SPR, Part B
SPR21B4J

MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION

MARYLAND DEPARTMENT OF TRANSPORTATION STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

ADVANCING GEOTECHNICAL ASSET MANAGEMENT - PHASE I

NATHAN MOORE, P.E.,
MADAN GADDAM, P.E.,
GETANEH WOLDETSADIK, P.E.,
KAREN SANDKUHLER, P.G.,
LIJUN ZHANG, P.E.,
ABU BAKARR JALLOH, Ph.D.,
ARMOUND MOURADYAN
GREGORY STORMS
MICHAEL LOCHARY

Maryland State Highway Administration

In-House Research

FINAL REPORT

MARCH 2024

This material is based upon work supported by the Federal Highway Administration under the State Planning and Research program. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Federal Highway Administration or the Maryland Department of Transportation. This report does not constitute a standard, specification, or regulation.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Advancing Geotechnical Asset Management, Phase I

5. Report Date
March, 2024

6. Performing Organization Code
SHA OMT

7. Author(s)
Nathan Moore, P.E., Madan Gaddam, P.E., Getaneh Woldetsadik, P.E., Karen Sandkuhler, P.G., Lijun Zhang, P.E., Abu Bakarr Jalloh, Ph.D., Armound Mouradyan, Gregory Storms, Michael Lochary

8. Performing Organization Report No.
SPR21B4J

9. Performing Organization Name and Address
SHA Office of Materials and Technology
Engineering Geology Division
7450 Traffic Drive
Hanover, Maryland 21076

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Maryland Department of Transportation (SPR)
State Highway Administration
Office of Policy & Research
707 North Calvert Street
Baltimore MD 21202

13. Type of Report and Period Covered
SPR-B Final Report May 2021- March 2024.

14. Sponsoring Agency Code
(7120) STMD - MDOT/SHA

15. Supplementary Notes

16. Abstract
Multi-faceted advancements were implemented in the management of highway cut slopes, embankments, and ground modifications. An initial inventory of highway slopes and ground modifications was developed. Planning-level condition assessments, criticality assessments and risk of geotechnical assets were then applied to the inventory. This research can be used for future strategic rehabilitation of geotechnical assets to reduce the risk of slope instability and local subsidence, to improve the resilience of the highway system.

17. Key Words
Geotechnical Asset Management, Geotechnical Engineering, Transportation System Management

18. Distribution Statement
This document is available from the Research Division upon request.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
None	None	38	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

1. Background 1

2. Purpose 1

3. Geotechnical Asset Definitions 1

Embankment 1

Cut Slope 2

Ground Modification 2

4. Highway Slope Inventory 3

5. Highway Slope Condition 6

6. Highway Slope Criticality 11

7. Highway Slope Risk 13

8. Highway Slope History 16

9. Ground Modification Inventory 16

10. Subsurface Void Identification 16

11. Geotechnical Areas of Maintenance Concern 18

12. Geotechnical Design Support 18

Surface Vegetative Cover 19

Flow Control 20

Surface Hard Cover 21

Stability Reinforcement 25

Pipe Rehabilitation 26

Internal Flow Control 27

Reconstruction 28

Observation and Monitoring 31

13. Recommendations and Next Steps 32

14. References 33

Appendix A – Geotechnical Design Manual Outline 34

1. Background

Geotechnical Asset Management (GAM) includes strategic processes to support a resilient highway system. While some geotechnical assets have been incidentally managed as needed through design, construction and maintenance processes, a comprehensive planning-level framework is advanced through this research to support proactive characterization and cost-effective repair of valuable earthwork assets. Implementation of GAM requires the development and maintenance of several structured datasets including inventory, condition, criticality, risk, design support and work history. Recently accessible data and analysis tools allowed for cost-effective implementation of GAM and are utilized by this project to develop foundational datasets and processes.

2. Purpose

The purpose of this research is to build proactive planning-level components of GAM to assist with strategically managing geotechnical assets in a state of good repair. Stable geotechnical assets support pavements, bridges, culverts, retaining walls, signs, guardrails, and other highway infrastructure assets. Geotechnical instability distresses such as erosion gullies, landslides, sinkholes, and settlement have been common problems throughout highway construction and maintenance, and often develop over long periods of time, allowing for proactive identification and treatment before the distress impact the other assets they support. Strategic mitigation of geotechnical distresses requires a more comprehensive geotechnical asset inventory and with accompanying comprehensive condition surveys. The outcomes of GAM aim to improve highway resilience to floods, excessive precipitation, and sinkholes to minimize the risk of impacts to traveler safety, mobility, and related infrastructure. Specifically, this research provides incremental, multi-faceted progress with 1) Inventory; 2) Condition; 3) Subsurface Void Detection; and 4) Geotechnical Design Support.

3. Geotechnical Asset Definitions

The definitions and illustrations below are based on and modified from those proposed in NCHRP Research Report 903 for the purposes of implementing GAM within the Maryland State Highway Administration (SHA).

Embankment. Embankments are the constructed controlled fill portion of a highway that supports pavement and other structures, enabling the roadway to maintain an elevation above adjacent ground. Embankment assets include the foundation, fill slopes, and any reinforcement. Four functional sub-categories of embankments include culvert embankments, bridge approach embankments, side hill embankments and other highway embankments. Embankment materials may include rock, soil, concrete, controlled low strength material (CLSM), lightweight cellular concrete, lightweight aggregate, and potentially recycled materials. The minimum threshold height for an embankment to be included in the inventory is 10 feet above the adjacent grade, although shorter embankments with specific concerns or issues can also be included on a case-by-case basis.

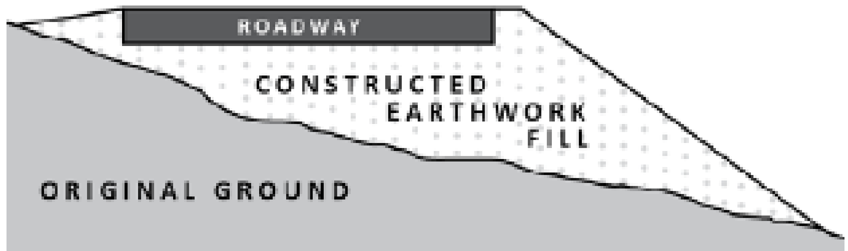


Figure 1: *Embankment*

Cut Slope. A cut slope asset enables a roadway to maintain an elevation below adjacent ground. The cut slope retains the adjacent soil or rock and maintains vertical separation between the highway and the property above the slope. Cut slopes serve a similar function as retaining walls, except with a flatter slope angle. Two sub-categories of slopes are engineered cut slopes and natural slopes. Engineered cut slopes are permanently excavated into terrain, while natural slopes have been formed through geologic processes such as a river or through other natural means. Engineered cut Slopes can be comprised of soil, bedrock or both. If any bedrock excavation was required to construct the slope, it will be considered a rock cut slope; otherwise the cut slope will be a soil cut slope. The minimum threshold height for a cut slope to be included in the inventory is 10 feet separation from the adjacent grade, unless the cut slope is judged to create an unacceptable hazard to the safety of users and maintenance personnel.

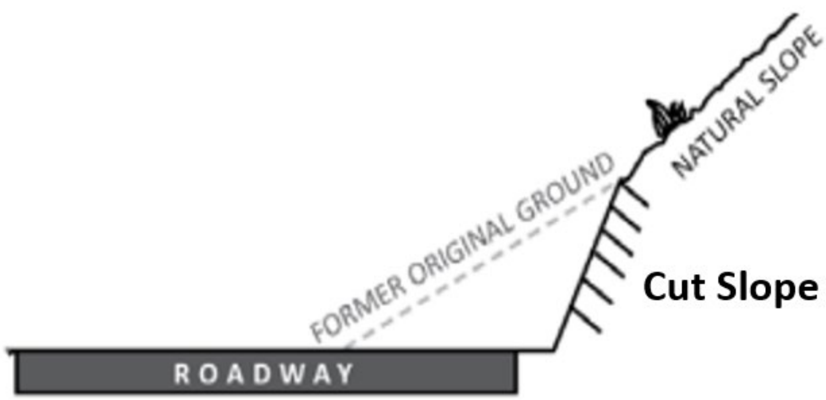


Figure 2: *Cut Slope*

Ground Modification. A ground modification asset is the altered foundation or earth structure constructed to support operational loads on subgrades or foundations. Examples of ground modifications include grouting zones from sinkhole repair, aggregate columns, wick drains, deep compaction, pushing riprap into very soft soil for a construction platform, and soil mixing. Pavement subgrade stabilization techniques, while appropriately considered ground modifications, are organizationally managed at SHA with pavement assets as part of the subgrade.

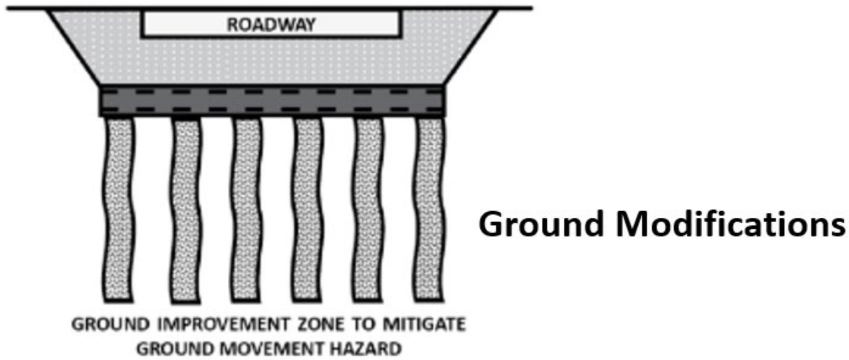


Figure 3: *Ground Modifications*

Other geotechnical assets including retaining walls more than 6 feet high and pavement subgrades, are not addressed in this report, and are managed outside of SHA's GAM framework.

4. Highway Slope Inventory

Both embankments and cut slopes, assets are managed as polygons in GIS with a corresponding height/length/area. The slope and embankment assets are associated with the adjacent highway inventory per each slope. Additional reinforcement components and historic slope activities will be documented in tables related to the slope asset polygon.

ArcGIS Pro was used to develop initial slope inventory using available aerial imagery and lidar elevation data.

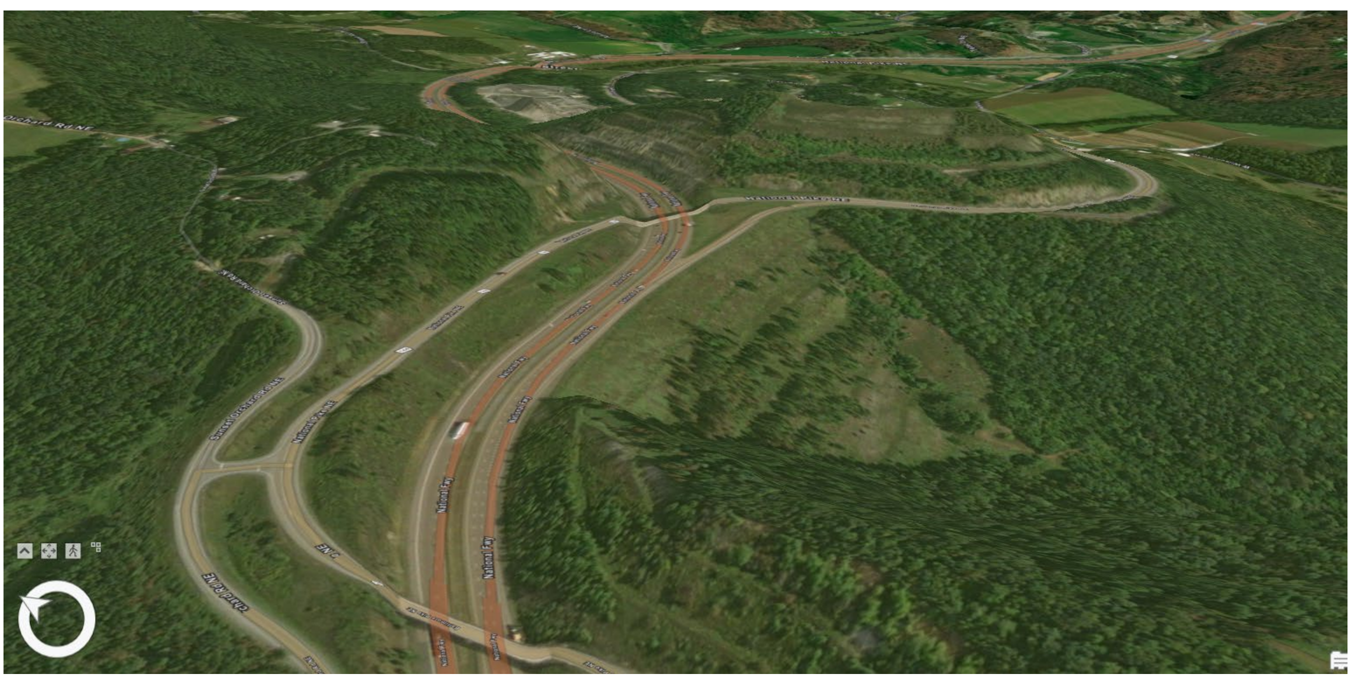


Figure 4: *Aerial Imagery used to discern highways*

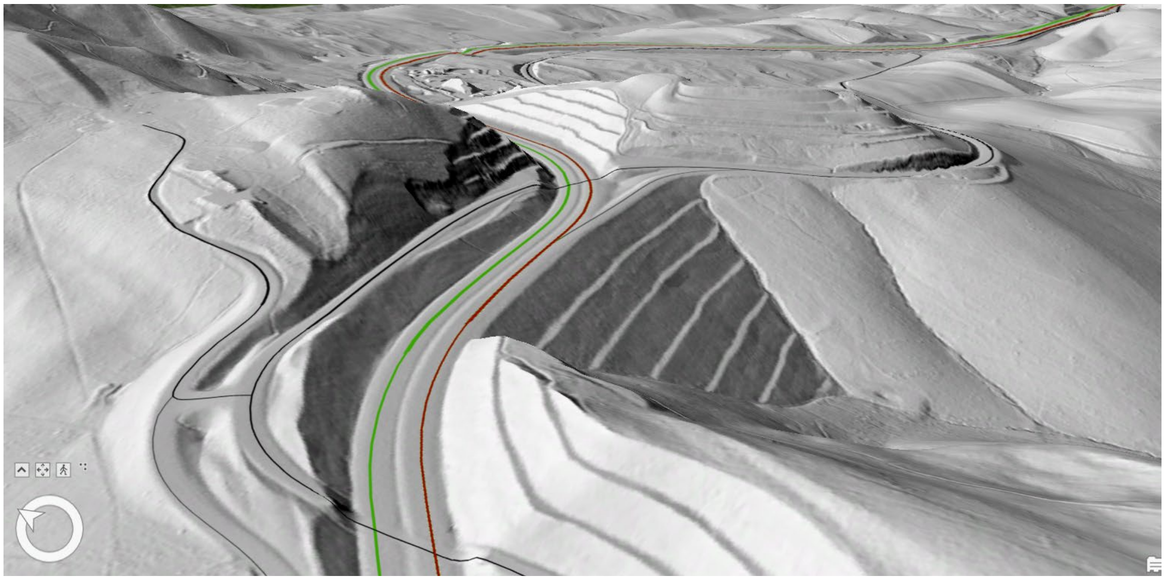


Figure 5: *Lidar Hillshade, Courtesy of Maryland iMAP, illustrating the digital elevation model used to identify zones of elevation change adjacent to highways*

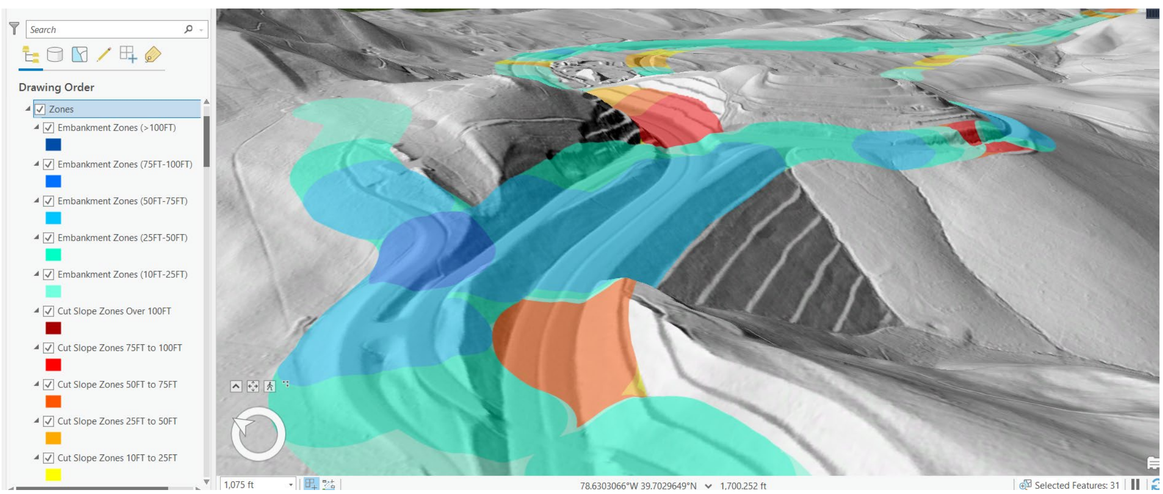


Figure 6: *Colored zones of elevation change from highway mile points. Elevation of highway milepoints was compared with elevations of the surrounding 150 feet. Shades of blue indicate embankment zones. Shades of yellow and red indicate cut slope zones.*

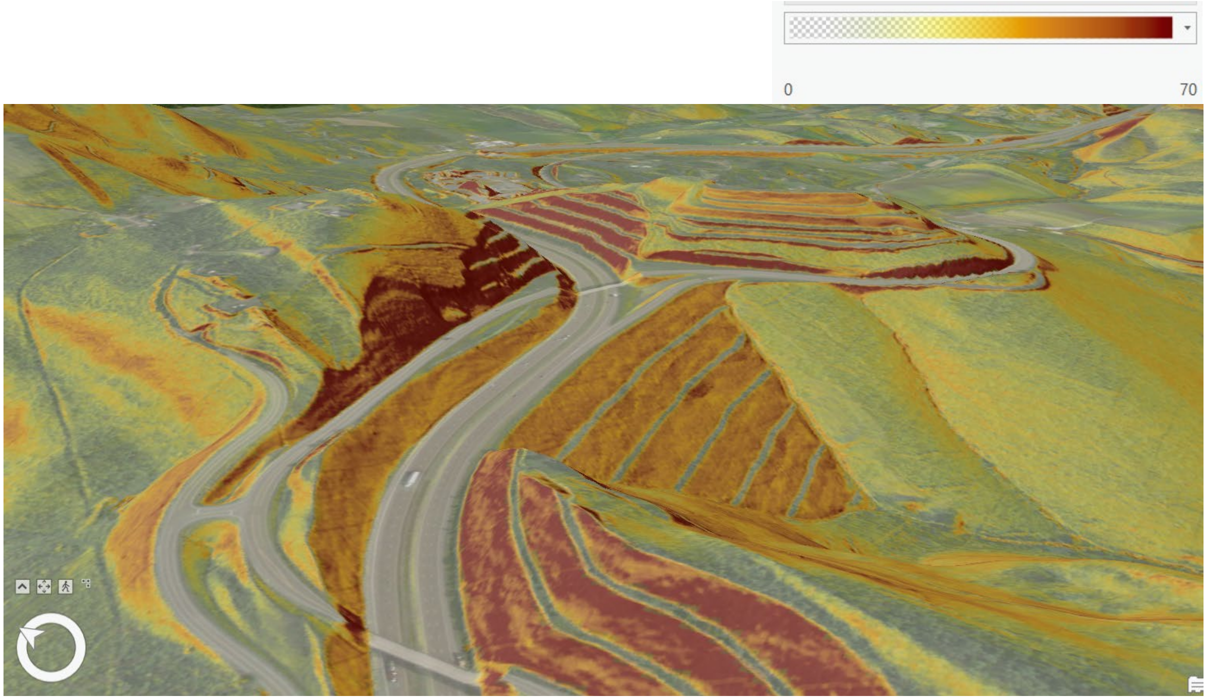


Figure 7: *The slope derived from Lidar, courtesy of Maryland iMAP, was overlaid on the aerial imagery to assist with identifying the boundaries of slope assets during polygon generation. The slope is rendered transparent less than 15 degrees, and fully opaque at 35 degrees, transitioning from yellow to red at the maximum rendered slope value of 70 degrees.*

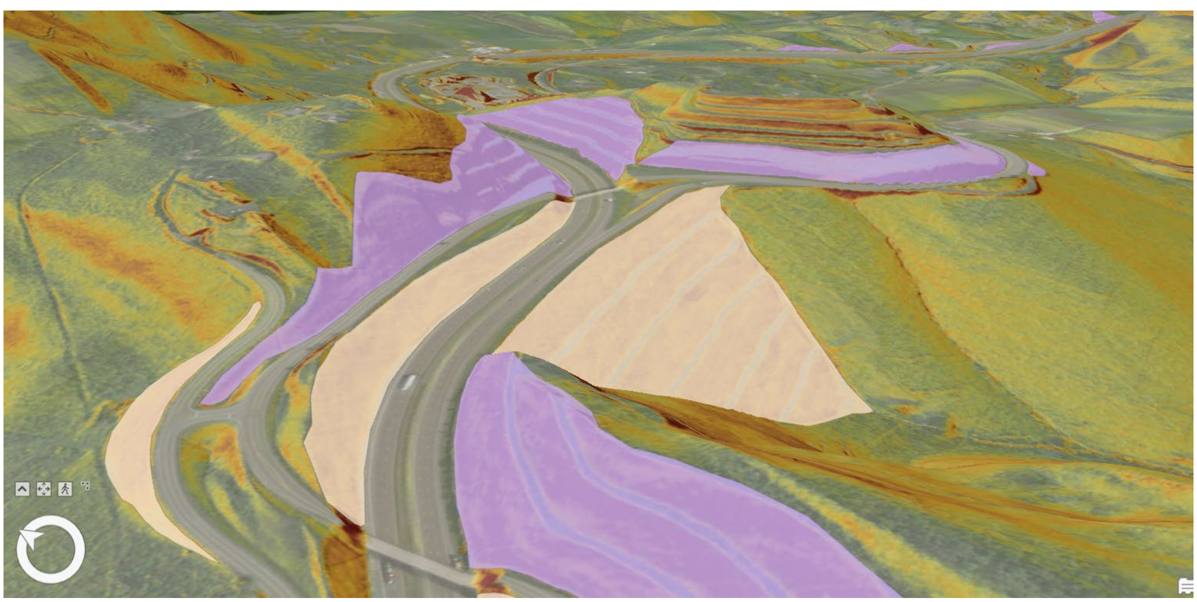


Figure 8: *Polygons of slope assets were developed. The polygons represent inspectable slope faces which do not cross beneath bridges or over pavement.*

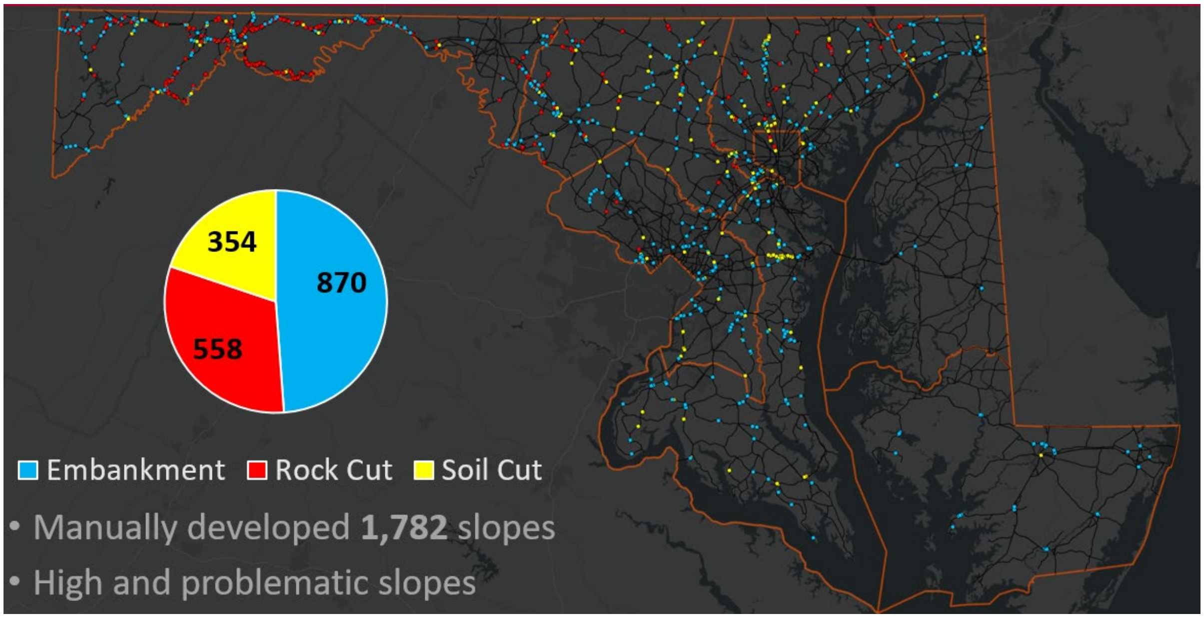


Figure 9: *Map of initial asset inventory locations, including all slopes over 50 feet high and other slopes where past maintenance concerns were documented.*

The depreciated present value of geotechnical assets is dependent on the current unit cost of excavation, embankment construction, and ground modification construction. Current estimates of comprehensive slope inventory above 10 feet are over 10,000 slopes, with an estimated depreciated present value likely in the top 5 of the 14 asset classes managed by SHA.

5. Highway Slope Condition

One a scale from 1 to 5, slope Assets with a score of 3.0 or higher are generally considered in a state of good repair (SGR); assets with a score of 2.01–2.99 are considered marginal; and assets with a score of 2.0 or less are considered not in SGR.

To calculate a condition rating score for soil cut slope and embankment assets, a desktop evaluation was conducted to establish risk, followed by field condition evaluations for selected medium- to high-risk assets. Rock cut slopes do not have a desktop evaluation process. Instead, only field evaluations are conducted. The rating criteria for geotechnical assets is presented below. Soil cut slopes and embankments have the same rating criteria, while rock cut slopes follow a different set of guidelines. These asset class specific rating scores are then converted to a consistent 1-5 rating score for all assets.

Condition assessment for soil cut slopes and embankments is currently based on ***precipitation sensitivity***, which is the estimated critical inches of rain required to initiate instability of 1 square meter of soil, 6 feet deep. The methodology is based on the calculations included in the report "Storm-Induced Slope Failure Susceptibility Mapping" from Minnesota Department of Transportation by Omid Mohseni (2018). The calculation combines elevation and slope terrain data from Maryland iMAP LiDAR, along with estimated cohesion, friction, bulk density, and specific gravity estimations derived from soil survey mapping published by the US Department of Agriculture. The soil data was developed using parent material descriptions from USDA and estimating the USCS classification. The corresponding geotechnical engineering properties of the soil are estimated correlations based on agency experience. The process of calculating precipitation sensitivity is summarized below.

First, H_{cr} (the critical head of water) is calculated using the following equation:

$$H_{cr} = \frac{\frac{\dot{C}}{Y_w} - SG \cdot Z \cdot cos^2\theta(tan\theta - tan\widehat{\varphi})}{cos^2\theta[(SG_{sat} - SG)(tan\theta - tan\widehat{\varphi}) + tan\widehat{\varphi}]}$$

Where:
θ = Slope angle
$\hat{\varphi}$ = Effective internal angle of friction
$\dot{C}$ = Apparent cohesion
SG = Specific gravity of soil
SG_{sat} = Saturated specific gravity of soil
Z = Soil layer depth

Table 1 – *Friction and Cohesion used for USCS Soil Classes Estimated from USDA Parent Material*

USCS Soil Class	Description	Maximum Effective Peak Friction angle ϕ' (deg)	Cohesion (psf)
GW	well-graded gravel, fine to coarse gravel	40	0
GP	poorly graded gravel	38	0
GM	silty gravel	36	0
GC	clayey gravel	34	0
GM-GL	silty gravel	35	0
GC-GL	clayey gravel with many fines	29	0
SW	well-graded sand, fine to coarse sand	38	0
SP	poorly graded sand	36	0
SM	silty sand	34	0
SC	clayey sand	32	0
SM-SL	silty sand with many fines	34	0
SC-CL	clayey sand with many fines	28	63
ML	silt	33	0
CL	clay of low plasticity, lean clay	27	209
CH	clay of high plasticity, fat clay	22	251
OL	organic silt, organic clay	25	104
OH	organic clay, organic silt	22	104
MH	silt of high plasticity, elastic silt	24	63

The critical head of water is then used to calculate F, the precipitation sensitivity, in the following equation:

$$F = H_{cr} cos^2\theta(\eta - \vartheta_{FC})$$

Where:
H_{cr} = Critical head of water
$\eta - \vartheta_{FC}$ = Field capacity status of soil
F returns the inches of rain required to initiate instability.

Table 2 – *Estimated Field Capacity by USDA Soil Type*

Soil	Field Capacity
Sand	0.17
Loamy sand	0.09
Sandy loam	0.14
Loam	0.25 to 0.32
Silt loam	0.28
Clay loam	0.32
Silty clay loam	0.30 to 0.37
Clay	0.32

Low values of precipitation instability (F) typically highlight distressed portions of slopes and embankments and are useful for desktop condition ratings. Table 4 identifies condition thresholds. In the future, detailed field assessments of soil cut slopes and embankments will be conducted on slopes with medium or higher risk or those with observed instability. Preferably, these field assessments would use Lidar or other methods to observe the ground surface beneath vegetation to assist with measuring distresses.

Condition assessment for rock cut slopes is based on a geologist's field visual manual inspection of bench condition, presence of launching factors, catchment adequacy, geologic character, and block size. Each of these factors is given a sub-score on a 0-3-9-27-81 scale that can be translated later to the standard SHA approach (excellent, good, adequate, marginal, and poor). These individual sub-scores are then added together to give a total condition score for the rock cut slope. The sub-scores are assigned according to the guidelines presented in Table 3.

Table 3 - *SHA Rock Cut Slope Sub-Score Rating Definitions*

Sub-Score	Rock Cut Bench Condition	Launch	Catchment	Geologic Character (Higher Score from Case 1 or Case 2)				Block Size
				Case 1 (Sum of the following sub-scores)		Case 2 (Sum of the following sub-scores)		
				Structural Planar Condition	Rock Friction	Structural Erosion Condition	Measured Differential Erosion	
0	No Bench	No Launch Factor Present	Does not meet conditions for 81, 27, 9, or 3 points and: Catchment Width >= 25 feet	--	--	--	--	<0.5 foot average linear dimension of potential falling rock
3	Bench Good Condition	-	Does not meet conditions for 81, 27, or 9 points and: Catchment Width <25 feet	Discontinuous failure planes, favorable orientation	Rough, Irregular	Minor differential, not distributed	<1 foot	0.5 to <1 foot average linear dimension of potential falling rock
9	Bench with Woody Vegetation	Launch Factor Present	Does not meet conditions for 81 or 27 points and: Catchment Width <15 feet and slope height < 50 feet OR Catchment Width <25 feet and slope height >= 50 feet	Discontinuous failure planes, random orientation	Undulating	Occasional differential erosion features	1 to <2 feet	1 to <2 feet average linear dimension of potential falling rock
27	Bench Portions Filled with Debris	-	Does not meet conditions for 81 points and: Catchment Width <2 feet and is not sloped toward road OR Catchment Width <10 feet OR Catchment Width <25 feet and is sloped toward the road	Discontinuous failure planes, adverse orientation	Planar	Many differential erosion features	2 to <4 feet	2 to <5 feet average linear dimension of potential falling rock
81	Bench Failed/Fallen	-	Catchment Width <=2 feet and Catchment Slope is sloped toward road	Continuous failure planes, adverse orientation	Clay infilling, or slickenside	Major differential erosion features	>=4 feet	>=5 feet average linear dimension of potential falling rock

To obtain a consistent condition assessment score from 5 to 1 for all assets, condition scores for soil cut slopes/embankments and rock cut slopes are converted following the guide presented in Table 4.

Table 4 - *Slope and Embankment Condition Assessment Scoring*

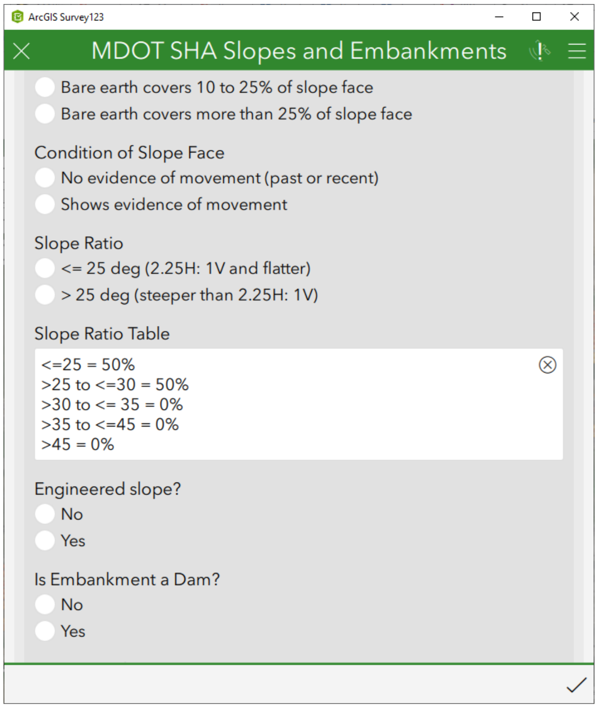
RATING SCORE	SOIL CUT SLOPES AND EMBANKMENTS RATING DEFINITION	ROCK CUT SLOPES RATING DEFINITION
5 (Excellent)	<25% of area with F <15 inches of precipitation sensitivity	Condition Score <25
4 (Good)	<25% of area with F <10 inches of precipitation sensitivity >= 25% of area with F < 15 inches for precipitation sensitivity	Condition Score 25 to <75
3 (Adequate)	<25% of area with F <5 inches of precipitation sensitivity >= 25% of area with F < 10 inches for precipitation sensitivity	Condition Score 75 to <125
2 (Marginal)	<25% of area with F <0 inches of precipitation sensitivity >= 25% of area with F < 5 inches for precipitation sensitivity	Condition Score 125 to <150
1 (Poor)	>= 25% of area with F < 0 inches for precipitation sensitivity	Condition Score >=150

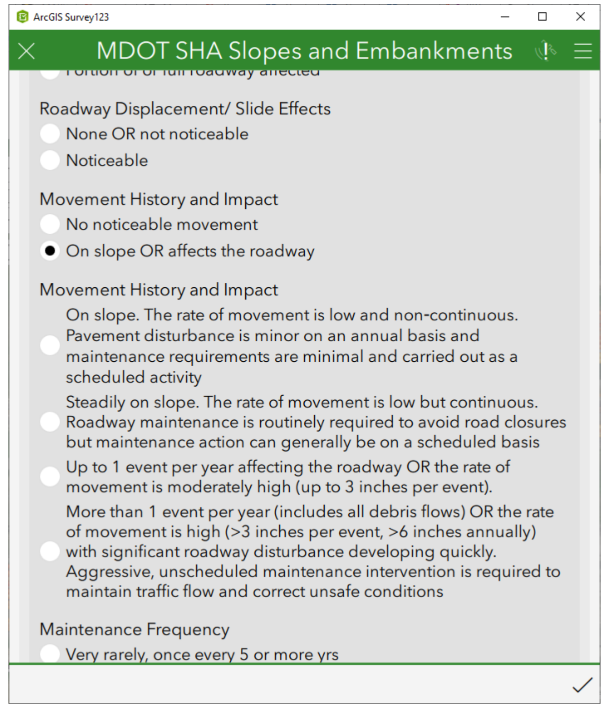
Note: Condition scoring criteria are under development for soil cut slopes and embankments, where condition scores derived from field inspections will supersede ratings developed solely on precipitation sensitivity.

Table 5 - *SHA Asset Condition Assessment Scoring Descriptive Intent (1 to 5 scale)***)**

RATING SCORE	DEFINITION	DESCRIPTION
5	**Excellent:** New or like new with no visible defects	**New or Excellent Condition**
4	**Good:** Minor defects with minor signs of wear and/or corrosion and some slight defects and/or visible deterioration, but with no expected functional or level of service impact	**Minor Defects Only**
3	**Adequate:** Moderate deterioration with moderate signs of wear and/or erosion and some moderate defects and/or or visible deterioration, with moderate corrective/capital maintenance needs and minimal functional or level of service impact, but generally does not yet exceed useful life	**Moderate Deterioration**
2	**Marginal:** Significant deterioration with major signs of wear and/or erosion and major defects and/or visible deterioration, with major corrective/capital maintenance needs and moderate functional or level of service impact; generally, exceeds useful life	**Significant Deterioration**
1	**Poor:** Critical defects with significant signs of wear and/or erosion and critical defects and/or visible deterioration, with major impairment of asset functionality and level of service provided; substantial asset overhaul required; generally, well past useful life	**Virtually Unserviceable**

Field Condition rating surveys were also conducted using a field rating application developed with Survey123. The following images identify the rating form.





Slope distresses were more difficult to discern from in-person field ratings than from Lidar elevation ground because of significant vegetation over the slope surfaces. Distresses are more likely to be observable and ratable during winter months with minimal vegetation cover. A desired alternative to in-person ratings in the future is regularly scheduled aerial lidar flights over each direction of highways at a QL 1 t. SHA has successfully mapped slope surface distresses over gullies, embankment scour, scarps, and bulges using ArcGIS Pro over similar renderings as was used to develop the slope inventory boundaries. Electronic ratings are deemed more reliably comparable for proactive, comparable, and quantitative condition assessments due to the removal of vegetation from Lidar elevation data. At the time of this writing, it is not clear whether a 1-meter resolution is sufficient for distress mapping, or if 0.5-meter resolution should be used. To date, existing Lidar datasets are available at 1-meter resolution, while only a portion of Maryland counties have been mapped with Lidar to develop 0.5-meter DEM resolution. 2-meter resolution lidar is sufficient for mapping the outline of assets for inventory development purposes but is not sufficient for condition assessments to identify slope distresses. While precipitation sensitivity data is useful for basic planning level slope stability calculations, future condition data should utilize distress mapping over Lidar elevation data.

6. Highway Slope Criticality

As part of SHA's overall geotechnical condition assessment methodology, it is important to integrate criticality (consequence of failure) into an overall risk-based approach that enables prioritized decisions and supports long-term planning. This is an important step that will allow SHA to move beyond SGR or condition-based decisions toward a true asset management framework.

SHA will initially apply criticality to prioritize the inspection program and subsequently use criticality as an input to prioritize capital decisions as well as maintenance, renewal, and replacement strategies.

Table 6 - *MDOT Asset Criticality Assessment Scoring (MDOT Enterprise)*

RATING SCORE	DEFINITION	DESCRIPTION
5	Insignificant to no meaningful impacts will result from the failure of a process/subprocess, including noticeable service impacts, regulatory violations, injuries, minor financially losses, and minimal/typical operations and/or maintenance response/restoration.	**Very Low Impact**
4	N/A	**Low Impact**
3	Moderate impacts will result from the failure of a process/subprocess, including localized/regional service impacts, moderate regulatory violations, moderate injuries, financially impactful losses, and significant but routine/typical operations and/or maintenance response/restoration.	**Moderate Impact**
2	N/A	**High Impact**
1	Severe to catastrophic impacts will result from the failure of a process/subprocess, including extended widespread service impacts, severe regulatory violations, media/public coverage, severe injuries, financially severe losses, and extensive and difficult operations and/or maintenance response/restoration.	**Very High Impact**

The detailed criticality rating for geohazards is divided into six weighted factors. Many of the items are related to data available within SHA GIS layers. Scoring for each asset will be calculated, using automation as much as possible. Below is a high-level summary of the factors and considerations used in the criticality scoring, with weighting included in heading parentheses:

Table 7 - *MDOT Asset Criticality Assessment Scoring Methodology Slope*

Overall Rating Score	Pavement Criticality (50%)	Slope height (25%)	Floodplain (10%)	Expected 3-day 100-year storm precipitation amount (5%)	Curvature (HPMS Class) (5%)	Minimum Roadway Width (5%)
5	5	<25 feet	Not 1, 2, 3, or 4	6 or more inches expected	More than 100 feet away from any curve	>40 feet width
4	4	>=25 to <50 feet	Not 1, 2, or 3 and partially within the 500-year floodplain	7 or more inches expected	Not 1,2, or 3 and within 100 feet of a Class A curve	>32 to 40 feet

3	3	>=50 to <75 feet	Not 1 or 2 and entirely within the 500-year floodplain	8 or more inches expected	Not 1 or 2 and within 100 feet of a Class B curve	>24 to 32 feet
2	2	>=75 to <100 feet	Not 1 and partially within the 100-year floodplain	9 or more inches expected	Not 1 and within 100 feet of a Class C curve	>20 to 24feet
1	1	>= 100 feet	Entirely within the 100-year floodplain	10 or more inches expected	Within 100 feet of a Class D, E, or F curve	<=20 feet

7. Highway Slope Risk

The purpose of risk-based analysis is to incorporate a consistent condition and criticality scoring process and prioritize SGR needs on an ongoing basis. The asset level risk assessment fits within the larger enterprise risk management framework, and is illustrated in the following diagram:

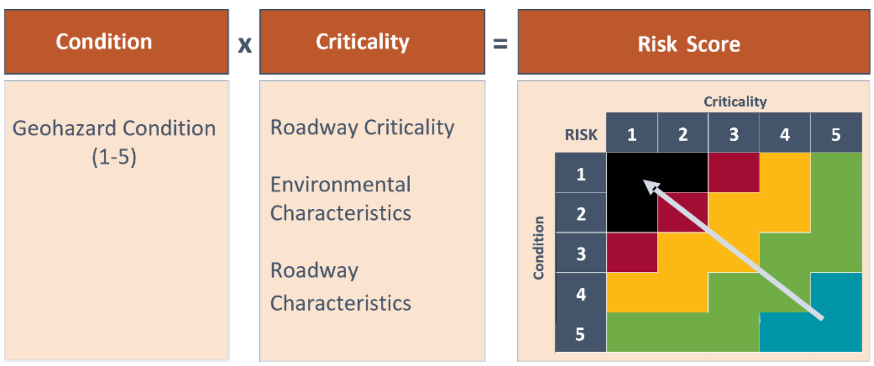


Figure 10: *Risk Based Prioritization Approach*

Geotechnical risks vary from ongoing asset deterioration and construction cost volatility to catastrophic events and climate change. The risk register is used to document and monitor risks and determine the appropriate mitigation strategies. SHA intends to embed risk management more formally by appointing an owner and/or responsible party for the highest risks. Identified risks can change frequently, and the risk register will be reviewed on a regular basis through standing asset management committees and annual AMP updates. The most common risk categorizations for SHA are:

- **Monitor/Manage** – Common risks should be evaluated on an ongoing basis through periodic risk review meetings and to ensure they do not increase or reach a threshold that is unacceptable to the organization.
- **Mitigate** – Higher levels of risk should have active mitigation strategies to actively lower risks to a threshold that is more acceptable to the organization. Specific mitigation strategies should be determined and implemented.

- **Accept** – Some common risks are inherent to a sector or asset class and may require "acceptance" by an organization with some level of recurring review to identify if potential drivers or impacts change where more active monitoring/management/mitigation is required.

The following table summarizes the most significant geotechnical risks as identified through stakeholder work sessions and discussions with management and technical teams. A qualitative assessment of the likelihood (probability) and impact (consequence) was also assigned to determine the highest priority risks that require an active mitigation strategy. Medium and low priorities risks are typically managed through a monitoring or acceptance strategy.

Table 8 - *Geotechnical Risk Register (High Priority Risks Only)*

ID	Risk Type	Description and Scope	Likelihood (1-5)	Impact (1-5)	Priority (H/M/L)	Monitoring/Mitigation Strategy
GEO1	Public Safety, Reliability, Resiliency	Cut Slope Failures/Landslides: If a landslide occurs, the safety of the traveling public is at risk, and full or partial closure of the road is required until the slope and affected highway infrastructure are repaired.	3	1	High	**Mitigate:** Annually inspect cut slopes with high or significant risk. Inspect moderate risk slopes on a 5-year cycle. Inspect and clear storm drainage systems from regular debris accumulation. Develop an alert system comparing actual precipitation mapping with planning-level precipitation sensitivity levels to trigger inspections.
GEO2	Public Safety, Reliability	Sinkholes: If a sinkhole occurs within a roadway, the safety of the traveling public is at risk, and full or partial closure of the road is required until the ground is modified to support the highway. This risk is related to ground modification assets.	3	1	High	**Mitigate:** Identify highways through karst geology. Train maintenance staff to recognize indicators. Perform periodic subsurface scanning of highways within karst terrain, prioritized by the risk of sinkhole development.
GEO3	Public Safety, Resiliency	Washouts/Flooding: If an embankment washout occurs due to flooding or poor drainage conditions, public safety is at risk along with the highway above the washout, and full or partial closure of the road is required until the embankment is repaired.	1	3	High	**Mitigate:** Routinely inspect embankments within the 100-year floodplain. Inspect and clear storm drainage systems from regular debris accumulation. Develop an alert system comparing actual precipitation mapping with planning-level precipitation sensitivity levels to trigger inspections and maintenance.
GEO4	Funding	If limited or non-existent funding is provided for inspections of geotechnical infrastructure, cost-effective and proactive solutions are not used, relying instead on chance observation of failure or unexpected impact to the public, thereby putting the asset at greater risk of expensive emergency repairs.	1	2	Very High	**Mitigate:** Use any funding source available including recent provisions in the Infrastructure Investment and Jobs Act relating to resiliency and preservation of natural infrastructure. Maintain regular communication with maintenance staff to document concerns.
GEO5	Funding	If limited or non-existent funding is provided for design and construction of preventive maintenance and rehabilitation, the assets are at greater risk of expensive emergency repairs.	1	3	High	**Mitigate:** Begin using federal funding sources, including recent provisions in the Infrastructure Investment and Jobs Act relating to resiliency and preservation of natural infrastructure.

8. Highway Slope History

Initial slope history data has been populated from information managed by more mature peer asset databases, including estimates for the year build based on the bridge, culvert, or initial pavement construction year. A data framework was also created to manage additional future entry of construction and maintenance work history on slopes. Work type includes new construction, preventative maintenance, major and minor rehabilitation, and reconstruction. Roadway widening which results in building new embankments or cutting new slopes is considered new construction. Each activity is included in the historical timeline of work types as a new record. Records include the Construction Contract number, and financial tracking numbers. Maintenance activities are identified with the maintenance codes. However, limited categories currently exist within maintenance codes, and these need further research to determine whether the ditch trimming, drainage improvements or debris cleanup activities also included slope work. Treatments are specific activities within a work type.

9. Ground Modification Inventory

The most common ground modification assets were constructed as grout injected through boreholes. Therefore, ground modification assets are managed as points in GIS, where each point represents one borehole with the quantity of material injected. No condition data is expected to be collected for existing ground modifications. The asset management of ground modifications is for design support purposes during future design, construction, or maintenance activities in the same location. Over 3,000 boreholes were inventoried in GIS. Additionally, past sinkhole locations have been mapped in GIS, allowing for the sinkhole susceptibility to be visually assessed relative to past sinkhole activity.

10. Subsurface Void Identification

Subsurface void characterization capabilities are being developed with newly available in-house tools, including a Kontur Ground 1820 3D Step Frequency Ground Penetrating Radar (GPR) Antenna with 20 channels; along with a single-channel 250 MHz GPR; measurement while drilling (MWD) sensors on one drill rig and a borehole camera. GPR surveys in karst terrain have limited depth penetration due to fine grained cohesive soil. The step frequency GPR is more promising than the single antenna to identify subgrade movement and to maximize resolution with depth. The pilot GPR investigation surveys have indicated the most promising results granular embankments with distressed subsurface drainage pipes to identify the portion of the embankment requiring repair.

The following figure is an example of 3D GPR usage to characterize the vicinity of subsurface voids within a granular embankment in 2023. The GPR clarified that only the median shoulder and fast lane were affected by the voids and isolated the region requiring excavation to a depth of 18 feet and pipe replacement. The outside lanes were protected and monitored but were allowed to remain open. New drainage connections were made, and subsurface drainage components were replaced. The excavation was backfilled with controlled low strength material in stages allowing for proactive, rapid ground modification repair work to be done without a sinkhole developing through the roadway surface.

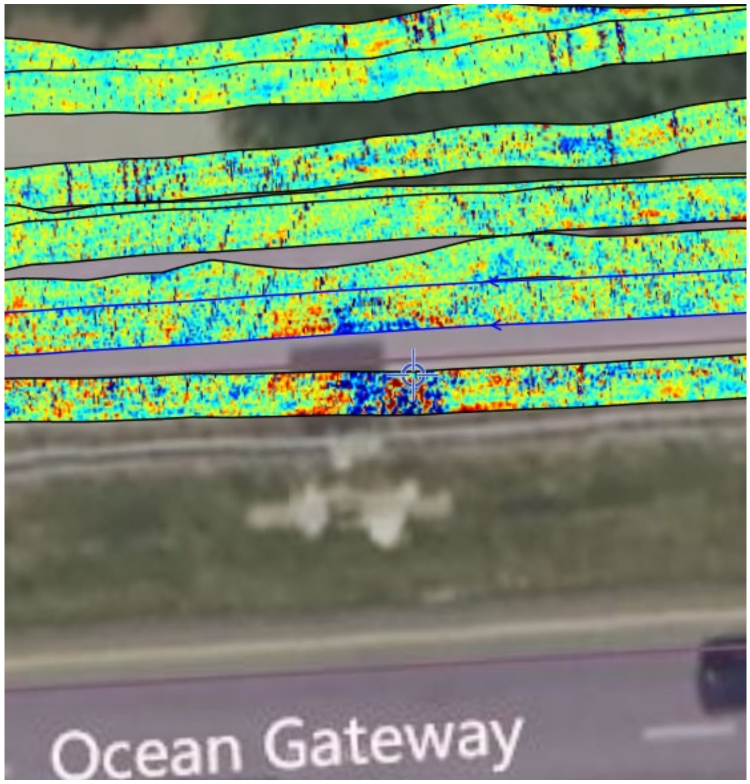


Figure 11: *Overhead view of 3D GPR identifying the vicinity of a subsurface void over a failed pipe. This assisted with defining the region of excavation, allowing the outside travel lanes to remain open during repair.*

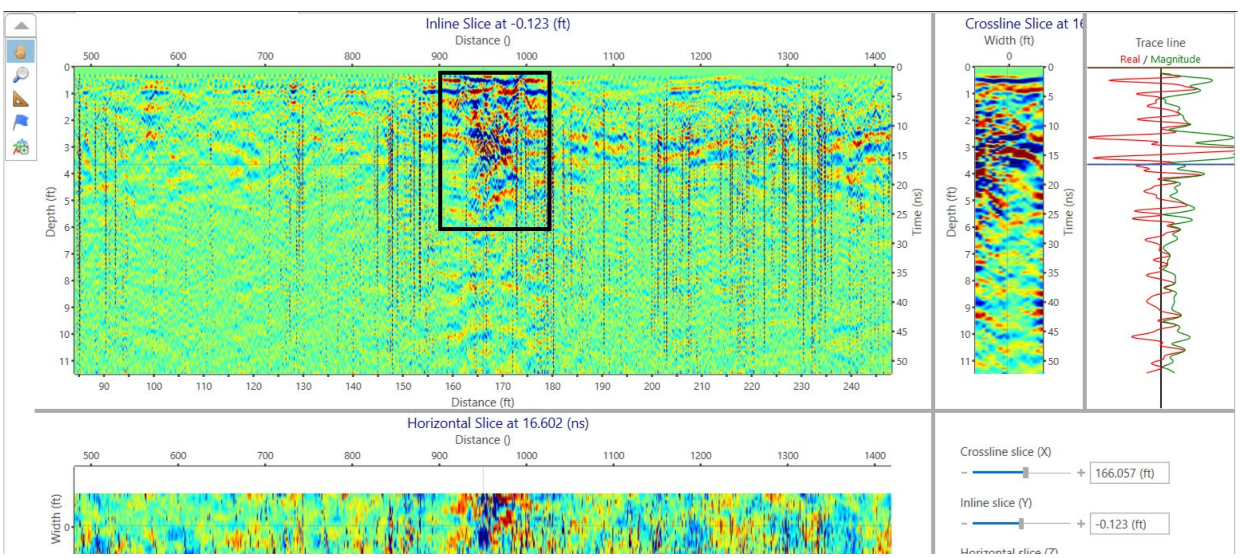


Figure 12: *GPR Results above void*

Figure 13: *Damaged Corrugated Metal Pipe after Extraction. This pipe was the cause of the subsurface void.*

11. Geotechnical Areas of Maintenance Concern

In addition to planning-level mapping data, geotechnical distresses have been mapped using experiential knowledge of highway maintenance staff. Areas of geotechnical concern, including cut slope instability, embankment instability, depressions, springs, and frequent flooding areas, were mapped together during virtual meetings with staff from the SHA Engineering Geology Division and knowledgeable staff from each of the 28 maintenance shops in 2021 and 2023. These areas of concern triggered site-specific conceptual repair investigations. Critical sites requiring repair can then be considered for project development using capital funding to rehabilitate the distressed geotechnical asset. Over 400 areas of concern were mapped during these meetings.

12. Geotechnical Design Support

An outline of a geotechnical design manual for non-routine geotechnical design has been developed and is included in the Appendix. The first chapter has been completed, addressing geotechnical asset management and includes much of the same content as this report. Significant portions of chapters 3 and 8 have also been drafted. Additionally, the feasibility of various culvert embankment treatments was developed and is included below. This planning level list of problems and treatments provides an initial list of options for design consideration.

Table 9 – *Culvert Embankment Problems and Locations*

		Embankment Location						
Problem Category	**Problem**	**Head Wall**	**Upstream Slope**	**Crest (or Roadway)**	**Internal Embankment**	**Culvert**	**Downstream Slope**	**End Wall**
Embankment Movement / Instability	Sinkhole		X	X	X		X	
	Tension Cracks		X	X			X	
	Settlement		X	X			X	
	Bulges		X				X	
	Sloughing		X				X	
	Depression		X				X	
	Embankment Edge Misalignment		X				X	
	Surface Erosion		X				X	
	Riprap/Stone Displacement		X				X	
	Seepage with Internal Erosion (Piping)				X		X	
	Soft or boggy (wet) areas		X		X		X	
	Boils at or beyond toe				X		X	
Unprotected Slope	Animal Borrows		X				X	
	Inadequate Vegetative Cover		X				X	
	Inadequate Riprap Protection		X				X	
	Inadequate Ditch or Bench protection		X				X	
Structural Deficiency	End Structure Undermining / Instability	X						X
	Culvert Cracking							
	Culvert Joint Failure					X		
	Culvert Corrosion Failure					X		

The following describes the options under each treatment category. References are noted at the end of this document. If a chapter or section is identified this is the relevant information location within the reference document.

Surface Vegetative Cover

Hydroseeding Reference 5 – Chapter 6

Hydroseeding is a planting process that uses a slurry of seed and mulch. It is often used for erosion control on construction sites instead of traditional broadcasting or sowing dry seeds.

Potential remediation of:

- *Surface Erosion*
- *Inadequate Vegetative Cover*
- *Inadequate Ditch or Bench Protection*

Woody Vegetation Removal
Woody vegetation removal targets trees and large bushes that may have roots that penetrate the embankment. These roots have the potential to provide flow paths within the embankment.
Potential remediation of:

- *Woody Vegetation Present*

Soil Stabilization Matting (SSM) and Turfgrass
Material used to temporarily or permanently stabilize channels and steep slopes until groundcover is established. On newly seeded surfaces this prevents the applied seed from washing out; in channels and on steep slopes where the flow has erosive velocities or conveys clear water; on temporary swales, earth dikes, and perimeter dike swales as required by the respective design standard to address potential erosion; and, on stream banks where moving water can potentially wash-out newly installed vegetative plantings.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Ditch or Bench Protection*

Geocells with Topsoil Reference 5 – Chapter 9.1.2
A cellular confinement system (CCS), commonly referred to as a geocell, is commonly made from polyethylene strips connected in a honeycomb pattern that is filled with topsoil to provide a medium to grow grass or other plantings.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Flow Control
Surface Drainage Berm, Swale or Ditch
Surface drainage structures can divert drainage away from critical slopes and culverts that are over capacity.
Potential remediation of:

- *Surface Erosion*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*

- *Boils at or Beyond Toe*

<u>Debris Removal</u>
Cleaning and removing of debris, which commonly can occur with storm events.
Potential remediation of:

- *Debris Buildup*

<u>Pipe Sediment Cleanout</u>
Cleaning and removing of sediment in and around a pipe or culvert.
Potential remediation of:

- *Sediment Accumulation within pipe or inlet/outlet areas.*

Surface Hard Cover
<u>Riprap Buttress</u> Reference 5 - Chapter 8
A riprap cover on the downstream slope of an embankment dam can generally provide some protection against embankment erosion during overtopping flow. Riprap is generally composed of high-quality quarried rock (e.g., granite, volcanics, or limestone), or occasionally recycled concrete rubble that is placed over a suitable filter bedding layer. With riprap in place, the overtopping flow is conveyed both through and above the riprap layer, thus preventing erosion by reducing flow velocities and shear stresses along the surface of the erodible embankment materials.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

<u>Geocells with Stone</u> Reference 5 – Chapter 9.1.2
A cellular confinement system (CCS), commonly referred to as a geocell, is commonly made from polyethylene strips connected in a honeycomb pattern and is filled with stone or concrete.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Grouted Riprap Reference 5 - Chapter 8
Grouted riprap is an alternative method that uses grout slurry to partially or fully fill the void spaces between the riprap pieces. Typical applications for grouted riprap include the protection of bed and bank slopes in spillway entrance channels, turbulent areas adjacent to energy dissipators, drainage ditch linings, culvert and storm pipe outfalls, and drainage through conventional riprap. Grouted riprap is also used to prevent vandalism to riprap placements and to provide and improve access across riprap-protected areas.
Potential remediation of:

- *Sinkhole*
- *Sloughing*
- *Depression*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*
- *End Structure Undermining/Instability*

Gabion Mattress Reference 5 - Chapter 5
Gabion Mattresses are rectangular-shaped fabricated from wire mesh that is tied together with wire, filled with select stone. These are assembled to form structures such as lined channels, overflow weirs, hydraulic drops, and other erosion control structures. Gabions are also used for spillways and as overtopping protection for small embankment dams. Gabion mattresses are generally placed parallel to a slope. Mattresses can be used at the toe of gabion walls to help prevent undercutting.
Potential remediation of:

- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Reinforced rockfill Reference 5 – Chapter 7
Reinforcement can be incorporated into rockfill to hold the surface rock particles in place during overtopping and flow-through conditions. Improvement to the mass slope stability is also a benefit but is considered secondary. The reinforcement is a system has two essential components of a mesh and anchor bars. The mesh is located on the outside of the rockfill and is intended to hold the rock particles on the outer embankment slope in place, while the anchor bars are attached to the mesh and embedded deep within the rockfill to hold the mesh securely in place.

Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Articulating Concrete Block Revetment Systems Reference 5 - Chapter 4
An ACB system is comprised of a matrix of individual concrete blocks placed together to form an erosion-resistant revetment with specific hydraulic performance characteristics. The term "articulating" implies the ability of the matrix to conform to minor changes in the subgrade while remaining interconnected with geometric interlock and/or additional system components such as cables or anchors.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Cast-in-place Concrete Surface Reference 5 - Chapter 3
Overtopping protection for embankment dams utilizing conventional or mass concrete relies on a continuous layer of concrete to serve as the flow surface for overtopping flows. This normally consists of a smooth, continuously-reinforced concrete slab (CRCS) constructed over a filtered drainage layer. The concrete slab and drainage layer protects the underlying embankment from high velocity flows discharging along the downstream face of the dam.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Energy Dissipation Devices
Energy dissipators are used is to control/help prevent erosion at the downstream end of a culvert. In its simplest form, this is a riprap lined channel or shallow pool in the stream channel at the downstream end of a culvert. Larger, more complex energy dissipators could be concrete stilling basins with "dragon's teeth" designed to dissipate energy from large flows.
Potential remediation of:

- *Riprap/Stone Displacement*
- *End Structure Undermining/Instability*

Concrete Surfacing using Filled Geocells Reference 5 – Chapter 9
Roller compacted concrete (RCC) is a mix of cement/fly ash, water, sand, aggregate, and common additives, but contains much less water than more traditional concrete mixes. The produced mix is drier, so it essentially has zero slump. RCC is placed in a manner similar to paving; the material is delivered by dump trucks or conveyors, spread by small bulldozers or specially modified asphalt pavers, and then compacted by vibratory rollers.
Potential remediation of:

- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Boils at or Beyond Toe*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Roller Compacted Concrete Protection Reference 5 - Chapter 2
Roller compacted concrete is a mix of cement/fly ash, water, sand, aggregate, and common additives, but contains much less water than more traditional concrete mixes. The produced mix is drier and essentially has zero slump. RCC is placed in a manner similar to paving; the material is delivered by dump trucks or conveyors, spread by small bulldozers or specially modified asphalt pavers, and then compacted by vibratory rollers.
Potential remediation of:

- *Tension Cracks*
- *Bulges*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Stability Reinforcement

Soil Nails and Steel Mesh

Soil nails are reinforcing, passive elements that are drilled and grouted sub-horizontally in the ground to support excavations in soil, or in soft and weathered rock. Soil nails are connected to a facing system at the excavation face or slope surface. Facings most commonly consist of an initial facing (welded wire mesh and short reinforcement bars called waler bars and vertical bars around the nail heads) of shotcrete and a final facing of shotcrete or CIP concrete.

Potential remediation of:

- *Tension Cracks*
- *Bulges*
- *Sloughing*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Soil Nails and Shotcrete

Soil nails are used to reinforce a soil slope to improve stability. The nails are installed along soil slopes in a grid pattern into pre-drilled holes and grouted. Shotcrete is applied to the surface of the slope to tie the nails together and to help prevent erosion.

Potential remediation of:

- *Tension Cracks*
- *Bulges*
- *Sloughing*
- *Surface Erosion*
- *Riprap/Stone Displacement*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Inadequate Riprap Protection*
- *Inadequate Ditch or Bench Protection*

Sheet Piling

A row of interlocking, vertical pile segments driven into the ground to form an essentially straight wall. The plan dimension is sufficiently large that its behavior may be based on a typical unit (usually 1 foot) vertical slice. Sheet-piles are usually installed using impact or vibratory hammers.

Potential remediation of:

- *Tension Cracks*
- *Sloughing*
- *Embankment Edge Misalignment*
- *Seepage with Internal Erosion (Piping)*
- *End Structure Undermining/Instability*
- *No Impervious Core*

Gabion Wall Reference 5 - Chapter 5
Gabion basket walls are rectangular-shaped baskets fabricated from wire mesh tied together with wire, filled with rock, and assembled to form structures. Gabion baskets are generally stacked in a stair-stepped fashion to form a gravity retaining wall.
Potential remediation of:

- *Tension Cracks*
- *Bulges*
- *Sloughing*
- *Depression*
- *Riprap/Stone Displacement*
- *Soft or Boggy Areas*
- *Animal Borrows*
- *Inadequate Riprap Protection*
- *End Structure Undermining/Instability*

Pipe Rehabilitation
Pipe Slip Lining Reference 6 – Section 12.1
Slip-lining an existing conduit through an embankment dam generally consists of installing a new, smaller-diameter pipe. The annulus between the new pipe and the existing conduit is grouted. New inlet and outlet structures are sometimes constructed if the existing structures were deteriorated or were required for removal to facilitate installation of the slip liner.
Potential remediation of:

- *Sinkhole*
- *Culvert Cracking*
- *Culvert Joint Failure*
- *Culvert Corrosion Failure*
- *Sediment Accumulation within Pipe or Beyond Toe*

Joint sealing
The system consists of a polyurethane/rubber seal held in place by stainless steel retaining bands or cement grout. Each seal is custom-made. The seals can be interlocked to span long lengths of pipe and can include a backing band to remediate pressure piping and cooling water expansion joints.
Potential remediation of:

- *Sinkhole*
- *Culvert Cracking*
- *Culvert Joint Failure*
- *Culvert Corrosion Failure*
- *Sediment Accumulation within Pipe or Beyond Toe*

Cathodic Protection
Cathodic protection retards electrochemical corrosion through the application of reverse direct current to the protected metal and to another metal which acts as a sacrificial anode. This sacrificial anode, typically consisting of either zinc, magnesium, graphite, or aluminum alloys, must be periodically replaced.

Potential remediation of:

- *Culvert Corrosion Failure*

Cured-In-Place Pipe Lining (CIPP) Reference 6 – Section 12.2

Plastic cured-in-place pipe (CIPP) liners are a common rehabilitation method of pipes. CIPP is a flexible liner “sock” inserted inside an existing pipe and inflated then exposed to heat or ultraviolet light to "cure," or harden, the liner inside the pipe. The liner essentially forms a smooth surface that replaces the existing pipe.

Potential remediation of:

- *Sinkhole*
- *Culvert Cracking*
- *Culvert Joint Failure*
- *Culvert Corrosion Failure*

Spray Lining Reference 6 – Section 12.3

Spray lining typically involves the spraying of a cement mortar mixture or epoxy resin onto the inside walls of the existing conduit. Trowels that trail the rotating sprayer head smooth the sprayed material. Spray lining helps to retard iron pipe corrosion and reduce the deterioration of the existing walls of water mains.

Potential remediation of:

- *Sinkhole*
- *Culvert Cracking*
- *Culvert Joint Failure*
- *Culvert Corrosion Failure*

Internal Flow Control

Seepage Interception Trenches

Seepage interception trenches can divert water drainage away from existing seepage.

Potential remediation of:

- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy/Wet Areas*
- *Boils at or Beyond Toe*

Void Filling with Grout (Polyurethane or Cement Grout)

Void filling with grout is typically used in the event of a void or sinkhole is observed in an embankment. Grout of polyurethane or cement is pumped in the void or sinkhole to stop additional water flow and erosion within the embankment. Further investigation and possible repair would be required.

Potential remediation of:

- *Sinkhole*
- *Settlement*
- *Depression*
- *Seepage with Internal Erosion (Piping)*
- *Animal Borrows*

- *End Structure Undermining/Instability*
- *No Concrete Cradle*
- *Gravel Bed Present*

<u>Cut Off Walls (Bentonite, Steel Sheet Pilling or Concrete)</u>
Cut off walls for embankments can be defined as a barrier constructed with bentonite, steel, or concrete. A cutoff wall is installed through the center of the embankment suitably far into undisturbed earth to provide a definite barrier to seepage flows through the embankment. Potential methods include sheet piles, concrete slurry wall, cement-bentonite slurry wall, secant piles, and jet grouting.
Potential remediation of:

- *Seepage with Internal Erosion (Piping)*
- *No Impervious Core*

<u>Filter Diaphragm</u> Reference 6 – Section 6.4 and 6.5
A filter diaphragm is a designed zone of filter material constructed around a conduit. This zone can act both as a drain to carry off water and as a filter to intercept soil particles being transported by the water. The filter diaphragm intercepts both intergranular flow through the embankment dam and flow through cracks in the earth fill or along the interface between the conduit and the earth fill. Any fines being eroded from the embankment will be filtered by the diaphragm of sand that surrounds the conduit. The fines carried by the flowing water will accumulate on the surface of the diaphragm and develop a filter cake. The filter cake that develops on the upstream face of the filter diaphragm reduces the flow and prevents further erosion of cracks caused by this flow. The filter diaphragm must extend far enough from the conduit that it can intercept all potential water flow paths associated with the conduit.
Potential remediation of:

- *Seepage with Internal Erosion (Piping)*
- *No Impervious Core*
- *No Filter Diaphragm*

Reconstruction
<u>Benched Slope Regrading with Borrow</u>
Slopes can be regraded to add benches that provide additional support for the embankment structure and slowing of water flow down the embankment.
Potential remediation of:

- *Settlement*
- *Bulges*
- *Sloughing*
- *Depression*
- *Embankment Edge Misalignment*
- *Surface Erosion*
- *Soft or Boggy Areas*
- *Inadequate Vegetative Cover*

Benched Slope Regrading with Riprap
Slopes failure locations requiring regrading by removing the distressed slope section or loose soils followed by benching into the existing slope and placing geotextile and riprap.
Potential remediation of:

- *Settlement*
- *Bulges*
- *Sloughing*
- *Depression*
- *Embankment Edge Misalignment*
- *Surface Erosion*
- *Soft or Boggy Areas*
- *Inadequate Vegetative Cover*

Upstream Slope Regrading with Liner (Clay, Geomembrane, Asphalt, Steel or Concrete)
A low permeability liner along the upstream slope may provide reduced internal seepage into the embankment. Liner types that could be considered are compacted clay layer, geomembrane, asphalt, steel or concrete liner.
Potential remediation of:

- *Settlement*
- *Bulges*
- *Sloughing*
- *Depression*
- *Embankment Edge Misalignment*
- *Surface Erosion*
- *Soft or Boggy/Wet Areas*
- *Inadequate Vegetative Cover*

Reconstruction Embankment with Chimney filter and drain Reference 6 – Section 6.3
A chimney filter that extends upward to the highest probable pool level and extends across the length of the embankment from abutment to abutment is a common element for most high and significant hazard dams. Chimney drains are also valuable for sites with a high permanent water storage level because they intercept and lower the phreatic line and maintain a stronger downstream zone of unsaturated soil.
Potential remediation of:

- *Settlement*
- *Bulges*
- *Sloughing*
- *Depression*
- *Embankment Edge Misalignment*
- *Surface Erosion*
- *Soft or Boggy Areas*
- *Boils at or Beyond Toe*
- *Animal Borrows*

- *Inadequate Vegetative Cover*
- *Gravel Bed Present*
- *Woody Vegetation Present*
- *Sediment Accumulation within Pipe or Beyond Toe*
- *No Impervious Core*
- *No Filter Diaphragm*

Reconstruct Embankment with Internal Membrane (Clay Core, Geomembrane, Asphalt, Steel, or Concrete)

Removal and replacement of a culvert and embankment is expensive and is a last resort compared to other options. This could include construction of a new embankment that meets dam safety standard. Within the new embankments, a low permeability barrier is typically constructed with compacted clay. The clay core provides a greatly reduced water flow through the embankment.

Potential remediation of:

- *Settlement*
- *Bulges*
- *Sloughing*
- *Depression*
- *Embankment Edge Misalignment*
- *Surface Erosion*
- *Seepage with Internal Erosion (Piping)*
- *Soft or Boggy Areas*
- *Boils at or Beyond Toe*
- *Animal Borrows*
- *Inadequate Vegetative Cover*
- *Gravel Bed Present*
- *Woody Vegetation Present*
- *Sediment Accumulation within Pipe or Beyond Toe*
- *No Impervious Core*
- *No Filter Diaphragm*

Culvert Reconstruction - Open Cut Reference 6 – Section 13.1

Removal and replacement of an existing conduit through an embankment consists of excavating down to the existing conduit, stockpiling the material, removing the existing conduit, constructing a new conduit and possibly new entrance and terminal structures, installing a filter diaphragm or collar around the downstream portion of the conduit, and replacing the embankment material.

Potential remediation of:

- *Sinkhole*
- *Settlement*
- *End Structure Undermining/Instability*
- *Culvert Cracking*
- *Culvert Joint Failure*

- *Culvert Corrosion Failure*
- *No Concrete Cradle*
- *Gravel Bed Present*
- *No Filter Diaphragm*

Culvert Reconstruction – Trenchless Technology

Trenchless Technology is an option for culvert replacement or additional conduits for locations where open cut is not feasible. Trenchless technology involves tunneling construction that can be done by jack and bore, tunnel boring machines, or hand excavation with liner plates. Careful consideration should be taken with this technique since voids can be introduced along the outside of the tunnel during the tunneling operations. These voids may provide paths for internal erosion, if not addressed. Grouting of the annular space outside of the tunnel should be required to fill these potential voids.

Potential Applications:

- *Sinkhole*
- *End Structure Undermining/Instability*
- *Culvert Cracking*
- *Culvert Joint Failure*
- *Culvert Corrosion Failure*

Reconstruct Culvert End Structure

Removal and replacement of a culvert end structure is typically done when the structure is deteriorating or is causing erosion to the surrounding embankment soil.

Potential remediation of:

- *End Structure Undermining/Instability*

Observation and Monitoring

Post-Treatment Inspection

Depending on the type of treatment used for retrofitting or enhancing roadway culvert embankments, a post treatment inspection should be conducted. This should confirm that the work completed as specified, is functioning properly and no adverse effects are caused. The post-treatment inspection requirements should be included with the project contract documents.

Standard Monitoring

Depending on the level of concern for the existing embankment culvert conditions, standard monitoring could be used as an alternative to the other treatments discussed to document the embankment conditions and performance when detailed as-built information is unavailable to address potential concerns.

Real Time Monitoring

Embankments of significant concern can be subjected to remote continuous monitoring to provide real time data and alerts for changing conditions. Depending on the level of concern for the current embankment culvert conditions, expanded monitoring could also be used as an alternative to the other treatments discussed.

13. Recommendations and Next Steps

The GAM processes established are highly valuable for identifying vulnerable areas to consider improving with appropriate treatments to result in a state of good repair and resilient highway infrastructure. Future work should include the following:

- Regularly scheduled data collection of elevation data at maximum resolution of 1 meter, likely derived from aerial lidar data collection along highway corridors. Digital Elevation Models can be evaluated in a similar manner that pavement depth images are used for pavement cracking and potholes, only at a coarser scale. Such surveys can facilitate slope condition assessments. Year over year comparisons can assist with identifying areas of slope movement, which are common but often unnoticed.
- Identify slope distresses including gullies, scarps, bulges, embankment scour within the slope inventory.
- Identify and prioritize areas which are susceptible to subsurface voids, including karst terrain and distressed subsurface pipes. Conduct regular surface and subsurface surveys to identify any depressions. Walking surveys through karst right-of-way to isolate areas of geophysical investigation. This will lead to with maintaining a list of ground modification needs to mitigate the risk of sinkholes.
- Populate slope components including geotextiles, geogrids, and toe walls to complement the slope inventory.
- Begin project development efforts to improve resilience by rehabilitating distressed slopes and poorly supported subgrades.
- Planning level feasibility of slope treatments needs to be developed for other asset types, including ground modifications for subsurface voids, soil cut slopes, bridge embankments, side hill embankments and rock cut slopes.

14. References

1) Vessely, M., et al. 2019. NCHRP Research Report 903: Geotechnical Asset Management for Transportation Agencies. Transportation Research Board of the National Academies of Science, Engineering, and Medicine, Washington, D.C.
2) Mohseni, O, et al. 2018. Storm-Induced Slope Failure Susceptibility Mapping. Minnesota Department of Transportation.
3) Gordan, R., Hassaballa H., Presentation. Landslide Susceptibility GIS model of the SPC Region. University of Pittsburgh, Center for Impactful Resilient Infrastructure Science and Engineering https://www.engineering.pitt.edu/contentassets/15adc7d54434434aa61d2e0ac0c47b07/gordon_gis-model-for-landslide-susceptibility_pitt_8-29-19.pdf Accessed on 3/28/2024.
4) U.S. Army Corps of Engineers. (2020, November). Engineering and Design Instrumentation of Embankment Dams and Levees. Retrieved from https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EM%201110-2-1908.pdf?ver=SZ5K1AeyStmXACafxcvJ_g%3d%3d
5) FEMA. (2014, May). Overtopping Protection for Dams. Retrieved from https://damfailures.org/wp-content/uploads/2015/06/Technical-Manual_Overtopping-Protection-for-Dams.pdf
6) FEMA. (2005, September). Conduits through Embankment Dams. Retrieved from https://www.swc.nd.gov/pdfs/conduits_embankment_dams.pdf
7) U.S. Department of the Interior Bureau of Reclamation. (2012, December). Reclamation Managing Water in the West. Design Standards No. 13. Embankment Dams. Chapter 2: Embankment Design. Retrieved from https://www.usbr.gov/tsc/techreferences/designstandards-datacollectionguides/finalds-pdfs/DS13-2.pdf

Appendix A – Geotechnical Design Manual Outline

1. Introduction
1.1. Purpose and Overview of the Manual
1.1.1. Overview of the Engineering Geology Section
1.1.2. Geotechnics, New Products Research and Specifications
1.1.3. Geology and Groundwater
1.2. Manual Description and Development
2. Geotechnical Asset Management
2.1 Asset Inventory
2.1.1 Location and Identification
2.1.2 Slope History
2.2 Condition
2.3 Consequence
2.4 Valuation
2.5 Strategy
2.5.1 Financial Project Forecasting
2.5.2 Life Cycle
2.5.3 Treatment Options
3. Geotechnical Project Planning
3.1. Purpose, Scope and Responsibility
3.2. Desktop Study
3.2.1. Review of Location (Slope) History
3.2.1.1. Review of Topographic Maps and LiDAR maps
3.2.1.2. Review of Aerial Photographs
3.2.1.3. Review of Maintenance Records
3.2.1.4. Review of Historical Distresses
3.2.1.5. Review of Inspection Photographs
3.2.1.6. Review of As-builts data (refer to PAGD Manual Section 2.03)
3.2.2. Natural Resources Conversation Service Soil Surveys
3.2.3. USDA Soil Survey Maps
3.2.4. Regional Geological Context
3.2.4.1. Review of Geological Maps
3.2.4.2. Geologic Anomalies (e.g., Voids, Caves, Karst formation (sinkholes), Mines
3.2.4.3. Soil Types & Properties (e.g., Peat, Muck, Marlboro Clay, Marine Clays, Micaceous silts, running sand, Glauconites, Pyritic Soils)
3.2.4.4. Corrosion (Acid mine drainage, dredged material)
3.2.4.5. Landslides & Slope Failures (sensitive to inclination)
3.2.4.6. Rock Slopes and Falls
3.2.4.7. Groundwater Conditions
3.2.4.8. Surface Waters (Wetlands & Flood Plains)
3.2.4.9. Land Use History (e.g., abundant mine areas etc.)
3.2.4.10. Environmentally Impacted Areas
3.2.4.11. Underground Utilities and Storage Tanks
3.2.4.12. River Scour (Add flood prone area-ArcGIS link)
3.2.4.13. HAZMAT/ Contaminated Materials

3.3. Field Reconnaissance
3.3.1. Visual Inspection
3.3.2. LiDAR
3.3.3. UAS
3.4. Development of the Subsurface Exploration Plan
3.5. Development of Laboratory Testing Plan
4. Subsurface Investigation
4.1. Preliminary Subsurface Investigation
4.2. Initial Environmental Site Assessment (Phase 1)
4.3. Phase 2 Environmental Site Assessment
4.4. Final Subsurface Investigation
4.4.1. Subsurface Investigation Methods
4.4.1.1. Geophysical Methods (Refer to PAGD Manual Section 3.07)
4.4.1.2. Fea
ture Comparison Matrix from TRB Webinar
4.4.1.3. In-situ testing
4.4.1.4. (SPT, SPT with MWD, CPT, CPTU, DMT, VST, DCP, LWD, Monitoring Wells, Piezometers) etc.
4.4.2. Subsurface Exploration Guidelines (Number, spacing, depth and sampling)
4.4.2.1. Bridge Foundations
4.4.2.2. Retaining Walls
4.4.2.3. Embankments
4.4.2.4. Cut Excavations/Slopes
4.4.2.5. Culverts
4.4.2.6. Noise Walls
4.4.2.7. Trenchless Pipe Installation
4.4.2.8. Miscellaneous Structures
4.4.2.9. Emergency Geohazards (Landslides-Slope Failures, Karst-Sinkholes, Underground Mines, Artesian Conditions, Hazardous Materials, etc.)
4.4.3. Field Instrumentation (Construction QA/QC, Geohazard Monitoring)
4.4.3.1. Control Points/ Movement Monitoring
4.4.3.2. Slope Inclinometers
4.4.3.3. Settlement Plates
4.4.3.4. Piezometers
4.4.3.5. Tiltmeters
4.4.3.6. Crack Gauges
4.4.3.7. Extensometer
4.4.3.8. Borehole Camera
4.4.3.9. Vibration Monitoring
4.4.3.10. Special Instrumentation
5. Laboratory Testing
5.1. Visually Review Samples before Testing
5.2. Development of Laboratory Program
5.3. Guidelines for Selecting Laboratory Tests and Soil and Rock Samples
5.4. Disturbed, Undisturbed, And Remolded Soils Samples
5.5. Geotechnical Soil, Rock, And Water Laboratory Tests

5.5.1. Minimum Testing Rates
5.5.2. Moisture Content Tests
5.5.3. Unconfined Compression Tests for Soils and Rock
5.5.4. One Dimensional Consolidation Tests
5.5.5. Triaxial Compression Tests
5.5.6. Direct Shear Tests
5.5.7. Permeability Tests
5.5.8. Unit Weight Tests
5.5.9. Specific Gravity Tests
5.5.10. Atterberg Limit Tests
5.5.11. Grain Size Analysis
5.5.12. Organic Content Tests
5.5.13. Corrosion Tests (pH, Chlorides, Sulfate, etc)
5.5.14. Environmental Tests (PID, TClip, etc)
5.5.15. Surface Water Testing and Groundwater Testing
5.6. Soil and Rock Classification
6. Geotechnical Analysis
6.1. Development of Subsurface Profile
6.2. Selection of design parameters for Geotechnical Design Elements
6.3. Geotechnical Design Criteria
6.4. Roadways
6.4.1. Slope Stability Analysis
6.4.2. Settlement Analysis
6.4.3. Bearing Capacity Analysis
6.4.4. Lateral Squeeze
6.5. Structures
6.5.1. Structure Foundation (Refer to OOS Design Manual)
6.5.1.1. Driven Piles
6.5.1.2. Drilled Shafts
6.5.1.3. Spread Footings
6.5.1.4. Micropiles
6.5.2. Retaining Walls
6.5.2.1. MSE Walls
6.5.2.2. Gravity Retaining Walls
6.5.2.3. Modular Block Retaining Walls
6.5.2.4. Soil Nail Walls
6.5.2.5. Anchored Walls
6.5.2.6. Temporary Geosynthetics Wall
6.5.3. Noise Walls
6.5.4. SWM Structures (e.g. Riser) Foundations
6.5.5. Drainage Pipes and Culverts
6.5.6. Rock Scour Analysis
7. Geotechnical Design
7.1. Geotechnical Design Criteria - Factor of Safety, Threshold Values, etc.
7.2. Roadway and Bridge Approach Embankments
7.2.1. Stability Improvement Options (Include matrix for embankment options from P3 study)

7.2.1.1. Materials – Specified Borrow Material, Light Weight Fills, Rock fill, etc.
7.2.1.2. Reinforced Soil Slopes (RSS)- (Within 1H:1V and 2H:1V)
7.2.1.3. Geosynthetics - Geotextile Inclusion
7.2.1.4. Soil Nails
7.2.1.5. Anchor slope with wire mesh
7.2.1.6. Imbricated stone wall
7.2.1.7. Cellular Confinement Anchor System
7.2.1.8. Driven Guardrail Posts
7.2.2. Settlement Mitigation
7.2.2.1. Load Reduction
7.2.2.1.1. Geofoam
7.2.2.1.2. Lightweight Fill
7.2.2.1.2.1. Light Weight Aggregate
7.2.2.1.2.2. Low Density Cellular Concrete
7.2.2.2. Ground Improvements (e.g., for construction in Wetlands)
7.2.2.2.1. Wick Drains
7.2.2.2.2. Column/Pile Supported Embankment
7.2.2.2.3. Remove and Replacement
7.2.2.3. Stage construction with quarantine periods
7.2.2.4. Void Filling
7.2.2.4.1. Polyurethane Injection
7.2.2.4.2. Grouting
7.3. Soil Cut Slopes
7.3.1. Groundwater Control
7.3.1.1. Slope Drainage Blanket
7.3.1.2. Interceptor Drains
7.3.1.3. Horizontal Drains
7.3.1.4. Spring Control Devices
7.3.2. Slope Stability
7.3.2.1. Reinforcement
7.3.2.2. Soil Anchors and wire mesh
7.4. Rock Slopes
7.4.1. Blasting
7.4.2. Rock Fall Prevention
7.4.3. Catchment Design (Ohio Table)
7.5. Slope Maintenance and Treatment
7.5.1. Landslide Analysis and Mitigation
7.5.2. Slope Maintenance Alternatives
7.5.3. Slope Treatment Alternatives and Cost
7.5.3.1. Matrix of treatment alternatives with cost
8. Construction Support, Monitoring and Instrumentation
8.1. Review contractor blast designs
8.2. Vibration Monitoring
8.3. Geotechnical Construction Support
8.3.1. Temporary Support of Excavation
8.3.2. Compaction Issues

8.3.3. Foundation Issues
8.3.4. Weather related
8.3.5. Ground water issues
8.4. Sinkhole Mitigation
8.5. Drilled Shaft Installation Inspection
9. Geotechnical Reports and Reviews
9.1. Geoconcern Concept Report
9.2. Slope Repair Design and Recommendations Memo
9.3. Subsurface Explorations Report
9.4. Geotechnical Report for Embankments and Cut slopes
9.5. Geotechnical Specifications
9.6. Geotechnical Data Report for Design Build Projects
9.7. Geotechnical Performance Specification for Design-Build Projects
10. Geotechnical Software