Geotechnical Asset Management for Slopes

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WisDOT ID no. 0092-21-06

October 27, 2022

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October 27, 2022

Project No.: 2122 001

David Staab, Geotechnical Engineer
Bureau of Technical Services, Wisconsin Department of Transportation
3502 Kinsman Blvd
Madison, WI 53704

Dear Mr. Staab,

Re: Geotechnical Asset Management for Slopes, Wisconsin Project ID: 0092- 21-06 (G21-06)

Attached is BGC Engineering USA Inc's report in support of the Wisconsin Highway Research Program. We appreciate the opportunity to work with WisDOT on such a challenging and interesting project.

Yours sincerely,

BGC ENGINEERING USA INC.
per:

Scott Anderson, Ph.D., P.E. (CO)
Principal Geotechnical Engineer

DISCLAIMER

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1. Report No. 0092-21-06	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Geotechnical Asset Management for Slopes, Wisconsin Project ID: G21-06	**5. Report Date** October 27, 2022
	6. Performing Organization Code
7. Author(s) Scott Anderson, Richard Carter, Casey Dowling, Mark Vessely	**8. Performing Organization Report No.** If applicable, enter any/all unique numbers assigned to the performing organization.
9. Performing Organization Name and Address BGC Engineering 600 12th St – Suite 300 Golden, Colorado USA 80401	**10. Work Unit No.** **11. Contract or Grant No.** **0092-21-06**
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Research & Library Unit 4822 Madison Yards Way Room 911 Madison, WI 53705	**13. Type of Report and Period Covered** January, 2020 – October 2022 **14. Sponsoring Agency Code**

15. Supplementary Notes

If applicable, enter information not included elsewhere, such as translation of (or by), report supersedes, old edition number, alternate title (e.g. project name), or hypertext links to documents or related information.

16. Abstract

The Wisconsin Department of Transportation (WisDOT) engaged with BGC Engineering Inc. (BGC) as part of the Wisconsin Highway Research Project (WHRP) to develop a Geotechnical Asset Management (GAM) process for slopes along Wisconsin highways using susceptibility mapping and analysis. The study corridor used to develop and validate the process was the Wisconsin Highway 35 Corridor in Crawford county in southwest Wisconsin. The process includes a Geographic Information System (GIS) -based slope failure susceptibility model which considers the hazard factors that lead to slope failures on Wisconsin State Highway 35 (WI-35). The output from the susceptibility model can be used within a GAM framework that provides WisDOT engineers and officials with information to prioritize and plan future projects and maintenance efforts. The methodology employed for this work utilized a statistical approach to slope hazard susceptibility mapping which reduces information extracted from geometric and geospatial data at known hazard locations to quantify slope failure susceptibility along the study corridor. The statical approach was validated through field observations and anecdotal information from WisDOT Maintenance staff, and guidance for extrapolation statewide is provided. An interactive web-based map showing the slope failure susceptibility and input data such as terrain and field observation forms was used for the duration of the project.

17. Key Words Geohazards, Geotechnical Asset Management, GAM, slope failure, weights of evidence, spatial analysis, rockfall, shallow landslide, landslide susceptibility	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** Enter the total number of pages in the report, including front cover and appendices.	**22. Price**

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EXECUTIVE SUMMARY

The Wisconsin Department of Transportation (WisDOT) engaged with BGC Engineering Inc. (BGC) as part of the Wisconsin Highway Research Project (WHRP) to develop a Geotechnical Asset Management (GAM) process for slopes along Wisconsin highways. The main output of the project is a slope-failure susceptibility model which considers the hazard factors that lead to slope failures on Wisconsin State Highway 35 (WI-35). The results of this exercise can be used within a GAM framework to provide WisDOT engineers and officials with the information to prioritize and plan future projects and maintenance efforts.

The model developed for this project uses an inventory of known slope failures along with geometric and geospatial inputs that are extracted from topographic and geological data to inform a weights of evidence calculation of susceptibility to slope failure for any segment of highway within the study corridor. The raw susceptibility score is a numeric value representing the correlation between the properties extracted for a given location and those properties for the known slope failure sites. A positive score represents a positive correlation (relatively higher susceptibility) and a negative number represents a negative correlation (relatively lower susceptibility). The results of the calculation are then summarized into qualitative bins. The susceptibility mapping approach was validated through field observations and anecdotal information from WisDOT Maintenance staff. An interactive web-based map showing the slope failure susceptibility and input data such as terrain and field observation forms was used for the duration of the project. All development and testing of this model were carried out using data from the Highway 35 corridor within Crawford County, in southwestern Wisconsin. However, the model was developed in such a way that is deployable at the statewide scale. The data extraction methods along with the general principles applied to the susceptibility calculation are generic and can be deployed anywhere in the state, however, the geologic model utilized within the process is unique to the region and would not be applicable state-wide.

As part of the research the following recommendations are suggested for future applications of the model:

- Expansion of the shallow slope failure susceptibility model within the Driftless Area of Wisconsin
- Development of an embankment failure susceptibility model
- Statewide landslide susceptibility modeling.

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1.0 INTRODUCTION

The Wisconsin Department of Transportation (WisDOT) engaged with BGC Engineering Inc. (BGC) as part of the Wisconsin Highway Research Project (WHRP) to develop a Geotechnical Asset Management (GAM) process for slopes along Wisconsin highways. The process includes a Geographic Information System (GIS) -based slope failure susceptibility model which considers the risk factors that lead to slope failures on Wisconsin State Highway 35 (WI-35). The output from the susceptibility model can be used within a GAM framework that will provide WisDOT engineers and management with the information necessary to better prioritize and plan future projects and maintenance efforts.

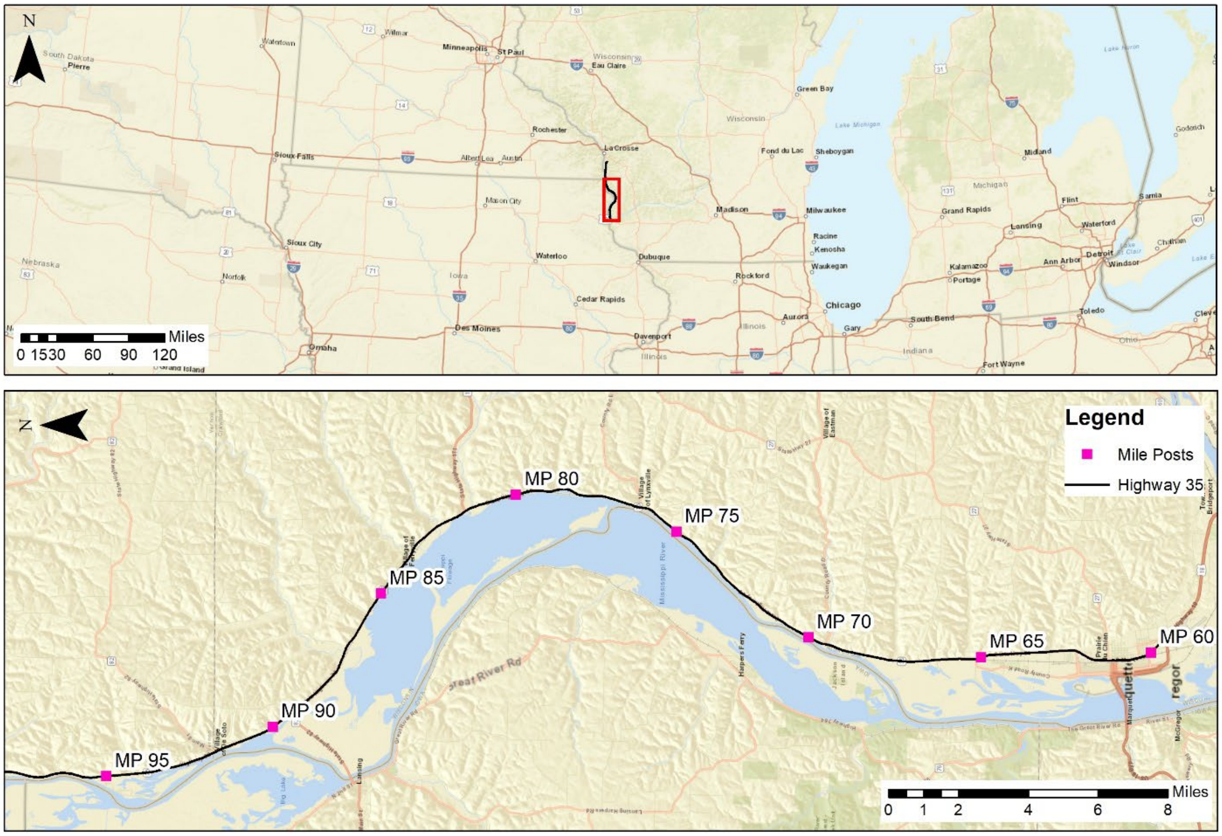
The work presented in this report is being carried out under the BGC Engineering USA Inc. (BGC) workplan dated September 9, 2020 and the WisDOT work authorization letter dated October 2, 2020 for Project ID 0092-21-06.

The scope of work for the research project consists of the following tasks.

Task 1 – Literature Review
Task 2 – Collection of Available Slope Failure Data
Task 3 – Collection and Review of Data from Known Slope Failure Sites
Task 4 – Development of a GIS-Based Slope Failure Model
Task 5 – Field Verification of GIS-Based Model
Task 6 – Development of Specific Slope Failure Risk Maps

This report summarizes the research activities completed by BGC in the execution of this scope of work and presents recommendations for further research. Based on conversations with WisDOT during workplan development, the research project was focused on identifying susceptibility to slope failure along Wisconsin State Highway 35 (WI-35) corridor through Crawford County from approximately milepost 60 to 90. The location and overview map for the study area is provided in Schematic 1-1. For the purposes of this study, “slope failure” specifically refers to upslope (cut-slope) side of the WI-35. While some embankment failures were documented during the field component of this study, the project scope and susceptibility model does not incorporate this information and is not applied to embankments—this decision was made through conversations between BGC and the WHRP Project Oversight Committee (POC).

Cambio™[1] was used throughout this project as a means of data management, data visualization and for interpretation of geotechnical data as it relates to other highway assets.



Schematic 1-1. Overview of study the corridor.

Over the course of this project, Cambio was populated with various datasets relevant to this study, including:

- Geo-assets – locations where shallow slope failure is possible and activity present; the geo-asset inventory utilized throughout this study was comprised of the slope failure database provided by WisDOT (described in Section 2.2) and observations made by BGC during the field campaign (described in Section 2.5).

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[1] Cambio is software developed by BGC to manage and prioritize geohazard sites for future inspections or mitigations systematically and objectively. The system uses risk-based screening algorithms to assist in allocating resources at the appropriate level based on the severity of the hazard and adverse impact on infrastructure. It is also used to store site-specific field observations, historical studies, or actions (e.g., surveys, as-built reports, inspections, etc.), recommendations, and to maintain a defensible audit trail that can be communicated to stakeholders and management.

- Non Geo-Assets – highway asset data provided in GIS format to BGC by WisDOT (location of bridges, culverts, medians).
- Geohazard events – location of previously documented slope failures. A database containing locations and photographs of 14 events was provided by WisDOT. Additional geohazard events were added by BGC through observations made while in the field and discussions with regional WisDOT personnel.
- Inspections – can apply to any of the above features, field inspections were carried out for all geo-assets as part of Task 5 – Field Verification of GIS Based model.
- Lidar data represented as a hillshade. Lidar data utilized was collected in 2011 at 3-foot pixel resolution and is maintained and distributed by the Wisconsin State Cartographer's Office (2011).

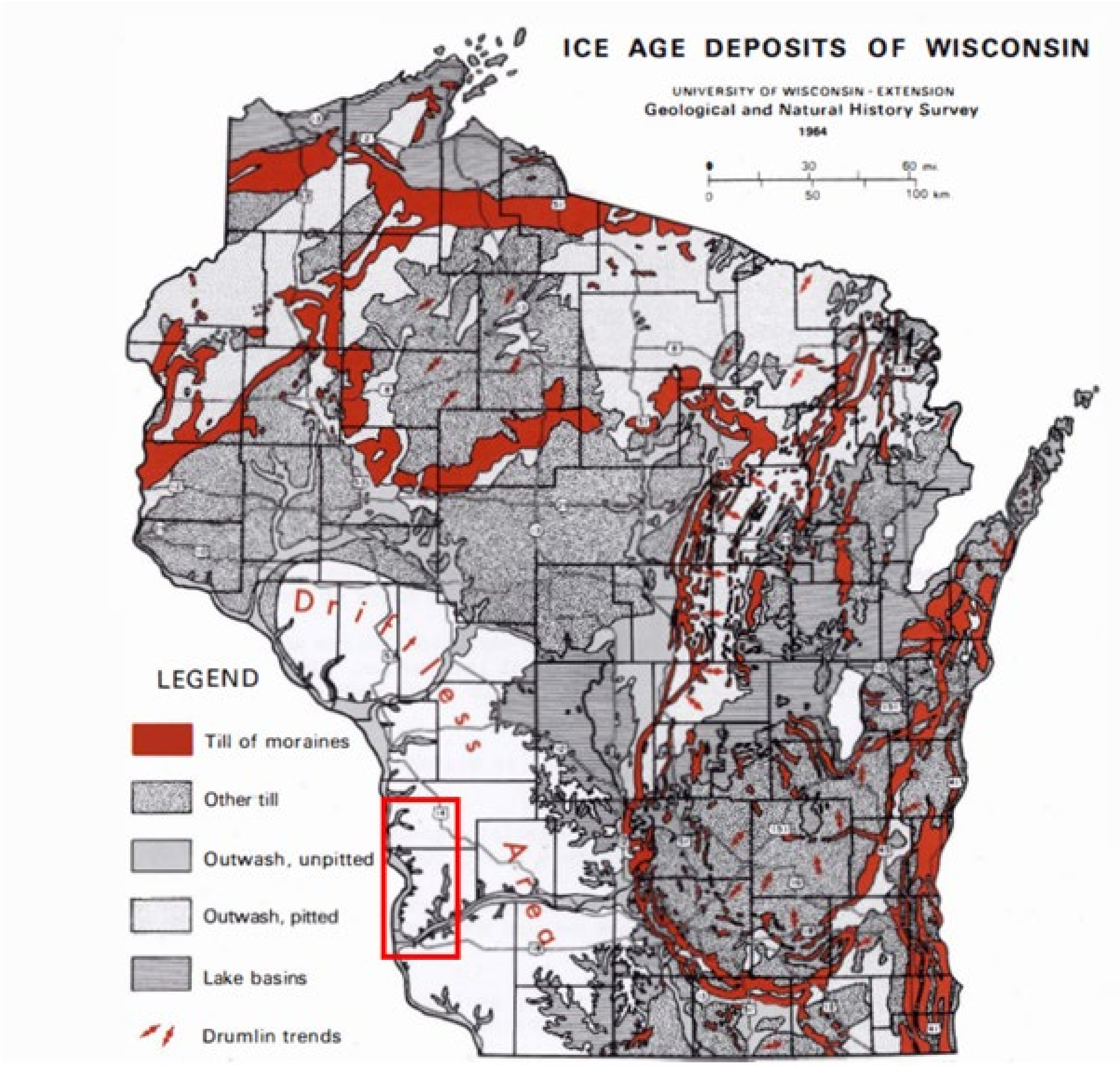
2.0 RESEARCH METHODOLOGY AND FINDINGS

2.1. Task 1 – Literature Review

BGC collected and synthesized information from regional and international literature based on sub-topics, such as the regional geological and geohazard context of the study area, factors contributing to slope failure, and current GAM practices among state DOTs.

2.1.1. Geology and Geological Hazards of Study Area

Physiographically, the study corridor is within The Driftless Area as shown in Schematic 2-1. This is an area of Wisconsin, Minnesota, Iowa, and Illinois which was not covered by ice during the most recent glaciation (Evans, 2003). The terrain in the region is characterized by rolling hills, exposed rock faces, and river valleys which cut through bedrock plateaus overlain by aeolian (wind transported) and colluvium (gravity transported) soil deposits. Within the study area, WI-35 cuts into the east slopes of the Mississippi River valley which has eroded through Paleozoic sedimentary units to form bluffs extending as high as 300 feet. Rock cuts adjacent to the highway consist of Oneota Dolomite, Jordan Sandstone, St. Lawrence Formation, and the Lone Rock Formation (Evans, 2003). Where WI-35 is not excavated into slopes, the roadway is mapped on fills and alluvial and colluvial soils. As-built information or borehole data was not provided or available within the study area, therefore it is assumed the subsurface conditions reflect those documented in the literature and observed during the field campaign.



Schematic 2-1. Map showing the glacial deposits of Wisconsin taken from the Wisconsin Geological and Natural History Survey (Thwaites, 1964). The approximate study area boundary is marked by the red rectangle.

This report adopts the terminology of Cruden and Varnes (1996) for describing landslide types and characteristics. Basic landslide types are classified according to material type (i.e., earth, debris or rock) and style of movement (i.e., slide, fall, topple, flow, spread). Landslides can be further classified according to other factors including shape and size, state of activity and velocity. Many factors can influence the frequency, duration and magnitude of landslides. Review of literature was focused broadly on landslides of any type within the study region. Few publications on this topic were found for the study region. However, relevant publications on this topic in similar geologic materials do exist for Illinois (Killey et al, 1985) and Minnesota (MnDOT, 2017; Dean et al., 2018). Dean et al (2018) classified landslide location, failure mechanism and geology for landslides within the Driftless Area in Wabasha and Goodhue counties in Minnesota, which are to the northwest and across the Mississippi River from the study corridor and found that the predominant mechanism of slope failure were rockfalls within the St. Lawrence, Oneota and Jordan Sandstone geological units. These same geological units have been mapped along the study corridor.

2.1.2. Contributors to Landslides

Within the literature, factors relevant to landslide identification and characterization generally fit into four categories:

1. Slope Geometry (e.g., slope angle, slope length, slope direction, slope curvature and local relief).
2. Moisture Profile (e.g., antecedent precipitation conditions, topographic wetness).
3. Physiographic conditions (e.g., surficial/bedrock geology, glacial history, terrain morphology, distance to water courses, density and type of vegetation cover).
4. Anthropogenic factors (e.g., slope modification, land use, deforestation, distance to roads).

There are examples within the literature of factors from all four of these broad categories being considered in the assessment of regional-scale shallow landslide hazards, however, slope geometry is most common. This is because to be capable of sourcing shallow landslides, a slope must be sufficiently steep to expose the discontinuities or erodible material which act as sources for shallow slope failure (Higgins and Andrew, 2012). Furthermore, the configuration of the discontinuity features guide what types of failure mechanisms are possible for a given slope. For example, planar/translational slides are structurally controlled and require that the slope face and discontinuity/slip surface plane be dipping in the same direction. Wedge failures, on the other hand, require that multiple discontinuity planes intersect along a line which plunges out of the slope at an angle steep enough to sustain movement; failure occurs along that intersection.

The findings from the literature review indicate landslide susceptibility research is common across international practice, with a large component of ongoing research occurring in Europe and Asia and a concentration of rockfall-specific research centered in Switzerland. While the practice of susceptibility mapping is relatively mature in Europe and Asia, it is a developing practice within North America (Reichenbach et al, 2018).

In terms of approaches, there is a range of mapping and analytical methods to produce an estimate of landslide susceptibility. These can be generalized in four broad categories:

- Inventory – use of a landslide inventory with simple statistics (e.g., clustering, hot spots).
- Heuristic – use of judgement-based rules to combine various spatial data themes.
- Statistical – the use of statistical methods, including traditional bivariate or multivariate methods, as well as data science or machine learning algorithms, to combine a range of potentially predictive geospatial datasets.
- Deterministic – the use of limit equilibrium (or other) slope stability assessment methods with assumptions of slope geometry, material strengths, groundwater conditions and external loads.

Statistical methods are reported in the literature far more commonly than the others. A review of the state of the art for statistical methods is given by Reichenbach et al. (2018). All statistical methods, regardless of their complexity, accomplish effectively the same task, which is to determine a “best fit” relationship between landslides and a variety of other spatial data. This is a multi-dimensional problem which can be analyzed using relatively simple or more complex methods. An advantage of simpler methods is that the logic is more transparent and intuitive. More complex methods, including multi-variate statistical methods and machine learning approaches, may yield a better fit, but it can be difficult to understand in a simple way.

2.1.3. Geotechnical Asset Management

For DOTs, there are many asset types with deterioration vulnerabilities that create threats to performance objectives. For instance, TRB Report 859 identifies over 25 asset types that have quantifiable consequences from deferred maintenance and can benefit from asset management. Within this group are slopes, embankments, and walls – assets commonly identified as geotechnical assets, and here also referred to as geo-assets. While this report names over 25 asset types, only bridges and pavements, are identified with management requirements within Federal funding authorizations. However, the legacy Federal transportation authorization encourages asset management for non-bridge and pavement assets, such as geo-assets. Thus, GAM should be expected to function based on economic and performance improvement benefits rather than regulatory requirements. This absence of federal rules and funding oversight allows DOTs the flexibility to develop GAM plans that are specific to their needs and objectives (NASEM, 2019). Considering slopes as geo-assets, even if potentially hazardous, is a helpful approach as it allows for costs associated with their maintenance to be on common terms with other assets owned by highway operators (e.g., bridges, retaining walls, culverts) (Overfield et al. 2015; Barr Engineering, 2018; Stirling et al., 2021).

At the state regulatory level, Minnesota is the only state known to require GAM through the legislative process based on a June 2021 authorization that requires an inventory of geotechnical assets on the trunk highway system (MN HF10, 2021). The proposed asset inventory taxonomy within the Minnesota statute aligns with the guidance outlined in the National Cooperative Highway Research Program (NCHRP) Research Report 903, Geotechnical Asset Management for Transportation Agencies and includes cut slopes, embankment fills, retaining walls and off right-of-way natural hazards (MnDOT, 2021).

Several state DOTs have initiated some form of GAM that extends beyond legacy rockfall and landslide hazard rating systems and following the recommendation that other assets are considered in state asset management plans. In the absence of federal funding or authorization, each state has generally initiated GAM in a unique way. For many states, GAM implementation has centered around adapting hazard-evaluation systems to add unstable slopes and in some cases, retaining walls under a newly created geotechnical asset management program (e.g., Alaska, Montana, Ohio, Indiana, and Vermont). In Colorado, the DOT has developed a statewide Geohazards program and a separate Retaining Wall Asset Management program. Louisiana DOT is another DOT that has initiated GAM in the form of a retaining wall asset management research project directed at developing an eventual program across the department. For most state DOT GAM programs, the work has been directed at inventory and condition assessment to support project prioritization needs and project funding requests.

The majority of state DOT bridge and pavement asset management programs assess assets based on condition ratings obtained through field inspection and develop consensus-based condition level performance targets for those assets. The evolution of these practices is based on several decades of practice that initiated through Federal rule making. In the absence of federal rules for geotechnical assets, state DOT practices for asset assessment and performance measurement are variable. States such as Alaska, Montana, Vermont assess and report on the condition of geotechnical assets using condition measures such as good, fair, or poor. Other states combine the condition of the asset with other inputs related to consequences of current or future poor asset performance to obtain an approximation of risk. The Indiana DOT and Federal Lands Highway Unstable Slope Management Program (USMP) use a risk estimation process that relies on the summation of inputs; while states such as Colorado and Ohio and NCHRP Research Report 903 use a product (multiplication) process of inputs to arrive at a risk value as a probability.

Data and data management practices can be a barrier to GAM implementation and NCHRP Report 903 provides an introduction to accepted and applied practices within the broader discipline of asset management. Among DOTs, the data management in support of GAM can be categorized into three general technology stacks. The first stack alternative consists of using primarily Microsoft Office spreadsheet and database software for input and management of asset inventory data. The second and likely more common alternative for GAM data management practice includes utilizing an off the shelf commercial geospatial software platforms, such as Esri geographic information system software that is used by many DOTs for all geospatial information. Tools such as these allow DOTs to build data entry forms and customized views. Example states using Esri to support GAM data management include Alaska, Ohio, Indiana, North Carolina, and Washington, as well as the Federal Lands Highway USMP. The third option for a GAM data management technology stack involves bespoke development of platforms that enable development to specific needs of the DOT and more complex analytics. Examples of this option include the Vermont Asset Management Information System which is a multi-year software development project to align up to 24 asset groups under one platform for data collection, deterioration modeling, and long-term planning. Colorado DOT is taking a similar approach and is also addressing deterioration modeling, using the Esri-based Cambio platform to manage understanding spatially.

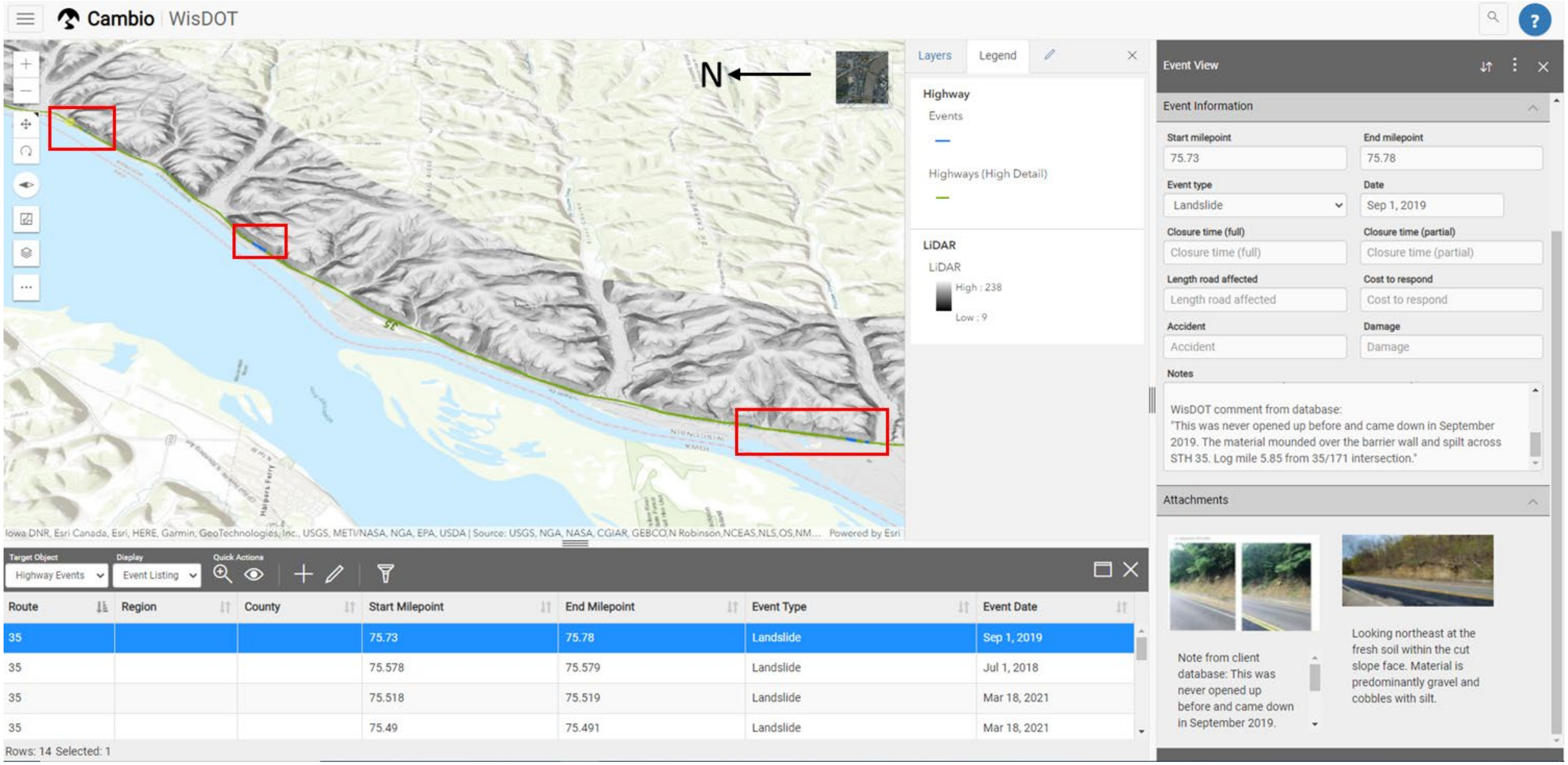
2.2. Task 2 – Collection of Available Slope Failure Data

2.2.1. Slope Failures within Study Area

The majority of known slope-failure data utilized for this study was drawn from a database provided to BGC by WisDOT containing the location, a brief description, and select photographs of 14 slope failure events documented within the study corridor. These failures were defined by a notable event that required intervention and may have disrupted traffic flow. The WisDOT event database is summarized in Table 2-1 and a map-view showing the events within the WI-35 study corridor is shown in Schematic 2-2. Based on information provided by WisDOT, BGC interpreted a suspected slope failure mechanism for each event. These mechanisms were confirmed during the field verification portion of the scope. Based on anecdotal information from WisDOT, observations during the field visit, and review of lidar, additional locations where slope failures have occurred but weren't previously documented were also identified and included as geo-assets.

Table 2-1. Slope failure database provided by WisDOT.

Latitude	Longitude	WisDOT Description	Suspected Mechanism (from WisDOT photos)
-91.214	43.481	2016 Large slide	Earthflow
-91.065	43.237	Minor slide	Rockfall
-91.066	43.236	Vegetated slide	Shallow colluvial slide
-91.071	43.232	2020 additional slide	Shallow colluvial slide
-91.064	43.238	Broken out barrier	Rockfall/shallow colluvial slide
-91.065	43.237	2018 slide	Shallow colluvial slide
-91.063	43.239	September 2019 slide	Rockfall/shallow colluvial slide
-91.080	43.223	2020 additional slide	Shallow colluvial slide
-91.100	43.210	2020 large slide	Rockslide/fall
-91.101	43.208	2018 large boulders fallen	Rockfall
-91.101	43.208	Past slide area	Unknown
-91.140	43.154	2020 additional slide	Shallow colluvial slide
-91.142	43.145	Large 2013 event	Embankment failure/ earth slide
-91.142	43.143	2020 additional slide	Shallow colluvial slide



Start milepoint: 75.73
End milepoint: 75.78
Event type: Landslide
Date: Sep 1, 2019
Closure time (full)
Closure time (partial)
Length road affected
Cost to respond
Accident
Damage
Notes: WisDOT comment from database: "This was never opened up before and came down in September 2019. The material mounded over the barrier wall and spilt across STH 35. Log mile 5.85 from 35/171 intersection."

Target Object: Highway Events
Display: Event Listing

Route	Region	County	Start Milepoint	End Milepoint	Event Type	Event Date
35			75.73	75.78	Landslide	Sep 1, 2019
35			75.578	75.579	Landslide	Jul 1, 2018
35			75.518	75.519	Landslide	Mar 18, 2021
35			75.49	75.491	Landslide	Mar 18, 2021

Rows: 14 Selected: 1

Note from client database: This was never opened up before and came down in September 2019.

Looking northeast at the fresh soil within the cut slope face. Material is predominantly gravel and cobbles with silt.

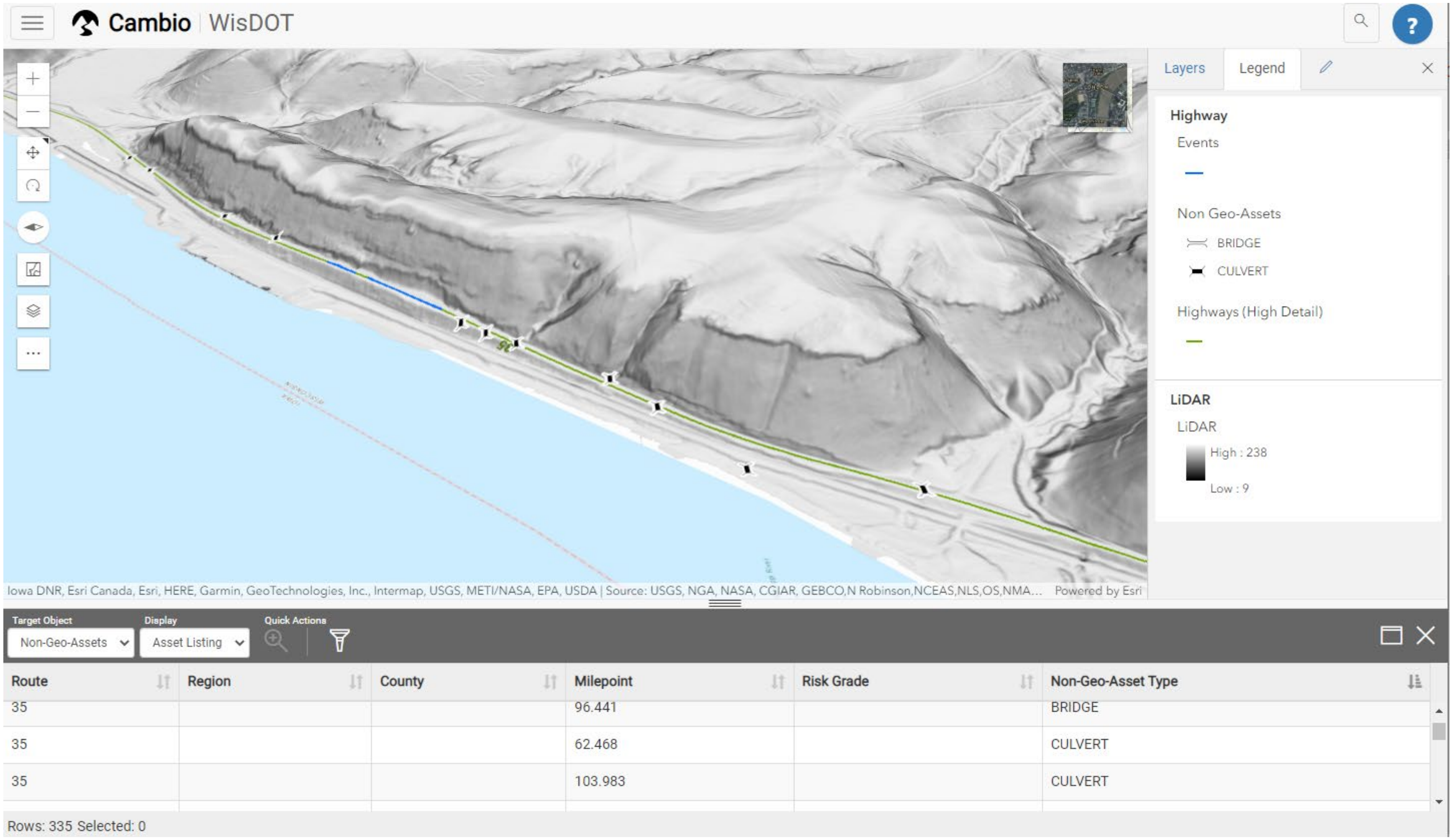
Schematic 2-2. **Map-view of WisDOT provided events within the study corridor. Events are shown as blue line segments along the highway corridor (highlighted in red boxes). Information on each event was geospatially tagged to it as part of the study. Lidar hill shade and ESRI topographic base map data is shown as the map base.**

2.2.2. GIS Data

Data sources included lidar-derived digital elevation model (DEM) data were acquired by BGC from WisDOT. The DEM was utilized to evaluate slope angle, slope height, slope aspect, and offset distances between the WI-35 corridor and slopes along the route. Open source bedrock and surficial geological maps were also acquired and used to derive information on the expected geology along the corridor. These data were combined with the documented slope failures provided by WisDOT in a GIS database to evaluate the spatial, geometric and geologic characteristics at documented failure sites.

In addition to topographic and geological datasets, point locations of culverts and bridges, and highway shoulder and median polylines were also provided.

A partial view of the GIS data and slope failure information provided by WisDOT and aggregated into the Cambio site is shown in Schematic 2-3.



Target Object: Non-Geo-Assets
Display: Asset Listing

Route	Region	County	Milepoint	Risk Grade	Non-Geo-Asset Type
35			96.441		BRIDGE
35			62.468		CULVERT
35			103.983		CULVERT

Rows: 335 Selected: 0

Schematic 2-3. **Representative 3D view showing the spatial representation of the WisDOT asset GIS data and event database provided by WisDOT. Lidar hill shade data as background.**

2.3. Task 3 – Collection and Review of Data from Known Slope Failure Sites

This task involved reviewing the slope-failure database presented in Section 2.2 and characterizing each event according to knowledge gained through the review of literature pertaining to landslide processes within the region and carrying out cursory assessment of lidar for each site.

The product of this task was a GIS-based landslide inventory for the study corridor with a brief description of the geology (extracted from bedrock geology maps), geometry (extracted from lidar) and the inferred failure mechanism. The intended use for this information was to aid in identification of statistically significant relationships between various geologic materials, topographic characteristics and other data that could influence slope stability and ultimately susceptibility to slope failure. These relationships are explored in Task 4. The relevant characteristics for the failure sites were verified and adjusted, if necessary, during the field visit conducted as part of Task 5.

Based on review of past slope failure sites, the cut-slope slope failure mechanisms appeared to share the commonality of being relatively shallow slope failures. As such, similar processes and conditions were suspected to govern their occurrence. These include kinematically admissible failures due to cut slope angle, discontinuities, and exposed height (geometric slope characteristics), the resistance to failure that comes from near surface geology (the character and shear strength of soil and rock), and near surface processes such as precipitation and runoff (temporal change in conditions). For these reasons, BGC considered all upslope failure mechanisms to be similar and called all “shallow slope failures” during the development of the corridor GIS-based model.

Through review of the slope failure database, BGC determined that the highest concentration of documented failures occurred on the southern portion of the study corridor. Key characteristics of this part of the highway includes relatively steeper slopes immediately adjacent to the WI-35 alignment, less offset between the WI-35 alignment and adjacent slopes, and upper Cambrian bedrock likely outcropping at or just upslope of the WI-35 alignment. Based on Evans (2003) and Iowa Geological Survey (2006), this outcropping bedrock was anticipated to be Oneota Dolomite, Jordan Sandstone, or St. Lawrence Formation, which tended to have higher correlation with slope-failure in Minnesota (Dean et al., 2018). Further to the north in the study corridor, the offset between the highway and adjacent slope increased, the slope angles of adjacent slopes were lower and the bedrock immediately along the alignment was mapped as lower Cambrian bedrock (Mudrey et al., 1982). Based on Evans (2003), this geology was anticipated to be associated with the Lone Rock sandstone which had a lower incidence of landslide in Minnesota (Dean et al., 2018).

2.4. Task 4 – Development of a GIS-Based Slope Failure Model

In Tasks 2 and 3, BGC developed a conceptual understanding of the common characteristics of shallow slope failure on the study corridor and determined that the predominant factors influencing the spatial distribution of susceptibility to shallow slope failures were the inherent strength properties of the near-surface geological materials and geometry of the slopes adjacent to the highway corridor as well as the proximity of those slopes to the highway. As geologic materials would need to be field verified, the GIS-based analytical model developed for this task focused on extracting geometric parameters of adjacent slopes and relating them to specific locations on the highway to quantify susceptibility to shallow slope failure over the entire corridor.

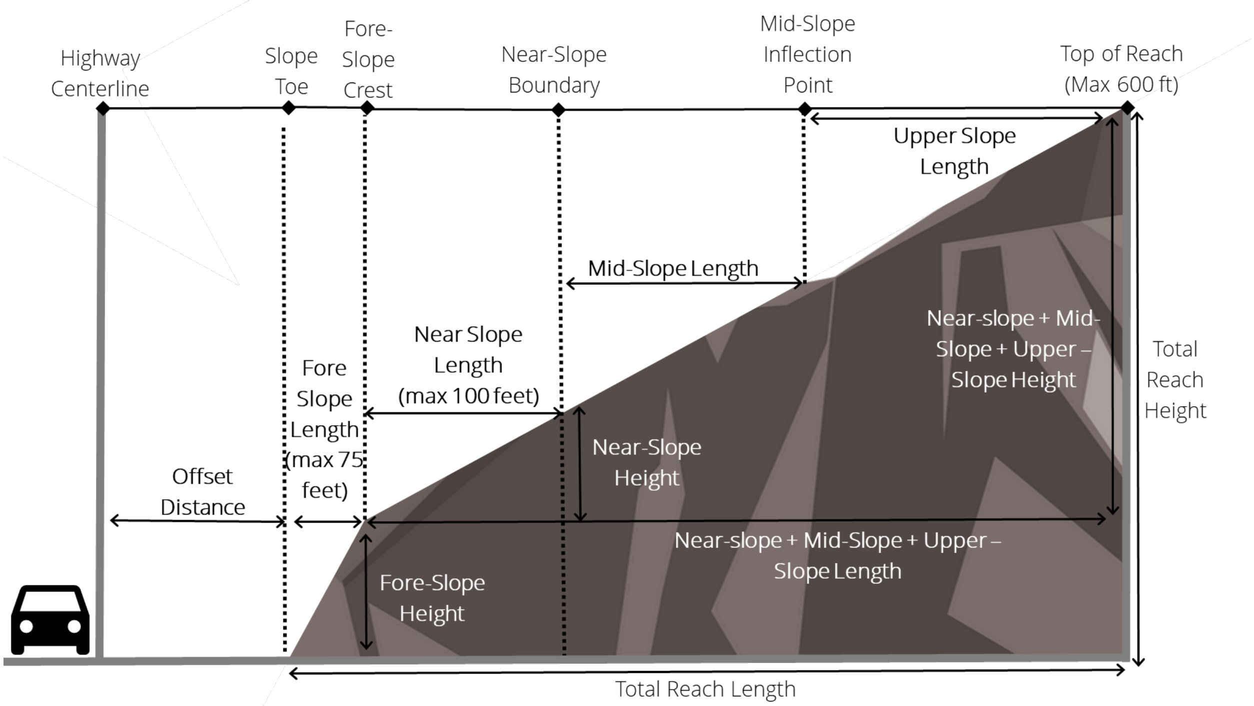
The highway centerline was divided into 25-foot segment spacing to begin the analytical process. For each segment a transverse 600-foot profile polyline was delineated in the upslope direction starting from the highway centerline using standard GIS tools. Elevation parameters were then extracted for each profile from the available lidar. Schematic 2-4 provides an illustration of the geometric parameters extracted from lidar using spatial analysis techniques and GIS software. The following parameters were extracted for each profile polyline.

- Offset Distance/Slope Toe Location – the point along the profile line which intersects with the boundary of a slope map with a minimum slope angle of 10 degrees (this eliminates road, shoulders and any flat areas from the profiles).
- Top of Reach – the point of maximum elevation within the profile (maximum 600 feet from the highway centerline).
- Fore-Slope Crest –point of minimum curvature (most concave) point upslope of the toe, within 75 feet of the highway centerline. This is the inferred boundary of modified cut slopes adjacent to the highway.
- Fore-Slope Height – difference in elevation between slope toe and fore-slope crest.
- Fore-Slope Length – the horizontal distance between the slope toe and the fore-slope crest.
- Top of Near-Slope – the highest point upslope within 100 feet of the fore-slope crest.
- Near-Slope Height – the difference in elevation between the fore-slope crest and top of near slope.

- Near-Slope Length – the horizontal distance between the fore-slope crest and the top of near slope.
- Mid-slope inflection point – the point of lowest curvature (most convex) above the fore-slope-crest (used as a means of identifying meaningful breaks in topography above the fore-slope).
- Height Above Fore-slope– the difference in elevation between the fore-slope crest and top of reach.
- Length Above Fore-slope– the horizontal distance between the fore-slope crest and top of reach.

In addition to these parameters, slope angles, expressed as the ratio of length to height, were calculated for the fore-slope, near-slope, mid slope and total slope within each profile.

Each of these parameters were automatically extracted by applying a pre-defined logic routine to the analysis of the profile polylines (e.g., maximum elevation within a given distance of a certain feature, identification of concave/convex features). In most cases, the parameters represent the features they are intended to identify, however, given the generalized logic and automated process, there are cases where the logic output was not representative of the desire parameter. For example, in a small number of cases, the “Top of Reach” parameter crossed a ridgeline and the end point is located on a slope in an adjacent valley and has no potential for sourcing shallow slope failure capable of reaching the highway, however, that point is stored as the “Top of Reach” because it is along the profile polyline and meets the criteria of being the highest point of elevation along that profile. The frequency of this occurrence is not deemed significant for this study; however, logic could be written to remove all such occurrences.



Schematic 2-4. Conceptual illustration of GIS-based parameter extraction from cross sections generated along the study corridor.

2.5. Task 5 – Field Verification of GIS-Based Model

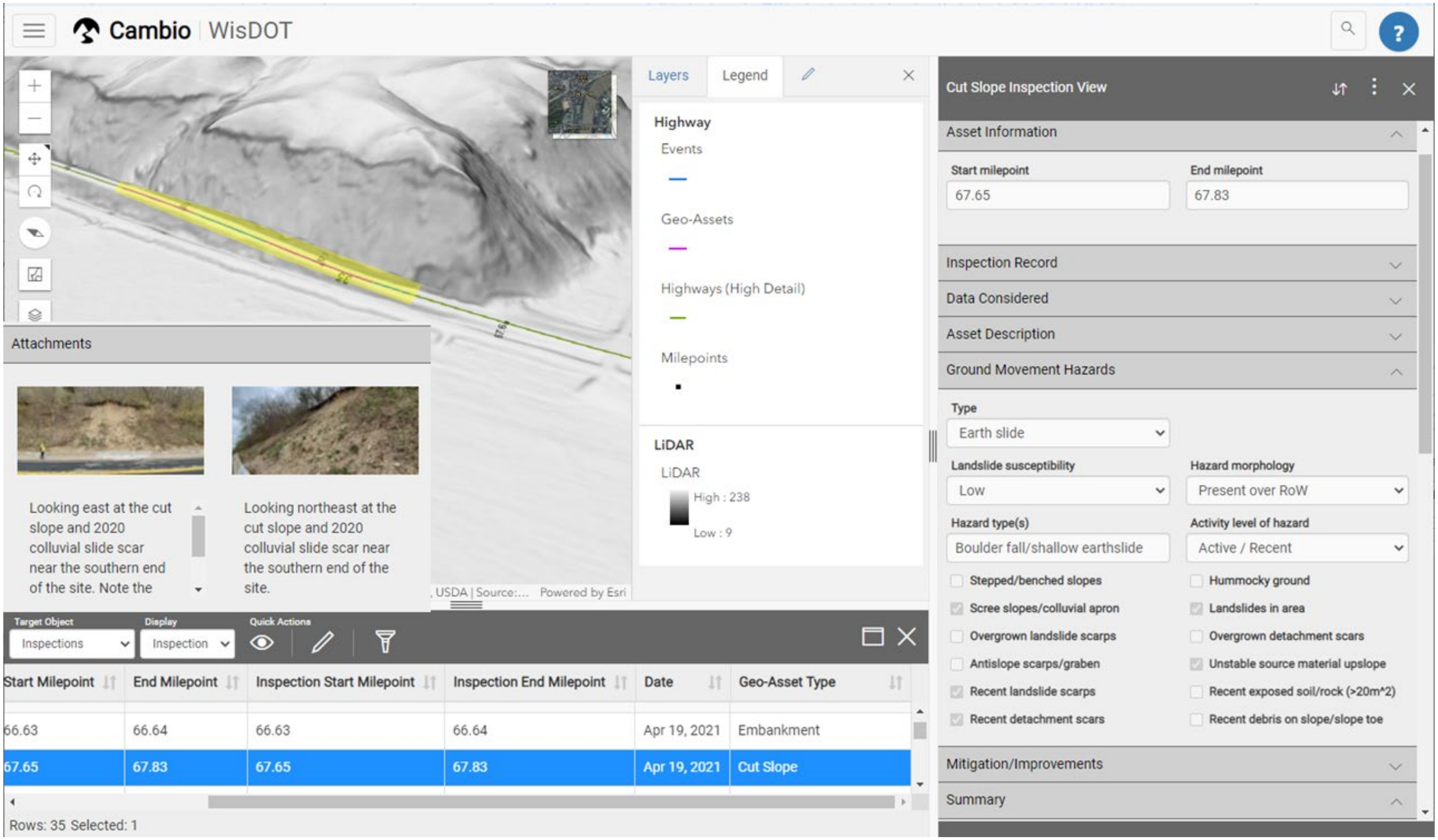
In April 2021, BGC performed field verification field work over a period of four days along the WI-35 corridor in Crawford County and BGC was accompanied by WisDOT staff periodically during the fieldwork. BGC visited slope failure sites identified by WisDOT prior to the trip and also located new sites identified by BGC while in the field. The goal of the field campaign was to verify the preliminary understanding of the geological and geohazard context for the study area developed through desktop assessment of available data. The outcome of this exercise was an updated geohazard database which extended beyond what was provided at the onset of the project and would inform the final susceptibility model. BGC also was able to confirm geological characteristics of the documented geohazard event locations as well as the characteristics of slopes where no geohazards have been recorded. Field observations were also used to develop a conceptual geological model of the cut-slope geology throughout the corridor which would act as a key parameter in the susceptibility model.

Key activities during the field verification task included:

- Documentation of regional and roadside geology (outcrop scale mapping of material type)
- Identifying dominant upslope hazard mechanisms (i.e., rockfall, shallow colluvial slides)

- Data collection for the susceptibility model.

Field observations were input into an inspection form which is tagged within Cambio to each geo-asset. A screenshot of the WisDOT Cambio application showing the various data extracted and stored in Cambio for the event database and field verification tasks is provided in Schematic 2-5.



Looking east at the cut slope and 2020 colluvial slide scar near the southern end of the site. Note the

Looking northeast at the cut slope and 2020 colluvial slide scar near the southern end of the site.

Target Object: Inspections
Display: Inspection

Start Milepoint	End Milepoint	Inspection Start Milepoint	Inspection End Milepoint	Date	Geo-Asset Type
66.63	66.64	66.63	66.64	Apr 19, 2021	Embankment
67.65	67.83	67.65	67.83	Apr 19, 2021	Cut Slope

Rows: 35 Selected: 1

Start milepoint: 67.65
End milepoint: 67.83

Type: Earth slide
Landslide susceptibility: Low
Hazard morphology: Present over RoW
Hazard type(s): Boulder fall/shallow earthslide
Activity level of hazard: Active / Recent

☐ Stepped/benched slopes
☑ Scree slopes/colluvial apron
☐ Overgrown landslide scarps
☐ Antislope scarps/graben
☑ Recent landslide scarps
☑ Recent detachment scars
☐ Hummocky ground
☑ Landslides in area
☐ Overgrown detachment scars
☑ Unstable source material upslope
☐ Recent exposed soil/rock (>20m^2)
☐ Recent debris on slope/slope toe

Schematic 2-5. Representative screenshot of data collected and stored with each geo-asset.

Each geo-asset was given a mileage interval for a start and end point that represented the judged location of a common hazard level. Using these mileage intervals, the profile data generated in Task 4 was updated to include a binary classification as being within a mapped hazard interval or not. This attribute is used as the known variable in the susceptibility mapping approach discussed in the next section. In most cases, individual hazard sites (e.g., individual small cut slope failures, individual rockfall locations.) were not documented as an individual geo-asset. Instead, for a highway section where multiple upslope failure sites were observed with similar mechanisms and characteristics, the sites were combined into a single geo-asset with an inspection form. For example, if a WisDOT documented failure site occurred along a cut slope where there was evidence of additional, undocumented past failure sites, the entire cut slope with similar processes would be called one geo-asset and an inspection form was completed to document the failure site observations. This geo-asset and inspection length, summed with the lengths of the other documented geo-assets, would be used in the susceptibility model development completed as part of Task 6.

BGC also observed regional and roadside geology during the field verification process. The interpreted bedrock geology along the research corridor included the Oneota Dolomite, Jordan Sandstone, St. Lawrence Formation, and the Lone Rock Formation.

Surficial geology primarily consisted of colluvium and embankment fills associated with roadway construction. Two distinct colluvial units were observed outcropping along the corridor. These colluvial units were differentiated by the bounding interpreted bedrock units. The Upper Colluvium was between the Oneota Dolomite and the Jordan Sandstone, and the Lower Colluvium was below the Jordan Sandstone and often obscured the underlying St. Lawrence and Lone Rock Formations.

Four dominant geohazards were observed along the research corridor—three were associated with cut slopes, and one was associated with embankments. Along the cut slope side (generalized as the east side of the highway), colluvial slides, rockfall from bedrock units, and rockfall sourced from erosion of colluvium were observed. Damage to the concrete barrier wall along the cut slope was a key indicator for adverse slope performance. Schematic 2-6 provides representative photos for each of these three cut-slope mechanisms as observed on the study corridor.

The colluvial slides observed were generally shallow, and in places included boulders of Oneota Dolomite and Jordan Sandstone within the colluvium. In the south, colluvium tended to be quite shallow, with thicker colluvium deposits in the north, particularly near Rush Creek State Natural Area and outside of the research corridor near Genoa, WI.

Rockfall hazards from bedrock observed in the corridor included wedge and topple failure types. Rockfall sources included intact Oneota Dolomite from the capping bluffs, intact Jordan Sandstone along cut slopes and higher on the slope, and St. Lawrence/Lone Rock exposures along cut slopes.

Where rockfall originated from colluvium, boulders and cobbles were observed either within colluvium or sitting on top of colluvium. As the colluvium erodes or weathers along the cut slope, boulders/cobbles are freed and fall towards the highway.

The field observations confirmed that the slope failures tend to be governed by slope geometry and the inherent strength of the rock mass and soils. This confirmed the preliminary modeling assumption that the various upslope failure mechanisms could be considered as one general failure class during the development of the slope failure susceptibility model.

Schematic 2-6. Representative photos for each of the three hazard mechanisms identified along the study corridor. A. Rockfall sourced from the upper colluvium (typically dislodged boulders that are >1yd^3). B. Fragmental rockfall and rockslides sourced from the Jordan Sandstone. C. Shallow colluvial slides in the upper colluvium and lower colluvium/Lone Rock Formation.

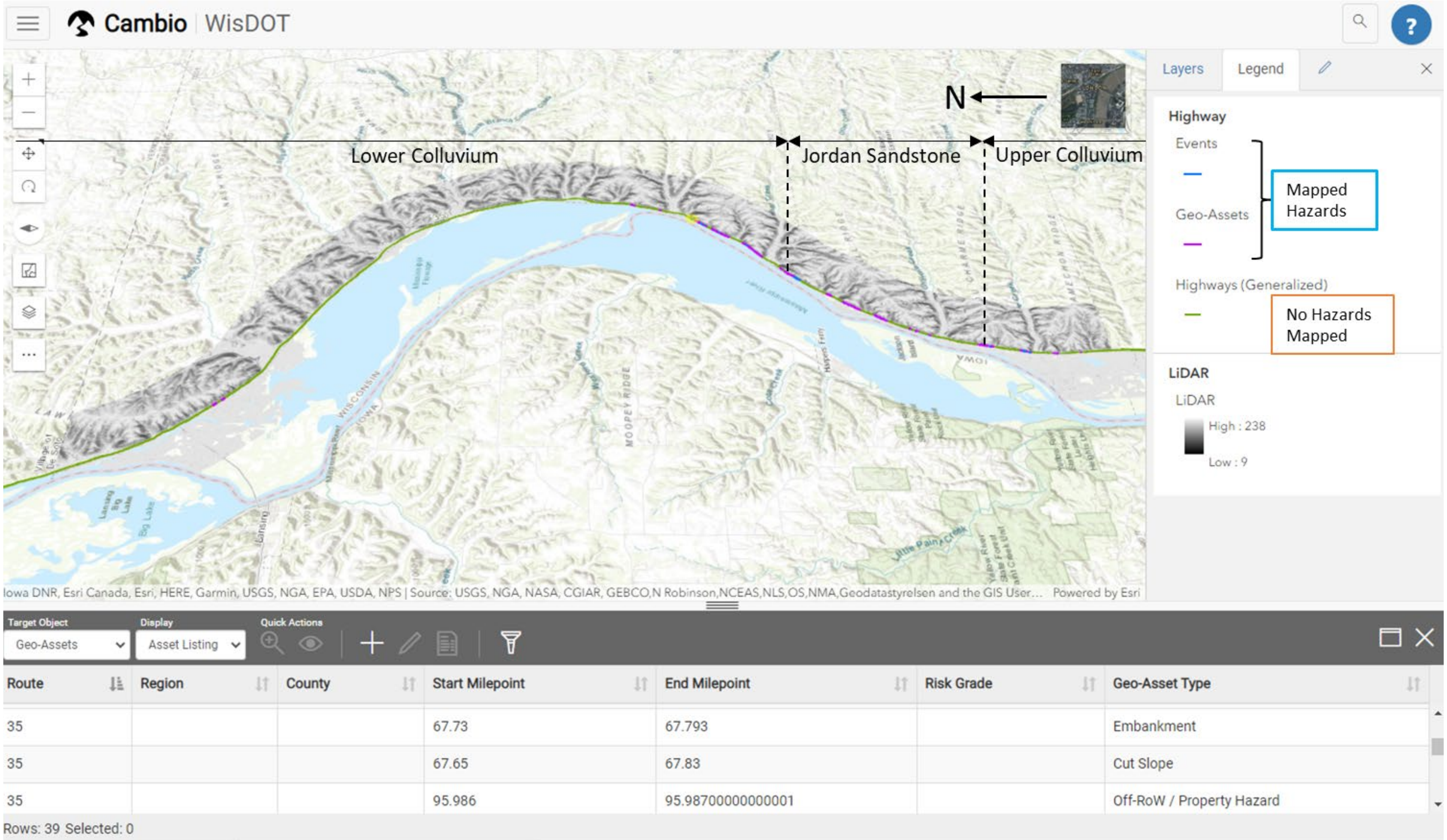
2.5.1. Development of Conceptual Engineering Geology Model

The field observations were used to develop a conceptual engineering geology model for the study corridor, which divided geologic materials into unique subsets with similar geologic material properties that may influence the likelihood of shallow upslope failures. The roadside cut slopes were observed to consist of three distinct geologic units which, from north to south, generally are the Upper Colluvium, the Jordan Sandstone, and the Lower Colluvium. The general cut slope characteristics and slope failure mechanisms are distinct within each of the three geologic units.

Table 2-2 shows the mileage range for each unit within the study corridor as interpreted by BGC. A map view of the geological model is provided in Schematic 2-7. Geologic materials crossed by WI-35 in the tributary valleys and on the downslope side of the highway are anticipated to be alluvium (river/stream deposited soils) and colluvium. These materials were not the focus of this assessment and were not directly observed during the field verification. As such, they have not been included in the slope-failure susceptibility model.

Table 2-2. Conceptual geological model developed for this study.

From Mile	To Mile	Geological Unit	Description	Dominant Hazard Mechanism
66	68.39	Upper Colluvium	Silt and sand with dolomite cobbles and boulders sourced form the overlying Oneota Dolomite.	Rockfall sourced from boulders that become dislodged from the colluvium and shallow colluvial slides.
68.39	73.2	Upper Colluvium/Jordan Sandstone	Fine to medium grained tan sandstone, thinly to thickly bedded. Sandstone is either outcropping or covered with a veneer of silt and sand colluvium with dolomite cobbles and boulders.	Fragmental rockfall and rockslides sourced from the Jordan Sandstone and shallow colluvial slides.
73.2	90.2	Lower Colluvium/Lone Rock	Silt and sand with dolomite and sandstone cobbles and boulders. Localized outcrops of very fine to fine grained sandstone. Slope failures tend to be shallow colluvial slides.	Shallow colluvial slides and rockfall from boulders dislodged in the colluvium. Isolated rockfall outcropping Lone Rock Sandstone and from off-RoW sources including the Jordan Sandstone and Boulders from the Upper Colluvium.



Target Object: Geo-Assets
Display: Asset Listing

Route	Region	County	Start Milepoint	End Milepoint	Risk Grade	Geo-Asset Type
35			67.73	67.793		Embankment
35			67.65	67.83		Cut Slope
35			95.986	95.98700000000001		Off-RoW / Property Hazard

Rows: 39 Selected: 0

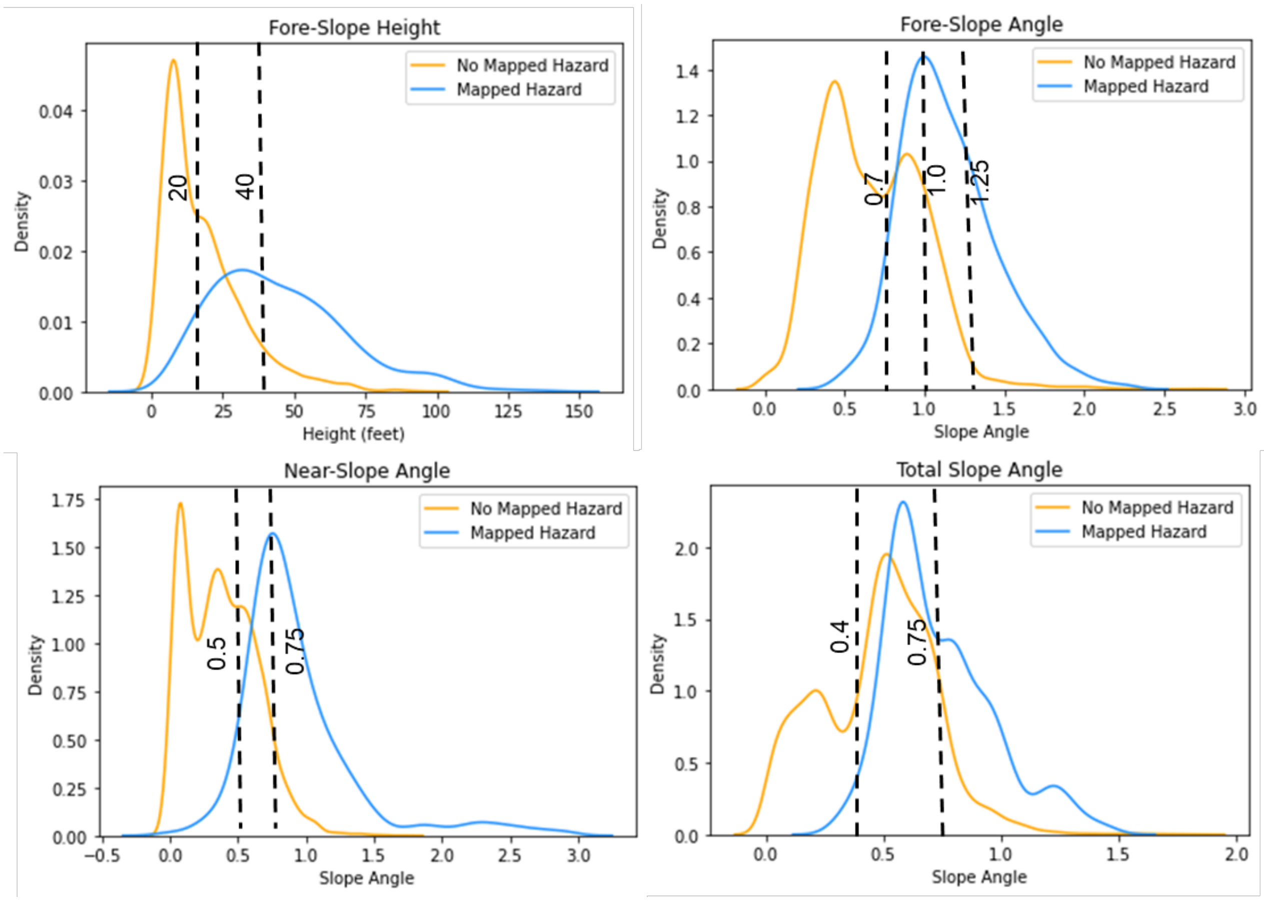
Schematic 2-7. **Plan view of the mapped geological units along with WisDOT events (blue segments) and mapped geo-assets (purple segments). WisDOT events and geo-assets are classified as mapped hazards, used in the development of the susceptibility model.**

2.6. Task 6 – Development of Specific Slope Failure Risk Maps

In this task, the information gathered through the preceding tasks was used to develop a statistically based approach to quantifying relative susceptibility to shallow slope failure within the study corridor.

2.6.1. Data Exploration

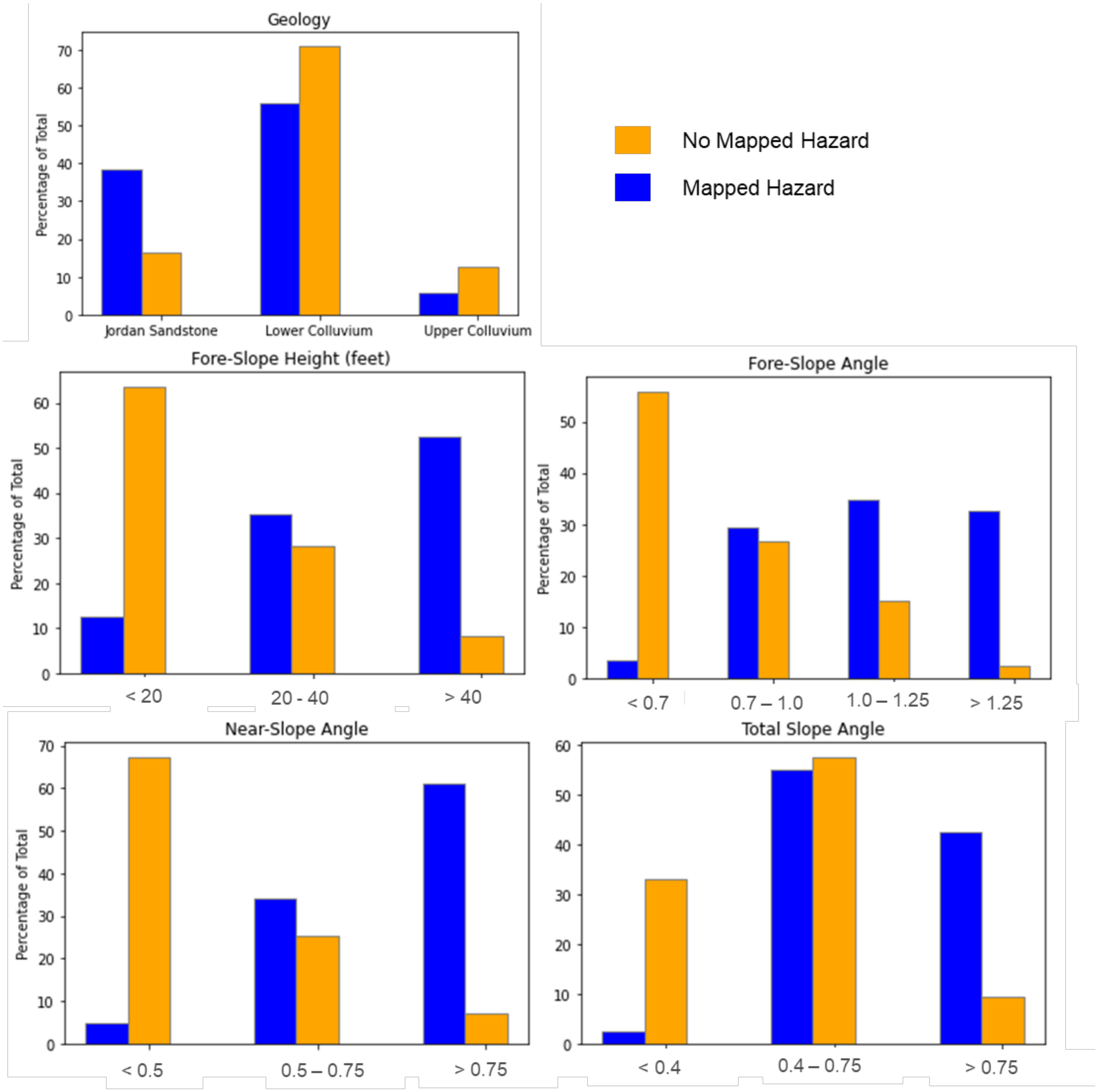
The dataset used in this portion of the analysis is the start point of each transverse polyline profile, spaced at 25 feet along the highway. Each point contains values for the exploratory parameters (geometric parameters extracted from lidar in Task 4 and a geologic material parameter inferred from the conceptual geological model developed in Task 5) and an observed value representing whether or not that segment of highway has an adjacent slope hazard (taken from the Cambio geo-asset inventory, see Schematic 2-7). For the geometric parameters, which are continuous variables, the observed value was used to generate two distinct statistical distributions for each parameter (the distribution of each parameter for mapped hazards and for portions of the corridor with no mapped hazards). The distributions were used to find statistical differences between these populations and identify optimal value cutoffs (bins) to be used to identify the presence or absence of a mapped hazard. Typically, ranges are binned to produce a minimal number of statistically significant categories with distinct weight values. All parameters illustrated in Schematic 2-4 were tested; however, the two with the best predictive capability (i.e., the most distinct differences between the two distributions) were found to be fore-slope angle, and near-slope angle. Fore-slope height was also deemed to be an important parameter to consider for highway slope-failure susceptibility as was total slope angle to account for off-RoW hazards and were therefore also included in the model, despite a relatively weaker predictive capability. Schematic 2-8 shows the distribution of the two statistical populations (5444 segments in total) tested for each continuous parameter as well as the optimal cutoffs determined based on the probability density distributions for each parameter. In this schematic, the orange line represents the probability density distribution for all segments of highway with no mapped hazard on the adjacent slope. The blue lines represent that for segments of highway with corresponding hazards mapped as geo-assets. The dashed black lines represent the statistically significant cutoffs noted above which were informed by qualitative assessment of the distribution plots as well as judgement based on knowledge acquired through field assessment and desktop study of slope hazards within the study area. The distributions shown in Schematic 2-8 and other figures illustrating statistical distributions within this report were generated by fitting a smoothed line to the histogram for a given variable. This results in a generalized representation of the probability density distribution of a given variable. Because of the smoothing, the tails on either end of a distribution can extend beyond the range of values within the histogram itself.



Schematic 2-8. Probability density distribution plots for continuous parameters. For plots including slope angles, the slope angle is given as a ratio of vertical to horizontal distance. Dashed black lines show the optimal cutoffs based on the probability density distributions for each parameter.

2.6.2. Susceptibility Analysis

The methodology applied for this aspect of the work draws from the weights of evidence method introduced by Bonham-Carter et al (1989). For all parameters considered above, the conditional probability - the probability of a point being part of a mapped hazard, given a certain condition (e.g., slope angle above or below a threshold) - was calculated. For continuous parameters, this was done using the statistical bin ranges illustrated in Schematic 2-8. For geologic materials, a discrete variable, the conditional probability was calculated for each material type within the conceptual geological model. The results of this exercise are summarized in Schematic 2-9. This schematic also further exemplifies the claim made above suggesting that fore-slope angle and near slope angle have the most distinctive differences when comparing hazards to non-hazards.



Schematic 2-9. **Bar plots summarizing conditional probability of mapped hazard given each parameter considered. For plots including slope angles, the slope angle is given as a ratio of vertical to horizontal distance.**

Conditional probabilities are converted into individual thematic positive weights (Wi), which are calculated by taking the logarithm of the ratio of spatial probabilities, shown in Equation 1, below and summarized in Table 2-3. Use of the logarithms for weights, rather than the probability values, is strictly for mathematical convenience, to allow their combination through simple addition. This is mathematically equivalent to multiplication of the natural probability values and is an accepted way to combine the probabilities of independent random processes to obtain an overall probability.

$$W_i = \log\left[\frac{P\{F_i|L\}}{P\{F_i|\bar{L}\}}\right] \qquad [1]$$

Where:

W_i = The positive weight for the ith thematic factor

F_i = The presence of a specific (ith) thematic factor

L = The presence of a landslide

$\bar{L}$ = The absence of a landslide

In the GIS environment, the spatial probabilities in Equation 1 are calculated by summing the highway length where landslides are present or absent and where a specific factor is also present. Equation 1, using algebra, hence becomes Equation 2, below.

$$W_i = \log\left[\frac{A_1/A_2}{A_3/A_4}\right] \qquad [2]$$

Where:

A_1 = The length of highway segments within the specific factor containing landslides

A_2 = The total length of highway segments within the analytical study area containing landslides

A_3 = The length of highway segments within the specific factor not containing landslides

A_4 = The total length of highway segments within the analytical study area not containing landslides

These weight values are calculated for a specific point, where the i^{th} theme (say, geologic material) has a specific value. The A_i values and calculated weight are the same at any other point on the map with the same thematic value, and therefore the number of different weight values for W_i depends on the number of different thematic values (e.g., number of different geologic material types). Variables that have weight values close to zero have secondary significance, while variables that have higher weights (positive and negative) are given preference for inclusion in the susceptibility model.

Landslide susceptibility for each segment is obtained by combining the thematic weights, W_i, to obtain an overall combined weight, as shown in Equation 3 below.

$$W_{Total} = W_{Soil} + W_{Bedrock} + W_{Slope} + \ldots \qquad [3]$$

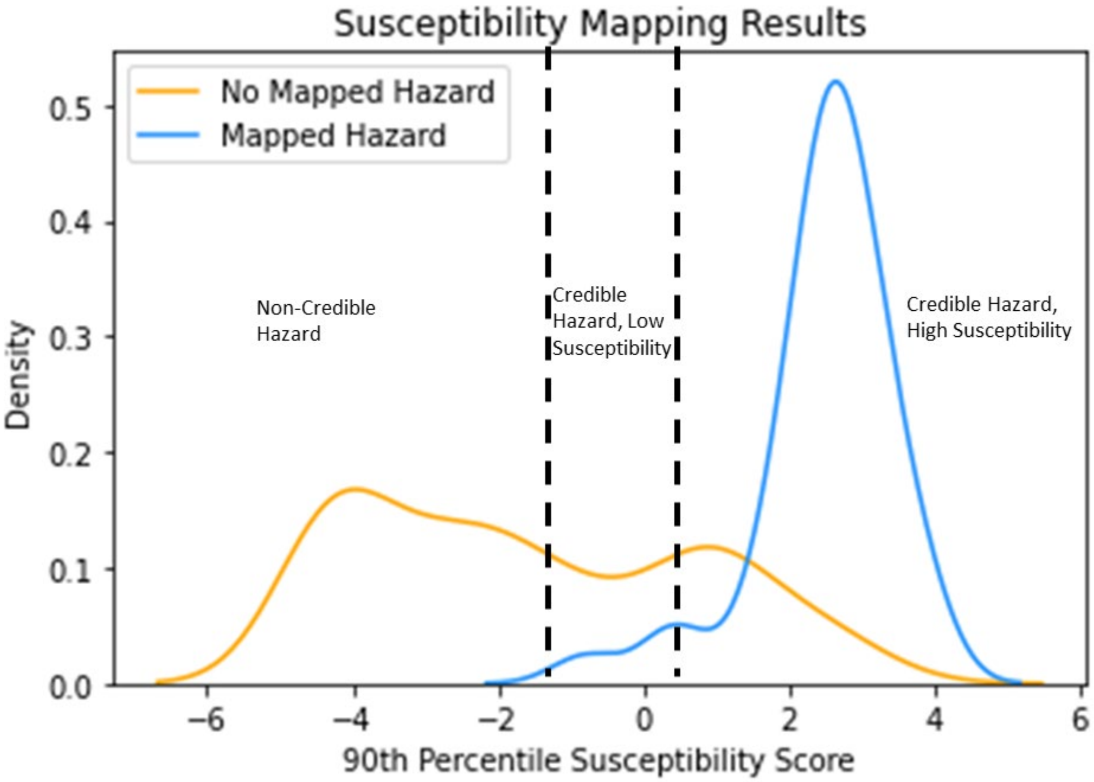
Table 2-3. Summary of conditional probabilities and weights assigned to each parameter.

		Points Within Range	Hazard Points within Range	Non Hazard Points within Range	Hazard Frequency within Range	Non-Hazard Frequency within Range	Ratio	Log Ratio
Fore-Slope Height	0 - 20	3064	97	2967	0.12	0.64	0.20	-0.71
	20 - 40	1586	275	1311	0.35	0.28	1.25	0.10
	>40	794	409	385	0.52	0.08	6.34	0.80
Fore-Slope Height/Fore-Slope Length	0 - 0.7	2633	26	2607	0.03	0.56	0.06	-1.23
	0.7 - 1.0	1470	229	1241	0.29	0.27	1.10	0.04
	1.0 - 1.25	972	272	700	0.35	0.15	2.32	0.37
	>1.25	369	254	115	0.33	0.02	13.19	1.12
Near-Slope Height/Near-Slope Length	0-0.5	3178	37	3141	0.05	0.67	0.07	-1.15
	0.5-0.75	1453	266	1187	0.34	0.25	1.34	0.13
	>0.75	813	478	335	0.61	0.07	8.52	0.93
Total Reach Height/Total Reach Length	<0.4	1563	20	1543	0.03	0.33	0.08	-1.11
	0.4-0.75	3115	429	2686	0.55	0.58	0.95	-0.02
	>0.75	766	332	434	0.43	0.09	4.57	0.66
Road Cut Geologic Material	Upper Colluvium	634	46	588	0.06	0.13	0.47	-0.33
	Upper Colluvium/Jordan Sandstone	1059	299	760	0.38	0.16	2.35	0.37
	Lower Colluvium	3751	436	3315	0.56	0.71	0.79	-0.10

The result of this exercise is a dimensionless "hazard" score for each point. In order to generate a useable result in the context of GAM, the hazard scores for each point were summarized into 0.1-mile clusters. This was done so that the generalized susceptibility score for given 0.1-mile stretch of highway is not based on a single data point but represents the compilation of weights for many points. This approach of segmenting in 0.1-mile intervals is similar to the approach used in presentation of pavement condition assessments. The results were summarized using the mean, median and the 90th percentile of all points for a given 0.1-mile segment of highway.

To translate these numbers into categories that can inform GAM, they were reclassified into qualitative bins denoting credibility of the hazard and the susceptibility rating. The divisions were made considering the general principles that negative meant that, in sum, there is an inverse correlation to the presence of a hazard when considering the modeled attributes, thus, the hazard is judged to be non-credible. When the value is positive, there is a positive correlation, in sum, of the attributes modeled to the hazard, thus the hazard is judged to be credible. Values that are near zero indicate that, while the hazard is credible, the section is not as susceptible to the hazard but does not have a higher likelihood of a hazard being present than the average likelihood of the entire study corridor. We used the geo-asset inventory created in the field to calibrate the boundaries between three qualitative ratings, shown statistically in Schematic 2-10. The three qualitative ratings are as follows and the values are discussed further in Section 3.0:

- High: Credible Hazard, High Susceptibility (<-1.15)
- Medium: Credible Hazard, Low Susceptibility (-1.15 – 0.9)
- Low: Non-Credible Hazard (>0.9).



Schematic 2-10. Statistical representation of susceptibility mapping results showing the distribution of non-hazard and hazards across susceptibility weight scores.

3.0 RESULTS AND DISCUSSION

3.1. Susceptibility Model Results

BGC has developed a shallow slope failure model for WI-35 in Crawford County, WI. Based on GIS modeling and field verification, the parameters with the strongest correlation to existing and past documented up slope failures along the corridor include:

- Fore-slope height
- Fore-slope angle
- Near-slope angle
- Total slope angle
- Cut-slope geologic material.

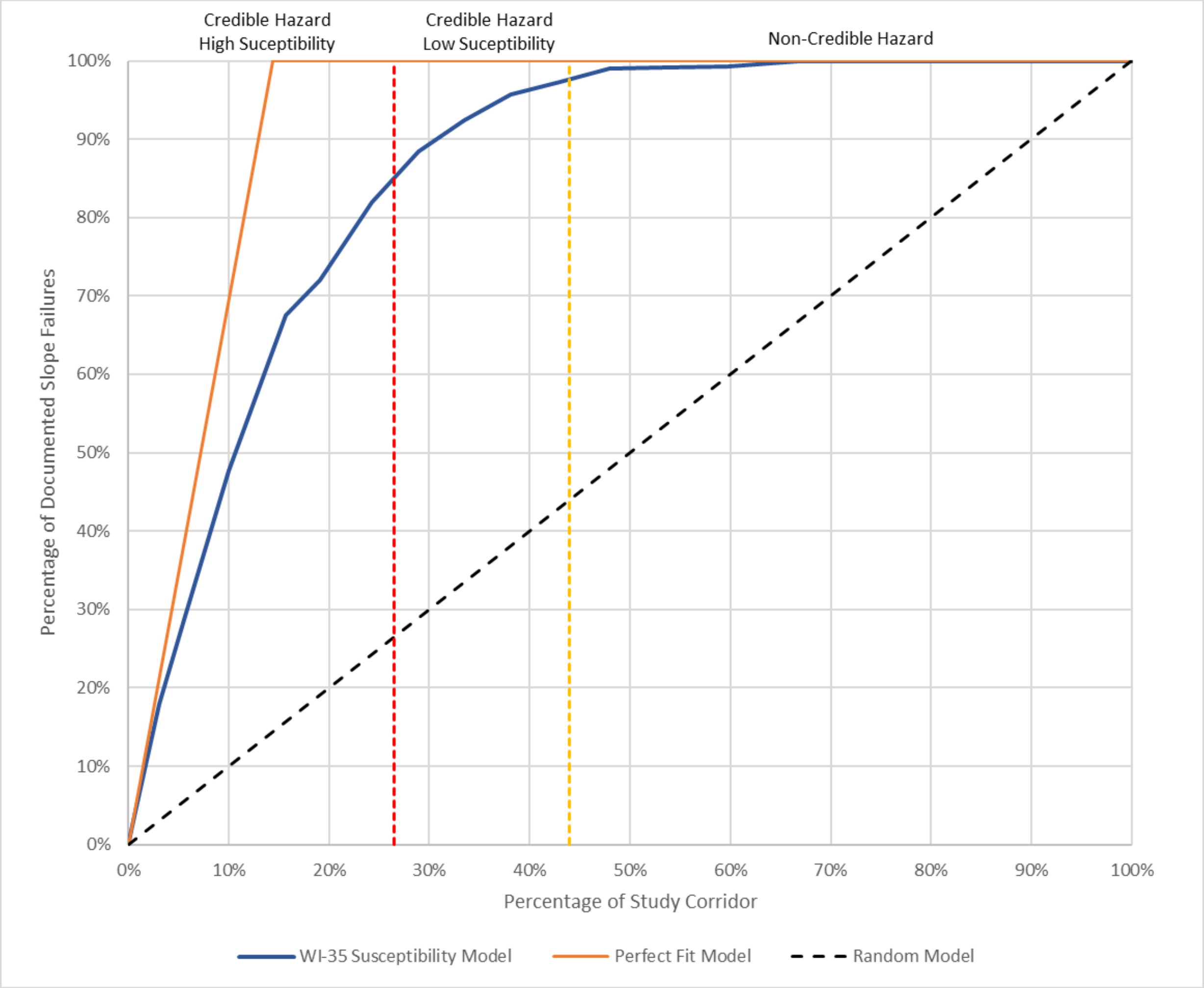
Based on the classification system developed as part of Task 6, the corridor has the following distribution for qualitative hazard susceptibility:

- 56% of the corridor falls into the Non-Credible Hazard category (low)
- 17.5% of the corridor falls into the Credible Hazard – Low Susceptibility category (medium)
- 26.5% of the corridor falls into the Credible Hazard – High Susceptibility category (high).

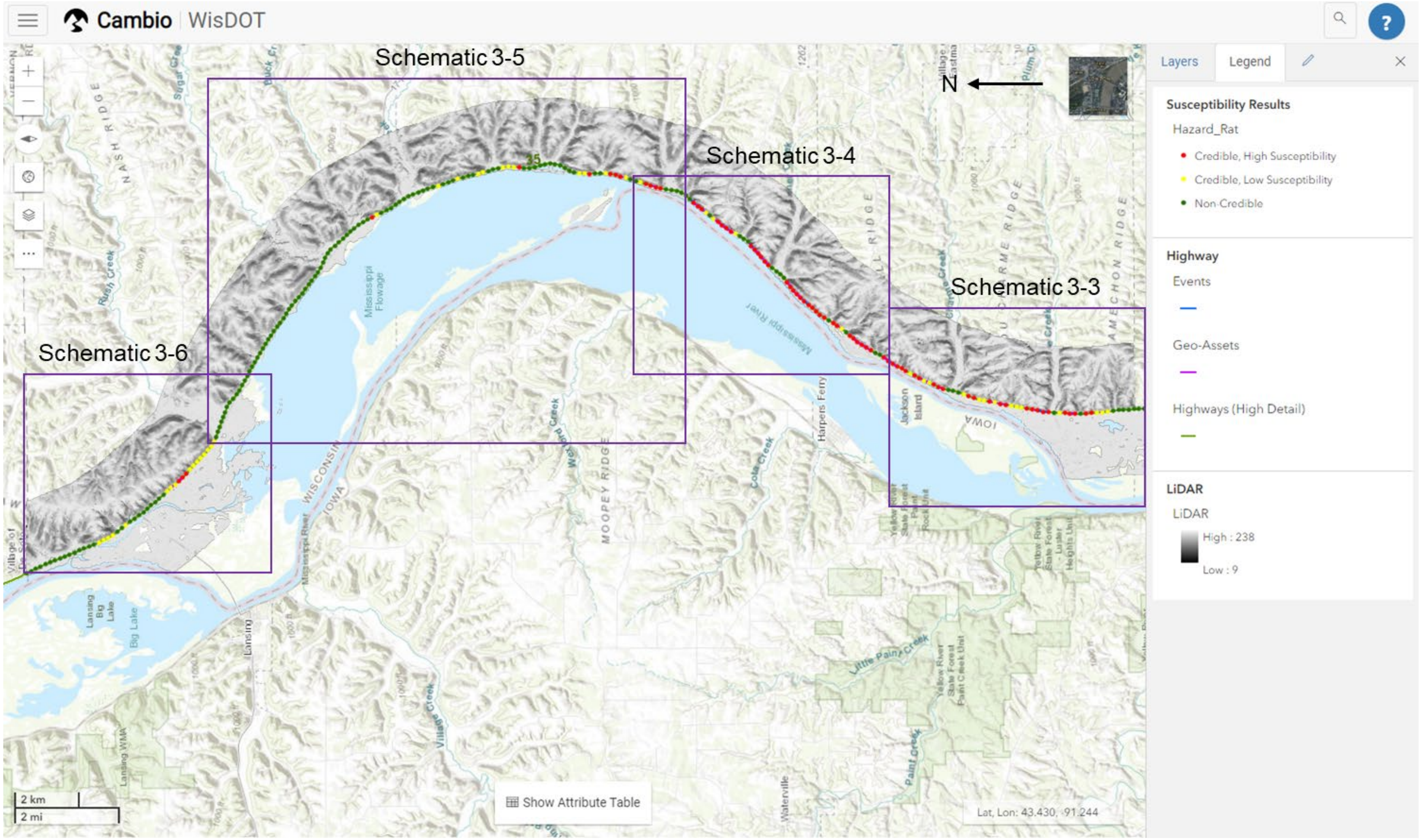
Schematic 3-2 through Schematic 3-6 show the results of the susceptibility model along the WI-35 study corridor binned into three classifications. This level of granularity is deemed appropriate for the relative simplicity of the model, and the type of inputs that go into asset management programs. The susceptibility model indicates that overall, the density of shallow slope failure susceptibility is highest in the southern portion of the study corridor and tends to decrease towards the north. In general, these results align with what was observed during the field verification exercise with the southern portion of the corridor having steeper and higher fore-slopes (a dominant factor in the susceptibility model) and has Jordan Sandstone, a documented rockfall-prone unit outcropping along the highway cut slope.

The mapped susceptibility output is a series of points spaced at 0.1 miles along the highway and identified in one of the susceptibility bins. Each point has a value representing the combined weight of all parameters considered in the susceptibility analysis; values within the results range from -4.3 to 3.8, though the smoothed distributions shown in Schematic 2-10 have tails ranging from approximately -7 to 6.5. The high and low values are associated with the highest and lowest probability for a slope failure, respectively, while values around zero represent a probability of slope failure which is approximately equal to the probability averaged over the study corridor (in this case a 14% chance). As seen in Schematic 3-3 through Schematic 3-7 some non-hazard highway segments fall into the Credible hazard categories. In these instances, the geometric and geologic characteristics of the slope are similar to those that have documented hazard segments and while no hazard has been currently documented, there may be a higher likelihood of a hazard developing in the future. This exemplifies the value in susceptibility mapping; the ability to identify potentially hazardous areas by extracting information from known hazards and applying it across a study area.

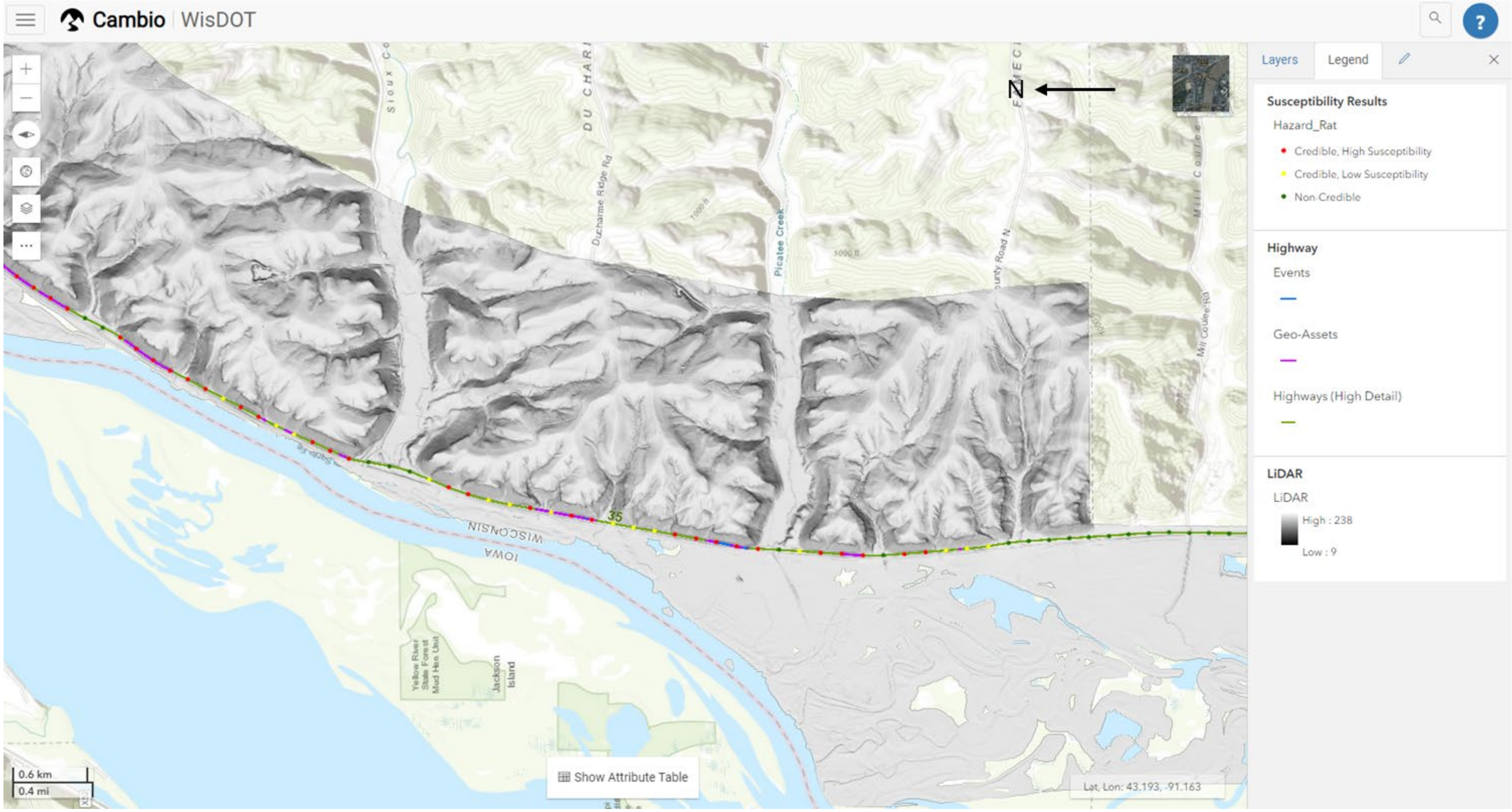
Schematic 3-1 shows the susceptibility map's predictive power within the study corridor. The orange line shows a "perfect" susceptibility model, one which could isolate all existing slope failures within the length of the corridor they occupy (i.e., 14% of the study corridor). The dashed black line shows a completely random model with no predictive capabilities at all. The blue line shows the performance of the susceptibility model generated as part of this scope. As can be seen in Schematic 3-1, the susceptibility model captures 85% of the documented slope failures in the Credible Hazard – High Susceptibility Category The orange line shows a "perfect" susceptibility model, one which could isolate all existing slope failures within the length of the corridor they occupy (i.e., 14% of the study corridor). The dashed black line shows a completely random model with no predictive capabilities at all. The blue line shows the performance of the susceptibility model generated as part of this scope., and 98% of the hazards within the combined Credible Hazard categories. Approximately 2% of the documented hazard segments fall within the Non-Credible Hazard category. This may be due to the way the susceptibility score is generalized between all points within a given 0.1-mile segment or measurement scale for documentation of the hazards in the field. Further assessment of these limited hazard segments could serve to improve the model; however, there may be a trade-off cost in obtaining the additional precision that is not justified.



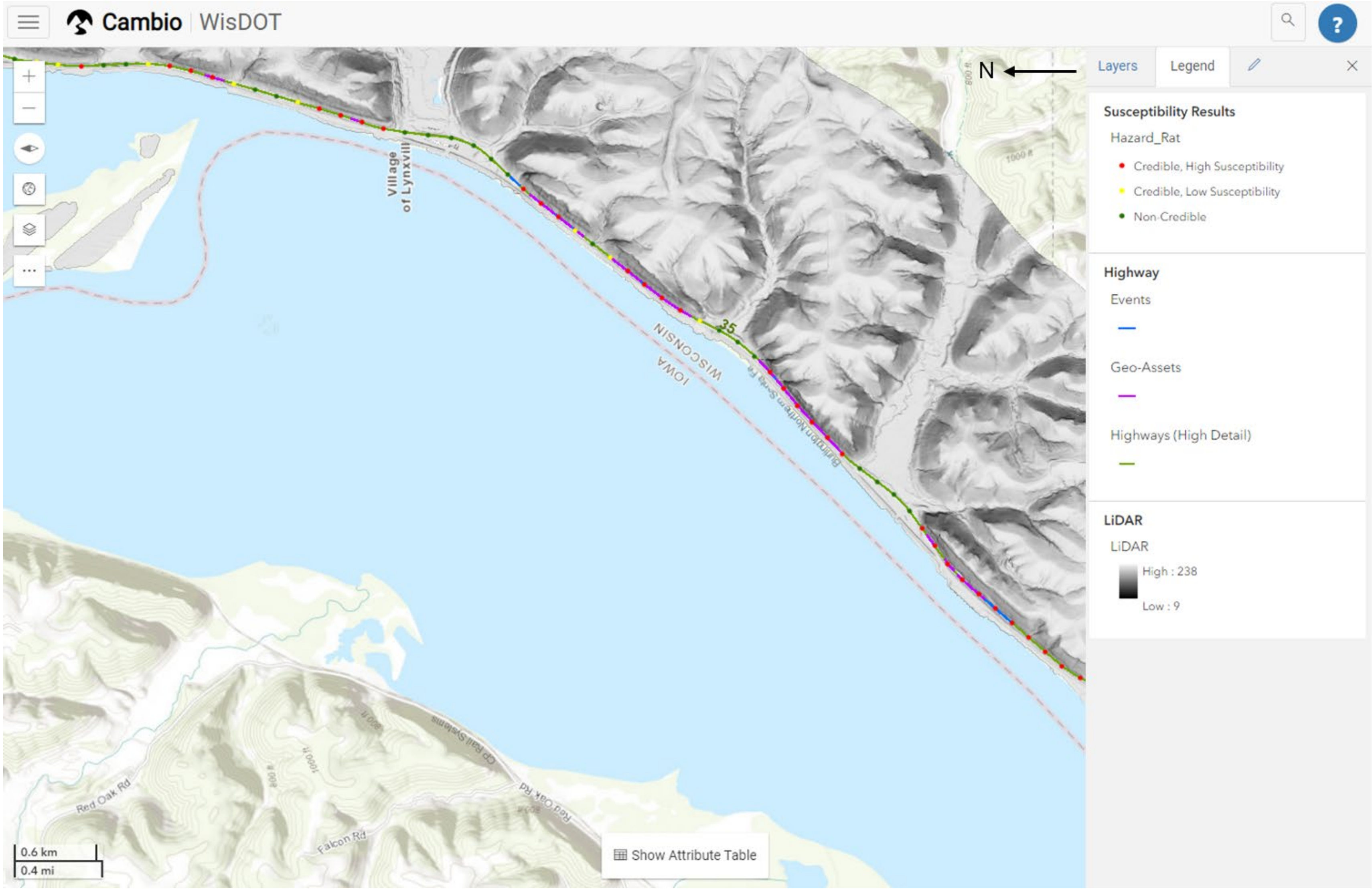
Schematic 3-1. Plot showing the predictive power of the WI-35 Susceptibility Model against a perfect fit model (orange) and a completely random model (black dashed line). The hazard categories are also shown.



Schematic 3-2. Plan-view showing the results of the WI-35 Shallow Landslide Susceptibility model and inset locations.

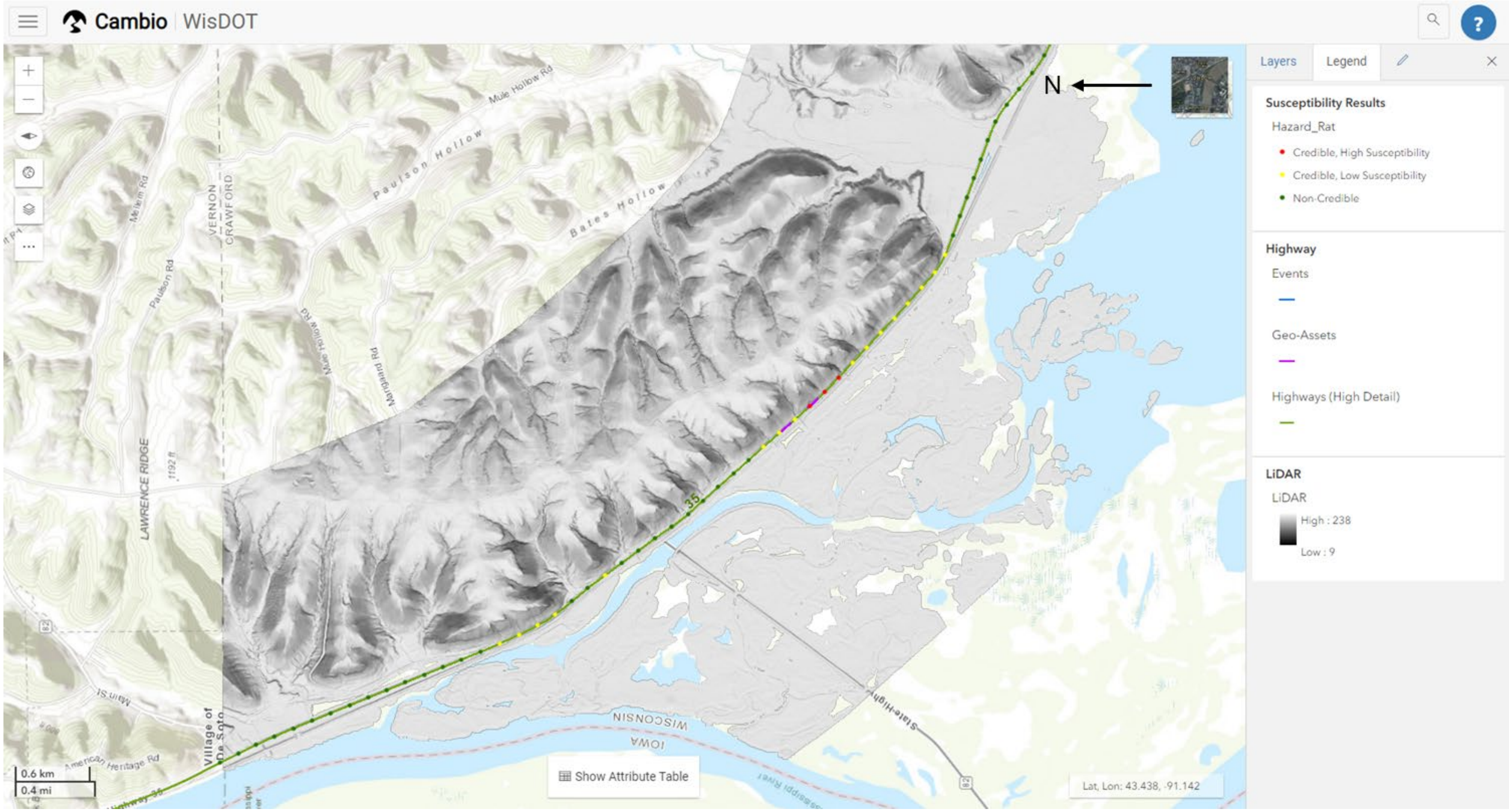


Schematic 3-3. **Plan-view showing the susceptibility results, WisDOT events, and documented geo-assets in the southern-most portion of the WI-35 study corridor.**



Schematic 3-4. **Plan-view showing the susceptibility results, WisDOT events, and documented geo-assets in the mid-southern portion of the WI-35 study corridor.**

Schematic 3-5. Plan-view showing the susceptibility results, WisDOT events, and documented geo-assets in the mid-northern portion of the WI-35 study corridor.



Schematic 3-6. **Plan-view showing the susceptibility results, WisDOT events, and documented geo-assets in the northern-most portion of the WI-35 study corridor.**

3.2. Susceptibility Model Limitations

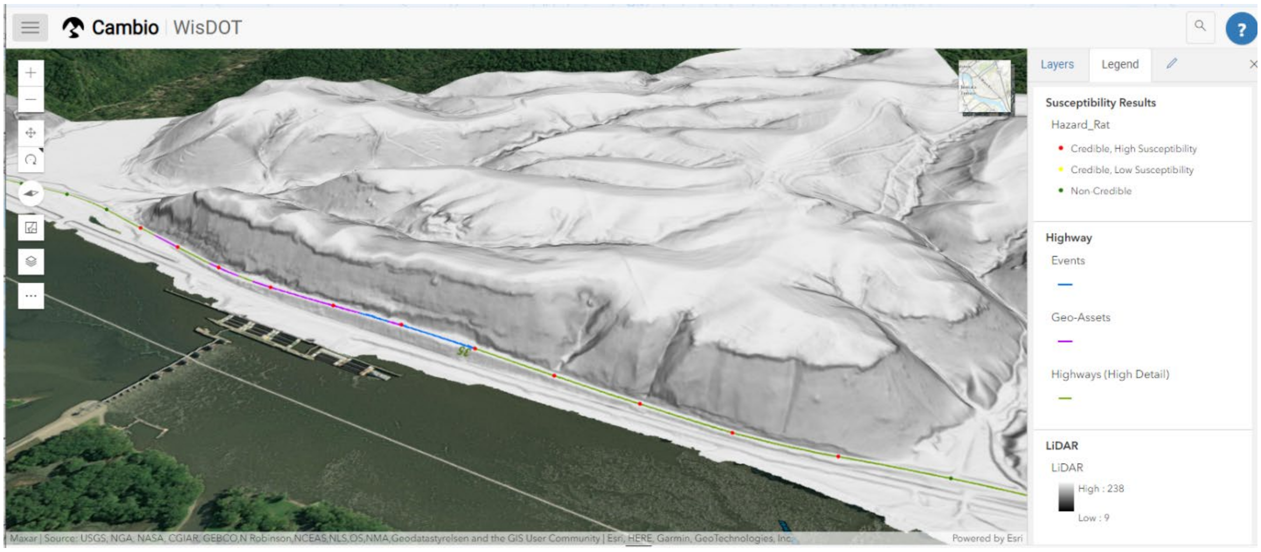
The model produced here does not distinguish between different up slope failure mechanisms. The training data which informed the model was used in a generic way to identify up slope hazards within the study corridor. Further study would be necessary to subdivide up slope susceptibility to different landslide types (e.g., colluvial slide vs rockfall). This may or may not be important depending on the deterioration rates or consequences of the various types of slope failure. If the slope failures all have similar consequences, continuing to use the generic classification may be an appropriate level of investment and enable expansion of susceptibility analysis over a wider geographic area.

Because the study corridor is relatively small and relatively homogenous in terms of physiography, it was possible to generate a thorough inventory of mapped hazards, thus driving up the number of hazard segments in the “High Hazard Susceptibility” category and improving the performance of the model. In order to expand the model across a similar physiographic region, outside of the study corridor, model validation is recommended. This would involve compiling other shallow slope failure locations in the region and assessing whether the weight and assigned category at that location is appropriate. Given that there is an incomplete hazard inventory outside of the study corridor, there likely would be an increase in the uncertainty and variability of the results (essentially the blue line in Schematic 3-1 would shift towards the black dashed line). It would be expected that at a regional scale the proportion of hazards falling into the “Credible Hazard, Low Susceptibility” classification would be higher than what these results suggest.

While the current model was able to predict hazard prone slopes in the study corridor, its applicability would be limited to similar physiographic regions with similar geologic materials. In other physiographic regions of Wisconsin, different geologic materials and topography would influence the dominant slope failure processes. While the current parameters may not be suitable, the process of model creation and calibration would still apply and it is anticipated that similar parameters (fore-slope height, fore-slope angle, geologic material, etc.) would still influence slope failures, albeit with different weights and hazard category ranges. Should further work continue elsewhere in the state, field validation would be recommended within a test area to calibrate the model and if the model is properly predicting slope failure occurrence outside of the test area. It is important to note that the process developed in this study for generating polyline profiles and extracting topographic information for them is generic and can be deployed anywhere, however the predictive parameters and the bin category boundaries will likely vary from one region to another.

3.3. Slope Susceptibility Mapping and Geotechnical Asset Management

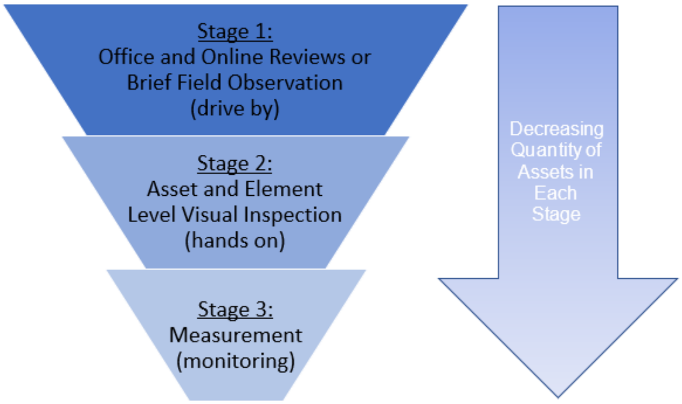
Slope susceptibility mapping offers WisDOT an opportunity to expand the knowledge of threats from natural hazards and deteriorating assets in a way that builds upon event history and is not limited by it. Historically, the practice of rockfall hazard and unstable slope management has developed from a knowledge of where events are occurring. This approach can create gaps in knowledge for sites that have a credible hazard but have not yet had a documented event. Examples of this may include rock outcrops with low frequencies of notable events or a cut slope that is in the later stages of deterioration and starting to exhibit rockfall when previously there was no known rockfall. A representation of how susceptibility mapping closes knowledge gaps in an event-based system is shown in Schematic 3-7. This schematic shows a 3D view of a portion of the WI-35 Corridor where known events are represented with a blue line. For the image in Schematic 3-7, the red points at 0.1 mile spacing indicate the slope above the highway is shown to have high susceptibility, yet only a portion of the slope has a mapped event.



Schematic 3-7. View of high susceptibility slopes near MP 72.5 without prior event history adjacent to slopes with prior activity.

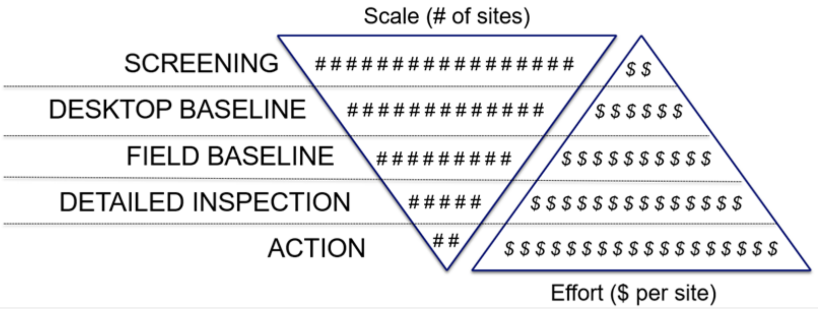
Using the slope susceptibility approach in GAM inventory management transitions a GAM program from an event-based inventory into an inventory that first considers credibility of an event. A susceptibility informed GAM inventory is larger than one limited by past event observation, and it is important to build the inventory in an efficient way that does not compromise the cost-benefit of performing the full cycle of asset management.

Across all types of asset management systems, a staged or phased approach for inventory development and ongoing measurement is a common approach for efficiency in the inventory step of asset management. Schematic 3-8 presents this concept for GAM as presented in NHCRP Report 903 (NASEM, 2019). Within a staged inventory workflow, not all assets or hazards will necessarily go to the final, detailed data-collection level. Inspecting an asset to the most detailed data state occurs only where justified.



Schematic 3-8. Staged approach for data collection in GAM (from NASEM, 2019).

Using a multi-level prioritization process for inventory and assessment requires a lower effort for the initial steps of hazard and risk measurement across a greater portion of the inventory. Once initial hazard and/or risk levels are estimated, a GAM program can complete further assessment steps, but for a smaller portion of the inventory where the levels are highest, or uncertainty is greatest. This process can be visualized in the graphic shown in Schematic 3-9, which expands on NASEM (2019) to include the relative investment level through some form of action or treatment. The slope susceptibility framework presented in this here, covers the first two levels of such a prioritization process for cut slopes – credibility screening and office (desktop) assessment.



Schematic 3-9. Conceptual relationship between staged inspection and action steps in GAM and relative effort.

Slope failure susceptibility modeling as demonstrated along the WI-35 Crawford County corridor can be used as a preliminary screening analysis in an overall phased GAM program. The WI-35 shallow slope failure susceptibility model identifies the majority of slope hazards within the corridor within the highest susceptibility category. This enables WisDOT to focus future efforts predominantly on these areas, rather than uniformly across the entire corridor. Similar maps could be developed for other slope hazards and in different geographies using the process outlined in this report.

The susceptibility maps continue to provide value outside of screening as well. During future rehabilitation or reconstruction projects, regional susceptibility maps may be used to identify highway sections requiring further investigation and locations where there is a cost-benefit relationship between performance and hazard mitigation options.

Further, GAM is a process that enables WisDOT to understand how credible hazards change with time based on heuristic or observation-based deterioration models and continuous learning across the system. By understanding the potential timing of changes in condition, WisDOT is able to forecast future investment needs.

4.0 RECOMMENDATIONS FOR FUTURE WORK

The model generated for this study was informed by a combination of geometric parameters extracted from regional-scale GIS data and slope failure information mostly derived from local scale geological observations (past events, activity, and outcrop mapping). The geometric parameters can be easily extracted for any location. However, the characteristics of slope failure mechanisms and their relationship to the underlying geological conditions will vary geographically. Therefore, further application of this specific model as developed within this scope should be limited to areas within the Driftless Area of Wisconsin. The geology and geohazard context are expected to be consistent throughout this region, though model validation using documented shallow upslope failures is recommended to assess what additional calibration, if any, is necessary.

Through the conduct of this research BGC identified subjects that could be steps for future research or GAM implementation at WisDOT. These topics are (a) expansion of the susceptibility model and GIS platform for management over larger areas and (b) initiating a GIS-based geotechnical asset management approach where susceptibility to landslides is the first step. This could be done on a pilot corridor, such as the one used here, or at different scale. These two ideas for implementation can be done in any order or simultaneously and then combined. They are discussed further in Section 4.1 and Section 4.2.

4.1. Expansion of the Susceptibility Model and GIS Platform

4.1.1. Expansion of the Shallow Slope Failure Susceptibility Model Within Wisconsin Driftless Area

This work would involve expanding the current model outside of the WI-35 corridor to the entire physiographic region of the Wisconsin Driftless area. This would test the model's validity outside of the calibration corridor and enable WisDOT to develop validation methods that would be necessary for expansion of this method at a statewide level. This study would include collecting or developing an expanded database of past slope failures along the highway system in this region and may require a small, targeted field program to document geologic materials in various locations throughout the region.

4.1.2. Development of Embankment Failure Susceptibility Model

Embankment distress was generally observed coincident to culverts intended to convey water from the cut slope side of the highway to the embankment side of the highway. The embankments hadn't failed completely, but there was evidence of cracking, patching and paving that shows that movement is occurring, and it could be worsening. WisDOT personnel indicated that these culverts are prone to clogging by debris (soil, rock, and woody debris). The susceptibility model would start with the presumed failure mode that clogging limits culvert capacity and causes overflow during storms, resulting in sheet flow across the highway to the embankment side. In addition, there could be increased erosion and pore water pressure increases caused by the backed-up stormwater at culvert inlets and the resulting sheet flow. As illustrated in part of Table 4-1 embankment failures could be assessed using a similar combination of thematic data as that used for the model developed in this study and using this presumed failure mode.

4.1.3. Statewide Landslide Susceptibility Modeling

The methodology here was intentionally chosen so that it could be expanded to inform a state-wide hazard management system. Theoretically, it would be possible to assign equivalent material types to the three geologic units included in weighting here, and then to use those weights and the weights for geometric characteristics found here, and simply apply them across the state, binning into three classifications (Non-susceptible, Low Susceptibility and High Susceptibility), as done here, but this model would likely be inaccurate. The inaccuracy would stem from the difference in material types, failure mechanisms, and their causal relationship to the parameters in the model.

Expansion of the methodology to a state-wide susceptibility model would require additional study of geologic materials and comparisons with geohazards throughout the state. The process used here would be directly applicable, but different physiographic regions would likely have different hazards, different key variables, and different weights of evidence. If the same process was used statewide to develop the ranking of susceptibility, the inventory of all sites statewide can be considered as one and there would be a reasonable equivalence between high susceptibility in one area with that in another. Parameters that were considered for this model are presented in Table 4-1 along with other parameters that could be added or be more valuable in other regions of the state.

Table 4-1. Summary of model parameters, how they were used in this model and how they could be used in future studies.

	Possible Parameters to include in Model	Embankment Failures	Up Slope Hazards	Off RoW Hazard	Source
Considered within this model	Cut Slope Height		X		Lidar, Highway Geometry
	Cut Slope Angle		X		Lidar, Highway Geometry
	Natural Slope Height			X	Lidar, Highway Geometry
	Natural Slope Angle		X	X	Lidar, Highway Geometry
	Geology	X	X	X	Geologic Maps, Field verification

	Possible Parameters to include in Model	**Embankment Failures**	**Up Slope Hazards**	**Off RoW Hazard**	**Source**
Possibly incorporated in future model development	Slope Setback Distance from Highway[1]	X	X	X	Lidar, Highway Geometry
	Condition of Slope (as Recorded in Cambio)	X	X	X	Site observation and recording forms
	Embankment Height	X			Lidar, Highway Geometry
	Embankment downslope Angle	X			Lidar, Highway Geometry
	Proximity to Culvert	X			Highway Geometry and features
	Proximity to waterway	X			Highway geometry, river network
	Upslope Catchment Area			X	Lidar, Highway Geometry
	Adjacent Land Use	X	X	X	Public data, earth observation images

Notes:

1. The slope offset parameter was calculated as part of the cross-section parameter extraction, however, it was not included in the statistical model.

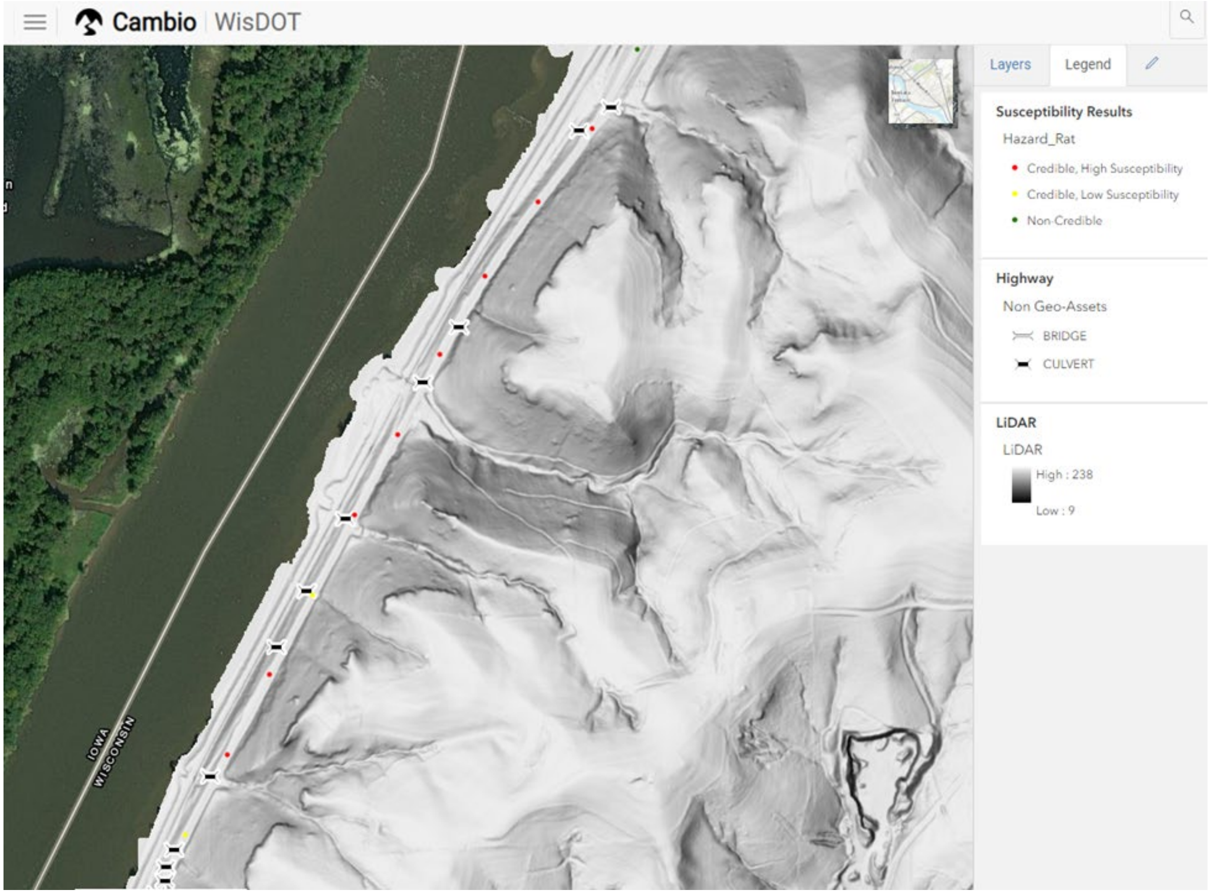
4.2. GIS-based Geotechnical Asset Management

Susceptibility mapping is an important step in risk-based GAM because it addresses the aspects of building an inventory and assessing the likelihood of an event occurring. Both the inventory and likelihood assessment can be refined through more detailed work and the outcome here helps in setting priority with where to start, and this could be done at the priority sites, which, in reference to Schematic 3-8 is moving down a row. Regardless, of the approach to inventory and likelihood (susceptibility), there are a few steps needed to get to risk-based GAM.

In particular, risk requires consideration of consequence, and that is also best done in a GIS framework because consequence involves the size of hazards, the proximity to elements at risk, temporal probability related to traffic volume, and interaction with other assets, such as walls, bridges and culverts. This type of interaction can be seen in Schematic 4-1. Consequence is measured with respect to performance objectives, so those need to be clearly established. It is possible to align those measures with performance measures established by the state's Transportation Asset Management Plan or a performance measurement plan. In the absence of these, GAM performance measures are usually established for safety, mobility (which is essentially a cost to users of the highway system), and owner cost, especially as related to operations and repair across a lifecycle.

Establishing the performance objectives and how they will be measured is an important first step, but after this step there are many reasonable approaches. Many states have started with a particular asset class and in one priority or experimental area, though there is no requirement to do so. Asset management involves making an investment now for a savings (dollars, risk, or other performance measure) later, and this doesn't often align well with historical funding streams, even if it makes good long-term sense, so it may be easier to start small, and add improvements later.

This current project has addressed cut slopes as the asset, so that can be a starting point. At this stage of GAM development for highway agencies, there are not a lot of data to describe the consequence of a certain event occurring, whether it is the likelihood of a fatality or serious accident, or a length of highway closure, or the cost of deferred maintenance rather than preservation activities. While many sources are sought to reliably inform risk assessment inputs, judgment is usually required to set the relationships between events and outcomes when starting GAM. Judgment is usually incorporated through a facilitated process of elicitations from experts with the hazards, the highway maintenance, and the familiarity with the system. As Wisconsin and other states become more mature with GAM, data recorded from consequences will largely replace judgment and the framework of the approach will stay the same. Interestingly, an integrated GIS platform also provides a valuable approach for recording data from past and future events and enabling learning from those data through various spatial relationships and calibration of risk assessment algorithms.



Schematic 4-1. Plan-view showing the WI-35 susceptibility map in relation to geotechnical assets along the WI-35 corridor.

5.0 CLOSURE

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