or repaired, what type of work was performed, and is it effective. The fields for mitigation presences and effectiveness are yes/no responses. The mitigation type field is a set of commonly used mitigation or repair options filtered by asset type. All these fields are optional during the rating. If no mitigation has been performed, the rater may select “none” to clarify that the field was not accidentally skipped. If an asset has already been mitigated, tracking the type of mitigation and its effectiveness can help

MoDOT develop mitigation life cycle costs, track effective mitigation types, and record improvements to asset condition. The options for this field are filtered based on the asset type selected at the beginning of the rating process. If a mitigation type is selected, the rater is prompted to assess its effectiveness, based on his or her engineering judgement. This category is for use in filtering the geotechnical asset dataset. It is not scored.

Table 4-12: Mitigation and repair options for each asset type.

Asset Type	Mitigation/Repair Options
Rock Slopes	• Slope regrading or scaling • Buttress • Erosion control (armoring, vegetating) • Attenuators or mesh • Dowels, pins, or rock bolts • Barriers • Horizontal drains • None
Soil Slopes	• Slope regrading or scaling • Buttress • Shear key • Erosion control (armoring, vegetating) • Deep dewatering (trench drains, horizontal drains) • Shallow dewatering (French drains, drainage blankets) • Ground anchors • None
Engineered Embankments	• Reconstruction • Drainage improvement • Slope regrading • Buttress • Retaining walls • Rock inlay • None
Ground Improvement	• Reconstruction • Drainage improvement • None
Subsidence	• Backfill (cement grout, gravel) • Drainage improvement • None
Retaining Walls	• Structural degradation repair • Structural crash damage repair • Repair of Existing Drainage System • Drainage Improvement • None

4.1.12 Rockfall Type

Assets Collected For:

- Rock Slope

This field collects more information about governing failure type at a given rock slope. Different failure types will make different mitigation types more or less effective. Over time, it may also help MoDOT assess if maintenance or emergency response costs are disproportionately associated with a specific failure type. This information could be used to help prioritize between different projects. This category is for use in filtering within the geotechnical asset dataset. It is not scored directly.

Table 4-13: Dropdown Options - Rockfall Types

Rockfall Type
Planar
Wedge
Toppling
Raveling/Undermining
Block

4.1.13 Side of Roadway

Assets Collected For:

- All

This field provides information on the location of the asset relative to the roadway. For divided highways, left and right is relative to the driver. For non-divided highways, left and right relative to a driver moving away from the log-mile zero point for the route. This field can also be used as a check on the travel way ID appended in TMS. This category is for use in filtering within the geotechnical asset dataset. It is not scored directly.

Table 4-14: Dropdown Options – Side of Roadway

Side of Roadway
Left
Right

4.1.14 Speed Limit

Assets Collected For:

- All

The posted speed limit at the site is manually recorded in this field. On turns, particularly in hilly or mountainous regions, posted speed limits at the asset location may be lower than the highway design speed. Speed limit is not scored, but it is used to calculate the Percent Decision Sight Distance and the Average Vehicle Risk scores.

4.1.15 Subsidence Location

Assets Collected For:

- Subsidence

Incorporating discussions with the Technical Committee, MoDOT currently addresses any sinkholes identified within its Right of Way. This field is intended to help the MoDOT track sinkholes within the right of away and capture any sinkholes of concern just beyond the ROW that MoDOT may address in the future. This field will help the Department monitor subsidence features and the performance of backfill operations over time. This category is for use in filtering within the geotechnical asset dataset. It is not scored.

Table 4-15: Dropdown Options - Subsidence Location

Subsidence Location
Within Roadway Prism
Within ROW Adjacent to Roadway
Beyond ROW

4.1.16 Subsidence Type

Assets Collected For:

- Subsidence

This field collects more information about the type of subsurface issue believed to be causing the subsidence. The “Utility Feature” referrers to pipelines, culverts, or other undercrossings that may undermine the roadway via piping of material or construction issues. This category is for use in filtering the within geotechnical asset dataset. It is not scored.

Table 4-16: Dropdown Options - Subsidence Types

Subsidence Type
Abandoned Mine
Karst Feature
Utility Feature

4.1.17 Retaining Wall Location

Assets Collected For:

- Retaining Wall

This field provides information on the location of a retaining wall relative to the roadway. Failure of walls located above the roadway may deposit material onto the roadway, while failure of walls located below the roadway may cause roadway subsidence. This category is for use in filtering the within geotechnical asset dataset. It is not scored.

Table 4-17: Dropdown Options – Retaining Wall Location

Retaining Wall Location
Above
Below

4.1.18 Wall Type and Subtype

Assets Collected For:

- Retaining Wall

This is a pair of fields to collect more information about the type of retaining wall constructed at a site. The main retaining wall type is selected first. This then opens a second, filtered, list that collects more information about the wall. It can be left blank if the rater is unsure. The data collected in these fields is intended to help MoDOT track degradation and life cycle of different wall types, determine effective mitigation measures for different wall types, etc. This category is for use in filtering the within geotechnical asset dataset. It is not scored directly.

Table 4-18: Dropdown Options - Retaining Wall Types

Retaining Wall Types
Anchored
Bin
Cantilever
Crib
Gabion
Mechanically Stabilized Earth (MSE)
Pile
Soil Nail

Table 4-19: Dropdown Options – Retaining Wall Subtypes

Master Retaining Wall Type	Retaining Wall Subtype
Anchored	Micropile
Anchored	Tieback H-Pile
Anchored	Tieback Sheet Pile
Bin	Concrete
Bin	Metal
Cantilever	Concrete
Cantilever	Sheet Pile
Cantilever	Soldier Pile
Crib	Concrete
Crib	Metal
Crib	Timber
Gabion	--

Master Retaining Wall Type	Retaining Wall Subtype
MSE	Geosynthetic Wrapped Face
MSE	Precast Panel
MSE	Segmental Block
MSE	Welded Wire Face
Pile	Tangent
Pile	Secant
Soil Nail	--

4.1.19 Within Known Karst/Mining Area

Assets Collected For:

- Subsidence

Sinkhole development is more common in areas underlain by soluble bedrock or an historic mining area. In these areas, local maintenance personnel are alert to new sinkhole development based on past experience. A sinkhole developing in an area not previously identified as having soluble bedrock or historical mining could indicate a previously unknown mining region. It could also indicate a different failure mode, such as piping around an abandoned culvert. Both scenarios would merit more investigation by MoDOT's geotechnical personnel. This category is for use in filtering within the geotechnical asset dataset. It is not scored.

Table 4-20: Dropdown Entry Option – Within Known Karst/Mining Area

Within Known Karst or Mining Area
Yes
No

4.1.20 Year Asset Constructed

Assets Collected For:

- All

This information is not easily available for most of MoDOT's geotechnical assets. It is likely most accessible for retaining walls, engineered embankments, and subgrades, but even there, complete data may be lacking for older assets. This is an aspirational field. If dates of construction are entered for future assets are new transportation projects are completed, MoDOT will be able to refine life cycle and degradation models for different assets over time. This would in turn make budget and returning-on-investment forecasting more accurate. It is currently included in the survey as an optional field. This field is not scored.

4.2 Geotechnical Asset Detailed Rating Categories

The following subsections describe the detailed rating categories and the field measurements needed to complete the calculations. Rating categories are presented in alphabetical order in this report, but in the Survey123 App, the detailed rating categories are filtered by asset type and only those relevant to the asset being rated are shown in the survey application. Rating categories that rely on data obtained from TMS after the survey is imported are not shown in the survey application but are present in the compiled dataset accessed through TMS.

4.2.1 Annual Average Daily Traffic (AADT)

Assets Collected For:

- All

This rating category captures route importance. It uses quantitative data obtained from MoDOT's Transportation Group. The Annual Average Daily Traffic (AADT) of a roadway provides a rough quantitative indicator of its impact on the regional economy and mobility of people, goods, and services. High traffic corridors will receive a higher risk score. The AADT score has been adjusted from the equation developed by Federal Highway Administration (FHWA) for their unstable slopes management program. The adjusted equation reflects the higher AADT counts on MoDOT's roadways. AADT score is based on the following equation (Equation 4-1), which is also plotted in the chart in Figure 4-1. Selected sample calculated scores are provided in Table 4-21.

Equation 4-1: Annual Average Daily Traffic Score

$$Score = 100 - 25 * \left(\sqrt{\frac{AADT}{1{,}000}} - 1\right);$$

$$maximum\ score = 100;\ minimum\ score = 0$$

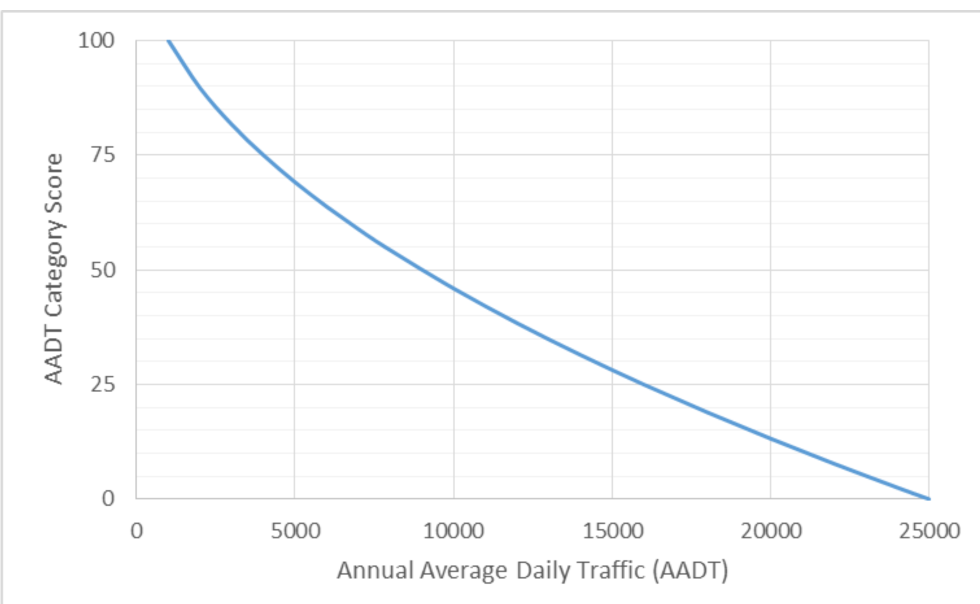


Figure 4-1: Chart illustrating the relationship between AADT and the category score. The category score maxes out below a minimum AADT of 1,000 vehicles and zeros out below an AADT of approximately 25,000 vehicles per day.

Table 4-21: AADT Sample Calculated Scores

Score	AADT
0 points	25,000 or greater
25 points	16,000
50 points	9,000
75 points	4,000
100 points	1,000 or less

4.2.2 Average Vehicle Risk Score

Assets Collected For:

- All

The Average Vehicle Risk (AVR) uses AADT, speed limit, and asset length to approximate how many vehicles are within the potential impact zone of an asset failure at any one time. It assesses risk to traffic as a function of the percentage of time a vehicle is actually present within the asset area. It assumes that AADT is spaced equally over the course of the day and does not take daily traffic fluctuations like rush hour into account.

Equation 4-2 is used to calculate the AVR score. A score of 0 means that, on average, a vehicle is within the defined section 100% or more of the time. The same equation (Equation 4-2) is used for all assets and is also plotted in Figure 4-2. Sample category scores are presented in Table 4-22.

Equation 4-2: Average Vehicle Risk Score

$$Average\ Vehicle\ Risk\ Score = 100 - 25 * \left(\left(\frac{\left(\frac{\frac{AADT}{24} \times slope\ length\ (miles) \times\ 100}{posted\ speed\ limit} \right)}{25} \right) - 1 \right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

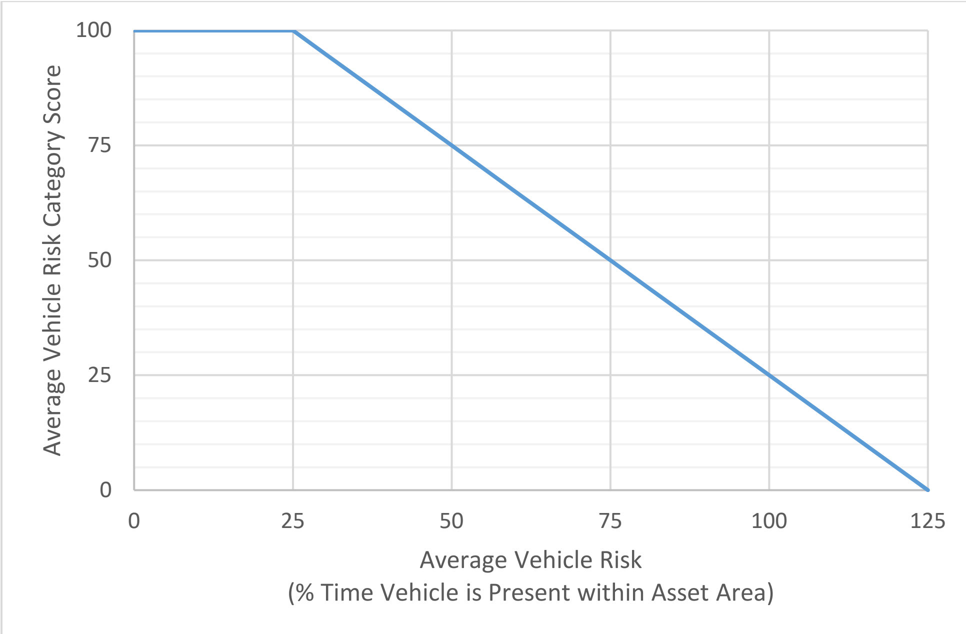


Figure 4-2: Chart illustrating the relationship between the average vehicle risk and the category score. The category score maxes out at an average vehicle risk of 125% and zeros out at an average vehicle risk of 25%.

Table 4-22: Sample Calculated Scores from Average Vehicle Risk Equation

Score	Average Vehicle Risk
0 points	Vehicle within unstable slope section 125% of the time
25 points	Vehicle within unstable slope section 100% of the time
50 points	Vehicle within unstable slope section 75% of the time
75 points	Vehicle within unstable slope section 50% of the time
100 points	Vehicle within unstable slope section 25% of the time

4.2.3 Block Size / Event Volume Score

Assets Collected For:

- Rock Slopes

Larger blocks or volumes of falling rock produce more total kinetic energy and greater impact force than smaller events. In addition, the larger events obstruct more of the roadway, reducing the possibility of safely avoiding the rock(s), and resulting in higher cleanup costs for the managing agency. The larger the typical block size or event volume; the greater the hazard created; thus, the higher the assigned score in this category.

This measurement should be representative of the type of rockfall event most likely to occur. Debris currently contained in the roadside ditch can help generate a reasonable estimate. If individual blocks are typical of the rockfall at a site, then block size should be used for scoring. If a mass of blocks tends to be the dominant type of rockfall, volume per event should be used. A decision on which to use can be determined from the maintenance history or estimated from observed conditions.

The category score is calculated according to the following equations. If the rater is uncertain which failure type is dominant at the slope, rate the rock slope using both equations. The application will record both scores and automatically use the higher of the two in calculations. A pair of charts showing the relationship between block size/event volume and category score is also presented in Figure 4-3 for reference, as are sample calculated category scores in Table 4-23.

Equation 4-3: Block Size and Volume Size Scores

$$Block\ Size\ Score = 100 - (25 * \left((block\ size\ (feet)) - 1\right);\ x = block\ size\ (ft)$$

$$Event\ Volume\ Score = 100 - 25 * \left(\left(\frac{event\ volume\ (yds^3)}{3}\right) - 1\right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

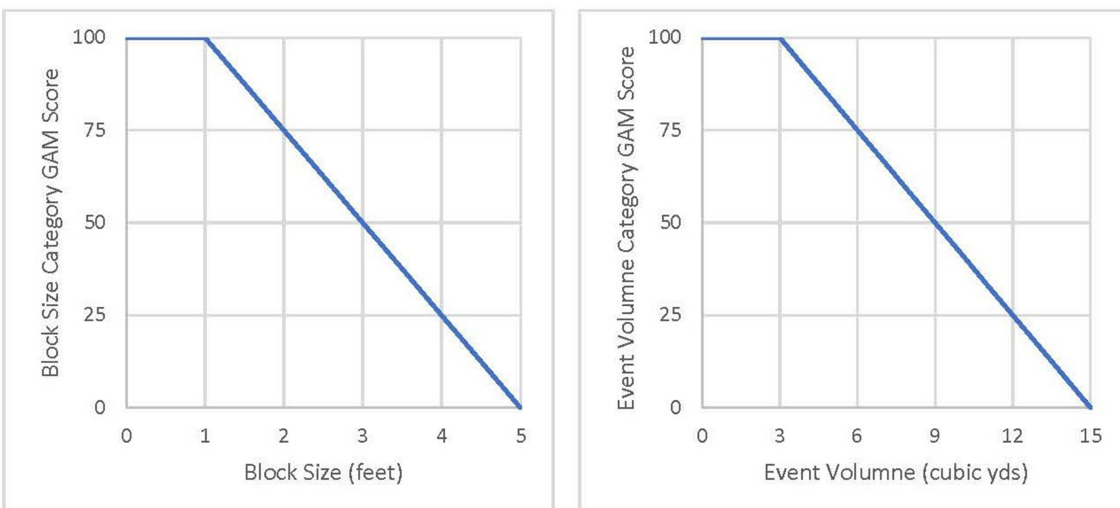


Figure 4-3: Chart pair illustrating the relationship between the block size and the category score and between the event volume and the category score.

Table 4-23: Block Size or Volume Size Sample Calculated Scores

Score	Block Size	Volume Size
0 points	5 feet	15 cubic yards
25 points	4 feet	12 cubic yards
50 points	3 feet	9 cubic yards
75 points	2 feet	6 cubic yards
100 points	1 foot	3 cubic yards

4.2.4 Geologic Condition Scores

Assets Collected For:

- Rock Slopes

The stability of rock slopes is largely controlled by one of two geologic conditions. The original Rockfall Hazard Rating System split controlling geologic conditions into two categories, which is used in the MoDOT program as well to maintain consistency with other DOT rock slope datasets. The two categories, Case 1 and Case 2, describe geologic differences in a rock slope that control rockfall. Case 1 is for rock slopes where joints, fractures, bedding planes, or other discontinuities are the dominant structural features controlling activity. Case 2 is for slopes where differential erosion within the rock slope face or oversteepening is the dominant condition causing events.

The case that best fits the slope should be used for the rating. If both situations are present, and it is unclear to the rater which dominates rockfall activity, both should be are scored, and the application will automatically use the worst case (highest score) for calculations.

4.2.4.1 Case 1

Movement along discontinuities controls rockfall in Case 1 slopes. "Joint" describes all possible types of discontinuities, including bedding planes, foliations, fractures, and faults. The term "continuous" refers to joints that are greater than 10 feet in length, which enable the release of larger blocks during failure events. The term "adverse" applies not only to the joint's spatial orientation within the slope, but also to such things as rock friction angle, joint filling, and the effects of water, if present.

4.2.4.1.1 Case 1 - Structural Condition

Jointed rock is more prone to rockfall than massive rock. Movement occurs along joints, where the resistance to movement is significantly less than through intact rock. When the joints are orientated adversely to the slope, potential for rockfall is greater. Adverse joints form planar, circular, block, wedge, or toppling failures, singularly or in combination. Except for toppling failures, the joints typically dip out of the slope. This category is analogous to the *Face Irregularity* factor in MoDOT's 2004 Rock Cut Rating System research project, which was based on a combination of joint spacing and rockfall history. Table 4-24 presents category narratives.

Table 4-24: Case 1 Structural Condition Category Narratives

Score	Narrative
100 points	Discontinuous joints with favorable orientations. Slope contains jointed rock with no adversely oriented joints.
60 points	Discontinuous joints with random (both favorable and unfavorable) orientations. Slope contains randomly oriented joints creating a variable pattern. The slope is likely to have some scattered blocks with adversely oriented joints, but no dominant adverse pattern is present.
30 points	Discontinuous joints with adverse orientations. Rock slope exhibits a prominent joint pattern with an adverse orientation, but these features have less than 10 feet of continuous length.
0 points	Continuous joints with adverse orientations. Rock slope exhibits a dominant joint pattern with an adverse orientation and a length greater than 10 feet.

4.2.4.1.2 Case 1 - Rock Friction

The potential for rockfall by movement along discontinuities is controlled by the condition of the joints. The condition of the joints is described in terms of micro and macro roughness. This is analogous to the Face Looseness factor in MoDOT's 2004 Rock Cut Rating System research project, which assessed the number of open joints present in a cut face.

This parameter directly affects the potential for one block to move relative to another. Friction along a joint, bedding plane or other discontinuity is governed by the macro and micro roughness of the surfaces. Macro roughness is the degree of undulation of the joint relative to the direction of possible movement. Micro roughness is the texture of the joint surface. On slopes where the joints contain hydrothermally altered or weathered material, previous movement has caused slickensides or fault gouge to form, or the joints are open or filled with water, the rockfall potential is much greater. Category narratives are presented in Table 4-25.

Table 4-25: Case 1 Rock Friction Category Narratives

Score	Narrative
100 points	Rough, Irregular. The joint surface is rough and joint planes are irregular, causing interlocking.
60 points	Undulating. Joint surfaces are macro and micro rough, but without interlocking ability.
30 points	Planar. Macro smooth and micro rough joint surfaces. Friction is derived strictly from the roughness of the joint surface.
0 points	Clay Infilling, Open, or Slickensides. Low friction materials separate the rock surfaces, negating any micro or macro roughness of the joint surfaces. Slickensided joints also have a lower friction angle and are rated in this category.

4.2.4.2 Case 2

This case is used for slopes where differential erosion or undercutting is the dominant condition leading to rockfall. Erosion features include over steepened slopes, unsupported rock units (overhangs), or exposed resistant rocks on a slope (such as limestone interbedded with shale), all of which may eventually lead to a rockfall event.

4.2.4.2.1 Case 2 - Structural Condition

Rockfall can be caused either by erosion that leads to a loss of support locally or throughout a slope. The types of slopes that may be susceptible to this condition are as follows: layered units (those containing more easily erodible rock layers that undermine the more durable rock as erosion takes place); over steepened talus slopes; highly variable units, such as conglomerates and mudflows that can weather differentially, allowing resistant rocks and blocks to fail; and rocky soil slopes where rocks fall out as the soil matrix material erodes. This category incorporates parts of the *Weathering* and *Face Irregularity* factors from MoDOT's 2004 Rock Cut Rating System research project. Table 4-26 contains category narratives.

Table 4-26: Case 2 Structural Category Narratives

Score	Narrative
100 points	Few Differential Erosion Features. Minor differential erosion features that are not distributed throughout the slope.
60 points	Occasional Differential Erosion Features. Minor differential erosion features that are widely distributed throughout the slope.
30 points	Many Differential Erosion Features. Differential erosion features that are large and numerous throughout the slope.
0 points	Major Differential Erosion Features. Severe cases such as dangerous erosion-created overhangs, significantly oversteepened soil and rock slopes or talus slopes.

4.2.4.2.2 Case 2 - Differential Erosion Rate

The materials that comprise a slope can have markedly different characteristics that control how rapidly weathering and erosion occur within the different materials exposed in the rock slope. As erosion progresses, resulting in portions of the slope becoming unsupported and the likelihood of a rockfall event increases.

The rate of erosion on a Case Two slope directly relates to the potential for a future rockfall event. As erosion progresses, unsupported or oversteepened slope conditions develop. The impact of the common physical and chemical erosion processes and the effects of man's actions (such as over excavating and steepening the roadside ditch) should be considered. The degree of hazard caused by erosion and, thus, the score given in this category should reflect the rate at which erosion is occurring; the size of rocks, blocks, or units being exposed; and the frequency with which events occur; and the likely amount of material released during an event. This category incorporates parts of the Weathering and *Face Looseness* factors from MoDOT's 2004 Rock Cut Rating System research project. Category narratives are presented in Table 4-27.

Table 4-27: Case 2 Differential Erosion Rate Category Narratives

Score	Narrative
100 points	Small Difference. Erosion features take many years to develop. Slopes that are near equilibrium with their environment are covered by this category.
60 points	Moderate Difference. The difference in erosion rates allows erosion features to develop over a period of a few years.
30 points	Large Difference. The difference in erosion rates allows noticeable changes in the slope to develop annually.
0 points	Extreme Difference. The difference in erosion rates allows rapid and continuous development of erosional features.

4.2.5 Ditch Effectiveness Score

Assets Collected For:

- Rock Slopes

This subjective category describes the ability of the ditch to capture falling rock and prevent it from reaching the roadway. The risk associated with a particular rock slope section is dependent on how well the ditch is performing in capturing rockfall. When little rock reaches the roadway, no matter how much rockfall is released from the slope, the danger to the public is low and the category score assessed is low. Conversely, if rockfall events are rare occurrences but the ditch is nonexistent, the resulting hazard is greater, and a higher score is assigned to this category. Many factors must be considered in evaluating this category. The reliability of the result depends heavily on the rater's experience. It can also be refined with input from maintenance personnel.

A wide fallout area does not necessarily guarantee that rockfall will be restricted from the highway. In estimating the ditch effectiveness, the rater should consider several factors, such as: 1) slope height and angle; 2) ditch width, depth and shape; 3) anticipated volume of rockfall per event; and 4) impact of slope irregularities (launching features) on falling rocks. Evaluating the effect of slope irregularities is especially important because they can completely negate the benefits expected from a fallout area. Table 4-28 below presents a graphic diagram of ditch effectiveness for guidance. Table 4-28 also provides narratives for the different categories.

Table 4-28: Ditch Effectiveness Category Narratives

Score	Narrative
100 points	Very Good Catchment. All or nearly all falling rocks are retained in the catch ditch, with ditch capturing >95% of rockfall.
75 points	Moderate Catchment. Falling rocks occasionally reach roadway, with ditch capturing roughly 75% of rockfall.
50 points	Limited Catchment. Falling rocks frequently reach the roadway, with roughly half of all rockfall retained in the ditch.
25 points	Poor Catchment. Nearly all falling rocks reach the roadway, with ditch capturing <25% of rockfall.
0 points	No Catchment. No ditch, or ditch is totally ineffective. All or nearly all falling rocks reach the road.

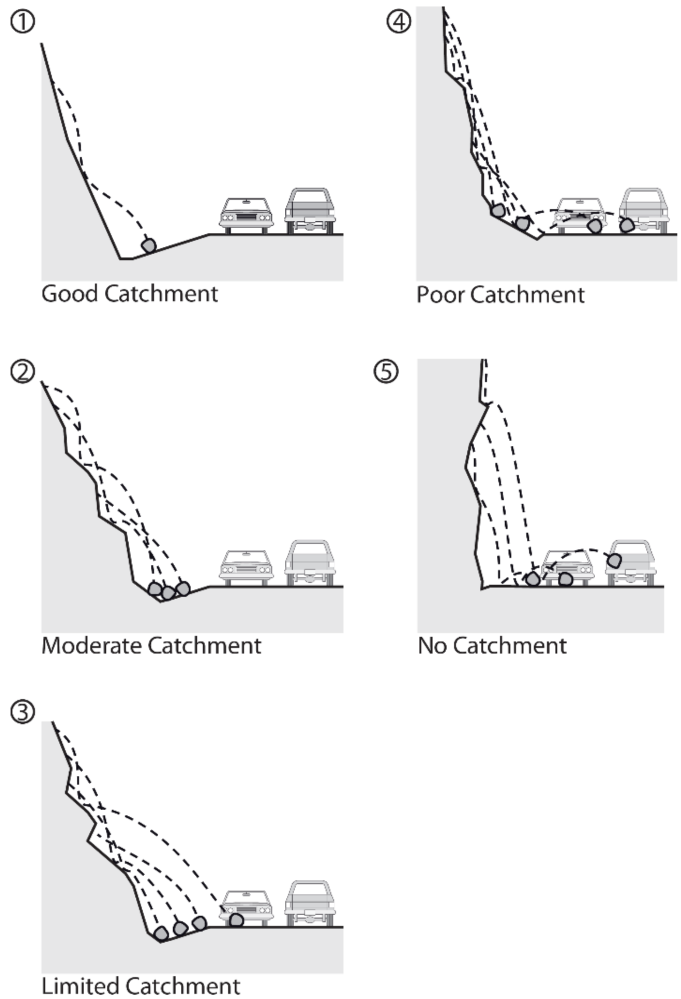


Figure 4-4: Ditch effectiveness explanatory diagram

4.2.6 Drainage Scores

Assets Collected For:

- All (with subtle wording differences)

In general, well drained geotechnical assets perform better because they are subject to fewer stresses. The presence of springs, damaged drainage measures, or uncontrolled drainage can impair the asset's ability to handle rainfall or freeze-thaw events and increase the likelihood of failure. This category is based on a subjective evaluation. Although the specific wording may change slightly between different asset types, the general intent is the same across all asset types. It is illustrated in Figure 4-5 below. The specific category narratives for the different asset types are provided in the sub-sections below. Note that rating this category at different times of the year may produce different results since poor drainage control is not as obvious during drier months, although the effects of poor drainage (staining, algae, vegetation, etc.) often do persist into the dry season.

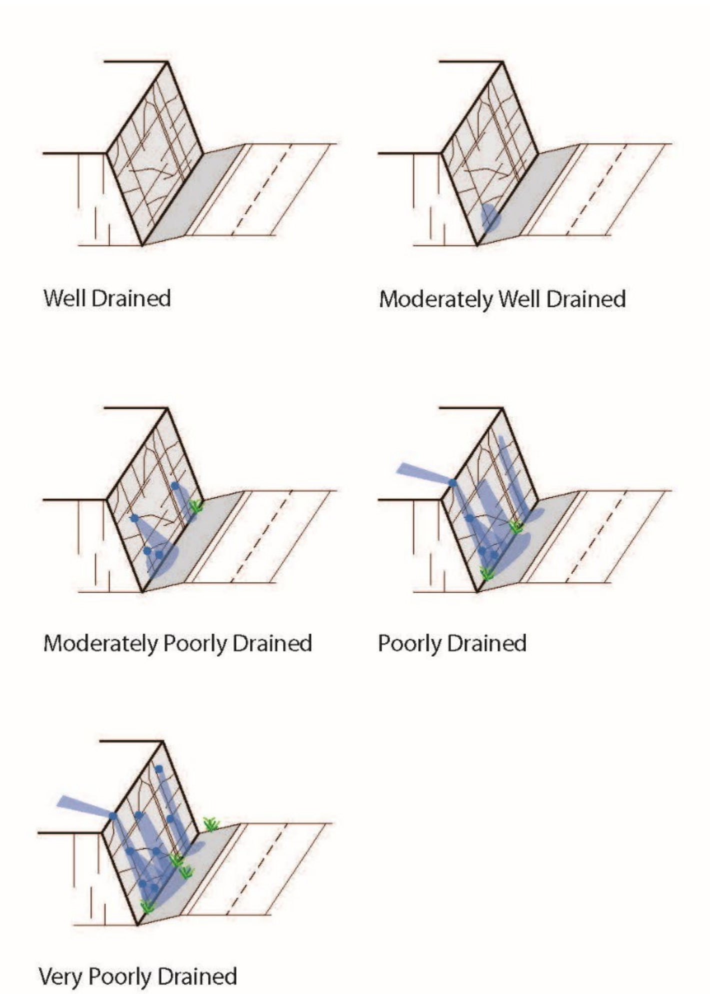


Figure 4-5: Schematic illustration of drainage categories using rock slope assets as an example.

4.2.6.1 Drainage Score – Engineered Embankments, Soil Slopes, Ground Improvement, and Rock Slopes

The drainage score narratives for slopes, embankments, and ground improvements are very similar. For ground improvement assets, which may include drainage features constructed within the roadway prism, only unintended seepage is considered in the rating.

Table 4-29: Drainage Score Category Rating – Embankment, Soil Slope, Rock Slope and Ground Improvement Category Narratives

Score	Narrative
100 points	Area dry, no evidence of seasonal seepage. Slope appears dry or well-drained. Surface run-off in the area is well controlled, and the slope is dry within hours of a rain event.
75 points	Generally dry, intermittent seasonal seepage. Water is intermittently present on the slope, and surface water is generally well-controlled. The slope is dry within days of a rain event.
50 points	Routine seasonal seepage. The slope is usually wet, particularly during the rainy season or after storm events. Surface runoff near the slope crest or base may be poorly controlled. Slope is still wet a week or two following rain events but dries out during prolonged dry spells.
25 points	Year-round seepage from slope or cut face. Water is always present on the slope, typically seeping from localized points, such as joints or springs. Surface runoff control is not present and any constructed drainage systems are clogged and inoperable.
0 points	Year-round measurable flow from multiple points on slope or cut face. Measurable flow seeps from multiple points on the slope face year-round. No surface water control is present or, if present, is completely ineffective.

4.2.6.2 Drainage Score – Subsidence

The drainage score for subsidence features includes drainage from or drainage into the feature.

Table 4-30: Drainage Score Category Rating – Subsidence Category Narratives

Score	Narrative
100 points	Area is dry, no evidence of seasonal seepage from, or drainage to, feature. Subsidence appears dry or well drained. Surface runoff in the area is well controlled and does not interact with the subsidence feature.
75 points	Intermittent minor seepage from, or drainage to, feature. Water intermittently seeps from or runs to the subsidence feature following heavy storm events. Surface runoff in the area is moderately controlled. Subsidence area is dry within days of a rain event.
50 points	Routine seasonal seepage from, or drainage to, feature. Seepage from or flow to the subsidence area during the wet season or following extended periods of heavy rain. Surface runoff in area may be poorly controlled or insufficient to meet demand. Area is still wet several weeks following rain events but may appear dry during prolonged dry spells.
25 points	Year-round seepage from, or drainage to, feature, with seasonally measurable flow. Subsidence area is wet year-round, but flow is only measurable during the wet season or after extended periods of heavy rain. Surface water drains to the area, and constructed surface water controls are ineffective.
0 points	Year-round measurable flow from, or drainage to, feature. The subsidence area acts as a spring or drain for a measurable amount of water that is present year-round. No surface water control present.

4.2.6.3 Drainage Score – Retaining Walls

Retaining walls are frequently built with drainage features, thus only unintended seepage is considered in the rating.

Table 4-31: Drainage Score Category Rating – Retaining Wall Category Narratives

Score	Narrative
100 points	Good performing drainage system; surface water well controlled. Wall appears dry or well drained. Drains installed in wall appear clean and free-flowing. Surface runoff near wall crest is well controlled. Wall face is dry hours after rain events.
75 points	Fair performing drainage system; surface water moderately well controlled. Water is intermittently on wall, particularly along cracks in the face. Drains installed are flowing, but partially obstructed by debris or vegetation or design drainage system may not be adequate for demand. Surface runoff near wall crest is moderately controlled. Wall face is dry within days after rain events.
50 points	Intermittent seepage from wall face. Intermittent seeps in the wall face. Installed drains are largely obstructed by debris. Surface runoff near wall crest may be poorly controlled. Wall face is still wet several weeks following rain events but may appear dry during prolonged dry spells.
25 points	Signs of routine seasonal seepage from multiple points on wall face. Poorly performing wall drainage system; surface water runoff control not present. Water regularly seeping from cracks in the wall face and wall drains appear fully obstructed or ineffective. No surface water control present or effective above wall crest. Wall face is wet year-round.
0 points	Year-round seepage from multiple locations on wall face. Non-performing wall drainage system; surface water runoff control not present. Water seeping from cracks in the wall face year-round and wall drains appear fully obstructed or ineffective. No surface water control present or effective above wall crest. Measurable flow from seeps on wall face year-round.

4.2.7 Embankment and Subgrade Settlement Rate Score

Assets Collected For:

- Engineered Embankments
- Ground Improvement

Higher settlement rates lead to higher maintenance costs and risks to roadway users. This category should be rated based on input from maintenance personnel since it is difficult to accurately assess a rate of movement from a single site visit. The settlement rate scores for embankments and subgrades are very similar to those for subsidence, but the narratives are slightly different, to reflect the different process at work.

Table 4-32: Settlement Rate Score Category Narratives – Embankments and Ground Improvement

Score	Narrative
100 points	Area of concern, no pavement distress detected. This rating is typically reserved for a newly constructed embankment or subgrade, or an embankment/subgrade known to be constructed of poor material or using a construction method that has failed in the past. It may also be used for a newly repaired area where the success of the repair will be monitored.
75 points	Sporadic subsidence or displacement with minor pavement cracking. The rate of settlement is low and non-continuous. Pavement disturbance is minor on an annual basis and maintenance requirements are minimal and carried out as a scheduled activity.
50 points	Steady annual subsidence/displacement, with extensive pavement cracking. The rate of movement is low but continuous and the pavement has been damaged. Roadway maintenance is routinely required to avoid road closures, but maintenance action can generally be on a scheduled basis.
25 points	Rapid subsidence/displacement: 1 to 6 inches in hours. The rate of settlement is high and requires immediate and unscheduled maintenance. The site is as a persistent maintenance problem.
0 points	>6 inches subsidence/displacement in hours. The rate of settlement is so high that aggressive, unscheduled maintenance intervention is required to maintain traffic flow and correct unsafe conditions.

4.2.8 Failure Extent Score

Assets Collected For:

- Embankments, Soil Slopes, and Ground Improvement

When a slump or slide undermines or blocks part of the roadway, accidents can occur when a vehicle impacts slide debris, drives off a scarp, or attempts an emergency evasive maneuver. The hazard is related to the proportion of the roadway width affected. This category is also used to describe hazard for side slope embankments and subgrade improvements

Table 4-33: Failure Extent Score Category Narratives

Score	Narrative
100 points	No impacts to roadway infrastructure. This category is typically reserved for a slide within the right of way that is not impacting infrastructure, or for a slope that has been repaired and is no longer moving.
80 points	Half of Shoulder. Portion of shoulder is still available for emergency maneuvers or maintenance work, but failure is impacting the roadway prism.
75 points	Shoulder only. The travel lanes are not affected by the landslide event, but the available paved surface is reduced. A detour or traffic control is typically not required except during maintenance activities.
60 points	¼ Roadway. Events affect 25% of the travel lanes, adequate paved surface is available to maneuver around the event without crossing into the opposite direction travel lanes. A detour is not required, but traffic control would be needed during maintenance/repair activities.
50 points	Half Roadway. Events affect 50% of the travel lanes but adequate paved surface is available to maneuver around the event. A detour is typically not required but traffic control would be needed during maintenance/repair activities.
25 points	3/4 Roadway. Events affect 75% of the surface dedicated to travel lanes. Maneuvering actions may still be possible by using paved or unpaved shoulders, if available. A detour or complete vehicle stoppage may be required.
0 points	Full Roadway. Events or deformation affect the entire road with no opportunity to maneuver around the event. A detour or halted traffic flow is required.

4.2.9 Height Score – Embankment or -Ground Improvements

Assets Collected For:

- Embankments
- Ground Improvements

This category considers the hazard associated with embankment height. A taller embankment contains more material and failures in the foundation or slope of a taller embankment are more likely to impact the roadway. Increased embankment height also makes access for maintenance more challenging. The embankment height used for this rating is measured as the greatest vertical distance between the embankment crest and toe. The score is calculated directly using Equation 4-4 below. Sample category scores are shown in Table 4-34.

Equation 4-4: Embankment Height Score

$$Embankment\ Height\ Score = 100 - 25 * \left(\left(\frac{embankment\ height\ (ft)}{10}\right) - 1\right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

Table 4-34: Sample Calculated Scores from Embankment Height Equation

Score	Embankment Height
0 points	50 feet
25 points	40 feet
50 points	30 feet
75 points	20 feet
100 points	10 feet

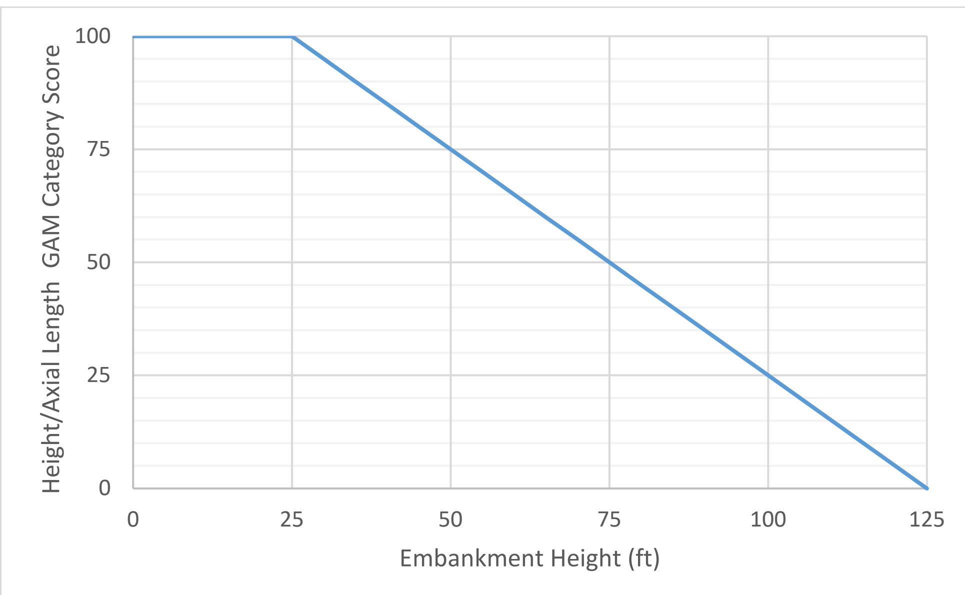


Figure 4-6: Chart illustrating the relationship between the embankment height and the category score. The category score maxes out at an embankment height of approximately 50 feet.

4.2.10 Height Score – Retaining Walls

Assets Collected For:

- Retaining Walls

This category considers the hazard associated with wall height. Taller walls retain more material and have a greater potential to impact the roadway and adjacent ROW in a failure. The wall height used for this rating is measured to the highest point at the crest of the retaining wall. The score is calculated directly using Equation 4-5 below. Sample category scores are shown in Table 4-35.

Retaining walls less than 4 feet tall are not entered into the asset management database.

Equation 4-5: Wall Height Score

$$Wall\ Height\ Score = 100 - 25 * \left(\left(\frac{wall\ height\ (ft)}{10}\right) - 1\right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

Table 4-35: Sample Calculated Scores from Wall Height Equation

Score	Wall Height
0 points	50 feet
25 points	40 feet
50 points	30 feet
75 points	20 feet
100 points	10 feet

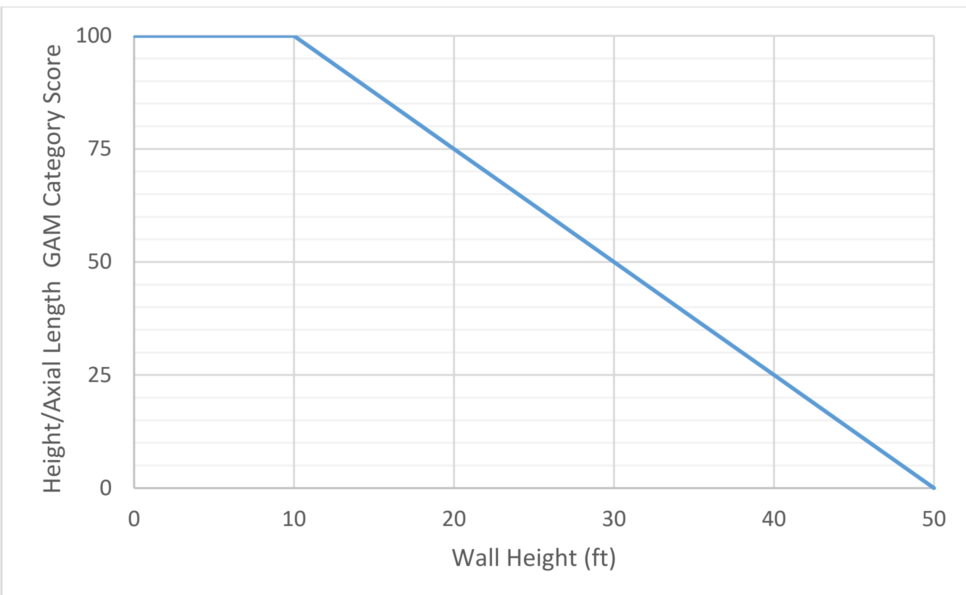


Figure 4-7: Chart illustrating the relationship between the retaining wall height and the category score. The category score maxes out at a wall height of approximately 50 feet.

4.2.11 Height Score – Rock and Soil Slopes

Assets Collected For:

- Rock Slopes
- Soil Slopes

This category evaluates the risk associated with the height of a rock slope or axial length of a landslide or debris flow. The slope height measurement is to the highest point from which rockfall is expected or the axial length (slope distance) of a landslide, as shown in Figure 4-8 below.

If rockfall is generated from the natural slope above the cut slope, the slope height measurement should include both the cut height and the additional vertical height on the natural slope to the rockfall source. On a landslide, the distance from scarp to toe should be measured. For debris flows the approximate axial or channel distance from the roadway to the source area should be entered.

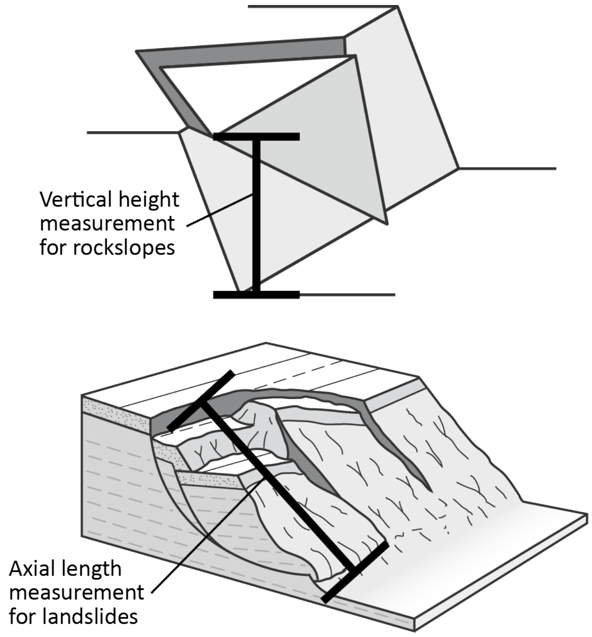


Figure 4-8: Examples of measuring vertical slope height on a rock slope and axial length on a landslide.

This category is directly measured and scored using the equation presented below. A chart relating slope height/axial length and category score is presented for reference, as is a table containing sample calculated category scores.

Equation 4-6: Slope Height or Slide Axial Length Score

$$Slope\ Height\ Score = 100 - 25 * \left(\left(\frac{slope\ height\ or\ slide\ axial\ length}{25}\right) - 1\right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

Table 4-36: Sample Calculated Scores from Slope Height or Axial Length Equation

Score	Slope Height or Axial Length
0 points	125 feet
25 points	100 feet
50 points	75 feet
75 points	50 feet
100 points	25 feet

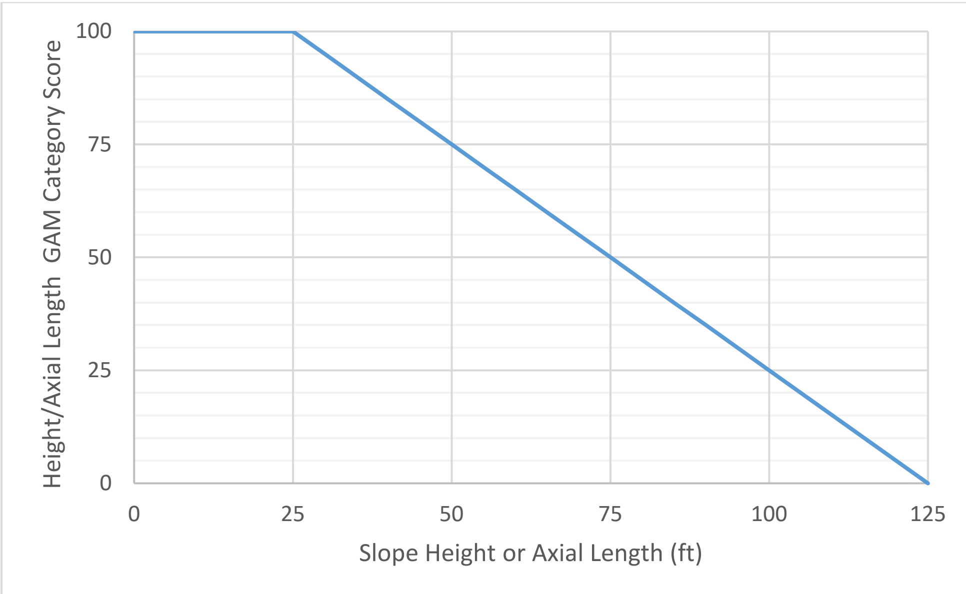


Figure 4-9: Chart illustrating the relationship between the slope height or axial length and the category score.

4.2.12 Length of Roadway Affected Score

Assets Collected For:

- All

The length of the roadway affected by an asset, impacts both public users and MoDOT's maintenance and mitigation plans. For MoDOT, the length is proportional to the maintenance required and the costs associated with treatment. For the travelling public, a greater asset length increases the likelihood of encountering the hazard, diverting into an adjacent lane, or increasing the distance or length of time the hazard will need to be avoided. Longer assets will also require longer (both time duration and spatial length) lane closures during maintenance or repair activities.

The length of roadway affected by a geotechnical asset is measured in the field, and the score is directly calculated from these field measurements, using the equation below. A graph of this equation is also provided for reference in Figure 4-10, as well as a table showing sample category scores, Table 4-37.

Equation 4-7: Length of Roadway Affected Score

$$Score = 100 - 25 * \left(\sqrt{\frac{length\ of\ roadway\ affected}{25}} - 1 \right);$$

$$maximum\ score = 100;\ minimum\ score = 0$$

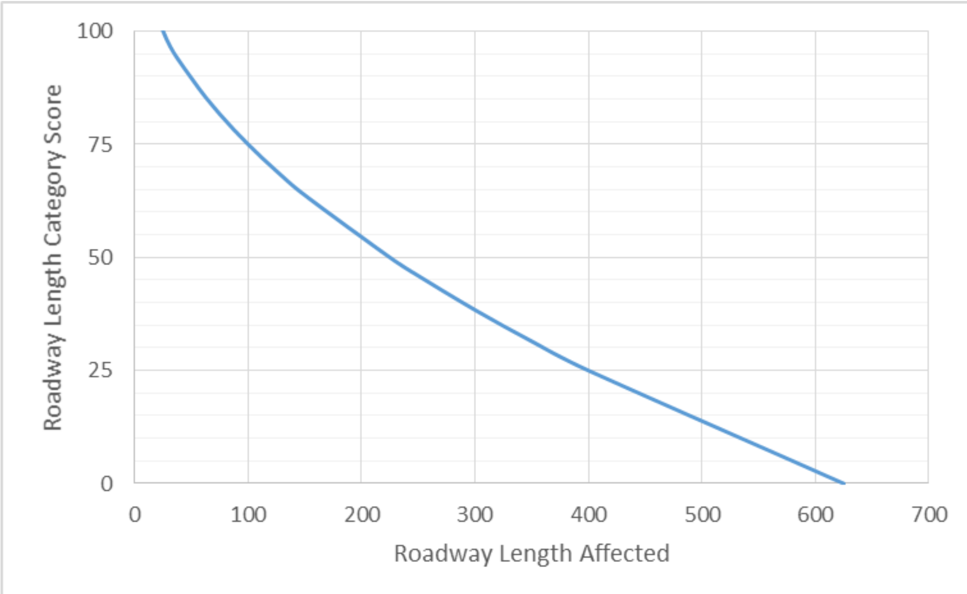


Figure 4-10: Chart illustrating the relationship between the length of roadway affected and the category score. The category score zeros out at an affected roadway length of about 625 feet.

Table 4-37: Roadway Length Affected Sample Calculated Scores

Score	Roadway Length Affected
0 points	625 feet
25 points	400 feet
50 points	225 feet
75 points	100 feet
100 points	25 feet

4.2.13 Movement History Score

Assets Collected For:

- Soil Slopes

The movement history combines event frequency and movement rate per event. Both relate to public hazard and maintenance requirements. Higher rates of movement typically result in more damage to the roadway and require immediate, unscheduled maintenance. Higher event frequency, even if each individual event is small and contained, requires more maintenance work at the site and may increase the likelihood of a larger failure. This user should choose the category that describes most severe of the movement rate or event frequency conditions at the slide. Ideally, this category will incorporate input from maintenance personnel since it is difficult to accurately assess an annual rate of movement from a single site visit.

Table 4-38: Movement History Score Category Narratives

Score	Narrative
100 points	No evidence of movement or creep. This rating is typically reserved for a mitigated soil slope. Effective mitigation has stopped movement on the slope or reduced it to the point that it is no longer observable on a yearly basis. Scheduled maintenance of the mitigation features may still be required.
75 points	Minor movement or sporadic creep. The rate of movement is low and non-continuous. Pavement disturbance is minor on an annual basis and maintenance requirements are minimal and carried out as a scheduled activity.
50 points	Up to 1 inch annually or steady annual creep. The rate of movement is low but continuous. Roadway maintenance is routinely required to avoid road closures, but maintenance action can generally be on a scheduled basis.
25 points	Up to 3 inches per event, one event per year. The rate of movement is moderately high. Events occurring more than twice a year that require immediate and unscheduled maintenance are a persistent maintenance problem.
0 points	>3 inches per event, >6 inches annually, or more than 1 event per year (includes all debris flows). The rate of movement is high with significant roadway disturbance developing quickly. Aggressive, unscheduled maintenance intervention is required to maintain traffic flow and correct unsafe conditions.

4.2.14 Observable Critical Components Score

Assets Collected For:

- Retaining Walls

As walls age, cracking and distortion of the wall face may develop, along with corrosion and/or loss of bearing elements, soil reinforcement and other components. Retaining walls are built of many different materials following many different construction methods. Each type of retaining wall can exhibit different performance problems and fail in different ways. Because of that, a comprehensive category is used to evaluate a range of operational issues while maintaining the ability to compare the performance of different wall types.

The general condition of the retaining wall and its *observable* components are scored during the field inspection based on the category descriptions in the following table. Components which are buried or otherwise obscured from view cannot, by definition, be captured in a field rating. Category narratives are presented in Table 4-39.

Table 4-39: Observable Critical Component Score Category Narratives

Score	Narrative
100 points	No evidence of corrosion, cracking, distortion, or lost bearing/missing elements. Wall face and all observable wall components are in excellent shape. Any cracking is minor (i.e., due to concrete curing process) and does not affect wall structure.
75 points	Minor corrosion, cracking, distortion. Minor cracking on wall face, wall alignment slightly distorted, or evidence of minor weathering or similar damage to wall elements.
50 points	Moderate corrosion, cracking, distortion, or lost bearing strength/missing elements. Moderate cracking on wall face, portions of wall are distorted, or exposed wall components are corroded or damaged.
25 points	Evidence of major corrosion, cracking, distortion, or lost bearing strength/missing elements. Extensive cracking on face, with crack widths >1/4”, sections of wall show poor alignment, or multiple exposed wall components are destroyed by corrosion, removed, or otherwise entirely broken.
0 points	Extensive corrosion, cracking, distortion, or lost bearing strength/missing elements throughout. Extensive cracking on face, wall shows poor alignment over length, or exposed wall components are destroyed by corrosion, removed, or otherwise entirely broken throughout the length of the wall.

4.2.15 Percent Decision Sight Distance Score

Assets Collected For:

- All

The Percent Decision Sight Distance (PDSD) category describes the available sight distance as a percentage of the AASHTO recommended minimum decision sight distance for a given highway speed, modified slightly to eliminate consideration of route type, stopping vs. avoidance, etc. (Pierson & Van Vickle, 1993). The recommended decision sight distances are those first developed in ODOT’s RHRS program and subsequently adopted by other state and federal DOTs that implemented rockfall asset management systems. This helps maintain compatibility between data sets when comparing scores in the decision sight distance category for different states.

Sight distance is the shortest distance that debris in the road would be continuously visible to a driver either approaching an asset or within the affected roadway length. Decision sight distance (DSD) is the distance required for a driver to see an obstruction in the roadway, process that information, and come to a safe stop. The required DSD increases with increased vehicle speed and this distance is critical when obstacles in the road surface are difficult to see, or when unexpected or unusual maneuvers are required. Decision sight distances for typical posted speeds are presented in Table 4-40 below.

Table 4-40: Simplified AASHTO Recommended Minimum Decision Sight Distance for selected speed limits from existing asset management systems

Posted Speed Limit (mph)	AASHTO Recommended Minimum Decision Sight Distance (ft)
25	375
30	450
35	525
40	600
45	675
50	750
55	875
60	1,000
65	1,050

Sight distance can change appreciably throughout a roadway section. Horizontal and vertical highway curves, along with obstructions such as rock outcrops, roadside vegetation, guardrails, etc. can limit a driver's ability to notice and react to a hazardous road condition. In calculating this category score, horizonal and vertical sign distances are evaluated, and the most restricted sight distance is used. On undivided roadways, the sight distance is also determined in both travel directions.

Sight distance is measured with a roller tape or laser range finder and is the distance required for a six-inch object on the fogline (or on the edge of pavement if there is no fogline) to disappear at an eye height of 3.5 feet above the road surface. The posted speed limit throughout the section is used to determine the sight distance and may be lower than the overall highway speed limit in that section.

The category score is calculated from the direct measurements described above using Equation 4-8, which is also plotted in Figure 4-11. The same equation is used for all assets. Sample calculated scores are also presented in Table 4-40.

Equation 4-8: Percent Decision Sight Distance Score

$$Percent\ Desciosn\ Sight\ Distance\ Score =$$

$$100 - 25 * \left(\left(\frac{120 - \left(\frac{Measured\ Minimum\ Sight\ Distance}{AASHTO\ Recommended\ Decision\ Sight\ Distance} \times 100\right)}{20}\right) - 1\right)$$

$$maximum\ score = 100;\ minimum\ score = 0$$

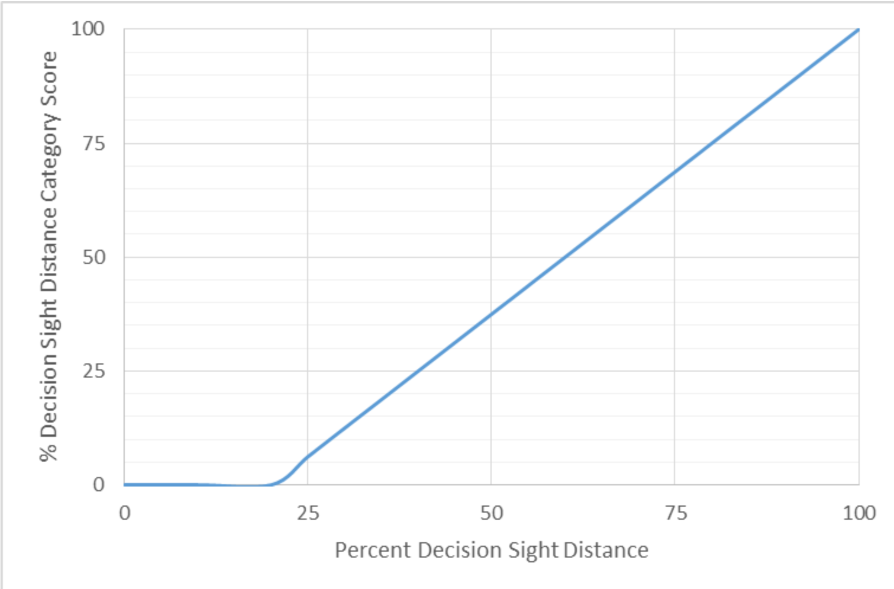


Figure 4-11: Chart illustrating the relationship between the percent decision sight distance and the category score. The category score maxes out at a percent decision sight distance of 100 % and is zero below a percent decision sight distance of 20%.

Table 4-41: Sample Calculated Scores from Decision Sight Distance Equation

Score	Percent Decision Sight Distance
0 points	Extremely Limited, 20% of design value
25 points	Very Limited, 40% of design value
50 points	Limited, 60% of design value
75 points	Moderate, 80% of design value
100 points	Adequate, 100% of design value

4.2.16 Retaining Wall Roadway Deformation Score

Assets Collected For:

- Retaining Walls

Failure of a retaining wall can undermine the roadway or deposit material in the travel lanes. Both outcomes increase the risk of unsafe driver maneuvers or loss of vehicle control. Deformation of the roadway adjacent to a retaining wall may be caused by wall movement and could worsen as the wall continues to deform. Larger roadway impacts increase the likelihood of an accident, require greater maintenance attention, and cost more to repair or patch. Category narratives are presented in Table 4-42.

Table 4-42: Roadway Displacement Category Narratives – Retaining Walls

Score	Narrative
100 points	No instability observed in embankment or roadway.
75 points	Observed instability in retained fill, no impacts to pavement. A noticeable crack in the wall or roadway. Wall and roadway maintenance continues as scheduled.
50 points	Undermined shoulder or material deposited on shoulder due to wall deformation. Wall deformation has removed result for the roadway shoulder, or damage to the wall face has released retained material onto the roadway shoulder.
25 points	Moderate deformation of pavement in travel lanes or deposit of fill material into travel lanes due to wall deformation. Noticeable drop in pavement or noticeable material deposit in travel lanes impacting traffic flow.
0 points	Severe deformation of pavement in travel lanes or deposit of fill material across all travel lanes. Major drop in pavement or a material deposit that cannot be traversed by typical vehicular traffic.

4.2.17 Roadway Displacement or Slide Deposit Score

Assets Collected For:

- Soil Slopes

This category describes the severity of the impact of slide movement on the roadway. Larger obstructions increase the likelihood of an accident and require more maintenance effort and cost to repair. The category is scored by following the rating category narratives in the table below. If maintenance regularly responds to slide movement by patching the roadway or clearing debris from the road, the rater should use the pre-maintenance response condition in rating this category.

Table 4-43: Roadway Displacement or Slide Deposit Score Category Narratives – Soil Slopes

Score	Narrative
100 points	No crack or material deposit on the road. This rating is typically reserved for a mitigated soil slope. Effective mitigation has stopped movement on the slope, and the roadway is no longer impacted. Scheduled maintenance of the mitigation features may still be required.
75 points	Visible crack or slight deposit of material on road/minor erosion. Slight pavement cracking or heaving, or a thin deposit of slide debris has occurred, but they are small enough not to disturb traffic flow or require evasive maneuvers. Scheduled roadway maintenance is required.
50 points	1 inch offset, or 6-inch deposit of material on road/major erosion will affect travel in <5 years. A noticeable drop or heave in the pavement or a deposit of slide debris has occurred that requires lower speeds to traverse. Maintenance attention is required.
25 points	2-inch offset or 12-inch deposit of material on road/moderate erosion impacting travel annually. A large drop or heave in the pavement or a deposit of slide debris has occurred that requires significantly lower speeds to traverse and may elicit unsafe driver reactions. Immediate maintenance attention is required.
0 points	4-inch offset or 24-inch deposit of material on road/severe erosion impacting traffic consistently. A major drop or heave in the pavement or deposit of slide debris has occurred that cannot be traversed. Unsafe driver reactions are likely and immediate maintenance attention is required to reestablish safe traffic flow.

4.2.18 Roadway Impedance Score

Assets Collected For:

- Subsidence

Subsidence features can develop rapidly and undermine the roadway. Therefore, they are typically addressed as soon as they are identified within MoDOT's ROW. However, proximity to the roadway can help prioritize repairs if multiple subsidence features are present. The category is scored by following the rating category narratives in the table below.

Table 4-44: Roadway Impedance Score Category Narratives – Subsidence

Score	Narrative
100 points	<u>Observed, but beyond agency ROW.</u> This rating is typically reserved for subsidence features that could impact the roadway in the future but are currently beyond the agency ROW and would be difficult to address at this time.
75 points	<u>Within ROW, no impacts to roadway or ditch.</u> The feature is within ROW and can be addressed but is not currently impacting any infrastructure. Scheduled roadway maintenance is required.
50 points	<u>Within ditch or embankment foundation.</u> The feature is in the roadside ditch or embankment foundation. Unscheduled roadway maintenance is required.
25 points	<u>Within shoulder.</u> The feature is within the roadway shoulder but is not impacting the travel lanes. Emergency roadway maintenance is required.
0 points	<u>Within travel lane.</u> The feature is within a travel lane, causing a road closure. Emergency roadway maintenance is required to reopen the road.

4.2.19 Roadway Damage Score

Assets Collected For:

- Engineered Embankments
- Ground Improvements

If engineered embankments or subgrades do not perform as intended, unanticipated settlement can damage the roadway. This damage requires maintenance attention and increases risk for the travelling public. Trying to avoid a damaged area can result in unsafe maneuvers or loss of vehicle control. Larger deformations, or damage over a longer area increases the likelihood of an accident and requires more maintenance effort and cost to repair. The category is scored by following the rating category narratives in the table below.

Table 4-45: Roadway Damage Score Category Narratives – Embankments and Ground Improvement

Score	Narrative
100 points	No cracking or evidence of settlement. This rating is typically reserved for a newly constructed engineered embankment being entered into the database, or for one that has been successfully repaired. If the area has been repaired, scheduled maintenance of the mitigation features may still be required.
75 points	Slight cracking or deformation, no disruption to traffic flow. Slight pavement cracking or settlement, but small enough not to disturb traffic flow or require evasive maneuvers. Scheduled roadway maintenance is required.
50 points	Moderate subsidence (6-12 inches over 450 feet). A noticeable drop in the pavement has occurred that requires lower speeds to traverse. Maintenance attention is required.
25 points	Significant subsidence (12-36 inches over 450 feet). A large drop has occurred that requires significantly lower speeds to traverse and may elicit unsafe driver reactions. Immediate maintenance attention is required.
0 points	Extreme subsidence (24 inches or greater over a 300 ft or shorter section). A major drop has occurred that cannot be traversed by standard passenger vehicles. Unsafe driver reactions are likely and immediate maintenance attention is required to reopen the road.

4.2.20 Roadway Width Score

Assets Collected For:

- All

A driver's first response to roadway damage is to take evasive action to avoid it. The more room there is for this maneuver, the better chance the driver has of avoiding the unanticipated hazard without hitting another roadside hazard or oncoming vehicle. The roadway width category score represents the available maneuvering room for the roadway.

The roadway width is measured perpendicular to the highway centerline. If roadway width is not constant, then the minimum width throughout the asset section is used. Unpaved shoulder adjacent to the roadway is not included in the width measurement. On divided roadways, only that portion of the roadway available to the driver is measured.

The category score is calculated from the actual roadway measurements using Equation 4-9. The equation is also plotted in the chart shown in Figure 4-12. Sample calculated scores are presented in Table 4-46.

Equation 4-9: Roadway Width Score

$$Score = 100 - 25 * \left(\left(\frac{52 - Roadway\ Width\ (feet)}{8}\right) - 1\right);$$

$$maximum\ score = 100;\ minimum\ score = 0$$

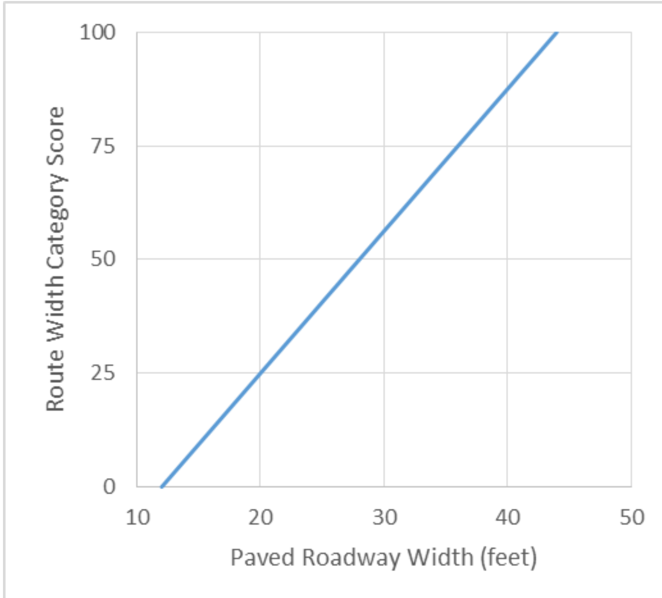


Figure 4-12: Chart illustrating the relationship between the paved roadway with and the category score.

Table 4-46: Sample Calculated Scores from Roadway Width Equation

Score	Roadway Width
0 points	12 feet
25 points	20 feet
50 points	28 feet
75 points	36 feet
100 points	44 feet

4.2.21 Rockfall Activity Score

Assets Collected For:

- Rock Slopes

Past rockfall activity predicts future rockfall activity. This information is best obtained from the maintenance personnel responsible for the slope. If that is not available, activity can also be estimated from the quantity of rock present in the ditch. There may be no history available at newly constructed sites or where documentation practices are poor.

Table 4-47: Rockfall Activity Score Category Narratives

Score	Narrative
100 points	Slope produces very little rockfall. Rockfalls occur only a few times a year (or less), or only during severe storms. This category is also used if no rockfall history data is available and evidence of rockfall is absent. (<2 rocks annually/100 feet of ditch)
75 points	Occasional Falls. Rockfall occurs regularly (several times per year) and is typically seasonal. (2-10 rocks annually/100 feet of ditch)
50 points	Regular Rockfall. Rockfall occurs frequently during a certain season, such as the winter or spring wet period, or the winter freeze/thaw, etc. However, rockfall at the site is not a significant problem during the rest of the year. (10 – 50 rocks annually/100 feet of ditch)
25 points	Frequent Falls. Rockfalls occur frequently throughout the year, regardless of season. This category is also for sites where severe rockfall events have occurred in the past but are not typical of the failure events observed at the site. (50-100 rocks annually/100 feet of ditch)
0 points	Constant Falls. Rockfall occurs year-round and severe rockfall events are common. (>100 rocks annually/100 feet of ditch)

4.2.22 Subsidence Settlement Rate Score

Assets Collected For:

- Subsidence

This category is similar to the settlement rate category for embankments and subgrade but is adjusted slightly to reflect the different subsurface processes for this asset. The rate of settlement associated with a subsidence feature gives MoDOT an idea of the time available to develop a solution to the problem. Higher rates of subsidence or expansion mean a higher risk to maintenance and roadway users. This category should be rated based on input from maintenance personnel, since it is difficult to accurately assess a rate of movement from a single site visit.

Table 4-48: Settlement Rate Score Category Narratives – Subsidence

Score	Narrative
100 points	Known sinkhole or mine, no settlement detected. This rating is typically reserved for a newly repaired sinkhole or mine, or for a site where a known abandoned mine is mapped within the ROW.
75 points	Sporadic subsidence with minor displacement. The rate of settlement is low and non-continuous. The feature does not appear to be changing or growing on an annual basis.
50 points	Steady annual subsidence or expansion. The rate of movement is low but continuous and the feature is growing from year to year. Maintenance action can generally be accomplished on a scheduled basis.
25 points	Rapid subsidence: 1 to 6 inches in hours. The rate of settlement is high, and the subsidence feature is changing on a monthly basis. Regular maintenance attention is required.
0 points	>6 inches subsidence/displacement in hours. The rate of settlement is so high that aggressive, unscheduled maintenance intervention is required. Adjacent roads may be closed even if the subsidence feature is not in the roadway.

4.2.23 Wall Alignment Score

Assets Collected For:

- Retaining Walls

Proper vertical or horizontal wall alignment is one of the most easily observed indicators of wall performance. Poor alignment can be related to construction deficiencies or an unstable wall foundation. Both indicate a greater potential for wall failure. This category is scored based on visual appearance. If possible, measure the vertical alignment of the wall at multiple locations and record the information in the site comments to create a benchmark for future reference. Category narratives are presented in Table 4-49.

Table 4-49: Vertical/Horizontal Wall Alignment Score Category Narratives

Score	Narrative
100 points	Good wall alignment. Wall appears stable with expected batter. Alignment matches that shown on as-built or plan sets, if available.
75 points	Satisfactory wall alignment. Acceptable alignment, but not as shown in available as-built drawings or plan sets. Condition may be related to the quality of construction or the use of poor materials.
50 points	Fair wall alignment. Localized sections of wall show inconsistent alignment, with possible cracking, settlement, or loss of retained material.
25 points	Poor wall alignment. Visible distress and/or displacement of multiple wall segments. Numerous cracks with measurable offset, deformation of individual components, localized settlement, or local loss of retained material.
0 points	Failed wall alignment, Entire wall shows poor alignment or failed, unrepaired sections. Wall is visibly distressed with extensive cracking with measurable offset along cracks, settlement or displacement in multiple areas, and/or loss of retained material.

5 QUANTIFICATION OF CONDITION AND RISK

The inventory process for the six asset types in MoDOT's GAM program compiles a variety of information to help describe both hazard and risk at a given site. The research team developed condition state and level of risk assessments for the different asset types through combining the data collected in the detailed ratings and the data appended from MoDOT's TMS database. The Condition State of an asset describes the hazard – how likely is a failure to occur at this site – in simple, non-technical terms. The Level of Risk score builds on the Condition State by incorporating information on roadway usage and geometry to provide a qualitative estimate of the impact of that failure on the travelling public. The methods and calculations are described in the following sections.

5.1 Condition State Score

Asset Condition State refers solely to the physical performance of a geotechnical asset. It does not assess the risk posed to the travelling public in the event of failure. The Condition State score combines scores from the user-selected dropdowns in the Survey123 to assign assets to one of five categories: Good/Satisfactory/Fair/Poor/Failed. These five levels track to the recommended condition state descriptions in the NCHRP GAM Implementation Manual, Report 903. This level of detail allows for fine-grained analysis of asset performance, degradation, and associated risk. The fields used to calculate asset condition for the various asset types in MoDOT's GAM program are summarized in Table 5-1 below. The individual scores in the rating category are averaged, generating a score between 0 and 100 that correlates with a Condition State. As in the individual rating categories, 100 is the best possible score and 0 is the worst.

Table 5-1: Individual Rating Fields used to calculate asset Condition States

Asset Types	Fields Averaged to Calculate Condition State
Rock Slopes	Ditch Effectiveness Score
	Rockfall Activity Score
Soil Slopes	Roadway Displacement/Slide Deposit
	Movement History Score
	Failure Extent
Retaining Walls	Alignment Score
	Observable Critical Component Health Score
	Roadway Deformation Score
Subsidence (Sinkholes/Mines)	Settlement Rate Score
	Roadway Impedance Score
Engineered Embankments	Roadway Damage Score
	Settlement Rate Score
Subgrades/Ground Improvements	Roadway Damage Score
	Settlement Rate Score

The rating categories used to calculate condition state for rock slopes and retaining walls have been previously applied to GAM programs in Alaska (rock slopes and walls) and Montana (rock slopes). The rating categories used to estimate condition state for soil slopes and retaining walls are like those used by Alaska DOT&PF in their GAM program, adjusted here to reflect lessons learned. Alaska's DOT&PF team included landslide length in the condition state, and the research team determined that slide length is not inherently related to the rate a slide moves or the damage it causes. By calculating asset condition state using methods already employed by other DOTs, MoDOT can incorporate their data into asset deterioration and life cycle analyses, expanding the available data while Missouri-specific data is in the statewide data collection phase.

At the time this project was developed, subsidence, engineered embankments, and subgrades had not previously been inventoried as individual assets by another agency. The three asset types were frequently included with soil slopes. This method did not meet MoDOT's concerns for different types of asset degradation and different department responses. Subsidence features, for example, are typically filled immediately after identification, even if the roadway is not yet impacted. The detailed rating categories used to describe the condition states of these assets were developed with input from the MoDOT technical committee. This helped ensure that the final GAM program supported MoDOT's current operations.

The Condition State descriptions match those recommended in the NCHRP GAM Implementation Manual, but standard TAM plans, (including MoDOT's finalized TAMP) use a Good/Fair/Poor asset classification. Previous GAM work completed by Alaska, Montana, and FHWA mapped the five GAM condition state classes to the 3 TAM classes as follows: Good = Good, Fair = Satisfactory/Fair, and Poor = Poor/Failed. The research team applied the same pattern for MoDOT's GAM system. Maintaining a TAM-compatible Good/Fair/Poor classification will make the GAM program data easier for the TAM group to directly incorporate into their planning and budgeting work. Mapping between the Condition State scores, GAM rating categories, and TAM categories are summarized in Table 5-2 below.

Table 5-2: Summary conversion table of Condition State score, GAM category, and TAM Condition

Condition State Score Range		GAM Rating Category	TAM Condition
Low	High		
80	100	Good	Good
60	79	Satisfactory	Fair
40	59	Fair	Fair
20	49	Poor	Poor
0	19	Failed	Poor

5.2 Level of Risk Score

The NCHRP GAM implementation manual recommends that agencies incorporate risk into their plans to yield better management of geotechnical assets, even if the risk estimates are imprecise (National Academies of Science, Engineering and Medicine , 2019). In addition to calculating a condition for each inventoried asset, the MoDOT GAM program will also provide an estimated Level of Risk (LOR) for each asset. The Level of Risk is a measure of perceived risk combining both event likelihood and probability of consequence.

MoDOT does not currently have sufficient data to link event frequency or event consequence (accident, fatality, delay, etc.) to specific geotechnical asset locations to develop quantitative correlations between asset condition and risk to the travelling public. Instead, the research team developed a qualitative Level of Risk (LOR) score that combines asset condition, traffic volume, and roadway geometry using data collected in the field and additional information on roadway usage appended from within MoDOT's TMS. The LOR equation is presented in Equation 10 below.

Equation 10: Level of Risk Equation with Event Likelihood and Probability of Consequence components.

$$Level\ of\ Risk\ = \frac{Event\ Likelihood + Probability\ of\ Consequence}{2}$$

Where:

$$Event\ Likelihood = Asset\ Condition\ State\ Score\ (0 - 100)$$

$$Probability\ of\ Conseqence = \frac{AADT\ Score + \ (\frac{Roadway\ Width\ Score + \%\ Decision\ Sight\ Distance\ Score}{2})}{2}$$

The event likelihood is equal to the asset condition state score because a poor condition asset possesses a higher failure probability than one in good condition. Good/Fair/Poor asset condition maps directly to Low/Moderate/High event likelihood. The relationship between condition state and event likelihood is unlikely to be linear, but there is currently no event data available in Missouri to develop a quantitative correlation between event likelihood and asset condition. The Montana Department of Transportation (MDT) was able to develop a quantitative correlation between condition and event likelihood for their rock slopes approximately 15 years after implementing their RHRS program. MoDOT may also be able to refine the event likelihood in the future as more data is collected.

Probability of consequence is a combination of roadway usage and roadway geometry. The research team considered two options for quantifying roadway usage. One option was to use the average vehicle risk (AVR) score, which approximates the percentage of time a vehicle is present in the section of roadway impacted by the asset over the course of a day. Using average vehicle risk had the advantage of having been collected as a scored rating category in Rockfall Hazard Rating Systems (RHRS) programs for over 30 years. AADT was collected for these programs but was only used to calculate the average vehicle risk score, as opposed to being directly scored in a category of its own. However, subsequent GAM programs have directly scored AADT in its own rating category. The research team favored transparency and ease of understanding and uses AADT-based scores instead of AVR to calculate the Level of Risk score.

For roadway geometry, the research team combined the sight distance score and the roadway width score to describe how much time the driver has to respond to an unexpected obstacle, and how much space they have for the maneuver.

The long-term goal of GAM and TAM is the ability to relate risk as a function of dollars to facilitate managerial decisions, but getting to that point will require additional research and long-term data collection. We recommended presenting Level of Risk for the inventoried MoDOT GAM assets as Low/Medium/High at this point, tied to a 0-100 index like that used to determine Condition State until this additional research is performed. Scores calculated in from the level of risk equation range from 0 to 100, with 100 being the lowest risk, and 0 being the highest. The scoring breakdown between Low, Moderate, and High level of risk is shown in Table 5-3 below.

Table 5-3: Summary conversion table of Level of Risk Score to Relative Level of Risk category.

Level of Risk Score Range		
Low	High	Relative Level of Risk
70	100	Low
40	70	Moderate
0	40	High

The relative impact of hazard (event likelihood) and consequence is also shown graphically in the risk matrix in Figure 5-1. This risk matrix breaks out “moderate/high” as a visual option not described in the score range in the table. This moderate/high band was developed to capture the relative risk situations like a good asset in a high consequence area. Although a failure at this location is unlikely, the consequences of such a failure are significant enough that they should be considered in department planning. A benefit of this approach is that it may be reasonable in some situations to improve an asset or the adjacent roadway before the asset itself begins to degrade. The register is likely less accurate when approaching the extremes on either axis. It is difficult to accruatly describe risk at a site with a condition score of 100/Good, just as it is difficult to descrobe risk of failure at on a wide, sparely traffic roadway with excellent sight distance.

The risk matrix bands are an initial estimate of that is most reasonable in describing department assets. As more information is collected, particularly data on events that require road closures, emergency maintenance response, or accidents, MoDOT will be in a better position to assess risk. In time, the current level of risk score may be adjusted, with different weights assigned to condition state, traffic volume, and roadway geometry. Alternatively, future research efforts may identify a detailed rating category that better correlates with increased risk to roadway users. In the future, MoDOT may use the risk register to help develop targets risk levels for geotechnical assets, or identify which axis (condition or consequence) are more cost-effective to address.

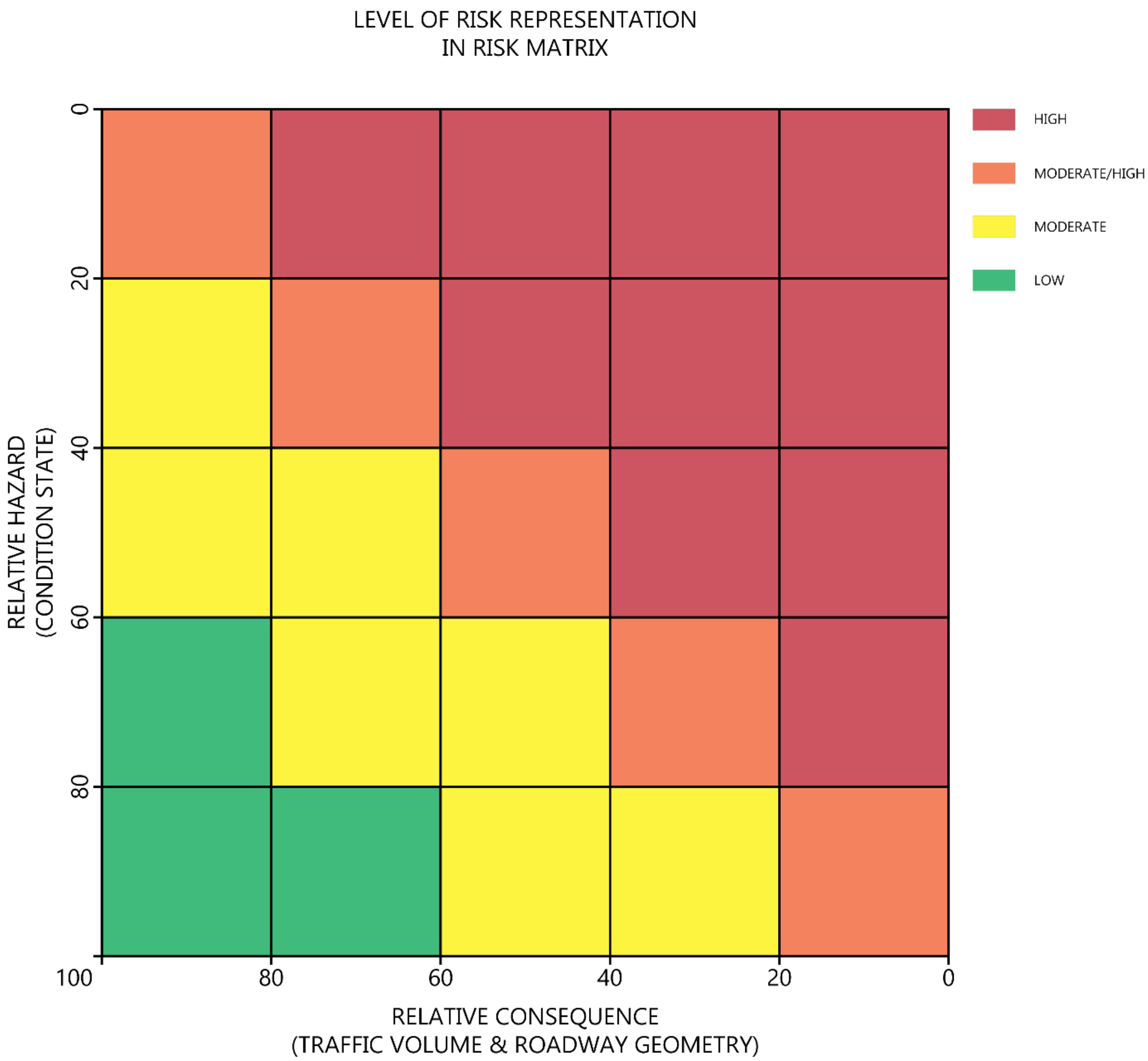


Figure 5-1: Risk Matrix for MoDOT GAM Program illustrating Level of Risk as a function of relative hazard (condition state) and relative consequence (traffic volume and roadway geometry).

6 DATA COLLECTION APPLICATION

The GAM program is supported by a mobile data collection application as requested by MoDOT. The application uses ESRI's Survey123 program, which is supported on Android, iOS, and desktop browser interfaces. Using ESRI's Survey123 programming templates as scaffolding, the research team developed a survey specifically for inventorying and assessing the six geotechnical asset types. After meeting with MoDOT's IT group to discuss license requirements, it became apparent that the mobile application needed to be published and maintained by MoDOT's IT group to align with both department procedures and overall project goals. Because the survey is managed by MoDOT, the future implementation of MoDOT's GAM program will require working within department regulations that are separate from the research conducted for this project and are not discussed in detail in this report.

6.1 Survey Development

The research team elected to use ESRI's Survey123 application for data collection because it runs on mobile devices, can collect an asset's location in the field, and supports calculations within the application, which is necessary to determine an asset's condition. ESRI applications are also widespread, run on both Android and iOS platforms, and are straightforward to use. There is also a robust community of ESRI users who can help answer trouble-shooting questions that may arise in the future.

The final survey uses the programming Landslide Technology developed for publication in ESRI's Survey123 Connect program. This is a desktop-based program for developing more sophisticated surveys using a spreadsheet program based on a modified Excel workbook. The spreadsheet can be previewed in a test space before being officially published to the Survey123 App for use in the field. A completed spreadsheet can also be exported as an Excel file. Once the IT group joined the team, LT sent the Excel sheet for the proposed survey to MoDOT's IT group. The IT group then revised the survey formatting as necessary to enable publication in ArcGIS Enterprise portal space. The survey is now available to MoDOT users with a MoDOT ArcGIS account though the Survey123 App. (https://mapsonlinesit.modot.mo.gov/portal)

The Survey123 application submits surveys to a geodatabase in ESRI's cloud space. In addition to publishing the GAM survey, the IT group also developed the necessary processes for MoDOT to "scrape" the data from the online geodatabase and incorporate it into MoDOT's TMS space. With this step, MoDOT's geotechnical asset data is now stored in the same space as all other roadway data, easily accessible to all department users. The post-processing work was not part of the research project and is discussed briefly in Section 6.4. More information on post-processing and programming within TMS space may be obtained from the MoDOT IT group.

6.2 Survey Users

The inventory and assessment of geotechnical assets is intended to be performed by an experienced geotechnical engineer or engineering geologist. For this reason, the GAM field application is available only to authorized users selected by the geotechnical engineering group in the central office. These users will be provided with the licenses necessary within MoDOT's ArcGIS space to download the Survey123 App and the "Geotechnical Asset Monitoring" survey to their MoDOT phones. It is LT's understanding that these users will be district geotechnical engineers or engineering geologists. We recommend that the Central Office, which will be administering the GAM program, develop a list of users and/or roles that can be easily updated or reassigned as people change jobs or retire. Because MoDOT does not store or process data on ESRI's servers, it maintains a smaller pool of licenses than agencies that rely on ESRI to store and share data. Therefore, it is important that the list of licensed users accurately reflect current users.

6.3 Survey Layout

The GAM Survey is published on the Survey123 App and is available to users who are signed into MoDOT's SIT online space. The user needs to be signed into both the MoDOT AnyConnect VPN and MoDOT's SIT online space to download the GAM survey to their phone. Once the GAM survey has been downloaded to the user's phone, it is not necessary to sign into either the SIT online space to the AnyConnect VPN to collect surveys in the field. The user does have to sign into the SIT online space and the AnyConnect VPN to submit completed asset surveys, an action that can be performed in the office or hotel at the end of the field day.

This report is not intended to be a how-to manual for using the Survey123 application to collect and submit a survey. Detailed guidance and trouble-shooting help is readily available on ESRI's website (https://www.esri.com/en-us/arcgis/products/arcgis-survey123/resources). This website is regularly updated to reflect changes in the Survey123 app. Instead, this section provides an outline of the GAM survey published in Survey123 to support MoDOT's GAM inventory and assessment project. It demonstrates what a user can expect to see in the field when collecting data, using a soil slope on Highway 54 as an example.

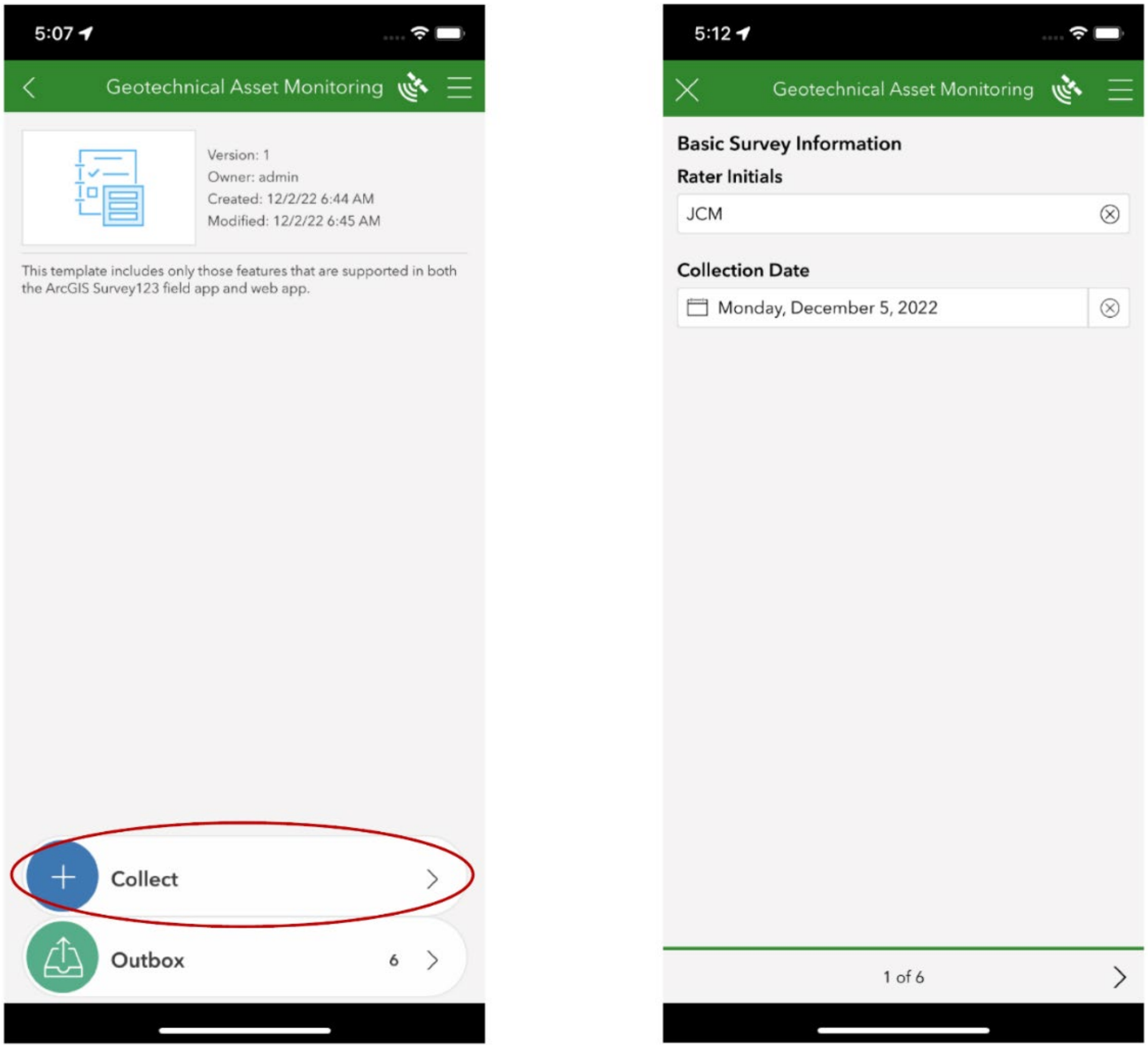


Figure 6-1: Splash page of GAM survey and first page of an in-progress survey

Figure 6-1 above shows the overview page for the Geotechnical Asset Monitoring (GAM) survey, and the first page of an in-progress survey. The overview page includes a brief description of the application, with information on version and publication date. At the bottom of this splash page, there is a "Collect" button to start a new survey. The "Outbox" includes surveys that have been completed but not yet submitted. Submitted surveys are moved to a "Sent" folder (not shown). Surveys are not automatically deleted from the Survey123 application. It is recommended that the user delete completed surveys after confirming they have been properly imported into TMS. The first page of the survey captures information on the rater and the date the survey was collected.

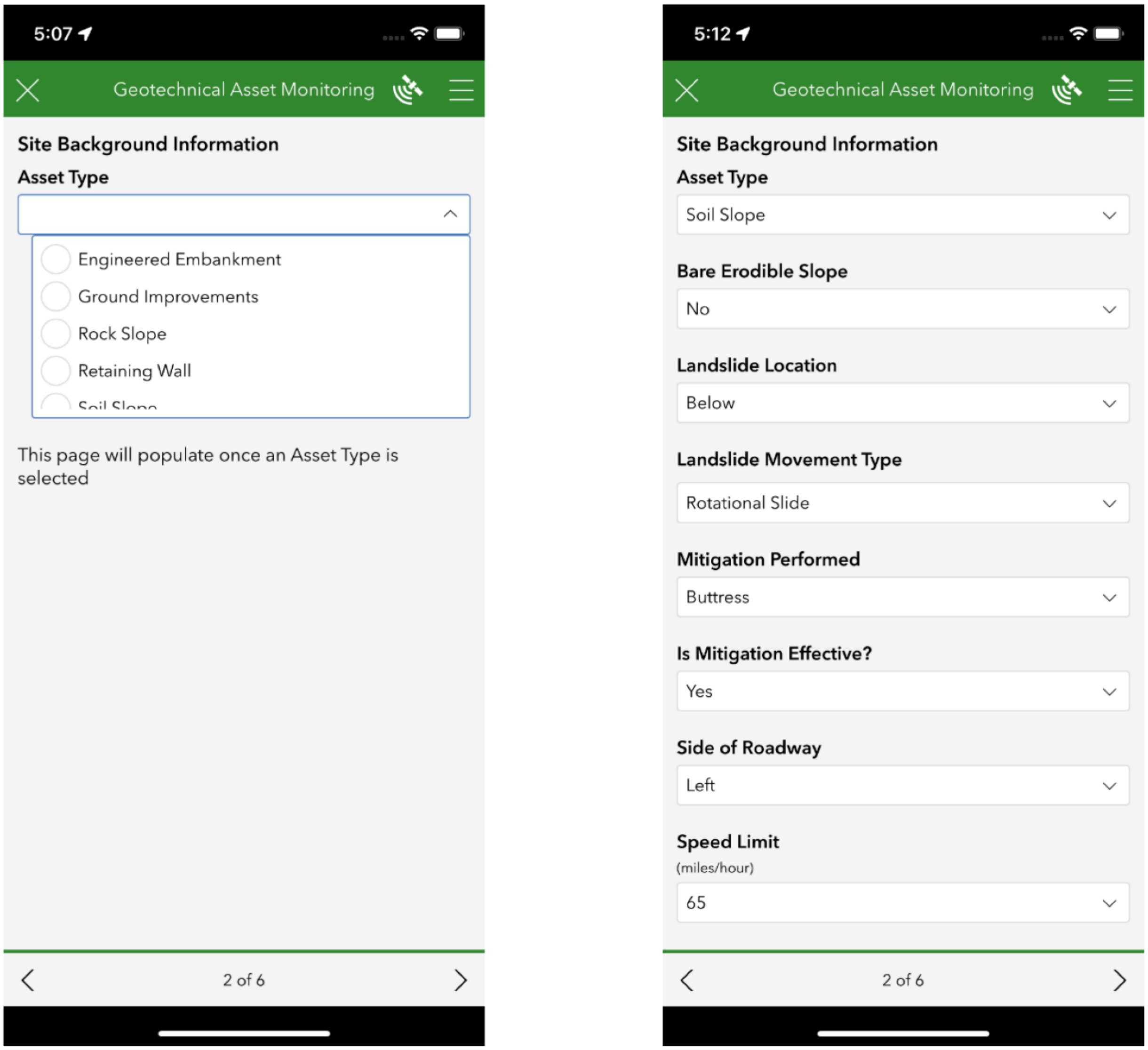


Figure 6-2: Page 2 of the GAM survey, containing general information fields.

The second page of the survey, shown in Figure 6-2, collects information on the asset. Because not all general information fields are answered for each asset, the page does not fully populate until an asset type has been selection (left image). In this case, the Soil Slope asset has been selected, and the user has filled out the background information fields based on site observations (right image).

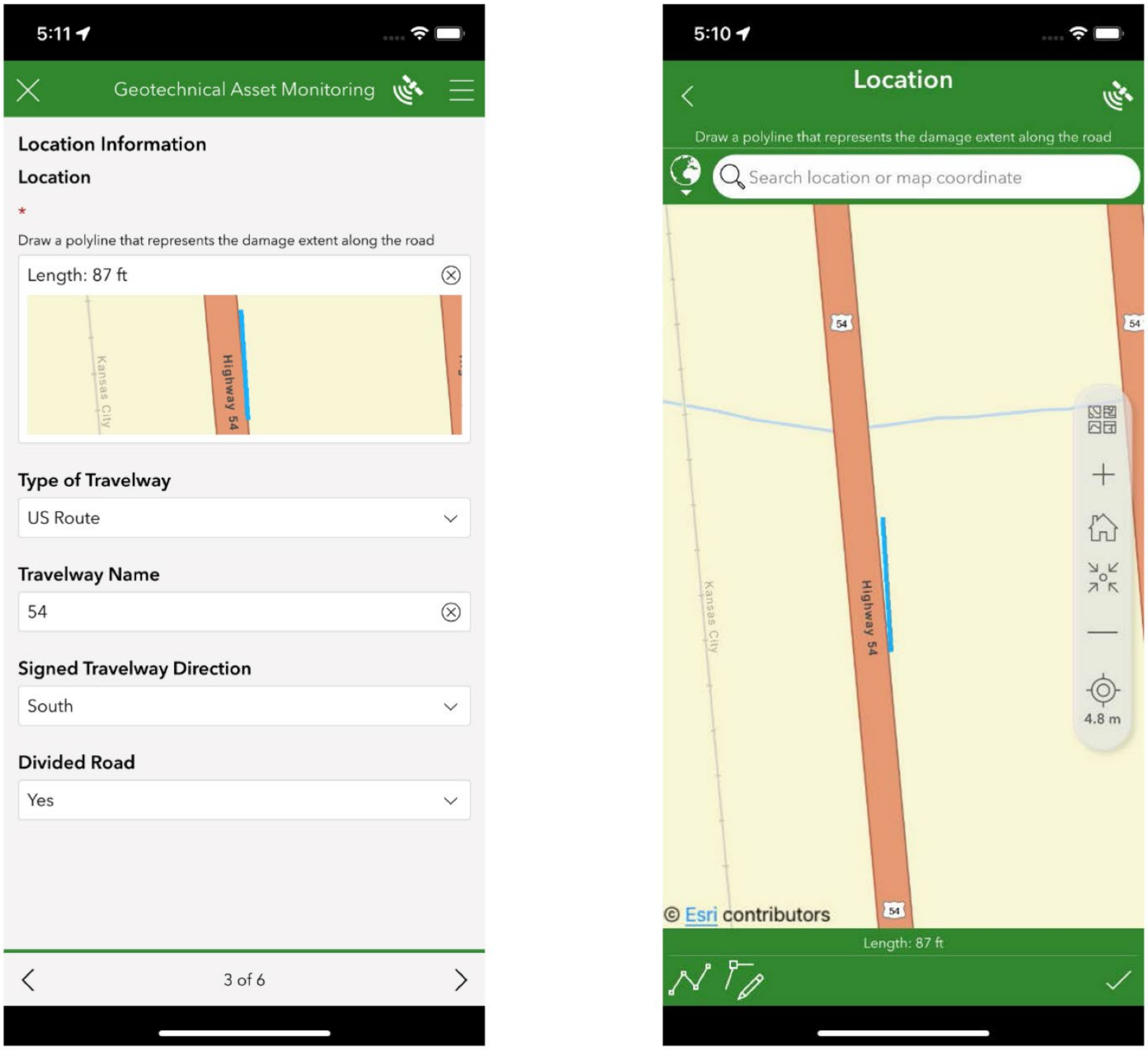


Figure 6-3: Page 3 of the GAM survey, showing location fields and polyline interface.

Once the background information has been collected, the survey advances to page 3, which includes asset location and basic roadway information, as shown in Figure 6-3. Asset locations are stored as polylines, so that MoDOT has both the start and end points of their geotechnical assets mapped in the field. The asset location automatically generated in Survey123 uses location data provided by the cellular phone, typically including GPS positions. These positions are typically accurate to +/- 20 feet. Using the basemap and surrounding features, the user can adjust the default locations to generate a more accurate polyline. The user should also check the calculated polyline length against what they measured in the field, with a goal of both measurements being within 5% of each other.

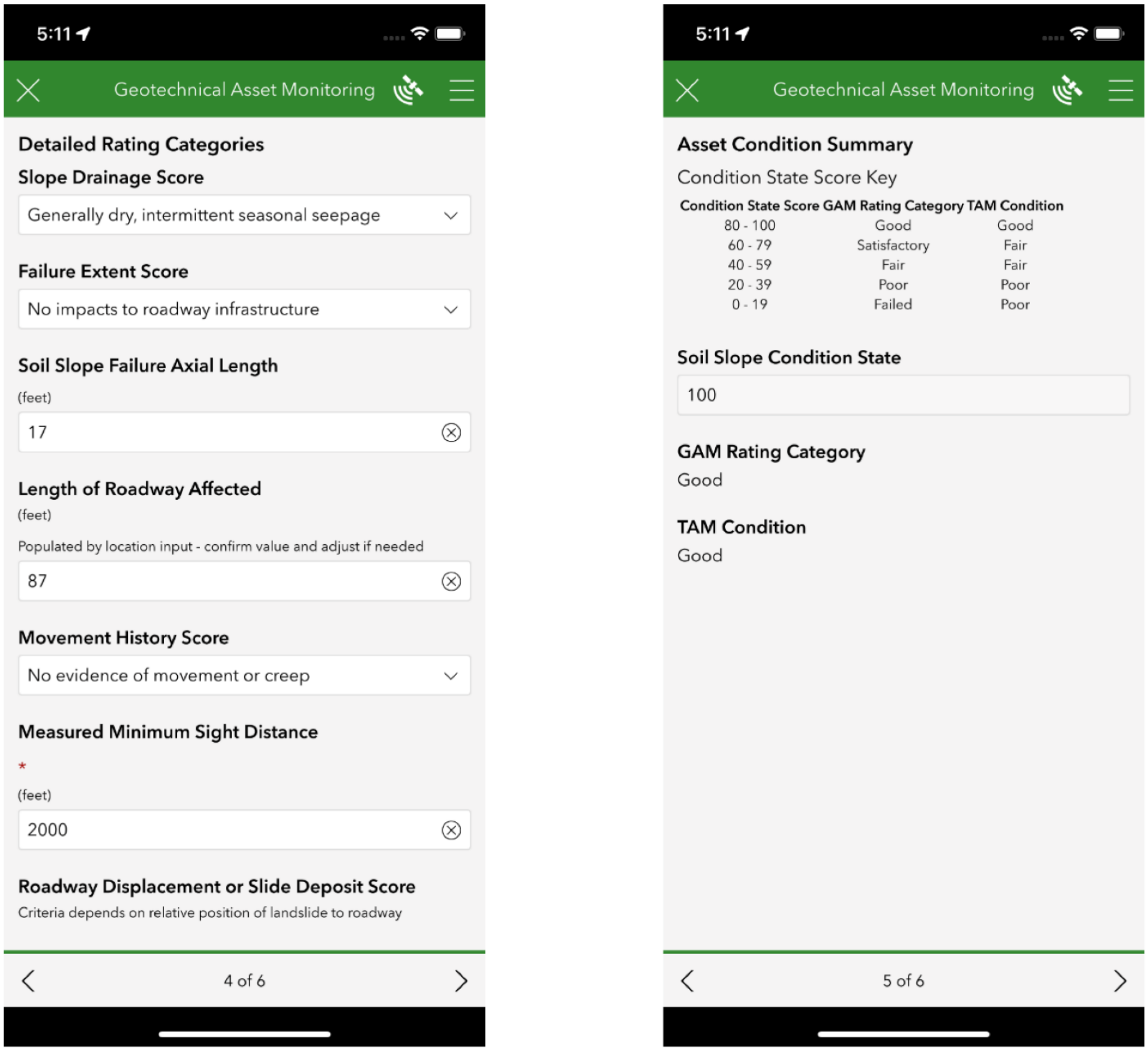


Figure 6-4: Pages 4 and 5 of the GAM survey showing a portion of the detailed rating categories for soil slope assets and calculated Condition State.

The fourth page of the GAM survey includes the detailed information categories, filtered based on asset type. In Figure 6-4 (left), the detailed rating categories for a soil slope asset are shown. The detailed rating categories are answered through a combination of dropdown options and field measurements. The dropdowns should be answered based on user judgment and to the best of their ability following the guidance in Section 4.

The asset condition is calculated numerically using a subset of these detailed rating categories, and shown on Page 5 of the survey (Figure 6-4, right). This calculated condition state should be compared to the rater's "gut feeling" about a site. For example, if the calculated condition state for an asset is "Good" but the site has required multiple unscheduled maintenance visits over the previous year, then the rater should review the scores and selected dropdowns on the Detailed Rating Categories page and identify where a mistake was made, or an inaccurate dropdown was selected. In general, the condition state rating should conform with what the department and field rater already know about the site while keeping in mind measurements that may have otherwise not been considered, such as percent decision sight distance or AADT scores.

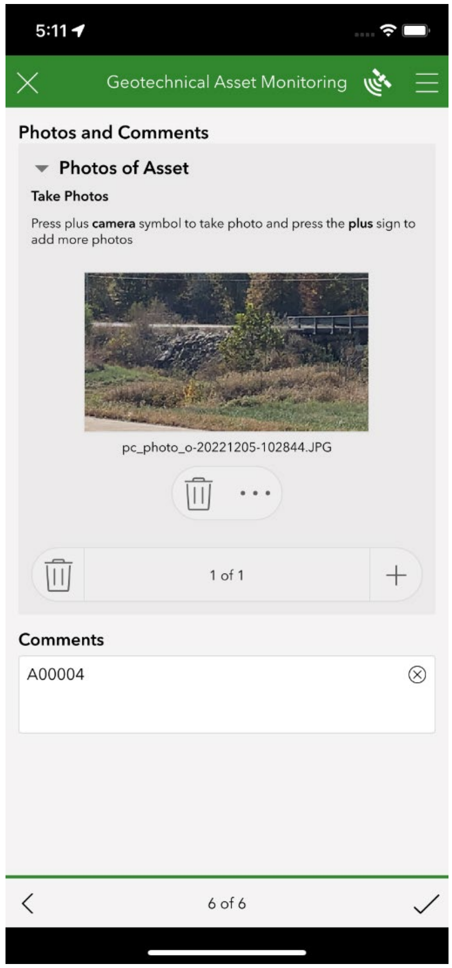


Figure 6-5: Page 6 of the GAM survey showing how to append site photos to the completed survey.

Finally, the last page of the survey prompts the user to append appropriate photos of the asset. A minimum of two photos is recommended, with more as needed for more active sites. Photos can be taken from within the app or appended from the user's phone. Based on experience during field testing, the research team recommends that the user take photos on their phone during the site visit, then append several of the most representative photos once the survey has been completed.

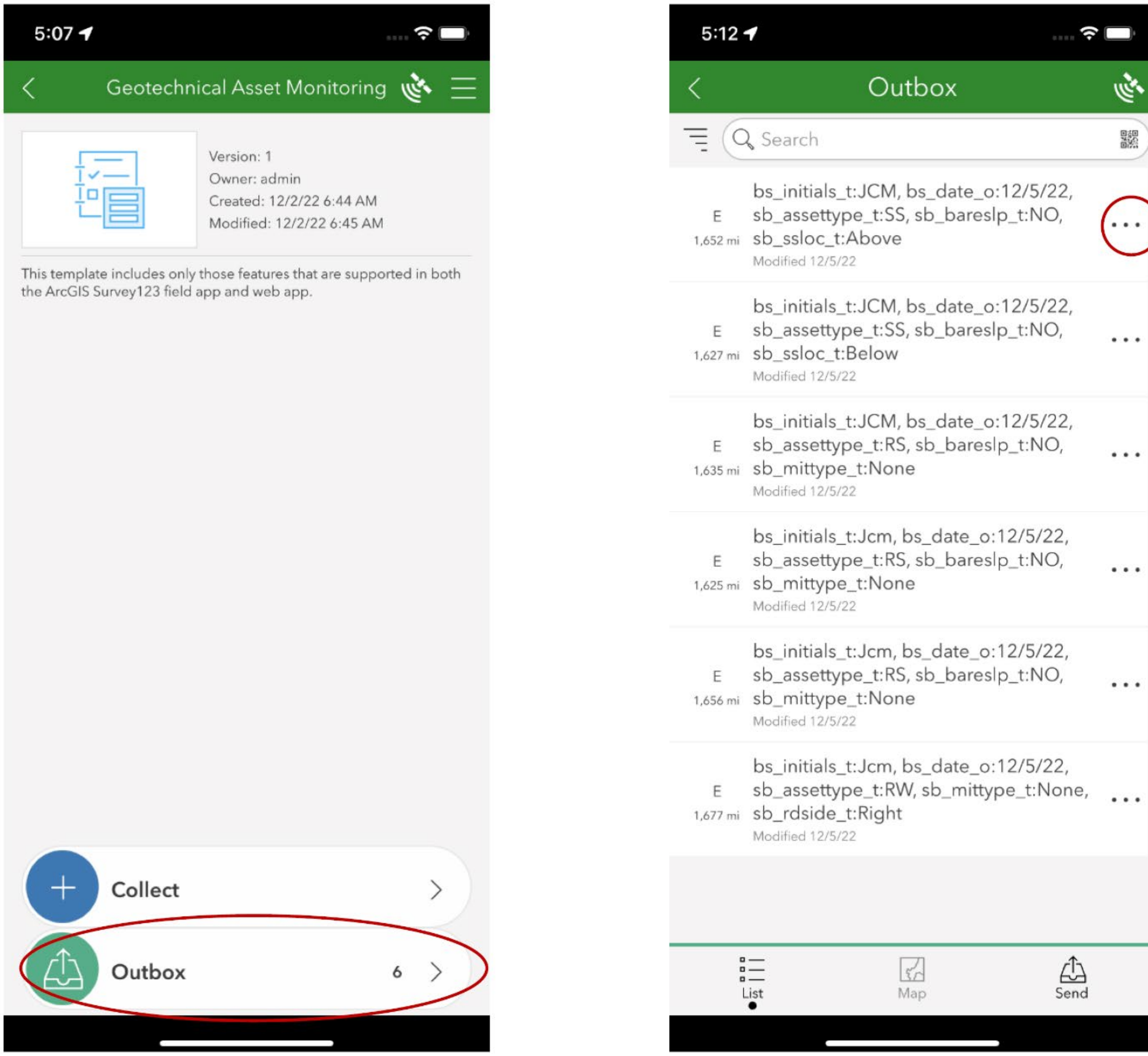


Figure 6-6: Pair of images showing how to access a completed survey from within the Survey123 Application for editing.

Surveys collected but not yet submitted can be edited within the field application. Figure 6-6 shows how to access this feature within the application. Open the outbox (circled in red) then navigate to the appropriate survey in the list. Click on the three dots (circled in red) to get into the survey and make edits as desired. If the survey has already been submitted and “scraped” to TMS, revising and resubmitting the survey will create a new feature in the TMS database. In that case, the old, incorrect feature should be deleted from the TMS database.

6.4 Post-Processing

As previously discussed in Section 6.1, the data collected through Survey123 is not stored on ESRI’s servers over the long-term. Once field work has been wrapped up and all completed surveys are submitted to ESRI’s cloud servers, the field rater notifies their project manager, who submits a request to IT to have the data scraped from ESRI’s servers. Once the data has been "scraped" to MoDOT's TMS space, it is deleted from ESRI's servers. This reduces the amount of information stored on the server, which in turn reduces MoDOT's cost for the service.

The data is "scraped" from ESRI as a JSON file. The IT group has written code that extracts the data from the JSON file and incorporates it into the Oracle-based TMS system. Because MoDOT stores all transportation-related data in the TMS, the IT group was able to add additional programming that populated fields like Average Annual Daily Traffic (AADT) based on asset location. These fields covered information that was important for describing the consequence of failure but cannot be measured in the field during a site visit. The IT group also elected to perform calculations not directly related to calculating the Condition State score in the TMS space. This includes scores for some of the detailed rating categories, as well as the Probability of Consequence and Level of Risk scores.

6.4.1 Correcting Errors in Post-Processing

During the 2022 field work, the most common error made when populating the survey was skipping a general site information field, like Travel Direction or Side of Roadway, and accidentally leaving it blank. During app development, the research team decided not to make any fields in the survey "required" to give the field rater more flexibility in tabbing back and forth between the six pages as they collected information at the site. The trade-off is that some additional QC effort is required before submitting survey data and in reviewing data that has been uploaded and processed.

If errors or omissions are identified in the processed TMS dataset, there are a couple options for revising the data.

1. If the user still has the survey on their MoDOT phone, they can update and resubmit the survey, request IT scrape the revised data to generate a new feature, and then delete the original, incorrect/incomplete feature from within TMS.
2. If the user has access to TMS, the user may also correct the missing data directly in TMS. This option was not available to the research team and therefore was not tested in the research project. Updating fields that are not used in any calculations, like "side of road" should be straightforward. Updating fields associated with calculations, like "rock slope block size" could impact multiple tables, depending on how the data scrape is processed. MoDOT's geotechnical group should review any potential pitfalls with the IT group before correcting data directly in TMS.

7 NORTHWEST AND NORTHEAST FIELD RATINGS

To field test the Survey 123 application, inventory and rating of geotechnical assets was completed along NHS routes in the Northwest and Northeast Districts between October 17 and 27, 2022 by a team of engineering geologists from Landslide Technology. Prioritization of NHS routes is recommended by FHWA and allowed the research team to inventory a variety of asset types while staying within the research project budget. MoDOT identified the Northwest and Northeast districts for the field-testing effort because an existing landslide dataset was already available for the Northeast District. The northern part of Missouri is also less geologically complex than the southern districts and has lower topographic relief.

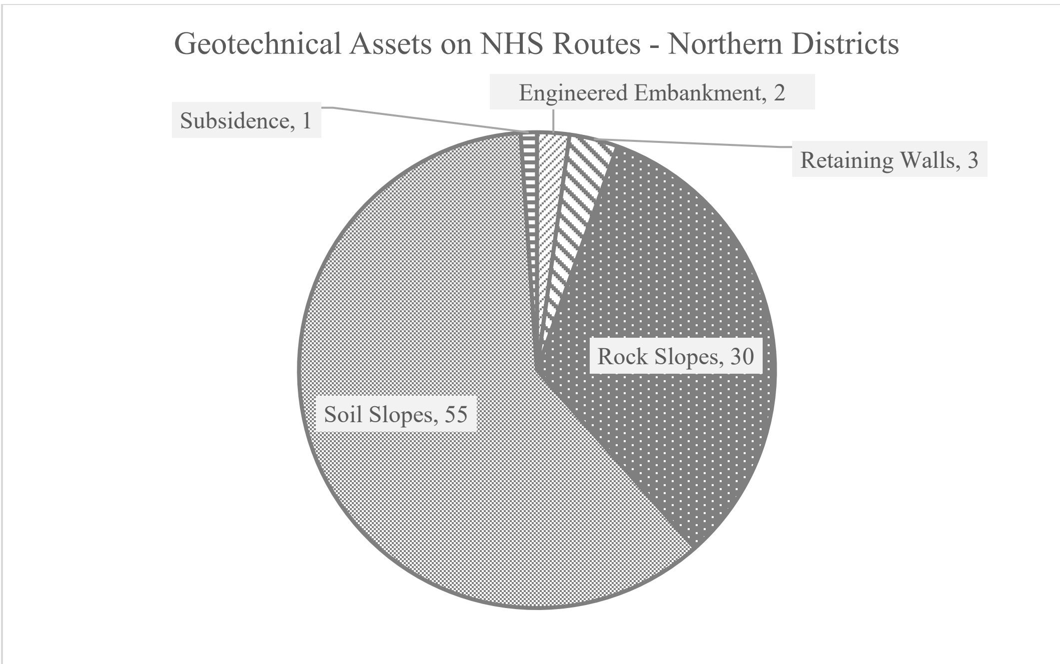


Figure 7-1: Summary of geotechnical assets inventoried along NHS routes in the Northwest and Northeast Districts

A total of 91 assets along NHS routes were inventoried in during the field testing. A breakdown of the various asset types is shown in Figure 7-1 above. Rock and soil slopes make up most of the inventoried assets. The 2019 landslide dataset was used to identify the location of most soil slope assets and the subsidence feature, and Northwest District maintenance personnel provided several additional slope failure locations. Other geotechnical assets not identified during field inventory may exist.

Most of the assets inventoried were in the Northeast District: 70 assets, or approximately 75% of the total. This was expected based on feedback received prior to field work. A comparison of the types of assets collected in the Northwest and Northeast districts is shown in in Figure 7-2 below. The breakdown between geotechnical asset types is similar for both districts, with rock and soil slopes comprising 93% of inventoried assets, and with soil slopes being more common than rock slopes. Asset distribution in other Missouri districts is likely to be different. Urban districts, for example, are expected to have a higher proportion of retaining walls, while southern districts are expected to have higher proportions of rock slopes.

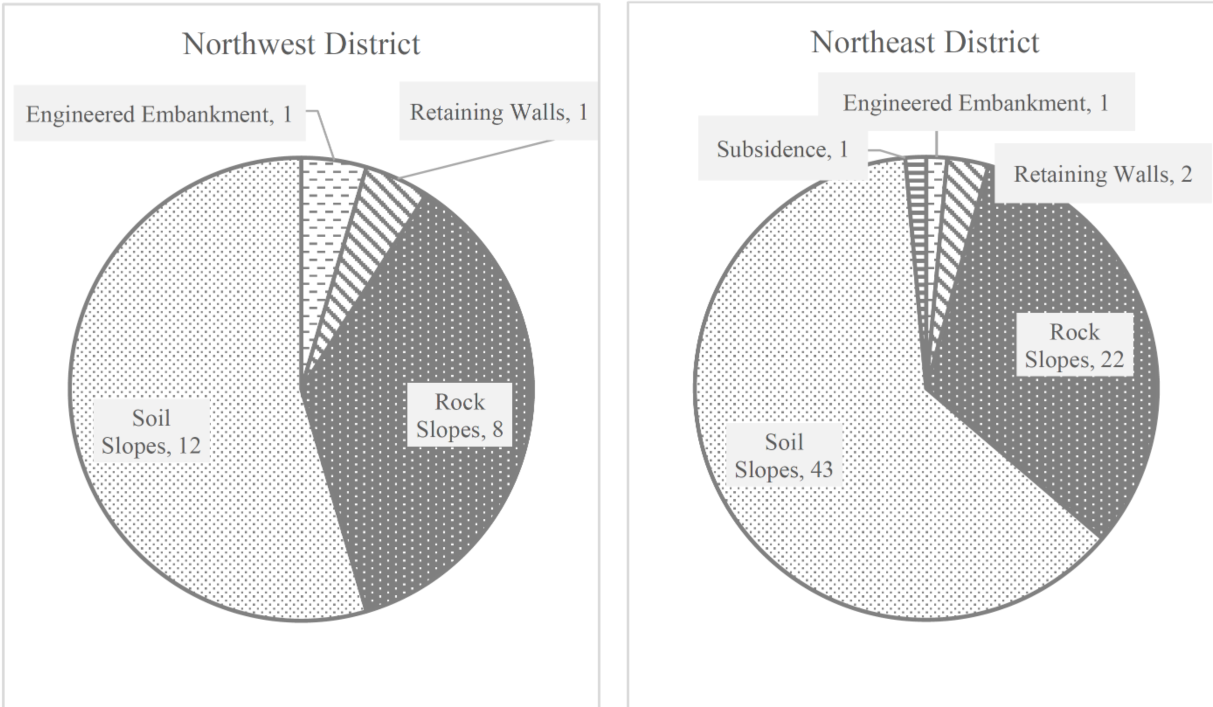
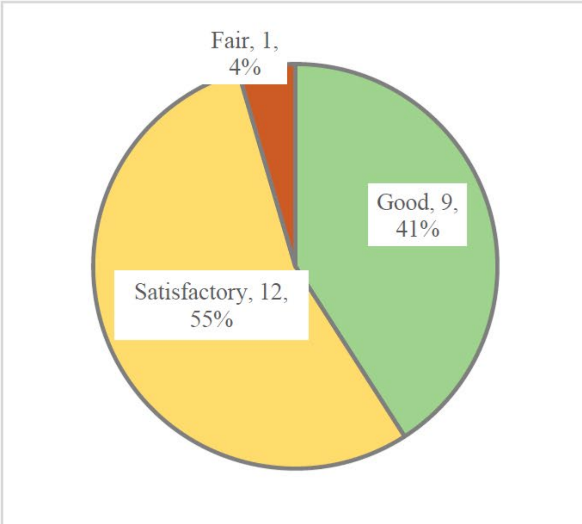


Figure 7-2: Summary of geotechnical assets inventoried by district.

7.1 Condition Analysis of Inventoried Assets

The average condition state score of all assets was 85, which translates to the Good category in both the TAM and GAM rating systems. This high score is due in part to the fact that the Northeast District included 29 mitigated sites in their landslide dataset, most of which were improved to Good condition through the mitigation work. By including mitigated sites in the inventory, MoDOT will be able to quantify the benefit of mitigation to overall asset condition and monitor the performance of mitigation work though its life cycle. For example, slope movement may be fully halted by a rockfill buttress, or it may be slowed enough that only extreme weather events trigger movement. Other mitigation techniques, such as rockfall mesh or horizontal drains typically degrade in the absence of maintenance and become less effective over time.

No assets in a Poor or Failed condition were identified during the field work. The percentage breakdown of asset condition state for the Northwest and Northeast districts is shown in Figure 7-3 The higher proportion of Good condition assets in the Northeast District reflects the fact that this district included mitigated assets in the data set provided to the field inspectors. Well mitigated assets below the roadway are particularly difficult to identify during field work. It is unlikely that any of the mitigated Northeast assets would have been located without the help of the 2019 dataset.



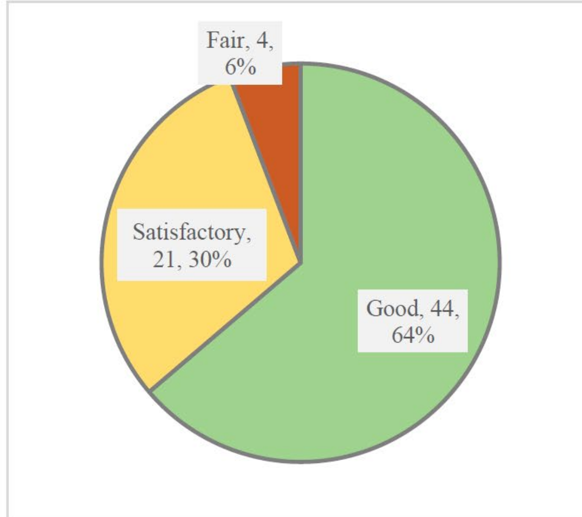


Figure 7-3: Summary of condition state distribution for all Geotechnical Assets on NHS routes in the Northwest District (left) and Northeast District (right).

The condition states summarized above were further subdivided by asset type to illustrate the relative condition of various asset types. The results are plotted in a box and whisker plot in Figure 7-4 below. The box and whisker plot shows the mean score of all inventoried assets, along with the medium, 25th and 75th percentile scores, and the maximum and minimum scores, excluding outliers. For assets where no median line is shown, the median overlaps one of the percentile scores. This is particularly likely to occur in groups that have only a few assets. For example, both engineered embankments had the same condition state score. The median and the mean are identical, and there are no calculated maximum and minimums.

Looking at this plot, engineered embankment and rock slopes assets in the Northern districts are in Satisfactory condition on average, which maps to Fair condition for TAM purposes. All inventoried retaining walls were in good condition. The sole subsidence feature has been successfully mitigated but remains in Satisfactory condition due to its location within the department's ROW.

Soil slopes on average were also in good condition. As discussed previously, this is due to the large number of mitigated soil slopes provided by the Northeast district for inclusion in the inventory. In the interest of time and budget, inherently stable soil slopes are not inventoried and assessed in GAM programs. For this reason, soil slopes enter GAM databases in Fair or Poor condition. The fact that MoDOT's soil slopes have an average condition state of 90/Good is an indicator of how proactive and effective the department is in mitigating degraded soil slope assets.

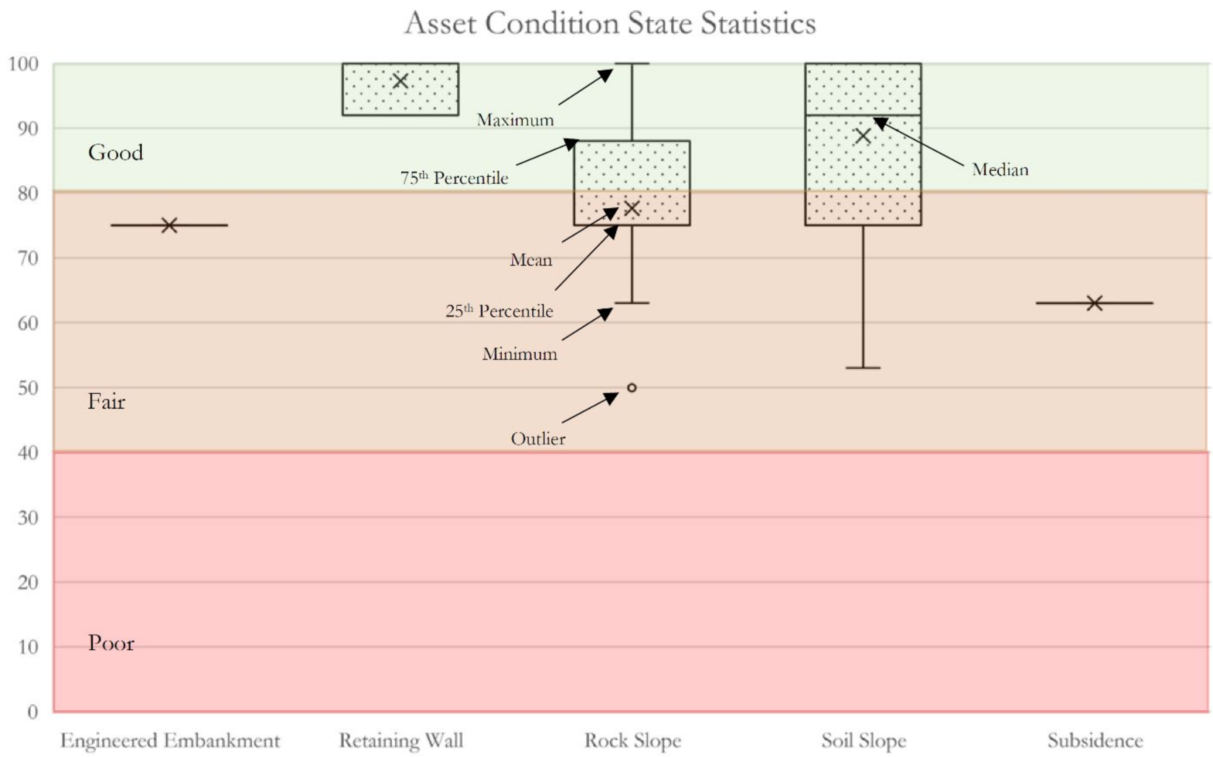


Figure 7-4: Bar and whisker plot summarizing the distribution of condition state of inventoried geotechnical assets. No subgrade assets were inventoried. Annotations were added to the plot to assist interpretation.

7.2 Level of Risk Analysis of Surveyed Samples

As discussed in Section 5.2, the level of risk metric developed for MoDOT's GAM program incorporates both Condition State and Probability of Consequence. This Probability of Consequence is approximated by combining vehicle traffic with roadway geometry. Traffic volumes for NHS routes are typically some of the highest in the state, but NHS routes are typically designed for these higher traffic volumes and prioritized for safety funding.

The average AADT category score for all assets was 68, which is equivalent to an AADT of roughly 5,200 vehicles per day. However, the roadway geometry of the inventoried sites was typically excellent, with good sight distance to identify an obstacle, along with multiple lanes and paved shoulders that provided space for emergency maneuvers. The calculated probability of consequence for all 91 geotechnical assets inventoried during field work are summarized in Figure 7-5 below. The 4 assets with High probability of consequence were locations where traffic volumes were particularly high and roadway geometry was impacted either by horizontal/vertical curves or guardrail installation.

By combining condition state and probability of consequence for all assets, the research team further calculated level of risk for the inventoried geotechnical assets, as summarized in the pie chart in Figure 7-6. No High risk assets were identified in either the Northwest or the Northeast district. This reflects the discussions between the research team and the technical committee. The technical committee shared multiple assets that are ongoing maintenance concerns, but none where an emergency response had been necessary.

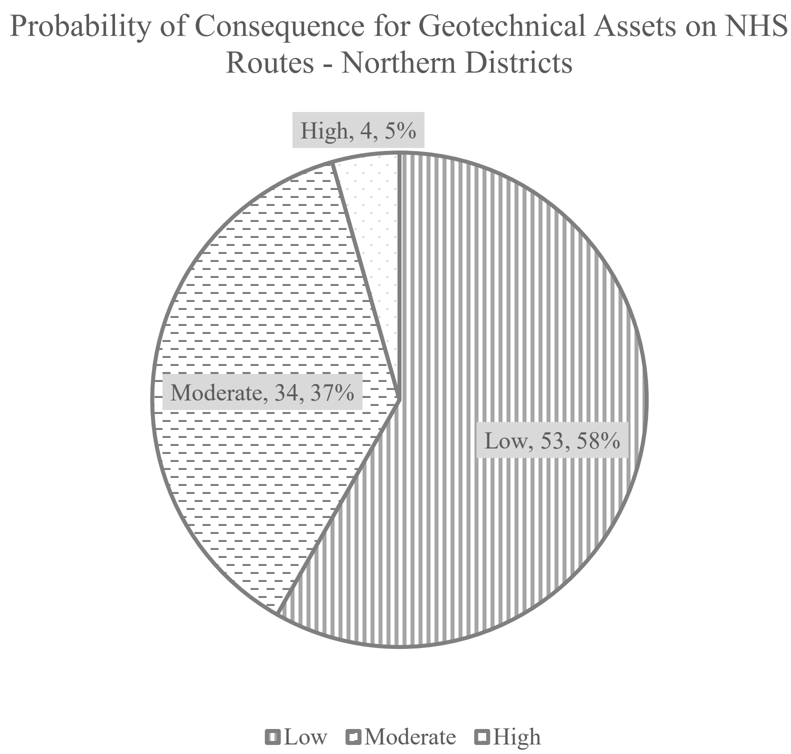


Figure 7-5: Calculated probability of consequence for inventoried geotechnical assets in northern Missouri

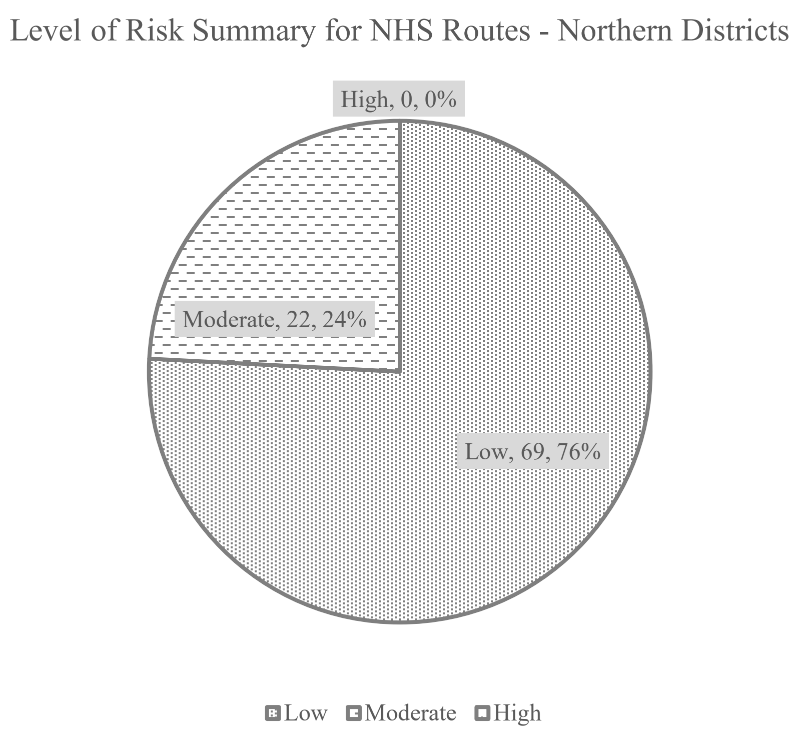


Figure 7-6: Summary of calculated Level of Risk for geotechnical assets in the Northwest and Northeast districts

To provide an overiew of how realtive hazard and relative consequence combine to describe the relative risk, a scatter plot of probability of consequence vs condition state was overlain on the risk register developed in Section 5.2. This plot illustrates how the low risk scores in the field work are a combination of Good condition assets on well constructed roads. The two Moderate/High risk sites are the subsidence feature in a relatively narrow section of roadway, and a rock slope on US 61 that had one of the highest AADT volumes encountered in the study. Another point that is graphically clear in this plot is that 100/Good condition sites can be found over a range of traffic volumes and roadway geometry, but the invesere is not true. A higher relative consequence is more likely to correspond with a lower condition state score. The controlling factor here appears to be roadway geometry. Narrower lanes and more restricted site distances tend to be associated with older slopes that have either degraded over time or were not constructed with modern techniques.

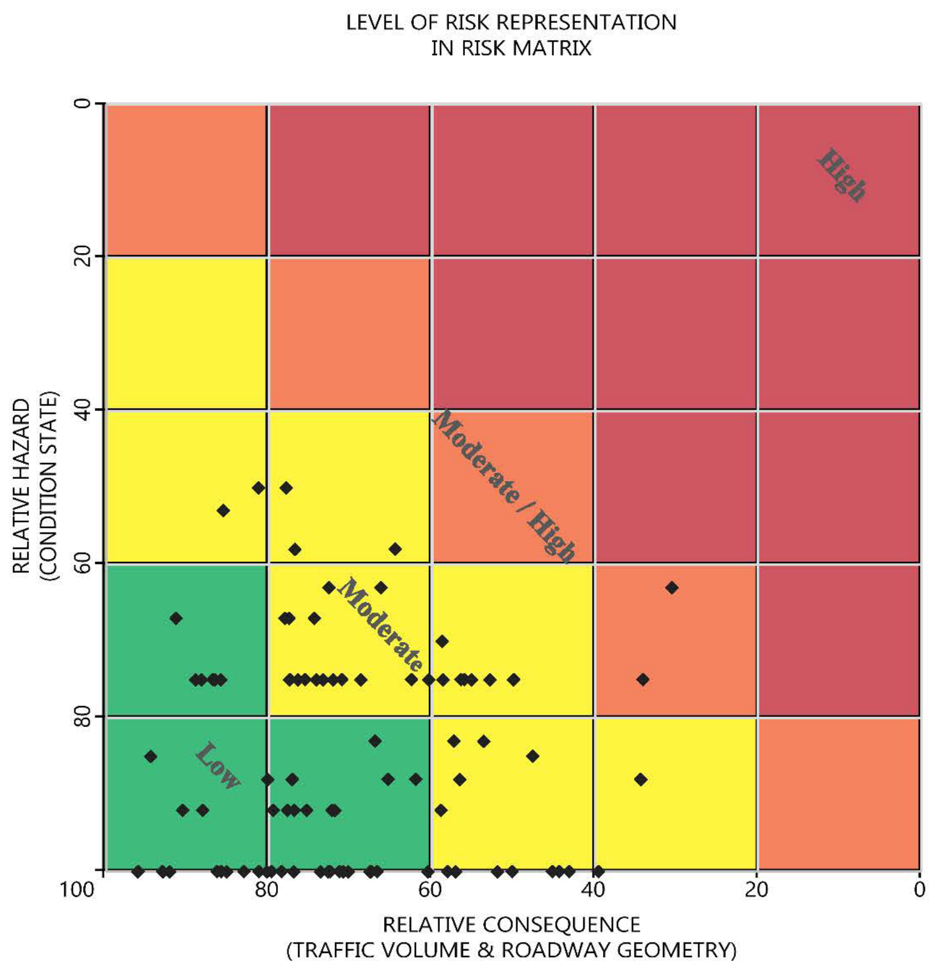


Figure 7-7: Scatter plot of relative consequence vs relative hazard for inventoried geotechnical assets overlain on the risk matric

As for the condition analysis in Section 5, the level of risk scores were further dividied by asset types to help with trend identification. Engineered embankments, retaining walls, and subsidence all had less than three inventoried assets so we did not ascribe trends to these assets. The single inventoried subsidence feature was located below the guardrail in the final approach to a bridge, so the available roadway score was one of the lowest described.

Broadly speaking, the fact that level of risk is higher for rock slopes than for soil slopes is reasonable. Rock slopes are expensive to design and excavate and typically occur only in areas where a rock cut cannot be avoided. Roadway widths through rock cuts are minimized, to prevent unnecessary, expensive excavation. Horizontal or verical curves are also common, as rock outcrops are frequently associated with grade changes. The lower level of risk for soil slopes reflects how many damaged soil slope assets have been mitigated by MoDOT, effectively adresseing risk at these locations. No mitigated rock slopes were inventoried in the northern districts.

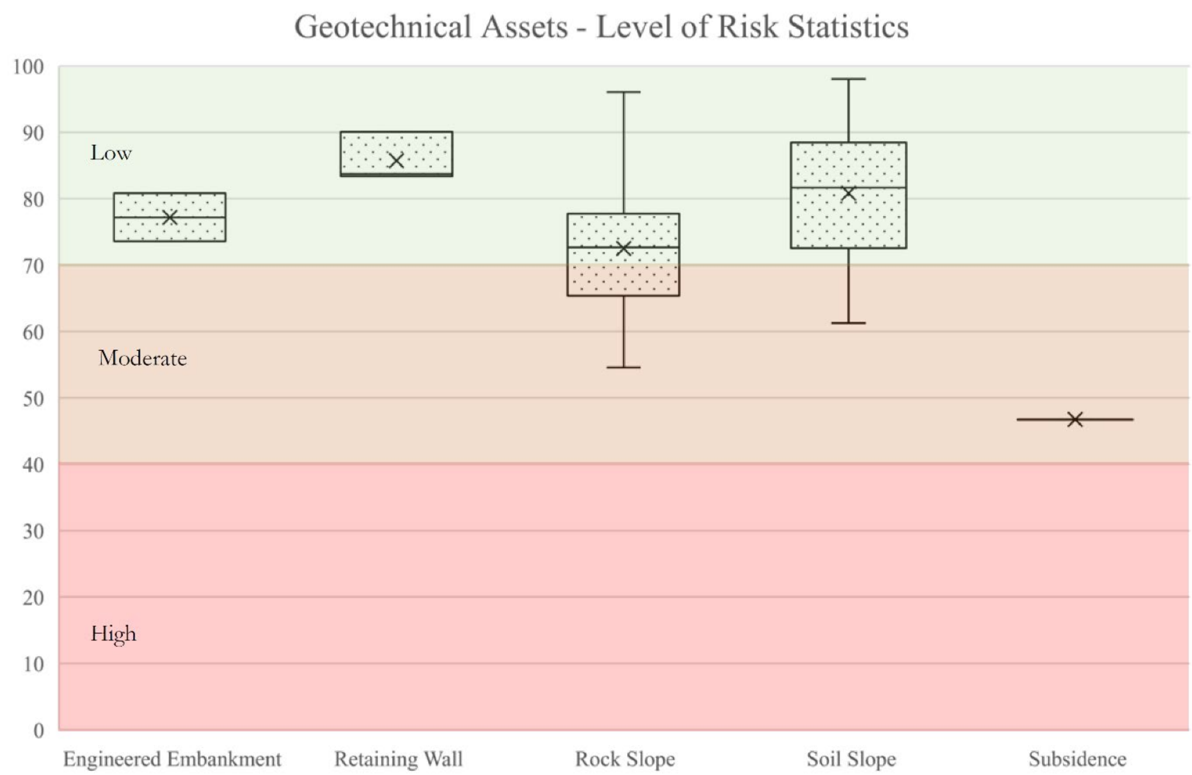


Figure 7-8: Bar and whisker plot summarizing the distribution of estimated level of risk for inventoried geotechnical assets. No subgrade assets were inventoried.

8 SAMPLE DECISSION SUPPORT TOOLS

In MoDOT's 2019 TAM plan the calculated replacement costs for the NHS routes is $53.0 billion. This cost includes pavement, bridges/culverts, signals/lighting, interchanges, and ROW (Missouri Department of Transportation, 2019). This replacement cost is an underestimate since it does not include the cost of replacing supporting geotechnical assets, such as rock-cut excavation or retaining wall construction. The GAM Inventory and Assessment piloted in this research project is the first step to developing an asset management program for geotechnical assets. MoDOT will need to use the data collected to develop target performance goals and track how well these goals are being met in order to move from inventory/assessment to management. This section includes a set of sample decision support tools that could be used to select and prioritize projects to improve the performance of geotechnical assets.

Drawing from MoDOT's 2019 TAM plan, the research team identified four roadway types already being used to set target conditions for individual assets. Using the target asset condition percentages for bridges and pavements as a guide, the research team developed preliminary target conditions for individual assets based on roadway type, as shown in Table 8-1. The target conditions are highest for Interstate routes and lowest for Minor routes. Based on the data in Section 7, the NHS routes in the Northwest and Northeast districts are already meeting the target asset conditions.

Table 8-1: Example Decision Support Tool using target asset conditions

Roadway Type	Target Condition % Poor Condition Assets	Target Condition % Good condition Assets	Target average Asset Condition
Interstate	0	80	85 / Good
Non-Interstate NHS	1	75	80 / Good
Non-NHS Major Routes	3	60	75 / Fair
Non-NHS Minor Routes (>400 ADT)	8	50	60 / Fair

In GAM programs developed by other state and federal agencies, a target level of performance is defined by the asset management team and used to guide project selection. The research team created target performance levels by combining target conditions from MoDOT's 2019 TAM plan with example performance definitions from the FHWA's USMP program (Beckstrand, et al., 2019) and Montana Department of Transportation's Rockfall Hazard Process Assessment (Beckstrand, et al., 2017). An example decision support tool using these performance definitions as targets is provided in Table 8-2. In this table, the roadway types were simplified, and the distinction between Interstate and Non-Interstate routes was removed. The basic expectation for all NHS routes is that only routine maintenance is required to keep these roadways open. Based on the October 2022 field inventory, MoDOT already manages all NHS routes with this in mind. Using the target performance definitions, the research team then developed target conditions for individual assets and corridor segments that would be most likely to support the target performance. Individual poorly performing assets may be addressed individually. A corridor segment where the average asset condition is lower than other corridor segments could indicate an aging roadway section, problematic underlying geology, or an insufficient initial design. Prioritizing a corridor segment would allow the department to improve multiple assets at once, which is more cost effective on a per-site basis.

Table 8-2: Example Decision Support Tool using target performance levels

Roadway Type	Target Performance Definition	Individual Asset Condition	Corridor Segment Condition
NHS (Interstate and non-interstate routes)	Roads require only routine maintenance to remain open	Sites scoring in the 15th percentile are considered for mitigation	Target corridor improvements where average asset condition is < 80 / Good
Non-NHS Major Routes	User delays caused by geotechnical assets occur up to 2x per year	Sites scoring in the 10th percentile are considered for mitigation	Target corridor improvements where average asset condition is < 75 / Fair
Non-NHS Minor Routes (>400 ADT)	User delays caused by geotechnical assets occur multiple times annually, and may be seasonally concentrated	Sites scoring in the 5th percentile are considered for mitigation	Target corridor improvements where average asset condition is < 60 / Fair

Both tables in this section are provided as examples only. Implemented decision support tools should be developed following input from the various department stakeholders and incorporate any unofficial performance targets already used by the department or by maintenance crews at the district level. The final decision support tools should also be similar to those already being used by the Department for pavements and bridges. The work to develop decision support tools may also identify data gaps that could be filled by future research project to strengthen asset management in Missouri.

9 CONCLUSIONS AND RECOMMENDATIONS

The research team is confident that the work completed on this project proves beneficial to MoDOT by providing tools for more effective management of geotechnical assets across their transportation system. The initial test of concept for a geotechnical program that combined Survery123 mobile data collection with the capabilities of TMS-based post processing was successful. Nurturing this initial proof of concept to a statewide program will require additional work. Considerations for program expansion and ongoing maintenance of the application and database as discussed in the following sections. The research team recommends including MoDOT's TMS group in planning for maintenance of the geotechnical asset inventory and field application.

9.1 Considerations in Program Expansion

The research team believes that data collection is ready to be expanded to other districts and roadway classifications based on the favorable results from the initial field test of the Survey123 application and the follow-up troubleshooting. Expanding the program will raise several considerations for MoDOT. These aspects of program expansion have varying degrees of logistical complexity and are summarized in the following paragraphs.

Current System Surveys. Now that work has been completed on NHS routes in the Northwest and Northeast Districts, the research team recommends that inventory and condition assessment work be expanded to all MoDOT NHS routes within the coming year, then expanding the inventory to other routes once the NHS is complete. Performing the initial round of data collection over as short a time window as possible will provide a more accurate "snapshot" of current asset condition statewide. It is our understanding that MoDOT plans to have district geotechnical engineers and geologists inventory assets going forward. Based on experience during the research program, we recommend two-person teams complete surveys where possible, primarily for safety but also for assistance and ongoing cross training in determining asset condition. In areas where the district geologist or engineer is intimately familiar with the asset to be rated, a two-person team may not be necessary.

Future System Surveys. Based on work conducted by other transportation agencies, the research team recommends that MoDOT plan to collect a new set of statewide surveys within the next 5 to 10 years. The new round of data collection will update the dataset being used by MoDOT's planning group, so that they are confident that current information is being used in budget forecasting and project selection. In general, geotechnical assets appear to degrade more slowly than pavements and bridges, despite noteworthy and memorable fast-moving and/or deep-seated geotechnical failures, and new surveys may occur over a longer timescale than for those original TAM assets. Collecting a second set of surveys will help capture asset degradation over time. It will also help capture degradation of any installed mitigation. This data can be used to refine estimates of asset lifespan, asset degradation, and life cycle costs. From a purely logistical standpoint, planning in advance for a future system-wide survey will also ensure that the department keeps the Survey123 application and ESRI-TMS scraping process up-to-date, as future updates to both programs may require the IT group to publish revised surveys or update programming for the "scraping" process.

Components of a Mature Geotechnical Asset Management Program. The work completed to date lays the foundation for a Geotechnical Asset Management Program, but future data analysis is needed to develop a complete asset management framework for the department's geotechnical assets. Most notably, the department needs to develop life cycle costs, replacement costs, and mitigation costs for various asset types in a range of conditions. This work may be performed internally, or as part of future research projects. A partial list of the components included in a GAM program, and how MoDOT might obtain them, are presented in the list below.

- Asset deterioration and life cycle may be initially estimated by analyzing data collected by other states who have implemented geotechnical asset management program. MoDOT could then refine these initial estimates by incorporating state-specific data from geotechnical assets monitoring over the coming decades. The detailed rating categories used for most of the assets in this research program are nearly identical to those used by other states to enable precisely this type of collaboration. Deterioration can also be initially estimated using Markov models and expert elicitation to develop investment models prior to a decade of deterioration and subsequent data collection.
- Asset maintenance and more complex mitigation costs may be available from within MoDOT, depending on how the department records these activities. Costs for specific tasks, such as backfilling a subsidence feature, may be readily available. In contrast, the cost of cleaning out rock slope ditches typically combines several rock slopes and/or as general debris cleanup within a corridor. Allocating that maintenance cost among rock slopes with varying rates of activity would require additional interviews with maintenance personnel to interpret the initial cost data.
- Item replacement costs may be estimated from MoDOT's bid tabs or neighboring states with similar construction costs. Prior research has developed methods for similar cost estimation (Beckstrand, Mines, Thompson, & Benko, 2016) and incurring those costs (Mines, et al., 2018) have been developed and could be adjusted for MoDOT.

Additional Data Collection Tools. Tracking event data that requires an unplanned maintenance response would also be beneficial to MoDOT. By tracking event data, MoDOT will be able to develop and refine correlations between asset condition and adverse event likelihood, event impacts, maintenance costs, etc. All of these are components of a mature asset management program. An early phase of this research project included a 5-question event tracker to be used by maintenance personnel. However, there were not enough ESRI user licenses available to support implementation of an event tracker within Survey123. As licensing costs or programs change, an Survey123 event tracker may become feasible. Using Survey123 as the framework is recommended because the TMS group has already developed the tools necessary to publish surveys to the MoDOT Enterprise Portal and "scrape" submitted data to department servers, reducing the need for new effort on IT's part. However, any mobile-based application that can easily transfer collected data to a central, easily accessible database would be acceptable for this purpose.

9.2 Considerations in Application Maintenance

The GAM field work relies on both an ESRI application – Survey 123 – and MoDOT's own TMS system. Both will need to be maintained and updated as needed so that users can submit data in the most current survey and the TMS group can scrape new surveys and append to the existing data set. Currently the application and database are maintained by the TMS group but used by the geotechnical group. Ongoing coordination between the two groups will play a vital role in the ultimate success of MoDOT's nascent GAM program. Based on experience during the research program, the team has compiled the following recommendations to help with maintenance of the GAM mobile application.

Identify a "GAM Lead." The research team recommends that both the IT and Geotech groups identify a "GAM lead." This person will be the main point of contact between the two groups, act as a point person for questions within their respective groups and help relay any trouble-shooting needs that arise to the appropriate team member. This is not expected to be a full-time role. Rather, because updates from ESRI or MoDOT are likely to occur over time in response to changes in operating systems, data processing capabilities, and user expectations, the IT and Geotech groups should proactively develop a structure to respond to any unforeseen complications of those changes before someone goes out in the field and isn't able to upload data as planned.

Identify a QC-Lead and QC Process. Mistakes during data collection may be minimized by training but cannot be avoided entirely. During the research project, the research team QC-ed the submitted data by comparing data exported from the TMS database with data collected in the field and stored on the mobile device. Several surveys with one or two fields missing were identified in post data collection QA/QC review. The researchers were required to submit revisions as a new feature as the research team does not have access to TMS. It may be easier for MoDOT employees to correct incomplete data within TMS instead. The GAM leads should work together to develop a best process for revising incomplete or incorrect data and disseminate that to their team members as appropriate.

Schedule Training. Once the initial system-wide inventory and assessment work is completed, a second system-wide round of data collection is not expected to be performed for at least 5 years. In the interim, data will be added in an ad-hoc fashion. For example, a roadway improvement project may create new rock cuts or retaining walls, or a severe weather event may trigger development of a new slope failure in a previously stable embankment. To ensure that the department can inventory these assets while the knowledge is fresh, the research team recommends that the Geotech GAM lead schedule an annual or biannual training session with any new district engineers or geologists, so that institutional knowledge of how to use the mobile application is maintained through time. This training session is expected to require about a day and will include confirmation of continued Survey123 functionality.

9.3 Closing

The benefits of implementing a GAM program are numerous, to MoDOT, the traveling public, and to taxpayers. This initial research project developed a mobile application to collect geotechnical asset data in the field and incorporate it into MoDOT's internal data storage system. The research team is confident that if the recommendations in this report are followed, the initial GAM program outlined in this report will lay the foundation for an effective management of geotechnical assets in Missouri for years to come.

First and foremost, inventorying and assessing geotechnical assets permits department planners to develop projects and forecast budgets with a more complete dataset. This reduces the likelihood of costly change orders resulting from incomplete, inaccurate information. Projects that do not address deficiencies in supporting geotechnical assets, such as persistent landslide movement, will have a shorter than anticipated lifespan. In contrast, projects that consider supporting geotechnical assets will be more resilient to extreme weather events and are likely to be perceived by the public as valuable, well-executed work.

Secondly, the ability to track asset condition over time, and to tie maintenance or mitigation costs to specific assets, will improve MoDOT's ability to accurately budget for maintenance/mitigation work over multi-year cycles. Analysis from other states has revealed favorable ROIs for mitigation/preservation dollars spent on geotechnical assets (Beckstrand, et al., 2017; Beckstrand, et al., 2017) and this is expected to be the case in Missouri as well. A mature GAM program will support lifecycle cost-based project decisions. This type of decision making will improve the overall condition of MoDOT's geotechnical assets over time while reducing overall life cycle costs.

Finally, having quantifiable data for geotechnical assets will help MoDOT communicate how they manage these assets to other agencies and the public. The department will be able to communicate how selection of specific project reduces risk, or how incorporating minor improvements into a larger corridor improvement project will reduce maintenance long-term costs. By incorporating geotechnical assets into MoDOT's overall asset management plan, the department will be positioned to confidently deliver higher quality projects with lower life cycle costs.

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10 REFERENCES

Anderson, S. A., & Rivers, B. S. (2013). Corridor management: A means to elevate understanding of geotechnical impacts on system performance. *Annual Meeting of the Transportation Research Board* . Retrieved 12 15, 2022, from https://docs.trb.org/prp/13-3018.pdf

Anderson, S. A., Vessely, M. J., & Ortiz, T. (2017). An Example of Risk-Based Geotechnical Asset Management. *Proceedings of the 68th Highway Geology Symposium.* Marietta, GA: Highway Geology Symposium.

Beckstrand, D. L., Stanley, D., Thompson, P. D., Bilderback, E., Wittie, M., Kanewala, U., . . . Anderson, D. A. (2019). *Unstable Slope Management Plan for Federal Land Management Agencies.* Vancouver, WA: Federal Highway Administration.

Beckstrand, D., Benko, B., Mines, A., Pierson, L. A., Thompson, P. D., & Kimmerling, R. E. (2017). *Statewide Geotechnical Asset Management Program Development: Final Report for Rock Slopes, Unstable Soil Slopes and Embankments, Retaning Walls, Material Sites.* Alaska Department of Transportation and Public Facilities. Retrieved from http://www.dot.state.ak.us/stwddes/research/assets/pdf/stp4000-126a.pdf

Beckstrand, D., Mines, A., Black, B., Jackson, J., Boundy, B., Helm, S., . . . Thompson, P. D. (2017). Montana's Rock Slope Asset Management Program (RAMP). *Proceedings of the 68th Highway Geology Symposium* (pp. 400-419). Marietta, GA: Highway Geology Symposium.

Beckstrand, D., Mines, A., Thompson, P., & Benko, B. (2016). Development of Mitigation Cost Estimates for Unstable Soil and Rock Slopes Based on Slope Condition. *Transportation Research Board Annual Meeting Proceedings*, (p. 14). Washington DC.

Brawner, C. O. (1994). *Manual of Practice on Rockfall Hazard Mitigiation Methods, Participant Workbook.* Federal Highway Administration, National Highway Institute: Training Course No. 13219; Publication No. FHWASA-93-085.

Cruden, D., & Varnes, D. (1996). *Landslide Types and Processes.* Washington, DC: Transportation Research Board.

Federal Highway Administration. (2022, 12 15). *Transportation Asset Management Plans.* Retrieved from FHWA: https://www.fhwa.dot.gov/asset/plans.cfm

Maerz, N. H., & Youssef, A. (2004). *Development of a Highway Rock Cut Rating System (MORPH RS) for Missouri Highways.* Jefferson City, Missouri: Missouri Department of Transportation.

Mines, A., Beckstrand, D., Thompson, P., Boundy, B., Helm, S., & Jackson, J. (2018). Estimating Event Likelihood for Rock Slope Assets on Transportation Networks. *Transportation Research Record*, 23-30.

Missouri Department of Transportation. (2019). *MoDOT's National Highway System Transportation Asset Managment Plan.* Jefferson City, MO: Missouri Department of Transportation.

National Acadamies of Science, Engineering, and Medicine. (2019). *Geotechnical Asset Management for Transportation Agencies, Volume I: Reserach Overview.* Washington, D.C.: The National Acadamies Press.

National Academies of Science, Engineering and Medicine . (2019). *Geotechnical Asset Management for Transportation Agencies, Volume II: Implementation Manual.* Washington, D.C.: The National Acadamies Press.

ODOT. (2011). *Asset Management Strategic Plan.* Oregon Department of Transportation.

Pierson, L., & Van Vickle, R. (1993). *Rockfall Hazard Rating System - Participant's Manual.* FHWA.

Shannon and Wilson. (2012). *Innovative Slide Repair Techniques Guidebook for Missouri.* Jefferson City, Missouri: Missouri Department of Transportation.

Turner, K. A., & Schuster, R. L. (2012). *Rockfall Characterization and Control.* Washington, D.C.: Transportation Research Board of the National Academies.

WSDOT. (2010). WSDOT's Unstable Slope Management Program. *Brochure*.

Wyatt, T. (2020). Potential Liability Associated with Unstable Slope Management Programs. *NCHRP Legal Research Digest 82*.

Wyllie, D. C. (1998, October). Rock Slopes Reference Manual. *Training Course in Geotechnical and Foundation Engineering, NHI Course No. 13235 – Module 5*. Washington, D.C.: Federal Highway Administration.

Wyllie, D. C. (2004). *Rock Slope Engineering. Civil and Mining* (4th ed.). New York: Spoon Press.

APPENDIX A: SURVEY123 MOBILE APPLICATION QUICK REFERENCE

GAM ENGINEERING SURVEY – QUICK REFERENCE SHEET

The following descriptions are meant to help clarify select questions (titles denoted by bold text) that require additional instruction or ask for unfamiliar information. Users should consult the [Rating Categories.docx] document for a description of questions not listed on this sheet or for more detail on the included questions.

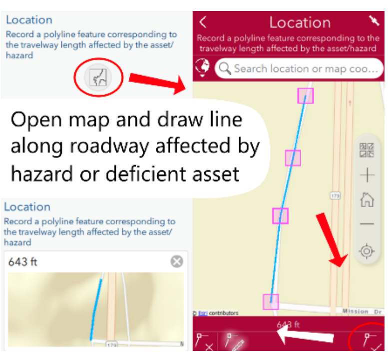
Each of the below headers corresponds with a page in the Survey123 *GAM Engineering Survey*. Users should work through the survey and refer to this sheet as needed. The first two headers do not include descriptions for all survey questions. Some questions have hints within the survey, or self-explanatory meaning, and have been omitted to save space.

Survey question titles are listed in **black bold** text. Page names are listed in **bold blue** text. All **other bold** text is included only for emphasis.

Overview Information

Prompts user for basic information about the hazard or asset's setting, including details about the travelway of interest.

Location: hazard/asset location is stored as series of connected points. Points are specified using device GPS or manual placement.



Travelway Details: Speed Limit and AADT should be written down in the office prior to a site visit, or accessed in the field using this application's supplementary map in ArcGIS Collector.

Hazard/Asset Information

Documents information about the selected type of hazard or asset. This information is for reference and filtering of results, but does not factor into the final condition state score.

- **Within Known Subsidence Area?** Say if there is a history of the selected **Type of Subsidence** in the vicinity.
- **Predominant Side of Road:** Applies to divided roads only – the side most affected or observed as the source of hazard, or the location of an asset – determined when facing in the direction of travel.
- **Above or Below Road:** Applies to Retaining Walls only – below means that wall supports road and above means that wall supports earth adjacent to road (common at overpasses).
- **Is Installed Mitigation Effective?** Effective mitigation has slowed or stopped negative impacts to the roadway.
- **Are Repairs Effective?** Effective repairs have prevented the problem from returning.

Field Measurements

Measurements meant to be collected during the field visit of a hazard or asset. Survey users will need distance measurement tools capable of measuring at least 1,000 linear feet.

User Determined Scores

Semi-quantitative observations made during the field visit of a hazard or asset. Responses are expected to be based on estimates, and do not require detailed measurement.

Drainage Scores: dry geotechnical assets tend to perform better. Wording varies depending on asset/hazard, but this score attempts to estimate the flow of water from the asset or slope.

Hazard Specific Scores:

- **Geologic Condition Scores (rock slopes):** rockfall may be caused by movements along discontinuities (Case 1) or by differential erosion (Case 2). Users
- **Ditch Effectiveness Score (rock slopes):** conveys the ability of a travelway's shoulder ditch to prevent fallen rock from entering travel lanes.
- **Failure Extent Score (soil slopes):** quantifies the extent of travelway impacted by the hazard.
- **Movement History Score (soil slopes):** describes both event frequency and movement rate per event.
- **Roadway Displacement or Slide Deposit Score (soil slopes):** survey choices include two parts, one for roadway displacement, one for slide deposit. Users should choose the one that's most applicable. *Slide Deposit* refers to scenarios when soil falls onto the travelway, while *Roadway Displacement* refers to scenarios when a landslide occurs beneath the road, causing a collapse to the shoulder or travelway
- **Roadway Deformation Score (subsidence):** the amount of right-of-way damaged by subsidence
- **Subsidence Rate Score (subsidence):** by capturing the rate of subsidence, the timing of repairs may be better determined.

Asset Specific Scores:

- **Height Scores:** failure of taller geotechnical assets can impact a greater area. Calculations are based on the **Embankment Height** or **Retaining Wall Height** measurements.
- **Observable Critical Components Score:** retaining walls rely on the performance of parts or materials. This score groups possible defects of those parts/materials that may indicate a failing asset.
- **Roadway Damage Score:** accounts for settlement or cracking in travelway caused by failing assets.
- **Settlement Severity Score:** version of the **Roadway Deformation Score** for Retaining Walls and Ground Improvements instead of Subsidence.
- **Wall Alignment Score:** alignment of retaining walls serves as a good indicator of performance. The user should visually inspect the batter of a wall.

Resulting Hazard/Asset Condition

Computes scores from field measurements and combines them with the user determined scores to determine an overall condition state score. All scores on this page are computed by application and cannot be edited by the user. If any of the scores appear empty, it is caused by blank values of the variable used to compute scores. Variables used in each calculation are listed in with bold text in the description

Annual Average Daily Traffic (AADT) Score: designed to capture route importance through quantitative data. Calculation is based on **AADT** alone.

Average Vehicle Risk (AVR) Score: describes how many vehicles are vulnerable to an asset failure at a single point in time. Calculation is based on the length of the **Location** line and **Speed Limit**.

Length of Roadway Affected Score: the length of travelway impacted by a hazard or failing asset is proportional to the severity of damage and the danger to travelway users. This score is only based on the failing length of an asset and is computed from the **Length of Roadway Affected**. This **Length** is measured from the line drawn in the **Location** question.

Percent Decision Sight Distance (PDSD) Score: computed from decision sight distance, or the distance required by a driver to perceive and react to an unanticipated problem, and the measured **Sight Distance**.

Roadway Width Score: based on space available in travelway for drivers to maneuver around road hazards.

Hazard Specific Scores:

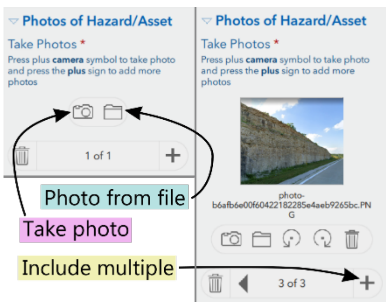
- **Block Size/Event Volume Score:** rockfall events can involve volumes of loose material, individual boulders, or some combination of the two. Users must input **Block Size**, **Block Volume** or both. A score is computed from each measurement, and the highest score is applied to the condition state score.

- **Height Scores:** the height of a slope may be proportional to the severity of damage. Rock and soil slopes are assessed differently. Calculations are based on the vertical **Height of Slope** for rock slopes and the **Axial Length of Landslide** for soil slopes.

Asset Specific Scores:

- **Height Scores:** failure of taller geotechnical assets can impact a greater area. Calculations are based on the **Embankment Height** or **Retaining Wall Height** measurements

Photos of Hazard/Asset: multiple photos may be taken of the hazard/asset, and they will be linked to the survey responses. These photos will be saved with reduced resolution, so it is recommended that users take photos using their phone or tablet's camera application and load them from file here.



Comments: users are welcome to add comments for anything that they feel is relevant to their survey. It is good practice to record when questions were answered with limited certainty (answers may be changed by survey administrators). Other beneficial information to record may include:

- Notes about parking at a site
- Weather conditions during visit
- Safety equipment needed at site (signage, flagging, etc.)

Example Measurements