ANALYSIS OF SLOPE FAILURES ALONG ALABAMA HIGHWAYS

by

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ABSTRACT

Slope stability management systems (SSMSs) have been developed by multiple state transportation agencies to assess landslides adjacent to highways—aiding in the effective allocation of resources for slope and/or roadway repairs. The Alabama Department of Transportation (ALDOT) does not have a SSMS which may hinder its ability to effectively manage landslide hazards. This thesis discusses the development and analysis of two SSMS components for ALDOT: the data collection system (Slide Spread), and the asset management system (the Landslide Hazard Prioritization system (LHPS)).

The data collected within Slide Spread were used to determine common trends and similarities between landslides and environmental factors, as well as between landslides and other landslides. The research identified geologic units with higher likelihoods of landslide events, as well as the impact of precipitation within the region. The Tuscaloosa Group, Midway Group, and Selma Group Chalk had a higher likelihood of landslide events along roadways. Whereas, slides were less likely to occur in limestone dominated regions. 25% of the landslides analyzed occurred within 1000 feet of converging geologic groups, possibly indicating regions of weaker soils near joints or boundaries. The rainfall analysis illustrated the number of slides within a region generally increased with increasing precipitation. However, few slides occurred within limestone dominated regions despite the amount of rainfall experienced.

In addition, Slide Spread was used to compare common landslide attributes. Approximately 40% of landslides occurred at or adjacent to a past failure, indicating possible weak soils located at joints and boundaries. 61% of slides occurred within fill sections along the roadway, displaying possible compaction flaws within their construction. 30% of landslides were located near culverts—however the number of failures at damaged and undamaged culverts were relatively equivalent. The majority of slides within the database were classified as either translational failures or shallow failures. Translational failures were likely triggered by to rainfall events, leading to slip surfaces within the slopes. The shallow failures consisted of failures within the fill and cut sections, as well as failures due to erosion.

The LHPS is a landslide rating system used to determine and rank the impact of a landslide on the adjacent roadway and the traveling public. The system determined Morgan, Bullock, Etowah and Macon Counties had the highest hazard score ratings, and I-85 was the roadway most affected by the landslides. The system does not currently consider the accident history along the roadway, maintenance frequency, length of roadway impact, or precipitation—which should be added in future studies. The results of this research will allow ALDOT engineers to better plan and mitigate roadway impacts from landslides.

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation
ADT	Annual Daily Traffic
ALDOT	Alabama Department of Transportation
AKDOT	Alaska Department of Transportation
ATD	Alabama Traffic Data
CARE	Critical Analysis Reporting Environment
DDIR	Detailed Damage Inspection Reports
ER	Emergency Relief Slides
FHWA	Federal Highway Administration
GIS	Geographic Information Systems
GSA	Geologic Survey of Alabama
GUI	Graphical User Interface
LHPS	Landslide Hazard Prioritization System
MDOT	Maryland Department of Transportation
MP	Mile Post
NWS	National Weather Service
ODOT	Oregon Department of Transportation
OHDOT	Ohio Department of Transportation
RHRS	Rockfall Hazard Rating System

SHA	Maryland State Highway Administration
SLIDO	Statewide Landslide Information Database for Oregon
SSMS	Slope Stability Management System
PDSD	Percent Decision Sight Distance
UDOT	Utah Department of Transportation
U.S	United States
USCS	Unified Soil Classification System
USGS	United States Geologic Survey
USMP	Unstable Slope Management Program
USMS	Unstable Slope Management System
VBA	Visual Basic for Applications
WSDOT	Washington State Department of Transportation

CHAPTER 1: INTRODUCTION

1.1 Background

Landslides along roadways are a significant concern for state and federal transportation agencies, leading to large direct repair costs as well as indirect costs—such as traffic disruption, driver inconvenience, commercial losses, road closure, and secondary maintenance. Landslide repairs and related maintenance are estimated to cost the United States between \$2.1 and \$4.3 billion annually (Klose 2015). However, fewer estimates are available for costs due to landslides along highways. Walkinshaw (1992) estimated state highway departments spend \$106 million annually (1992 dollars) on landslide repairs, although the author suggests that this is likely "only a fraction of the total annual costs of landslides to the state highway network."

A landslide, defined as "the movement of a mass of rock, debris or earth down a slope" (Cruden et al. 1996), occurs when an imbalance exists between the driving forces (e.g., weight of the slide mass) and resisting forces (e.g., strength of the soil) on the slope. The main triggers for landslides can be categorized as either increases in driving forces or reductions in the resisting forces (Duncan et al. 2014). Driving forces may increase due to events such as extreme rainfall (leading to saturated slopes or changes in the groundwater table), additional surcharge loading, or ponding of water. Reductions in resisting forces may occur due to decreases in effective stress (caused by an increased pore water pressure), strain softening in the soil, or removal of material from the toe of the slide. Very rarely can a single cause of failure be identified for a landslide, as failure often occurs due to a combination of factors (Duncan et al. 2014); for example, rainfall may lead to higher driving forces and reduced effective stresses.

Management of landslide hazards requires collecting detailed information on the physical and material characteristics of landslides, as well as their impacts on the traveling public. This task is often accomplished through the use of slope stability management systems (SSMS), or landslide mitigation programs, developed by state agencies to aid in the prediction or identification of landslide risk areas and implementation of remediation or mitigation methods based on a hazard rating system, while reducing costs and traffic disruptions.

The United States (U.S.) Federal Highway Administration (FHWA) has suggested all states develop and implement a landslide and rockfall inventory to aid in the future development of slope repair cost estimates and remediation plans (Hopkins et al. 2003). The landslide and rockfall inventories will assist the U.S. Congress with funding distributions as well as the formation of a national highway slope repair program devoted to providing additional funding to state transportation agencies (Hopkins et al. 2003). At least fifteen state transportations agencies within the U.S. have developed and implemented SSMSs to collect, track, and analyze landslide data for slides occurring along state highways (e.g., Aydilek et al. 2013, Badger et al. 2013, Burns et al. 2014, Calvin et al. 2009, Douglas et al. 2013, Eliassen et al. 2007, Eliassen et al. 2015, Hopkins et al. 2003, Maerz et al. 2004, NYSDOT 2007, ODOT 2001, Pack et al. 2002, Pack et al. 2007, Pensomboon et al. 2007, Pierson et al. 2005, Pratt et al. 2014, Rose et al. 2005, and Whitehouse et al. 2006).

SSMSs catalog and analyze slope failures through the use of three main components: a landslide data collection system, a Geographic Information Systems (GIS) database, and a hazard prioritization system. The components form a landslide management system used for the identification or prediction of landslide risk areas, and the determination of landslide hazards effecting motorists. The Alabama Department of Transportation (ALDOT) does not currently employ a SSMS, limiting the ability of the ALDOT to identify common failure categories, and effectively allocate funds based on hazard to the roadway and traveling public.

1.2 Objective and Scope

This paper discusses the development of two components of a SSMS for Alabama: (1) Slide Spread, and (2) the Landslide Hazard Prioritization System (LHPS). Slide Spread is a landslide collection system and database developed to improve the ability of ALDOT in the identification and repair of slope failures along Alabama highways. The data collected through Slide Spread was converted into a GIS database—which will be used to identify trends between landslides and additional spatial data, such as average precipitation and surface geology. This database was used to identify eleven case histories, representing common landslide failures throughout the state. The study of the landslide similarities and case histories is on-going.

In addition, this thesis examines the effects of landslides on roadways through an evaluation of effects on Alabama highways. The LHPS is the first step in developing an asset management system for landslide repairs along Alabama highways. The goal of the research was to develop a landslide hazard prioritization system prototype through the analysis of landslide data and the annual average daily traffic (AADT)—obtained through Slide Spread (the Alabama landslide database) and the Alabama Traffic Data (ATD) database, respectively. The paper discusses the development of a roadway analysis system for ALDOT meant to improve their ability to identify and address traffic disruptions caused by landslides.

The primary objective of this research was to determine common failure categories of landslides along Alabama highways, to assist in the future development of effective and efficient remediation and mitigation measures. This was accomplished through the development of a landslide data collection system and database, called Slide Spread—populated using data collected from landslide reports (consisting of ALDOT landslide reports and slope stability reports) and Detailed Damage Inspection Reports (DDIRs). The specific objectives of the development of this system listed below.

1. Develop a data collection system and database of recent landslides (occurring between the years 1990 to 2017) along Alabama highways including information of the location, failure geometry, failure timing, weather conditions, stratigraphy, geology, repair method, and failure category.
2. Identify trends between similar landslides in the database through the examination of failure category, geologic conditions, and weather events at the site.
3. Determine common failure mechanisms within each failure category through detailed examinations of representative case histories using of modeling software and data collected from field explorations and instrumentation (on-going).
4. Develop the framework for a landslide hazard prioritization system which ranks landslide hazard, aiding in the allocation of funds and resources during the remediation and mitigation of landslides along Alabama highways.
5. Complete a preliminary study of an asset management system (or landslide hazard prioritization system) using available data to evaluate the new system.

CHAPTER 2: BACKGROUND

2.1 Introduction

Landslides and rockfalls adjacent to highways may adversely impact both the roadway and the traveling public, leading to damages, road closure, and/or vehicle crashes. Therefore, many state transportation agencies have developed proactive approaches for managing landslide hazards—which examine the effects of the environment and climate conditions on slope stability, as well as the physical and material characteristics of the slopes. Several landslide databases have been developed throughout the world to collect and provide data on landslide hazards and risk assessments—producing probabilistic models which aid in remediation and mitigation efforts, and land planning. Rosser et al. (2017) estimated forty six countries have instituted landslide databases. In particular, the United States developed three landslide management programs through the federal government: (1) the Landslide Hazards Program, (2) the Global Landslide Catalog, and (3) the Rockfall Hazard Rating System (Rosser et al. 2017, Pierson et al. 1993). These programs consist of landslide inventories containing landslide and spatial data used to monitor sites, develop hazard warning systems, and reduce economic losses through the increased understanding of landslide causes and mitigation methods (Rosser et al. 2017, Pierson et al. 1993).

The United States (U.S.) Federal Highway Administration (FHWA) recommend states develop and implement landslide and rockfall inventories to assist with the development of slope repair cost estimates and remediation plans (Hopkins et al. 2003). At least fifteen state transportation agencies within the U.S. have followed these recommendations (Aydilek et al. 2013, Badger et al. 2013, Burns et al. 2014, Calvin et al. 2009, Douglas et al. 2013, Eliassen et al. 2007, Eliassen et al. 2015, Hopkins et al. 2003, Maerz et al. 2004, NYSDOT 2007, ODOT 2001, Pack et al. 2002, Pack et al. 2007, Pensomboon et al. 2007, Pierson et al. 2005, Pratt et al. 2014, Rose et al. 2005, and Whitehouse et al. 2006), developing state specific slope stability management systems (SSMSs) for highways. The SSMSs improve the documentation, study, and remediation process for landslides and rockfalls, specifically along highways, by tracking unstable slopes and repairs to form comprehensive state wide landslide inventories.

The purpose of state specific SSMSs is to aid in the identification of common slope failure mechanisms in the region, prediction or identification of landslide risk areas, and implementation of remediation or mitigation methods based on a landslide hazard rating system. This was generally accomplished through the development of three separate components within a SSMS: (1) a landslide data collection system, (2) a Geographic Information Systems (GIS) database, and (3) a hazard prioritization ranking system. This thesis documents the preliminary development of a SSMS for the Alabama Department of Transportation (ALDOT). The data collection system and database, called Slide Spread, and the hazard prioritization ranking system, called the Landslide Hazard Prioritization System (LHPS), were created to aid in the identification, tracking, and analysis of the effects of slope failures on highways and the traveling public, while accounting for the available data within Alabama landslide reports. The components were developed based on the implemented SSMSs of Alaska, Maryland, Ohio, Oregon, and Washington State. These systems were chosen for review due to the inclusion of a soil slope failure inventory, rather than or in addition to a rockfall and/or debris slide database.

The objective of this chapter is to present a review of the data collection systems and hazard ranking prioritization systems employed by other U.S. state transportation agencies, as well as to provide an overview of the historical landslide database and landslide susceptibility map currently employed in Alabama.

2.2 Slope Stability Management Systems

The SSMSs, or landslide and/or rockfall mitigation systems, are used to evaluate slope failures or potentially unstable slopes along highways, and prioritize remediation and mitigation based on the direct and indirect costs of the landslide and/or rockfall, as well as the impact to the roadway and traveling public. SSMSs have been designed and implemented by at least fifteen U.S. state transportation agencies: Alaska (Calvin et al. 2009), Colorado (Pratt et al. 2014), Kentucky (Hopkins et al. 2003), Maryland (Aydilek et al. 2013), Missouri (Maerz et al. 2004), Montana, New York (NYSDOT 2007), Ohio (ODOT 2001, Pensomboon et al. 2007), Oregon (Burns et al. 2014, Pierson et al. 2005), Tennessee (Rose et al. 2005), Utah (Pack et al. 2002, Pack et al. 2007), Vermont (Eliassen et al. 2007, Eliassen et al. 2015), Virginia (Whitehouse et al. 2006), Washington State (Badger et al. 2013), and West Virginia (Douglas et al. 2013). These systems were developed to aid in the management and mitigation of landslides along state highways through the documentation of landslide attributes, the assessment of failures, and the tracking and/or determination of repair methods.

The specialized SSMSs evaluate landslide hazards through the collection of physical and material attributes of the landslide, along with historical data, to create ranking systems, or risk management systems, used to prioritize landslide repairs based on the potential impacts of the failure and needs associated with each state. For example, the Utah Department of Transportation (UDOT) developed a rockfall hazard rating system (RHRS). The system consists of a rockfall database containing information on failure sites that were used to develop a risk prediction model, determining mitigation regions based on the probability of future failures (Calvin et al. 2009). The

Washington State Department of Transportation (WSDOT) developed and implemented the Unstable Slope Management System (USMS) for both rockfall and soil slides (Calvin et al. 2009). The USMS identifies and prioritizes landslide mitigation based on hazard risk and cost-benefit analyses, aiding in the repair of identified unstable slopes rather than the predicting regions under landslide risk (Calvin et al. 2009).

Several SSMSs employ a risk and hazard analysis through an asset management system (Badger et al. 2013, Burns et al. 2014, Calvin et al. 2009, Douglas et al. 2013, Eliassen et al. 2007, Eliassen et al. 2015, Hopkins et al. 2003, Maerz et al. 2004, NYSDOT 2007, ODOT 2001, Pack et al. 2002, Pack et al. 2007, Pensomboon et al. 2007, Pierson et al. 2005, Pratt et al. 2014, Rose et al. 2005, and Whitehouse et al. 2006). These systems actively conduct cost-benefit analyses based on the hazard to the traveling public and the life-cycle cost of the roadway repairs. Asset management in terms of slope stability within transportation engineering includes maintaining the functionality slopes over the life-cycle of the adjacent roadways, while reducing costs and traffic disruptions (Thompson 2016). This is achieved by conducting performance assessments and investment analyses to study the functionality and life-cycle cost-benefit relationship of the roadway, as well as the return on investment (Thompson 2016). The overall goal of asset management within SSMSs is to allocate resources (i.e. funding, expertise, and equipment) to improve the performance of the roadway based on the available funds and hazard to the road (Thompson 2016).

2.3 Data Collection System of Slope Stability Management Systems

SSMSs collect and retrieve information on hazardous and/or failed slopes, aiding in the analysis of physical and material characteristics of landslides and landslide sites. The following section summarize the data collection systems of SSMSs implemented by five state transportation departments—AKDOT, Maryland Department of Transportation (MDOT), Ohio Department of Transportation (OHDOT), ODOT, and WSDOT. The systems were chosen because they all include a soil slide database and have publicly available reports discussing their development. The following paragraphs summarize some general attributes of these systems. Details can be found in the respective references.

The databases of these systems consist of similar data collection and storage methods—generally featuring field failure sheets and/or computer databases with Graphical User Interface (GUI) input systems. The field failure sheets are generally completed by the maintenance crew and/or engineers, providing detailed information on site observations and field investigations. The information is then inputted into a database program (e.g., Microsoft Access or Microsoft Excel). The data input systems typically have a GUI consisting of a series of tables with limited selection options—such as drop down menus, multiple choices responses, or short responses with character limitations (e.g., maximum number of characters, data type specification, etc.). The GUI creates uniform output responses from different users, allowing data to be easily analyzed, and requiring little user training. The systems focus on inputting data one slide at a time which prevents data from being overwritten or copied due to user error. The databases are integrated with GIS software, accessible to multiple users within the department.

The design of each data collection system and database greatly depends on the overall goals of the SSMS, as well as the parameters and variables of greatest concern within each state transportation department. Therefore, the specific types of data collected vary between the SSMSs reviewed (Table 2-1). For example, the ODOT and WSDOT focus largely on the roadway and motorist impacts of a landslide. Whereas, the AKDOT developed a slope stability asset management system focusing on prioritizing remediation based on cost-benefit analyses conducted at each failure site. The analyses take into account the cost of the repair, the life-cycle of the design, and the benefit of the repair to the traveling public. Therefore, data is collected on the past maintenance and repair frequency/costs as well as the effect of the failure on traffic and vehicle safety. In addition, the MDOT developed a landslide prediction model. The system focuses data collection on physical features which may be used to predict vulnerable regions along state highways. Therefore the data collection focuses on weather events, cross-section geometry, and failure causes.

Generally, data is collected on the location of the site, previous landslides and/or repairs at or adjacent to the failure site, impact to the surrounding structures and roadway, hazard to motorists, landslide geometry, soil stratigraphy, groundwater and surface water, and presumed cause of failure. Although the systems collect many of the same attributes, there is not a universal collection system that works for all state transportation departments. The only attributes collected in all five systems are the average daily traffic and impact to the roadway. This is largely due to the objective of each individual system.

Table 2-1. SSMS database comparison (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon et al. 2007)

Attributes	AKDOT	MDOT	OHDOT	ODOT	WSDOT
Adjacent Structures		X	X		
Adjacent Utilities		X			
Average Daily Traffic	X	X	X	O	O
Average Vehicle Risk	X				
Cleanup	X				
Design Geometry		X	X		
Existing Remediation		X	X		
Failure Cause		X	X		
Failure Surface Geometry	X	X	X		
Failure Surface Soil Type	X	X	X		
Freeze/Thaw Cycle	X				
Groundwater	X	X	X		
Maintenance Frequency/Cost	X		X	O	
Probability of Additional Movement			X		
Rate of Slide Movement					
Recommended Remediation		X	X		
Repair Status		X	X		
Roadway Impact	X	X	X	O	O
Site Location	X	X	X		
Slope Angle	X	X	X		
Slope Height	X	X	X		
Slope Materials (Geology)	X	X	X		
Surface Water	X	X	X		
Traffic Impact	X	X			O
Type of Failure	X	X	X	O	
Vegetation/Land Cover		X	X		
Vehicle Accident History	X			O	O
Vertical/Horizontal Displacement	X				
Weather Preceding/at Failure		X	X		

X is used to indicate attributes collected within the database

O is used to indicate attributes used in the hazard rating system for the SSMSs in which the data was not available to on the information collected within the landslide database.

2.4 Hazard Prioritization Ranking Systems of Slope Stability Management Systems

Landslide hazard prioritization systems are used to aid in the prioritization of roadway and slope repairs as part of multiple SSMSs (Calvin et al. 2009, Pratt et al. 2014, Hopkins et al. 2003, Maerz et al. 2004, Pierson et al. 2005, NYSDOT 2007, Pensomboon et al. 2007, ODOT 2001, Burns et al. 2017, Rose et al. 2005, Pack et al. 2002, Eliassen et al. 2007, Eliassen et al. 2015, Whitehouse 2006, Badger et al. 2013, Douglas et al. 2013). The hazard prioritization ranking system, or hazard scoring systems, rank landslides based on their impact to the roadway and traveling public using a hazard scoring matrix. Each landslide is assigned a numerical score, determined using qualitative and/or quantitative data identified as risk factors to determine the level of priority for landslide mitigation or remediation. Many of the SSMSs include the hazard score calculation within the landslide database. These systems automatically calculate the landslide hazard score through the use of defined queries (or defined calculations within the database)—combining the weighted effect of each risk factor. The hazard ranking or prioritization may include a cost-benefit and/or traffic volume analysis, as well as cost estimates and remediation plans for potentially hazardous slopes. Although these systems may be embedded within the landslide databases, the hazard ranking system and prioritization systems are developed after the creation of the landslide database and are beyond the scope of the current project.

Four prioritization systems were reviewed for this thesis. These systems were implemented by the AKDOT, OHDOT, ODOT, and WSDOT. The MDOT was excluded from this review because the system did not employ a hazard ranking system at the time the report was published. The systems were chosen for review because they all include a soil slide database and have public reports discussing their development. The landslide hazard prioritization systems of the above agencies consist of matrix ranking score systems. The score rates the hazard level of a landslide through a numerical value calculated based on safety factor parameters which influence both the roadway and motorists (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 2001). Generally, the systems collect information on the accident history, average traffic volume, risk to motorists, impact on traffic, hazard to the roadway, decision time, and maintenance and cost frequency of the site. These risk factors were based on parameters employed by slope prioritization systems (for both unstable rock cut and soil slope systems) used by other U.S. state transportation departments and/or other countries with similar climates and geologies—altering the variables based on the needs of the agency and the expertise of department engineers. A comparison of the data collected through these four systems is provided in Table 2-2. Although the systems collect many of the same risk factors, there is not a universal collection system or ranking method that works for all state transportation departments. The only risk factors collected in all four systems are the accident history, and maintenance frequency and cost. The risk factors used within the traffic hazard rating systems are defined in Table 2-3.

Table 2-2. Landslide Hazard Rating System Comprehensive Summary (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 2001)

Risk Factor*	**AKDOT**	**ODOT**	**OHDOT**	**WSDOT**
Accident History	X	X	X	X
Annual Daily Traffic (ADT)		X	X	X
Annual Average Daily Traffic (AADT)	X			X
Average Vehicle Risk	X		X	X
Impact on Traffic	X		X	X
Hazard Class	X			
Maintenance Frequency	X	X	X	X
Maintenance Cost	X	X	X	X
Percent Decision Sight Distance (PDSD)	X		X	X
Repair Cost				
Roadway Impact		X	X	X

*Risk factors are defined in Table 2-3.

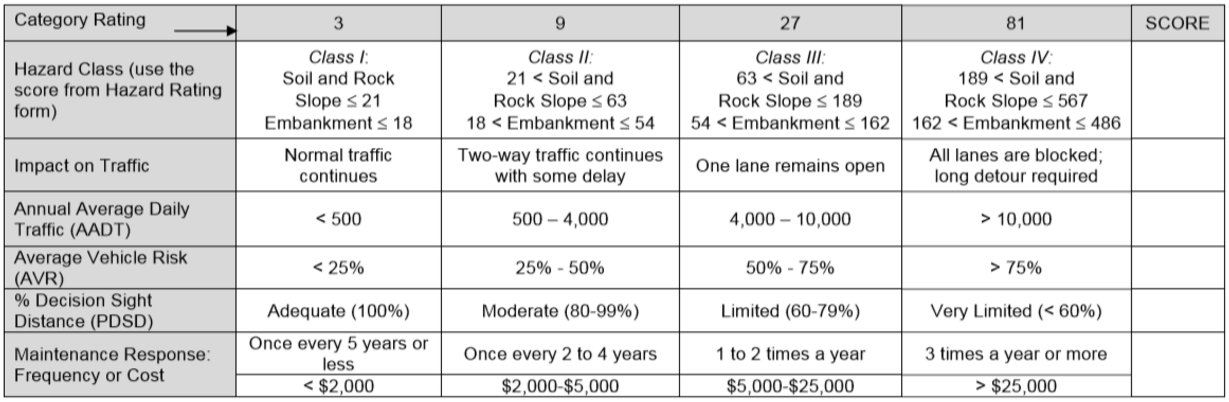
Table 2-3. Landslide Hazard Rating System Risk Factor Definitions (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 2001)

Risk Factor	**Definition**
Accident History*	The accident history is recorded in one of two methods: (1) the highest level of severity (i.e. property damage only, injury, and/or fatality) of traffic accidents due to the slope failures at or near the site over the past 10 years, or (2) the number of accidents occurring due to slope failure at or near the landslide site over the previous 10 years.
ADT	The straight line ADT along the roadway.
AADT	The total volume of vehicles traveling along a roadway per year divided by 365 days/year.
Average Vehicle Risk	The percentage of time a vehicle is within the zone of the slope failure. It is a function of the length of failure along the roadway, AADT, number of lanes, and the speed limit.
Impact on Traffic	The traffic disruption due to the slide (i.e. time delays, lane or road closures, and detours required)
Hazard Class	The hazard class accounts for the geometry of the slope (i.e. height, angle, etc.), the fill or native material, maintenance frequency, and roadway displacement (i.e. cracks, dips, and horizontal and vertical movement).
Maintenance Frequency	The number of failure events and maintenance repairs occurring over a five to ten year period at the site.
Maintenance Cost	The annual cost required to maintain the slope and roadway.
PDSD	The ratio of the actual sight distance to the Decision Sight Distance. It is road length a driver has to identify a 6 inch tall hazard in the roadway from a position of 3.5 feet above the ground.
Repair Cost	The cost required to repair the slope.
Roadway Impact	The effect of the landslide on the roadway—accounting for the remaining width of the roadway after the landslide event, the rate of movement of the slide, and the effect of the slide beyond the right of way.

*Only accidents resulting from landslide debris should be considered (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 2001).

The hazard score, a numerical value calculated using qualitative and/or quantitative data on identified risk factors, is used to determine the prioritization for roadway and landslide mitigation or remediation. Many of the SSMSs include the hazard score calculations within the landslide database by using defined queries based on the assigned numerical value indicating the effects of the risk factor, determined by the developers and/or the state transportation department. The hazard rank or prioritization may include a cost-benefit and/or traffic volume analysis, as well as cost estimates and remediation plans for potentially hazardous slopes. Table 2-4 provides an example of a hazard rating system, illustrating the scoring matrix employed by the AKDOT.

Table 2-4. The Slope Risk Assessment Form of the Unstable Slope Management Program (USMP) for the AKDOT (Calvin et al. 2009)



Category Rating →	3	9	27	81	SCORE
Hazard Class (use the score from Hazard Rating form)	*Class I:* Soil and Rock Slope ≤ 21 Embankment ≤ 18	*Class II:* 21 < Soil and Rock Slope ≤ 63 18 < Embankment ≤ 54	*Class III:* 63 < Soil and Rock Slope ≤ 189 54 < Embankment ≤ 162	*Class IV:* 189 < Soil and Rock Slope ≤ 567 162 < Embankment ≤ 486	
Impact on Traffic	Normal traffic continues	Two-way traffic continues with some delay	One lane remains open	All lanes are blocked; long detour required	
Annual Average Daily Traffic (AADT)	< 500	500 – 4,000	4,000 – 10,000	> 10,000	
Average Vehicle Risk (AVR)	< 25%	25% - 50%	50% - 75%	> 75%	
% Decision Sight Distance (PDSD)	Adequate (100%)	Moderate (80-99%)	Limited (60-79%)	Very Limited (< 60%)	
Maintenance Response: Frequency or Cost	Once every 5 years or less	Once every 2 to 4 years	1 to 2 times a year	3 times a year or more	
	< $2,000	$2,000-$5,000	$5,000-$25,000	> $25,000	

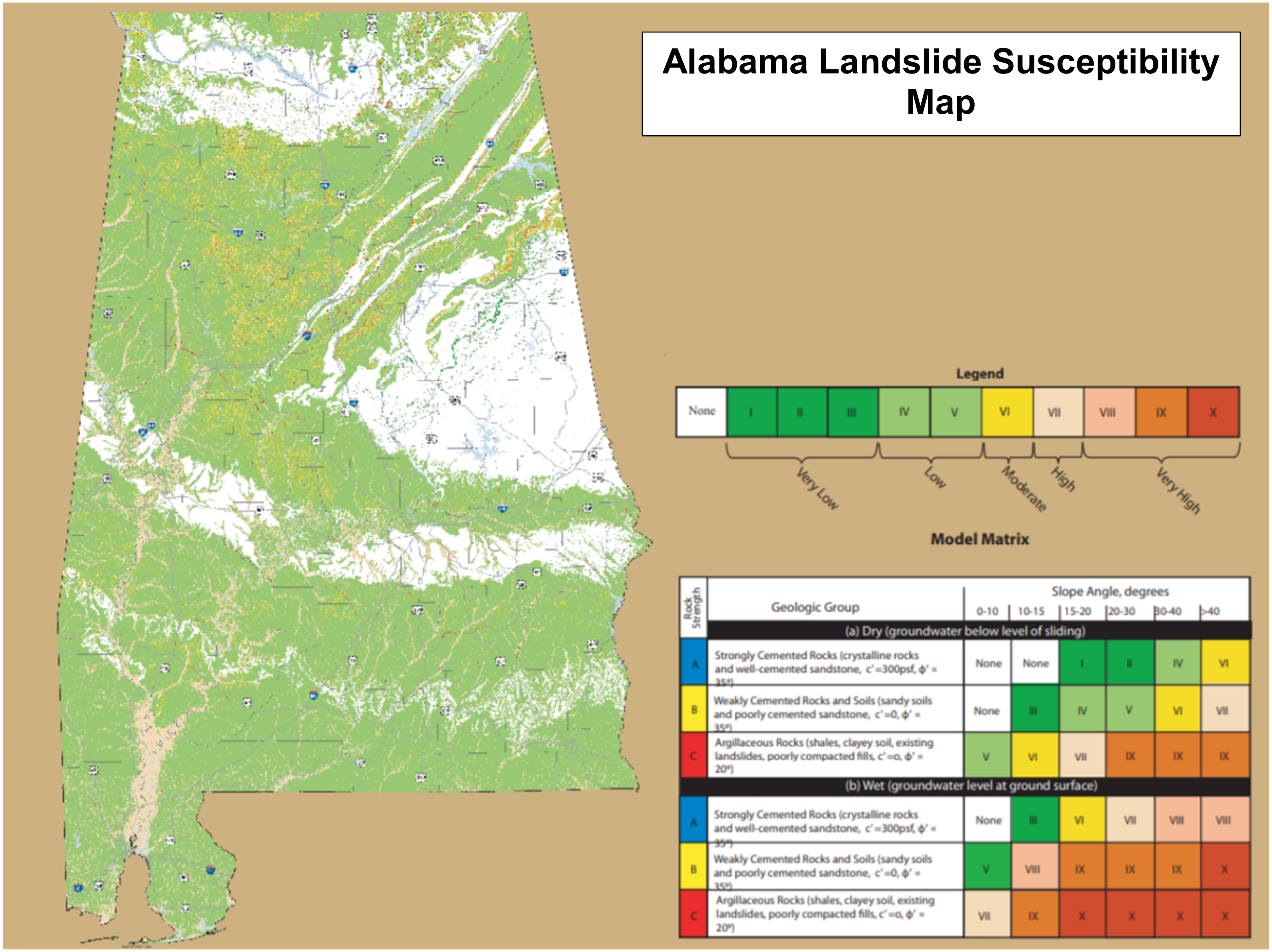
The rating matrices of the four landslide hazard prioritization systems consist of a continuous rating scale between the values of 1 and 100 (Pierson et al. 1990). The rating matrices were designed with an exponential scale, consisting of four defined breaks (i.e. 3, 9, 27, 81) (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 200, Pierson et al. 1990). The breaks in the scale provide ranking guidelines for score assessment. The scoring convention was created to cause a steep increase in scores to form a clear distinction between the increasingly hazardous landslide sites (Pierson et al. 1990**)**. The scale is subjective, requiring the user to rank the slides based on user experience and knowledge of the landslide impacts on both the roadway and motorists. The guide lines were created to allow users variability in score values based on the parameters and conditions at the site—accounting for the variability of site condition, as well as the variability of impacts on both the roadway and motorist (Pierson et al. 1990). For example, a user may rank the landslide traffic impact of a closed lane on a quiet roadway to be 15—indicating very little effect on traffic. Whereas, a user may rank the traffic impact of a closed lane on a major highway to be 50—indicating a sizable impact on traffic.

2.5 Historical Landslide Database for Alabama

Currently, ALDOT does not employ a SSMS or a database of landslides along Alabama highways. However, a historical database of landslides was developed by Rheams (1982). This database, complied by the Geologic Survey of Alabama (GSA), includes landslides from across the state. The database only includes the coordinates of the landslides and does not differentiate between slides occurring along roadways and slides occurring at other locations. No additional information was available on the types of slides, site attributes, or impacts to the adjacent roadways and/or residences.

2.6 Landside Susceptibility Mapping

The landslide susceptibility map of Alabama, shown in Figure 2-1, was developed by the Geologic Survey of Alabama (GSA). The map illustrates locations more susceptible to landslides based on the estimated rock strengths and the steepness of slopes. The map was developed using an overlay of raster datasets consisting of data collected on the geology of the region, the estimated strength of the rock, and the steepness of the slope—comparing the likelihood of failure within a given region to the average annual rainfall, seismic amplification, and historical landslide locations (Ebersole et al. 2011). The data on the estimated rock strength and steepness of the slopes were combined using a rating matrix, which assigned values to cells based on the attribute values at that location. The rating matrix assigned larger weights to attributes based on their influence to slope instability.



Model Matrix

Rock Strength	Geologic Group	Slope Angle, degrees 0-10	10-15	15-20	20-30	30-40	>40
	(a) Dry (groundwater below level of sliding)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c′=300psf, ϕ′ = 35°)	None	None	I	II	IV	VI
B	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, c′=0, ϕ′ = 35°)	None	III	IV	V	VI	VII
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c′=o, ϕ′ = 20°)	V	VI	VII	IX	IX	IX
	(b) Wet (groundwater level at ground surface)						
A	Strongly Cemented Rocks (crystalline rocks and well-cemented sandstone, c′=300psf, ϕ′ = 35°)	None	III	VI	VII	VIII	VIII
B	Weakly Cemented Rocks and Soils (sandy soils and poorly cemented sandstone, c′=0, ϕ′ = 35°)	V	VIII	IX	IX	IX	X
C	Argillaceous Rocks (shales, clayey soil, existing landslides, poorly compacted fills, c′=o, ϕ′ = 20°)	VII	IX	X	X	X	X

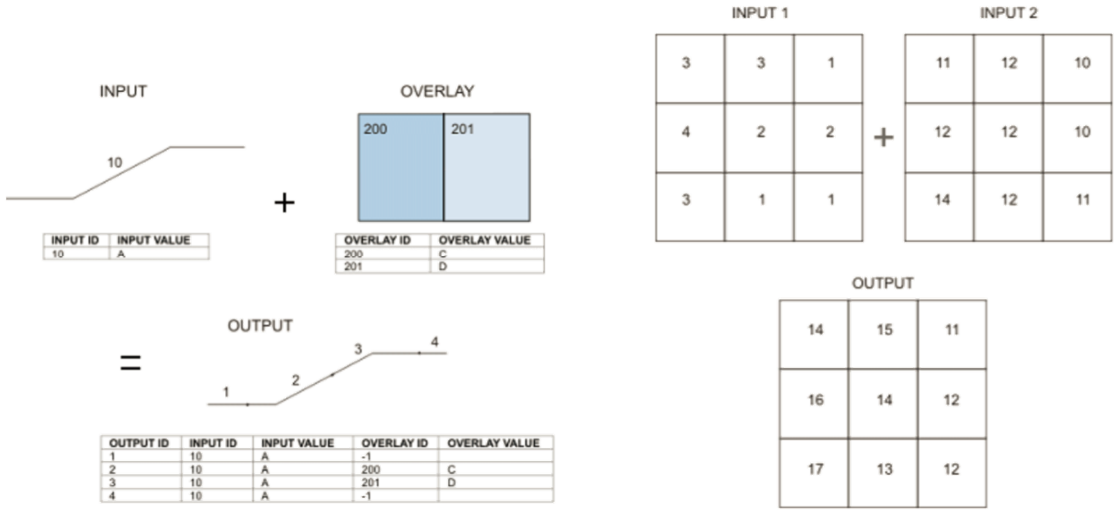
Figure 2-1. Alabama Landslide Susceptibility Map (Ebersol et al. 2011)

2.6.1 Development of the Landslide Susceptibility Map of Alabama

GIS technology has been used in slope instability mapping to predict regions where landslides are likely to occur in the future (Aydilek et al. 2013). These systems utilize raster data, or continuous data, to develop overlay maps highlighting regions of larger landslide risk. The data sourced used within the analysis provide information on the spatial and temporal attributes affecting slope stability (e.g., elevation, slope angle, soil deposits, lithology, precipitation, historical landslides, etc.) (Chau et al. 2004, Aydilek et al. 2013). The attributes within each data feature are weighted based on their influence to slope instability, assigning different weights for each attribute within the given category (e.g., a geologic formation that is more susceptible to landslides would receive a larger value within the raster dataset) (Chau et al. 2004). The files are used in an overlay analysis, displaying the landslide susceptibility of the region.

The overlay analysis, outlined by ESRI (ESRI 2017), in ArcGIS illustrates the additive effect of different data features occupying the same spatial coordinates. This analysis, within landslide susceptibility mapping, is used to combine the weighted effects of attributes within multiple datasets into one dataset—allowing the user to determine the estimated landslide hazard at a given location.

The overlay analysis may be conducted using two general methods: a feature overlay (overlaying the data from vector files—points, lines, or polygons), or a raster overlay. The feature overlay consists of two input datasets (the input layer and overlay layer) and one output dataset. The input layer is split into elements based on the boundaries and attributes of the overlay layer, producing a new dataset consisting of elements with spatial data from both input datasets. Figure 2-2 (a), from the ESRI tool guide, illustrates the function of the feature class overlay. The raster overlay consists of multiple input raster datasets and one output dataset. The method assigns each cell within the output raster dataset a value equal to the sum of the input layers—illustrated by the matrixes provided in Figure 2-2 (b). The raster overlay method is generally used to determine a rank for each cell, indicating the risk for an event, based on the weighted values of the input datasets.



INPUT ID	INPUT VALUE
10	A

OVERLAY ID	OVERLAY VALUE
200	C
201	D

OUTPUT ID	INPUT ID	INPUT VALUE	OVERLAY ID	OVERLAY VALUE
1	10	A	-1	
2	10	A	200	C
3	10	A	201	D
4	10	A	-1	

(a)

3	3	1
4	2	2
3	1	1

11	12	10
12	12	10
14	12	11

14	15	11
16	14	12
17	13	12

(b)

Figure 2-2. Overlay Analysis Models for the (a) Feature Overlay method and (b) Raster Overlay method (ESRI 2017)

2.7 Summary

Landslides along highways pose significant challenges for state and federal transportation agencies. These challenges include direct repair costs, and indirect costs associated with traffic delays and road closures. SSMSs and landslide susceptibility maps have been developed by multiple state transportation departments to help manage these impacts. SSMSs manage landslide hazards through the collection of slope and landslide attributes, whereas landslide susceptibility maps indicate regions likely to encounter landslides based on the combined effects of regional geology, topography, rainfall, seismic activity, and previous landslides, among others.

SSMSs generally contain a data collection system, GIS database, and hazard prioritization system to collect information on the landslide sites and adjacent roadways, analyze data to identify trends, and prioritizing remediation and mitigation efforts. The specific design of a SMSS is dependent on the overall goals of the landslide management program, as well as the specific factors that are of greatest concern within each state. For example, the AKDOT developed a slope stability asset management system focusing on prioritizing remediation based on cost-benefit analyses conducted at each failure site (Calvin et al. 2009). The analyses account for the cost of the repair, the life-cycle of the design, and the benefit of the repair to the traveling public (Calvin et al. 2009). Therefore, data is collected on the past maintenance and repair frequency/costs as well as the effect of the failure on traffic and vehicle safety. On the other hand, the ODOT developed a landslide rating system that focused on the data collection of physical features depicting the damage to the roadway (Pensomboon et al. 2007). Therefore the data collection focuses on roadway impact and repair frequency/cost.

ALDOT does not currently have a SSMS, but the GSA has collected information on historical landslides and developed a statewide landslide susceptibility map. The susceptibility map identifies approximate regions with high landslide susceptibility based on map overlays of rock strength and slope steepness through the use of a raster matrix map overlay. The map was developed to aid in the determination of the effects of rock strength and slope steepness on landslides throughout Alabama—comparing the results to the topography, rainfall, and seismic activity. However, it was created only to provide an approximation of the likelihood of landslides. It was not developed for use in land planning. Therefore, the susceptibility map is unsuitable for use at specific locations along highways. However, the map will be used to compare regions of high landslide density and to correlate these with locations of historical landslides within Alabama.

CHAPTER 3: SLIDE SPREAD DATA COLLECTION AND DATABASE

3.1 Introduction

Slide Spread is a landslide data collection system and database used to catalog and assess landslide data along Alabama highways. The system was based on the data collection system and database components of SSMSs employed by other state transportation agencies, reviewed in Chapter 2 of this thesis. The main purpose of Slide Spread is to collect, organize, and retrieve landslide data that may be used to analyze the physical and material characteristics of landslides along Alabama highways—assisting in the determination and selection of remediation and mitigation methods for slope failures. This chapter provides an overview of Slide Spread—defining its uses as a data collection system and landslide inventory, outlining the database development and structure, as well as describing data sources and information collected within the database. The description details the analysis purpose, database framework, and recorded information.

3.2 Slide Spread

Slide Spread is a landslide data entry system and database developed for ALDOT to aid in the determination of common failure categories impacting slopes adjacent to Alabama highways, as well as to assist in the identification of similarities between landslides, and spatial trends between landslides and external data (e.g., geology, and precipitation). Figure 3-1 presents the framework for the development of Slide Spread, displaying the methodology employed for its development. The program, largely based on the Slope Failure Investigation Management System created by the MDOT, follows the practices of the five SSMSs reviewed in Chapter 2, modified based on the needs of ALDOT. The system was designed to be an accessible landslide inventory compatible with ArcGIS software—allowing data to easily updated, queried, and displayed. The data sources, collected over a period of almost 30 years, contain ALDOT reports with various levels of detail. This required a flexible data structure to be able to combine sources with different levels of detail.

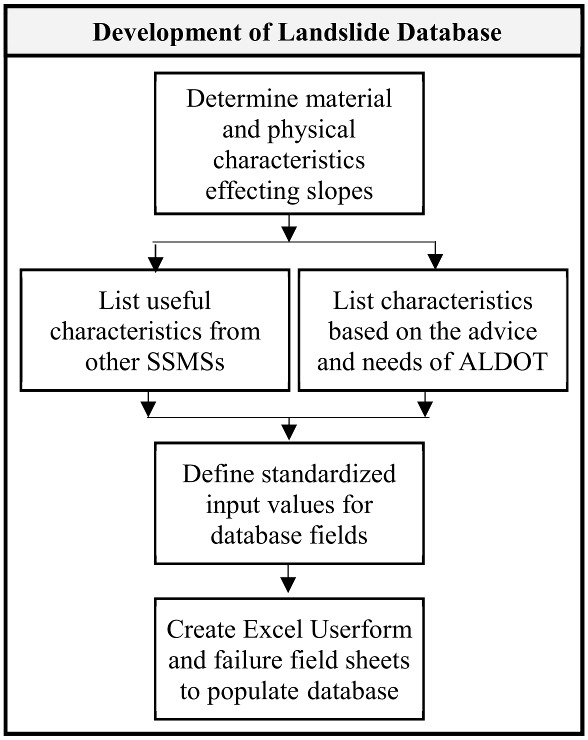


Figure 3-1. Framework for the development of Slide Spread

The data selected for collection was chosen based on the review of similar landslide collection systems and the purpose of the project—altered based on the expertise and advice from ALDOT engineers. Table 3-1 provides a comparison of the attributes collected within the reviewed SSMSs and the attributes collected within Slide Spread.

Table 3-1. SSMS database comparison (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon et al. 2007)

Attributes	AKDOT	MDOT	OHDOT	ODOT	WSDOT	ALDOT
Adjacent Structures		X	X			X
Adjacent Utilities		X				X
Average Daily Traffic	X	X	X	O	O	
Average Vehicle Risk	X					
Cleanup	X					
Design Geometry		X	X			X
Existing Remediation		X	X			X
Failure Cause		X	X			X
Failure Surface Geometry	X	X	X			X
Failure Surface Soil Type	X	X	X			X
Freeze/Thaw Cycle	X					
Groundwater	X	X	X			X
Maintenance Frequency/Cost	X		X	O		
Probability of Additional Movement			X			
Rate of Slide Movement						X
Recommended Remediation		X	X			X
Repair Status		X	X			
Roadway Impact	X	X	X	O	O	X
Site Location	X	X	X			X
Slope Angle	X	X	X			X
Slope Height	X	X	X			X
Slope Materials (Geology)	X	X	X			X
Surface Water	X	X	X			X
Traffic Impact	X	X			O	
Type of Failure	X	X	X	O		X
Vegetation/Land Cover		X	X			X
Vehicle Accident History	X			O	O	
Vertical/Horizontal Displacement	X					X
Weather Preceding/at Failure		X	X			X

X is used to indicate attributes collected within the database

O is used to indicate attributes used in the hazard rating system for the SSMSs in which the data was not available to on the information collected within the landslide database.

Nine attributes collected within other SSMSs were excluded from Slide Spread. These included the average daily traffic, average vehicle risk, cleanup, freeze/thaw cycle, maintenance frequency/cost, traffic impact, and vehicle accident history. Slide Spread, a landslide data collection system and inventory, was created primarily to aid in the future development of remediation efforts of landslides along Alabama highways—collecting details on slide attributes rather than landslide effects. This led to the exclusion of attributes related to the landslide effect on motorist as well as landslide cleanup efforts. In addition, Slide Spread does not account for the effects of freeze/thaw cycles due to the tropical climate of Alabama. Slide Spread, developed to assist in the determination of landslide failure mechanisms and repair methods, does not currently include a hazard prioritization ranking system (or asset management system) within the database framework. Therefore, the landslide impact on the vehicles and motorists (e.g., average daily traffic, average vehicle risk, traffic impact, or vehicle accident history) is beyond the scope of the project.

Currently, Slide Spread consists of two input UserForms and two output databases containing information on the landslide reports and the emergency relief slides, respectively (Figure 3-1). However, Slide Spread may be further adapted by adding additional UserForms in the future if additional sources of information are identified. This allows the program to continue to be adapted to meet the future needs of ALDOT after implementation. A summary of the two data collection methods used by Slide Spread are provided in Figure 3-2 (a) and (b). The figures illustrate the variety of attributes collected by the system, displaying the overall collection categories and the attributes collected. The following sections describe Slide Spread, detailing the development of the system, as well as presenting and defining the attributes collected during a landslide analysis. An instruction guide (Appendix B and Appendix C) was also developed for each Slide Spread database to assist users with term definitions, naming conventions, and input responses.

3.2.1 Slide Spread UserForms

Slide Spread consists of two GUIs, or a UserForms, developed using Microsoft Excel and Visual Basic for Applications (VBA). The software was chosen due to its accessibility (requiring no additional software to run the program) and adaptability (able to be easily changed based on the needs of the user). The structure of Slide Spread allows for multiple users with varying levels of experience to enter consistent data without the need to understand or edit the GIS database directly. Data is entered into the UserForm using drop down menus, check boxes, and short responses to help ensure information is collected uniformly from different users. Validation routines were written to ensure that the data entered could subsequently be used for spatial analysis within ArcGIS. The ArcGIS database organizes information on location, geology, failure conditions, and slope attributes—housing landslide data in one location where it may be updated, edited, and analyzed.

The two main sources of information about landslides along Alabama highways are landslide reports and Detailed Damage Inspection Reports (DDIRs). Landslide reports were written by a geologist or a geotechnical engineer to document the characterization and analysis of a landslide. DDIRs are completed for emergency relief slides where repair assistance is requested from the Federal Highway Administration (FHWA). The DDIRs contain significantly less information than the landslide reports; therefore, two databases were developed to efficiently collect information from these different sources (Figure 3-2). This was accomplished by developing two UserForms within Slide Spread, which contained different input options based on the data typically available in each report type. Both UserForms collect data on the location, weather at failure, failure geometry, repairs, and roadway effects of the landslide. The long form (used for the landslide reports) collects additional data on soil conditions, geology, groundwater, historical failures and repairs, land coverage, and availability of in-situ test results. The following sections detail the attributes collected in each database.

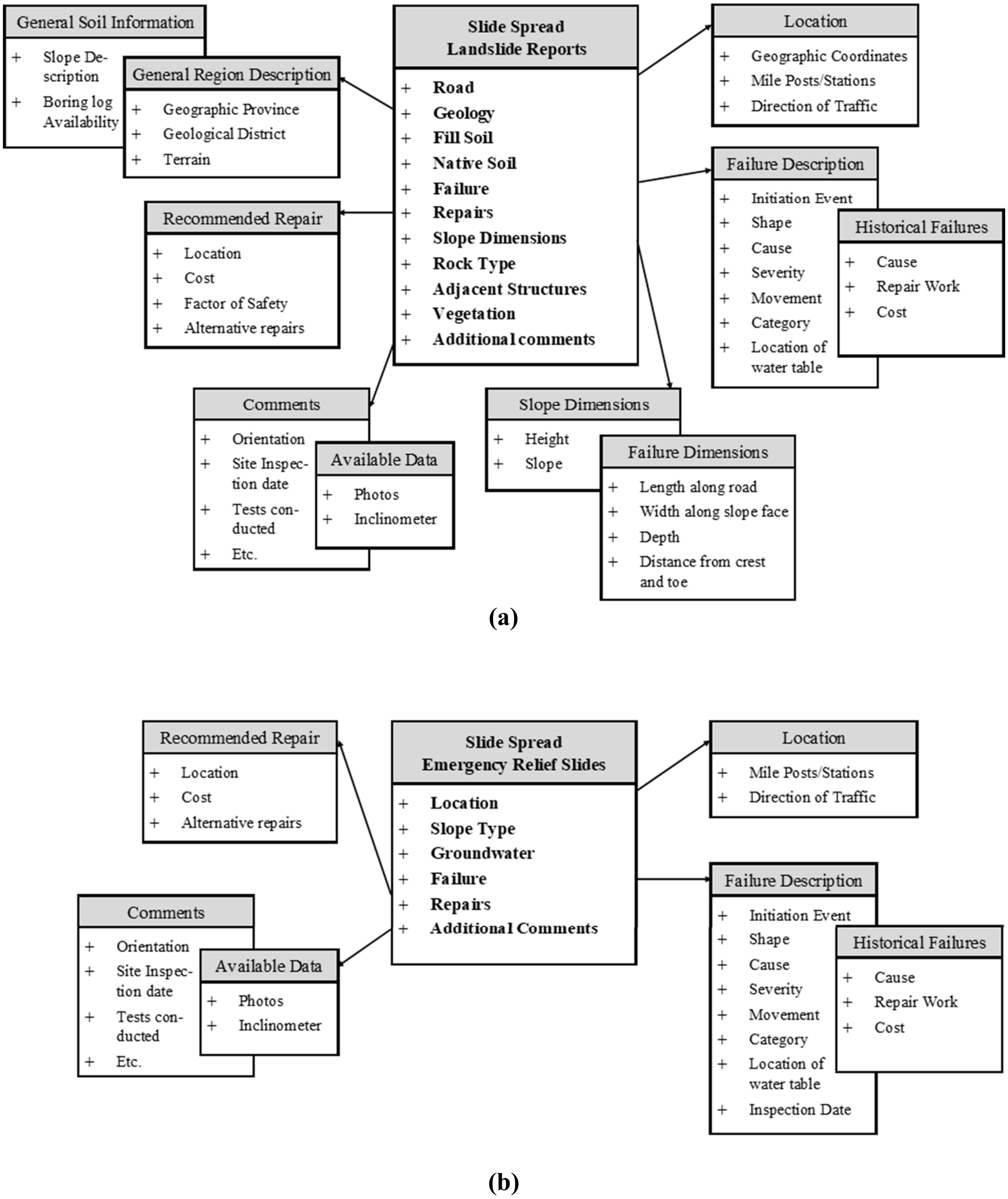


Figure 3-2. Slide Spread model. Data from each landslide is collected through either the (a) Landslide Reports UserForm or (b) Emergency Relief Slides UserForm, depending on the source type. Each box shows a tab within the model which group together similar attributes of both the roadway and the slide.

3.2.2 Landslide Reports Database

The first database (input forms shown in Appendix B) was designed to collect data from landslide reports collected from ALDOT archives. A focus was placed on documenting landslides which had occurred within the past 10 years; however, reports were collected for events ranging from 1990 to 2015. In total, 82 landslides were documented based on the landslide reports. Locations for these slides (Landslide Reports) are shown in Figure 3-3. A typical landslide report includes information on the slide geometry, soil conditions, and recommended repairs. However, few reports explicitly discussed the cause of the failure or provided repair costs. Landslide locations were often provided as mile posts, which were converted to latitude and longitude using a GIS-based conversion tool developed by ALDOT. These locations were then checked by hand using the maps provided in the report. Slides where an exact location could not be determined were excluded from further analysis.

The landslide report UserForm was organized into eleven sections (or tabs) which group together similar attributes of both the roadway and the slide (Figure 3-2)—(1) road, (2) geology, (3) soil type/fill soil, (4) native soil, (5) failure, (6) repairs, (7) slope dimensions, (8) rock type, (9) adjacent structures, (10) vegetation, and (11) additional comments. The data was inputted into the database directly from ALDOT reports using the UserForm. Table 3-2 summarizes the twelve sections included on the landslide report UserForm, including attributes collected within each group.

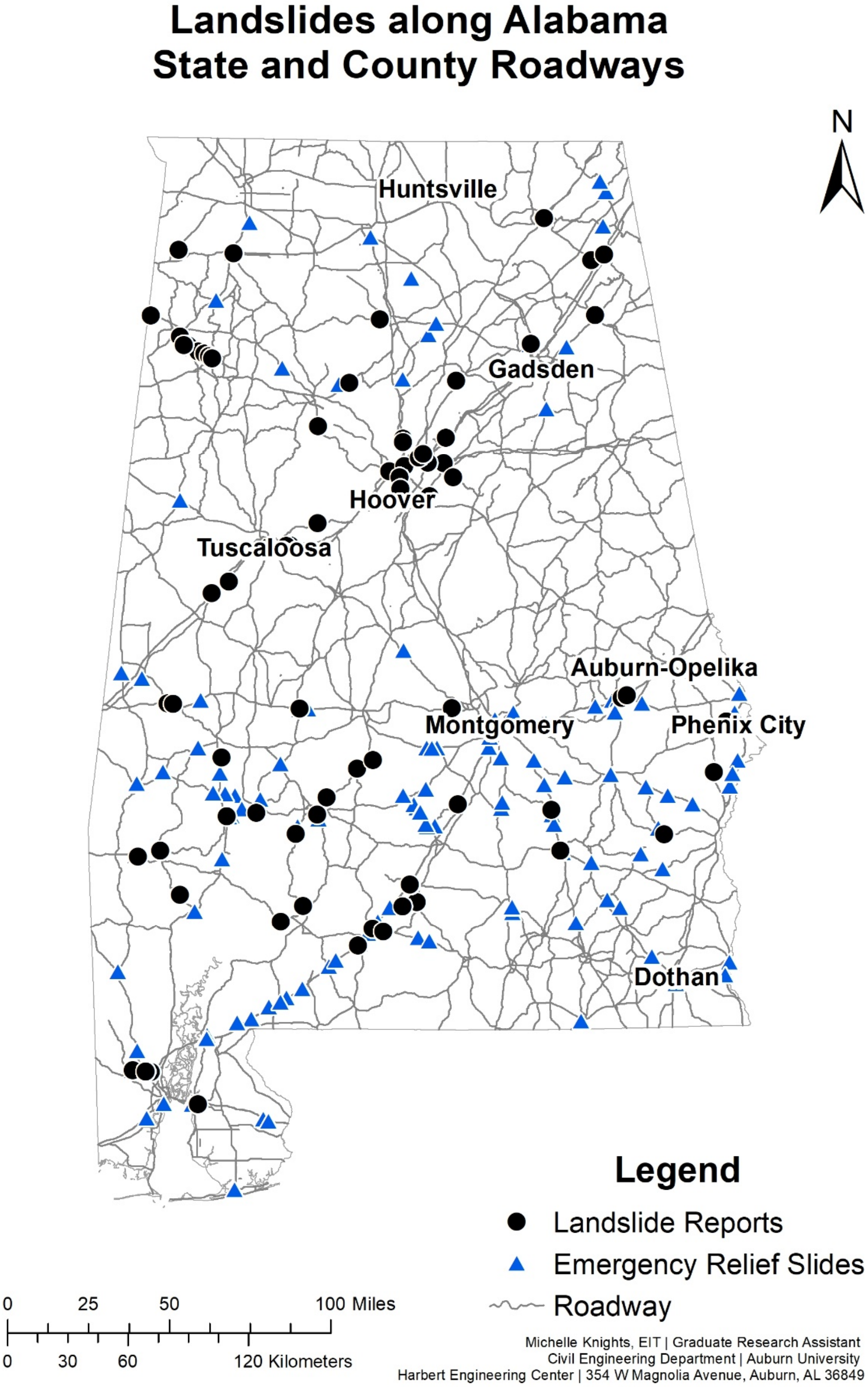


Figure 3-3. Landslides along state and county roads. The map displays the locations of the landslides in both the landslide reports database and the emergency relief slides database. Multiple slides may be located at the same latitude and longitude coordinates.

Table 3-2. Data Collection for Landslide Reports Database

Data Collection	**Definition**
Location	Collects information on the data source and location—such as the county, city, roadway, direction of traffic, and site coordinates. The failure site location may also be denoted by the station number, MP, and/or exit number.
Geology	The geology of the region is recorded using the physiographic province (a geographical region with similar physical features), and/or geological district (an area of rock with similar characteristics). The terrain of the region and sinkhole susceptibility is described.
Soil type	Identifies the slope type, indicating if failure occurred within native soil, a fill or cut section, a reinforced slope, a repaired Riprap layer, and/or a rock slope. Specifies the availability of boring logs for the site.
Fill soil	The fill soil refers to the soil moved to the slope site from a borrow site, or excavation. The soil is separated into two classification systems—the American Association of State Highway and Transportation (AASHTO) Soil Classification System, and the Unified Soil Classification System (USCS). The liquid limit, moisture content, and compaction of the soil may also be noted.
Native soil	Natural soil refers to the soil that was originally located at the site without the interference of humans. The native soil, like the fill soil section, may be classified by the AASHTO Classification System and/or USCS.
Failure	Collects general failure information (e.g., date of failure, number of failure sites, weather conditions at or before failure, failure severity, and historical failures). Detailed information is provided on the location of failure surface within the slope, as well as the location along the highway (e.g., front or back slope). The failure category is noted.
Repairs	Collects the list of repair options—indicating the recommend method, repair location and estimated repair cost.
Slope dimensions	The geometry of the slope and failure surface are noted using values and images. The dimensions give the profile of the failure surface as well as the cross-section of the designed slope before failure.
Rock type	The general rock type of the region is classified by rock formations and geological age. The rock and mineral specific to the failure site is also recorded.
Adjacent structures	The adjacent structures include structures, landforms, and utilities that may be located near a roadway.
Vegetation	Vegetation may be located on the top (crest), face (slope), or toe (ground surface) of the slope. The vegetation is indicated along the three areas of the slope.
Additional comments	Addition information that does not have a designated location on the form is recorded here.

3.2.3 Detailed Damage Inspection Report (DDIRs)

The database described above does not include landslides that are characterized and repaired without the development of an official landslide report. These landslides fall into two main categories for ALDOT: small slides (which are repaired by local maintenance forces as part of their regular duties), and emergency repairs (which are completed following major storms). The maintenance repairs could not easily be tracked using available information, but the emergency repairs were documented using DDIRs, as previously discussed. A second database (shown in Appendix C) was created using these reports. The database contains 165 slides, resulting from 10 weather events between 2004 and 2015. The locations of the emergency relief slides are shown in Figure 3-3.

The DDIRs contain less data about each landslide than the landslide reports; therefore a new UserForm was created to cater to the available information (Figure 3-2). The UserForm is separated into twelve groups, collecting information on the (1) source, (2) location, (3) ground water, (4) historical failures, (5) failure location, (6) ground water measurement, (7) soil type (8) failure severity, (9) failure, (10) boring log availability, (11) rate of movement, and (12) failure plane location. The sections collect abbreviated details about each slide, as less information is known about the slope failures. The twelve groups are summarized in Table 3-3, providing a list of attributes collected for each section.

Table 3-3. Data Collection for Landslide Reports Database

Data Collection	Definition
Source	Cites the report used in the data analysis.
Location	Collects the county, city, and roadway were the failure occurred, as well as the location along the roadway of the landslide (station number or MP).
Groundwater	Indicates the general elevation of the groundwater in relation to the slope geometry. It also records information on encountered groundwater or seepage.
Historical failure	Indicates whether a historical failure or repair has occurred at the site. The type of failure and repair are not noted because this information is not generally given a DDIR.
Failure location	Indicates the location of the failure in relation to the roadway (e.g. the front slope or back slope).
Groundwater	Indicates how the groundwater table was measured during the site investigation.
Soil type	Identifies if the slope is natural, fill, cut, cut and fill, reinforced, contains a Riprap layer, and/or is a rock slope.
Failure severity	Indicates the effect of the slope failure on the roadway and traffic. The severity may be a shoulder, lane, or road closure
Failure	Collects general failure information such as the weather conditions at or before failure, type of failure, assumed cause of failure, and descriptions of the failure site (e.g. cracks or sinkholes). The failure type is given as either erosion, rotation, translation, compound, or other.
Boring log availability	Indicates if the boring logs are available for the site location.
Rate of movement	Indicates whether the failure was catastrophic—occurring over a short period of time—or not catastrophic—occurring over a long period of time.
Failure plane location	Gives the location of the failure along the slope, for example the toe of the slope.

3.3 Limitations of Slide Spread

Slide Spread contains data on approximately 270 landslides that have occurred over the past 30 years. This data is not representative of all of the landslides occurring along Alabama roadways during this time period. However, it contains the slides within the available reports. The data was drawn from multiple reporting methodologies based upon the criteria established at the time of the project investigation; as a result, the reports may not contain the same levels of detail or capture the same categories of data. This has resulted in varying levels of recorded information for each slide, likely affecting the analysis. Therefore, Slide Spread has been designed to be routinely updated after its implementation within ALDOT, allowing engineers and geologists to input data during the investigation and design of the project rather than retroactively compiling data from reports.

Landslide report locations may not be representative of all areas of the state as the collection may be skewed based on common driving routes of ALDOT employees and on the visibility of landslides from the roadway. Landslides located along common driving routes are more likely to be identified, whereas other landslides may go unnoticed. Furthermore, landslides may be identified long after the landslide has occurred. This may lead to an inaccurate determination of failure conditions, affecting the presumed cause of failure and rate of movement of the slide. Therefore, Slide Spread may contain a spatial and temporal bias.

Asset management, further explored in Chapter 5, is not currently employed within the Slide Spread database. As Slide Spread continues to adapt, asset management will need to be added to the system. This may be through the creation of a prioritization system, as employed by other state transportation agencies—addressing life cycle costs as well as conducting cost-benefit analyses to allocate funds based on risk and hazard to the roadway and the traveling public. Chapter 5 presents the framework of a landslide asset management system within Alabama.

3.4 Summary

Slide Spread currently has two databases based on information collected from landslide reports and emergency relief slides. The first database was populated using landslide reports collected from ALDOT archives. A typical landslide report includes information on the slide geometry, soil conditions, and recommended repairs. Few reports explicitly discussed the cause of the failure or provided repair costs. Landslide locations were often provided as mileposts, which were converted to latitude and longitude for use in Slide Spread. This conversion was first done using a GIS-based conversion tool developed by ALDOT, then it was checked by hand using the maps provided in the reports. Slides where an exact location could not be determined were excluded from further analysis. A focus was placed on documenting landslides which had occurred within the past 10 years; however, reports were collected for events ranging from 1990 to 2015. In total, 82 landslides were documented based on the landslide reports. This number does not represent all landslides reports created during this period; the database is being updated as additional reports are made available.

The landslide reports database, described above, likely misses many slides across the state which are characterized and repaired without the development of an official landslide report. These landslides fall into two main categories for ALDOT: small slides (which are repaired by local maintenance forces as part of their regular duties), and emergency repairs (which are completed following major storms). The maintenance repairs could not easily be tracked using the available information; however, the emergency repairs were documented using DDIRs, as previously discussed. A second database was created using these reports. Slides within this database occurred between 2004 and 2016. The database contains 165 slides, resulting from 10 weather events.

CHAPTER 4: ANALYSIS OF THE LANDSLIDE DATABASE

4.1 Introduction

The objective of this chapter is to present an analysis of the Alabama landslide data collected within the historical landslide database and the Slide Spread databases (the emergency relief slides database and the landslides reports database). The analysis examined the trends between characteristics of similar landslides, as well as the relationships between landslide locations and external spatial data—examining the locations of the sites, the slope parameters, and the influencing environmental factors which may affect slope stability. This thesis follows the analysis procedures employed by Aydilek et al. (2013), identifying trends through the examination of individual landslide attributes and environmental features.

The landslide data examined was collected from three databases: the historical landslide database, the emergency relief slides database, and the landslide reports database. The historical landslide database, developed by Rheams et al. (1982) for the Geologic Survey of Alabama (GSA), contains the geographic coordinates for 458 landslides occurring before 1982. The emergency relief slides and the landslide reports databases—created through the use of the Alabama landslide data collection system and databases, called Slide Spread—contains information on the physical and material attributes of 165 emergency relief slides (occurring between 2004 and 2015) and 82 ALDOT report landslides (occurring between 1990 and 2017), respectively. The spatial data collected within the three landslide databases were compared to information on the geologic formations throughout Alabama and precipitation data from large storms impacting the state. This information was obtained from the United States Geologic Survey (USGS) and the National Weather Service (NWS), repectively.

The three separate data sources employed in this study provided varying levels of detail regarding each landslide. The historical landslide database contained only the landslide locations, while the Slide Spread databases contained data on numerous attributes based on the information provided within each landslide report type (e.g., ALDOT landslide reports, and DDIRs). Due to the varying levels of detail about each slide analyzed the data was assessed using the procedures developed by Aydilek et al. (2013) whose method examined the relationships between individual attributes or features affecting slope stability. The results were then compared to a statewide landslide susceptibility map (Ebersole 2011).

The landslide databases (historical landslides, emergency relief slides, and landslide report slides) were used to examine trends between landslides and the location of the site, the geology of the region, the proximity to other landslides (e.g., landslide density), the adjacent roadway, the weather at failure, and the historical landslides at the site (e.g., previous landslides occurring at or adjacent to the site of the current landslide). In addition, the study considered the relationships between landslides and their physical attributes—analyzing the failure type, the adjacent structures, and the slope ratio. In the future, this data will be used to determine effective remediation and intervention strategies that may be employed based on the failure category identified at a landslide site, and/or common failure types predicted within a region.

4.2 Analysis Methodology

Slide Spread, the landslide data collection system and databases developed for ALDOT, was used to populate the emergency relief slides database and the landslide reports database. The system closely mimicked the data collection topics and procedures of the SSMSs employed by other U.S. state transportation agencies (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon et al. 2007). However, inconsistent details provided for each landslide site examined due to the varying levels of data provided within individual landslide reports as well as the retroactive data collection method used to populate the Slide Spread database, lead to inconsistent data levels and causing gaps in available information. The varying levels of data provided within an individual landslide report may hinder the analysis of similarities between different landslide attributes, and the analysis of trends between landslide attributes and the external data.

The variation of available information was also encountered by Aydilek et al. (2013) in the examination of landslides along Maryland highways—affecting the quality and diversity of landslide data (Aydilek et al. 2013). Therefore, Aydilek et al. (2013) short-listed physical parameters based on the advice and experience of the Maryland State Highway Administration (SHA) engineers and obtained additional raster files to develop a statewide landslide susceptibility map. The short-listed parameters (e.g. elevation, slope angle, land cover, storm event precipitation, slope history, and physiographic provinces) were used in the identification of independent trends, which may be used in the future development of a quantitative mapping system for the SHA (Aydilek et al. 2013).

The analysis presented herein follows the process implemented by Aydilek et al. (2013), examining each landslide attribute separately. Therefore, the analysis does not account for the combined effects of the influencing parameters (e.g. geology, precipitation, slope steepness, slope geometry, etc.). The data is presented based on the information provided within the report types, as well as the spatial trends formed with the external spatial data.

4.3 Analysis Results

The following sections present the results of the landslide data analysis, expanding on trends identified between landslide attributes and external spatial data. The research examined the trends between landslides and the geology of the region, the proximity to other landslides (e.g., landslide density), the adjacent roadway, the weather at failure, and the past landslides at the site (e.g., previous landslides occurring at or adjacent to the site of the current landslide). In addition, the study considered the relationships between landslides and their physical attributes—analyzing the failure type, the adjacent structures, the slope height, and the slope ratio. The results are presented for the analyses in which trends were identified—geology, adjacent roadways, weather at or near failure, proximity to past landslide events, and slope geometry. These results are then compared to the state landslide susceptibility map.

4.3.1 Geology at Landslide Site

The geologic map of Alabama was used to determine the geologic characteristic at each landslide site (Dicken et al. 2017). The landslide locations were mapped in relation to both the geologic physiographic sections and geologic formations in Alabama. The geologic physiographic sections (defined in Table 4-1), or regions characterized by similar physiographical attributes, represent areas with distinct features and/or landforms. The geologic formations, or geologic units, characterize regions with similar rock classifications and lithology, providing details on the rock type, rock age, and soil layers. These classifications were used to determine landslide trends within Alabama based on the geology of the region, identifying soil and/or rock groupings more prone to landslide events. The databases used in the analysis consist of the emergency relief slides and landslide reports databases which collect data on landslides adjacent to roadways, as well as the historical landslides database which does not specify the land use of the failure site.

Table 4-1. Geologic Physiographic Sections of Alabama (Neilson 2007)

Geologic Physiographic Sections	Description
Alabama Valley and Ridge	The landscape is characterized by relief features, consisting of ridges (consisting of sandstone) and deep, steep valleys (made up of shale, limestone, and dolomite). The rock age ranges from Cambrian to Pennsylvanian.
Cumberland Plateau	The landscape consists of flat plateaus (made up of the Pottsville Formation, mainly consisting of sandstone) of high-elevation (1,500 feet) sloping generally from the northeast to southwest, separated by deep, steep valleys (consisting of shale, limestone, and dolomite). The rock ages range from the Cambrian to Pennsylvanian.
Highland Rim	The section consists of a ridge running east-west (consisting of sandstone), separating two valleys (made up of limestone formations)—resulting from differential erosion. The rock ages range from the upper Paleozoic era to the Mississippian period.
Piedmont Upland	The landscape is characterized by a plateau, sloping from north to south. The region contains numerous faults, and deformed metamorphic rock. The rock ages range from the Precambrian to Paleozoic era.
East Gulf Coastal Plain	The section is relative flat—containing rounded hills, cuestas and flatwoods, and floodplains for the Alabama River, Tombigbee River, and Black Warrior River. The region consists of young sedimentary rock (Mesozoic period), composed of chalk, sandstone, limestone, and claystone.

Figure 4-1 displays the landslide locations in relation to the geologic provinces in Alabama. Landslides occurred in all five geologic physiographic sections, with large clusters located near the northern border of the East Gulf Coastal Plain, the eastern border of the Highland Rim, and the lower section of the Alabama Valley Ridge. Few historical landslides and no landslides within the Slide Spread databases occurred within the Piedmont Upland.

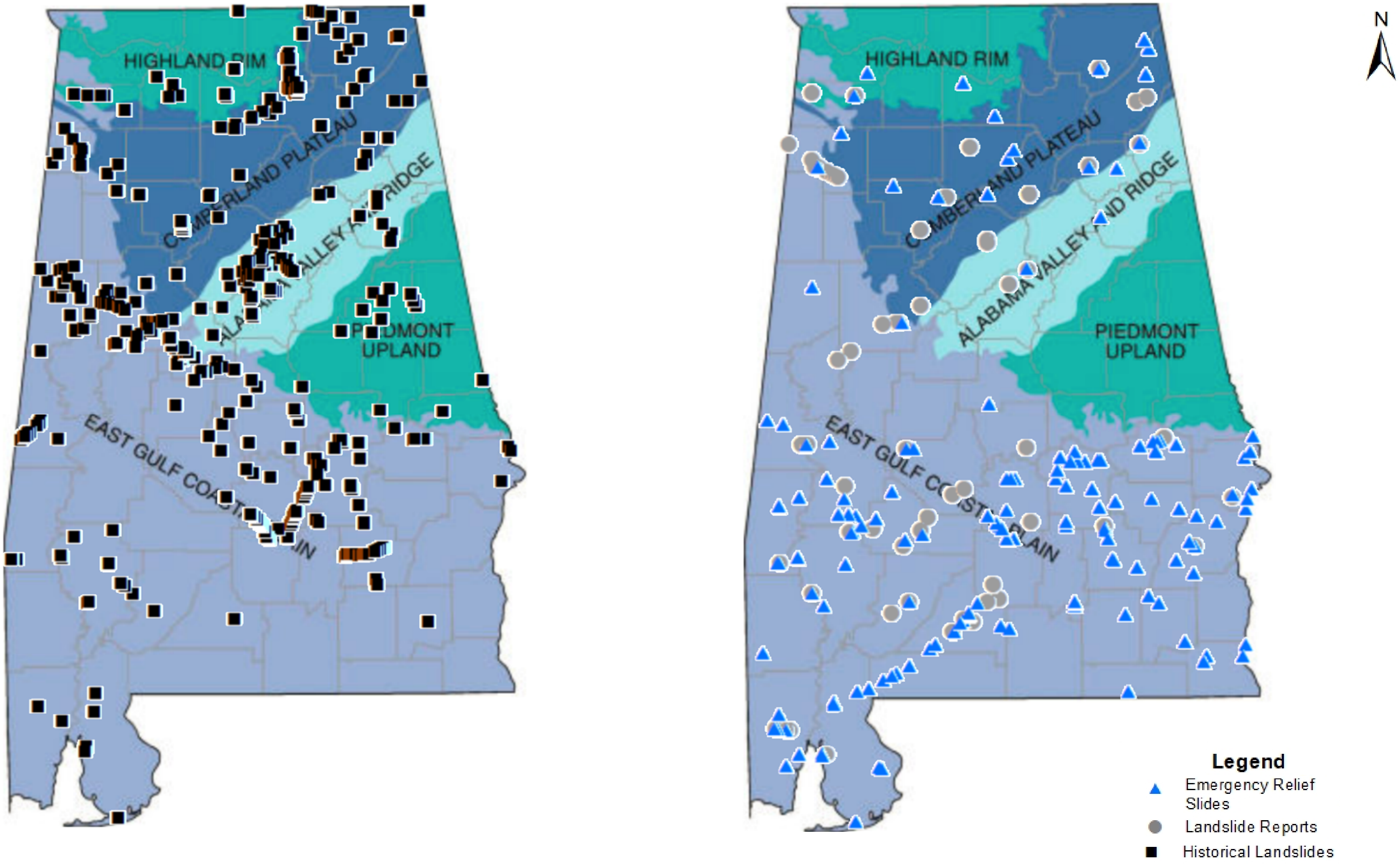

Landslides within the Geologic Physiographic Sections of Alabama

Figure 4-1. Landslide Locations within each Physiographic Section of Alabama, Displacing (a) the Locations of all Historical Landslides and (b) the Locations of the Landslides within the Slide Spread Databases (Rheams et al. 1982, University of Alabama).

The geology of the landslides sites were further examined by spatially correlating the landslide locations with the geologic units of Alabama data to determine the number of slides within each geologic formation. The distribution of landslides within each geologic unit is illustrated in Figure 4-2 through Figure 4-5. The slides recorded within the Landslide Reports database are presented in one group, rather than distinguishing between slides occurring in native soil (within cut sections) and slides occurring in borrowed soil (within fill sections). This was done because the borrow materials for the fill sections are generally taken from nearby cut sections. Therefore, the geologic formation of the region may be representative of the fill materials.

The results show the landslides occurred in 76 of the 163 geologic formations in Alabama. These geologic formations were combined into geological groups for the purposes of this thesis. These groups were based on the common characteristics within each geologic formation. Appendix D defines the geological units that make up each combination, providing descriptions of each individual unit within the groups. In particular, the alluvial, coastal and low terrace deposits was not paired with addition formations. The unit consists of sedimentary soil deposited by flowing water and may be composed of soil from numerous formations.

Table 4-2 shows the majority of slides occurred in the Tuscaloosa Group (103 slides), Midway Group (87 slides), Pottsville Formation (86 slides), and alluvial, coastal and low terrace deposits (74 slides). The historical slides occurred mainly within the Tuscaloosa Group (82 slides)—consisting of the Coker Formation and Gordo Formation—and Pottsville Formation (60 slides). Whereas, the majority of landslides with the Slide Spread databases occurred in the alluvial, coastal, and low terrace deposits (44 slides), Midway Group (33 slides), Pottsville Formation (26 slides), and Claiborne and Jackson Formation (25 slides). These formations, described in Appendix D, consist mainly of clays, sands, and shale.

Total Number of Landslides by Geologic Formation

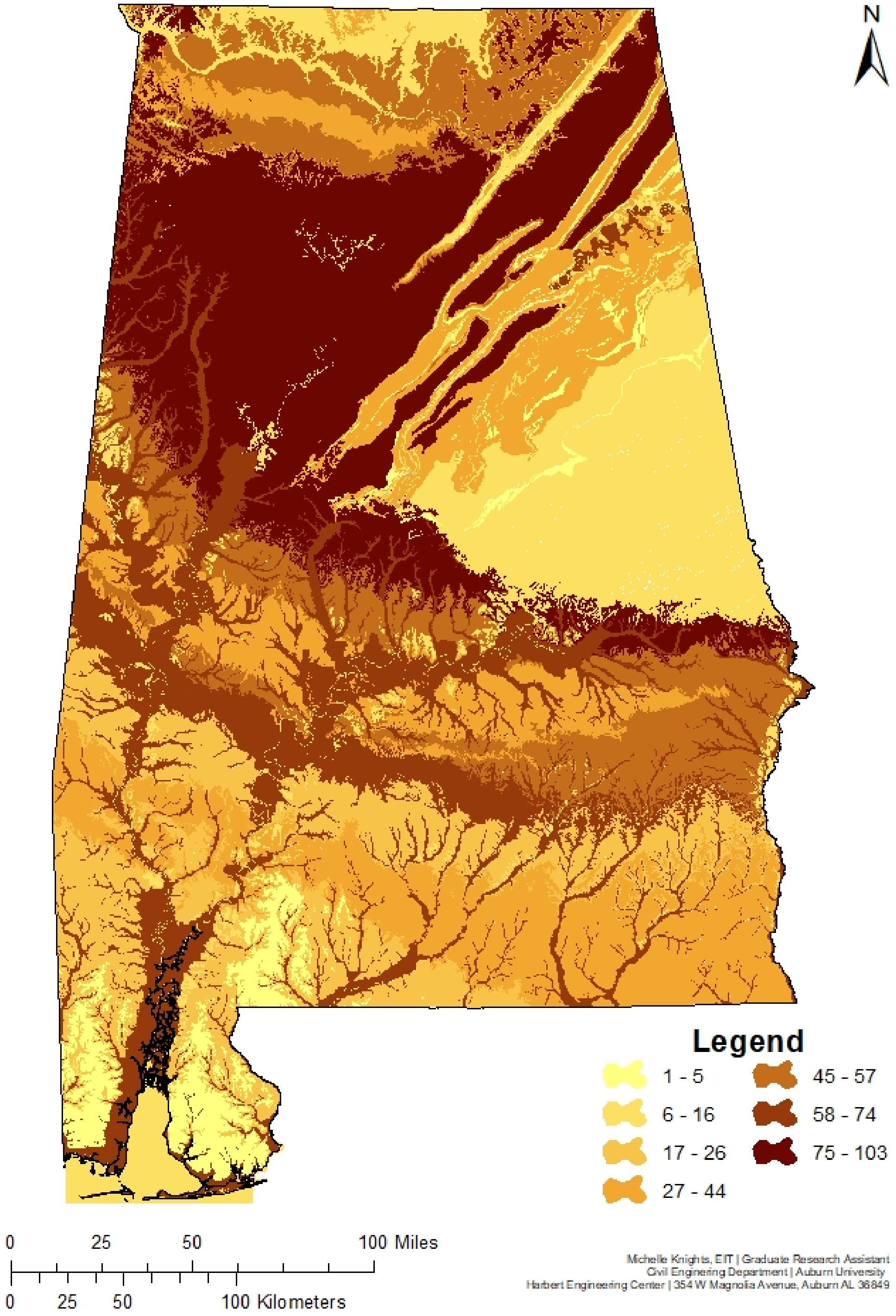


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Figure 4-2. Total Number of landslides by Geologic Formation by total number (Dicken et al. 2017, and Rheams 1982).

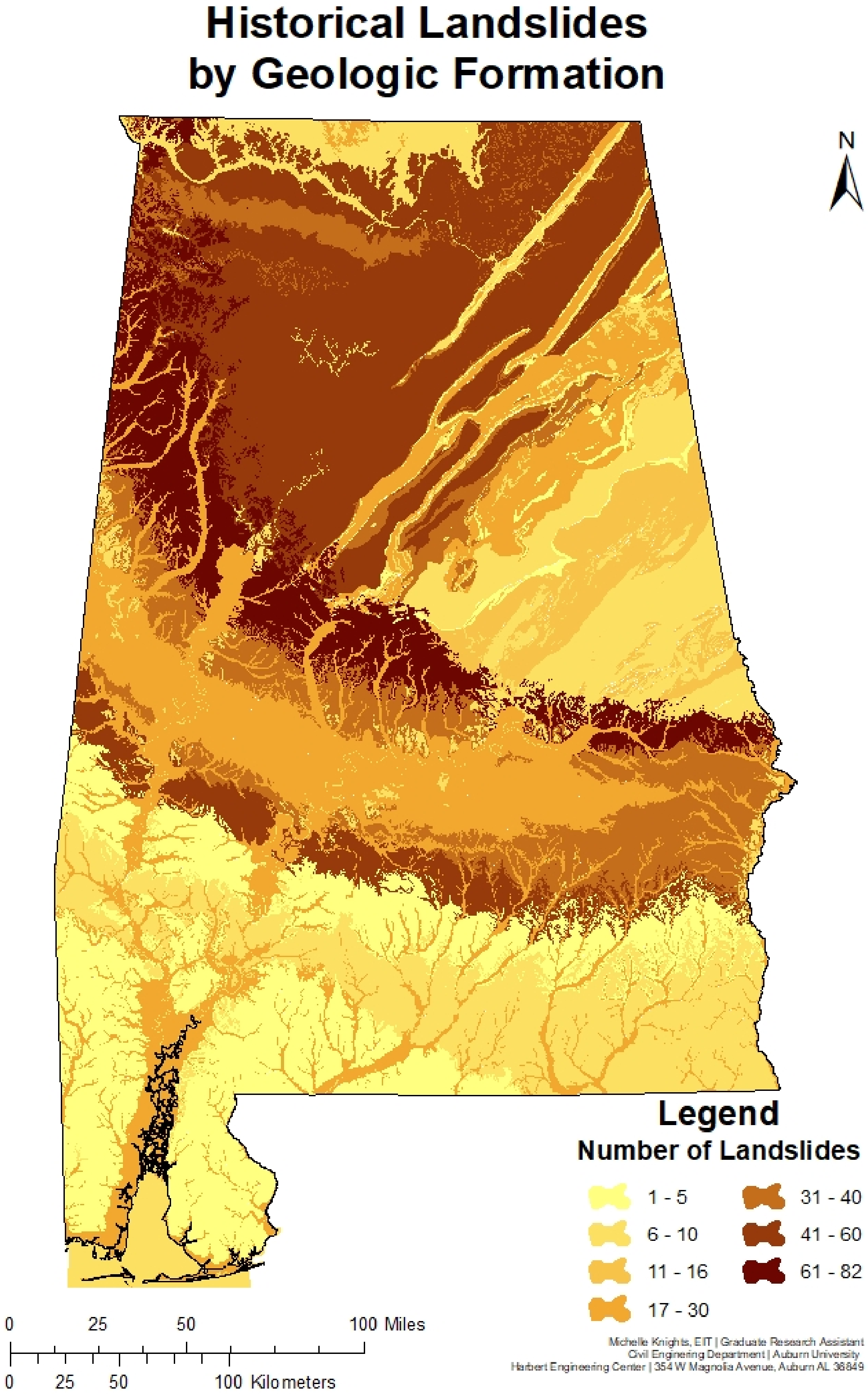
Historical Landslides by Geologic Formation

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Figure 4-3. Number of landslides within each geologic formation by total number (Dicken et al. 2017, and Rheams 1982).

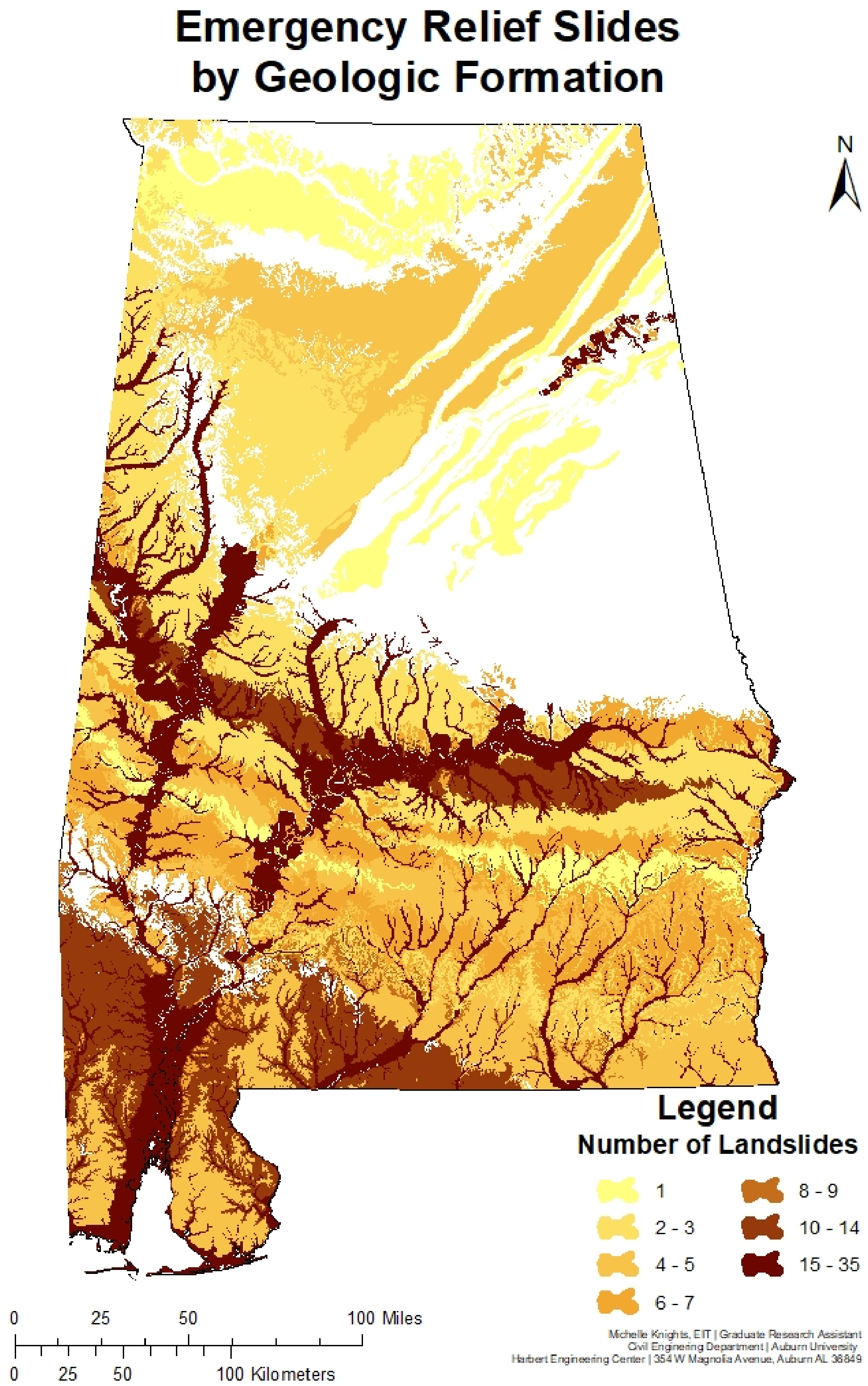

Figure 4-4. Number of emergency relief slides within each geologic formation by total number (Dicken et al. 2017, and Rheams 1982).

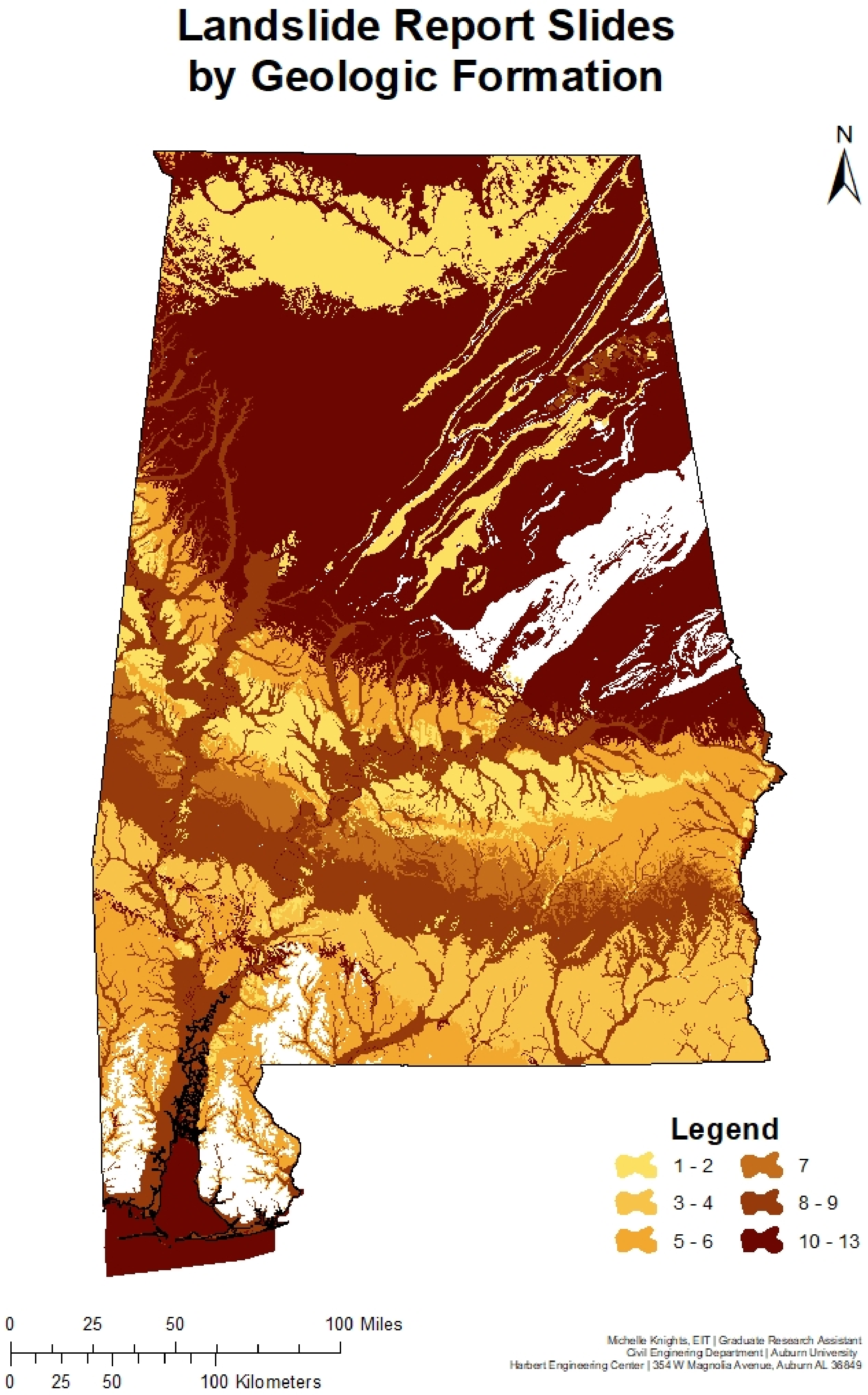

Figure 4-5. Total number of landslide report slides within each geologic formation by total number (Dicken et al. 2017, and Rheams 1982).

Table 4-2. Number of landslides by database within each geology group

Geological Group	Number of Landslides			
	Total	Historical Landslides	Emergency Relief Slides	Landslide Reports
Tuscaloosa Group	103	82	8	13
Pottsville Formation	86	60	13	13
Midway Group	82	49	26	7
Alluvial, coastal, and low terrace deposits	74	30	35	9
Selma Group Sand and Clay	57	36	15	6
Mississippian Limestone	53	51	1	1
Cambrian and Ordovician Limestone	50	35	3	12
Mississippian Sandstone and Shale	44	40	3	1
Selma Group Chalk	40	22	16	2
Claiborne and Jackson Formation	35	10	21	4
Wilcox Group	26	4	14	8
Precambrian to Paleozoic Schist and Gneiss	16	16	0	0
High Terrace Deposits	15	8	6	1
Miocene Series	10	5	0	5
Citronelle Formation	5	1	4	0
Cambrian and Ordovician Shale	4	4	0	0
Red Mountain Formation	1	1	0	0
Talladega Group	1	1	0	0

More highway adjacent landslides may be observed within a given geologic group due to either a higher landslide susceptibility, or a higher landslide exposure rate (i.e. a longer length of the highway present within the geologic group). The one-way Chi Square Test was conducted to determine the probability of slides occurring due to these two cases (Key 1997). The Chi Square Test is used to determine the differences between the actual sample (i.e. the distribution of slides within the geologic groups) and a predicted distribution (i.e. a uniform distribution of slides per length of roadway within a geologic group), or null hypothesis (Key 1997). The null hypothesis of this test assumed a uniform distribution of slides occurring per mile of highway within the geologic groups experiencing 1 or more landslides. The breakdown of landslides per mile of highway within each geologic unit is provided within Table 4-3.

Table 4-3. Number of landslides by database within each geologic group per mile of highway

Geological Group	Number of Landslides Per Mile of Highway			
	Total	Historical Landslides	Emergency Relief Slides	Landslide Reports
Midway Group	0.190	0.114	0.060	0.016
Tuscaloosa Group	0.089	0.071	0.007	0.011
Mississippian Sandstone and Shale	0.087	0.079	0.006	0.002
Selma Group Sand and Clay	0.074	0.047	0.020	0.008
Selma Group Chalk	0.068	0.037	0.027	0.003
Talladega Group	0.060	0.060	0	0
Pottsville Formation	0.049	0.034	0.007	0.007
High Terrace Deposits	0.047	0.025	0.019	0.003
Mississippian Limestone	0.045	0.044	0.001	0.001
Wilcox Group	0.042	0.006	0.023	0.013
Alluvial, coastal, and low terrace deposits	0.041	0.017	0.020	0.005
Red Mountain Formation	0.040	0.040	0	0
Precambrian to Paleozoic Schist and Gneiss	0.034	0.034	0	0
Cambrian and Ordovician Shale	0.031	0.031	0	0
Claiborne and Jackson Formation	0.027	0.008	0.016	0.003
Miocene Series	0.021	0.011	0	0.011
Cambrian and Ordovician Limestone	0.020	0.014	0.001	0.005
Citronelle Formation	0.010	0.002	0.008	0

The Chi Square Test (conducted using Equation 4-1) determined the likelihood of either event occurring within each geologic unit through calculating the difference between the observed frequency of slides and expected frequency (or uniform distribution) of slides within each geologic group (Key 1997). The test statistic, X^2, describes the evidence either supporting or against the null hypothesis for each geologic group (Key 1997). For example, a lower X^2 value would indicate greater evidence supporting the null hypothesis (i.e., a uniform distribution of slides between the geologic units), and a higher X^2 value would indicate greater evidence against the null hypothesis (i.e., a particular geologic group contains more slides than would be expected from the uniform distribution) (Key 1997). The p-value, calculated using the Chi Square Test distribution tables, determined the probability of the null hypothesis (Key 1997).

$$X^2 = \sum \frac{(Observed\ Frequencies - Expected\ Frequencies - 0.5)^2}{Expected\ Frequencies} \qquad \text{Equation } 4-1$$

The results, shown in Table 4-4 through Table 4-6, give the statistical difference between the observed and expected events. The p-value for each geologic group (determined using the Chi square distribution table and the test statistic) was used to determine the significance of the test results (or the validity of the null hypothesis). A p-value threshold of 0.05 was selected to reject the null hypothesis, indicating that more slides occurred within that geologic unit than would be expected based on the miles of roadway within the geologic group. The results show that the units with higher susceptibility vary between the different databases. For the landslide report database (Table 4-5), the Tuscaloosa Group and Midway Group, and Selma Group Chalk experienced more slides than predicted—indicating higher landslide susceptibility within these regions. Whereas the Mississippian Limestone experienced fewer slides than predicted, exhibiting the low landslide susceptibility of the geological groups. For the emergency relief database (Table 4-6), the Midway Group, alluvial, coastal, and low terrace deposits, Selma Group chalks and Wilcox Group all experienced more slides than expected, while the Limestone formations experienced less slides than expected. The emergency relief database has contributions from both geology and rainfall, so these results should not be interpreted solely in terms of the geologic group. This is discussed further in the next section.

Table 4-4. One-Way Chi Square Test for the Historical Landslides Database

Geological Group	Historical Landslides	Estimated Road Miles[1]	Expected Number of Slides[2]	Chi Square Test Statistic[3]	P-Value[4]
Tuscaloosa Group	82	1156	39	50.02	0.00
Pottsville Formation	60	1770	60	0.00	0.95
Midway Group	49	431	15	81.17	0.00
Alluvial, coastal, and low terrace deposits	30	1783	60	17.10	0.00
Selma Group Sand and Clay	36	768	26	3.67	0.06
Mississippian Limestone	51	1166	40	3.35	0.07
Cambrian and Ordovician Limestone	35	2534	86	36.41	0.00
Mississippian Sandstone and Shale	40	505	17	30.45	0.00
Selma Group Chalk	22	588	20	0.13	0.72
Claiborne and Jackson Formation	10	1310	44	28.68	0.00
Wilcox Group	4	621	21	13.65	0.00
Precambrian to Paleozoic Schist and Gneiss	16	472	16	0.02	0.90
High Terrace Deposits	8	319	11	0.51	0.47
Miocene Series	5	476	16	7.25	0.01
Citronelle Formation	1	518	18	15.29	0.00
Cambrian and Ordovician Shale	4	127	4	0.01	0.93
Red Mountain Formation	1	25	1	0.15	0.70
Talladega Group	1	17	1	0.01	0.93

Table 4-5. One-Way Chi Square Test for the Landslide Reports Database

Geological Group	Landslide Reports	Estimated Road Miles[1]	Expected Number of Slides[2]	Chi Square Test Statistic[3]	P-Value[4]
Tuscaloosa Group	13	1156	7	4.58	0.03
Pottsville Formation	13	1770	11	0.30	0.58
Midway Group	7	431	3	5.86	0.02
Alluvial, coastal, and low terrace deposits	9	1783	11	0.21	0.65
Selma Group Sand and Clay	6	768	5	0.15	0.70
Mississippian Limestone	1	1166	7	4.86	0.03
Cambrian and Ordovician Limestone	12	2534	15	0.70	0.40
Mississippian Sandstone and Shale	1	505	3	0.84	0.36
Selma Group Chalk	2	588	4	0.35	0.56
Claiborne and Jackson Formation	4	1310	8	1.70	0.19
Wilcox Group	8	621	4	3.80	0.05
High Terrace Deposits	1	319	2	0.11	0.74
Miocene Series	5	476	3	0.91	0.34

Table 4-6. One-Way Chi Square Test for the Emergency Relief Slides Database

Geological Group	Emergency Relief Slides	Estimated Road Miles[1]	Expected Number of Slides[2]	Chi Square Test Statistic[3]	P-Value[4]
Tuscaloosa Group	8	1156	14	2.51	0.11
Pottsville Formation	13	1770	22	3.61	0.06
Midway Group	26	431	5	79.54	0.00
Alluvial, coastal, and low terrace deposits	35	1783	22	8.33	0.00
Selma Group Sand and Clay	15	768	9	2.89	0.09
Mississippian Limestone	1	1166	14	12.57	0.00
Cambrian and Ordovician Limestone	3	2534	31	30.23	0.00
Mississippian Sandstone and Shale	3	505	6	1.22	0.27
Selma Group Chalk	16	588	7	9.93	0.00
Claiborne and Jackson Formation	21	1310	16	1.33	0.25
Wilcox Group	14	621	8	4.72	0.03
High Terrace Deposits	6	319	4	0.65	0.42
Citronelle Formation	4	518	6	0.57	0.45

The landslides locations were mapped along with the geological groups, shown in Figure 4-6. The map illustrated the many of the landslides occurred in regions near the convergence of two or more geologic groups—many of which seemed to include alluvial, coastal, and low terrace deposits. Therefore, ArcGIS was employed to determine geologic groups within a given distance form each landslide site. The geologic map developed by the USGS was used for this analysis. The accuracy of the geologic map was based on the 1:100,000 scale (Dicken et al. 2017). The map scale 1:100,000 generally produces an error of +/- 166.67 feet. However, additional errors may have been introduced within the USGS analysis (Dicken et al. 2017). The locations of the landslides were used to develop buffers, or polygons, around each site with a radius of 1000 feet—accounting for the error of the map as well as the accuracy of the landslide locations (many of which were determined using mile markers, images, and/or maps provided within the landslide reports, rather than geologic coordinates)—to account for slides located within regions consisting of changing geologic formations. The study estimated 279 landslides (182 historical landslides, 57 emergency relief slides, and 40 landslide report landslides) occurred within 1000 feet of two or more geologic units (or 39.5% of the landslides analyzed). The alluvial, coastal, and low terrace deposits experienced the larger number of slides within 1000 feet of the formation (79 slope failures).

In addition to the total number of landslides within each geologic database, the study was expanded to further examine the geologic trends of the emergency relief slides. The emergency relief slides database contains data on emergency slides occurring due to heavy rainfall events. The 165 emergency relief landslides, occurring over a period of 12 years, were located within 35 of the 163 geologic formations within Alabama. The locations where slides occurred may indicate regions more prone to landslides, or the landslide sites may be located within regions experiencing larger amounts of rainfall—leading to reductions in resisting forces within the slope. Figure 4-7 illustrates the locations of the slides in relation to the geologic groups—which combine the geologic formations with similar characteristics (see Appendix D). The map was used in conjunction with the rainfall data from each event (National Weather Service 2017), to determine trends within between the geology, precipitation, and total number emergency relief slides, described in Section 4.3.2.

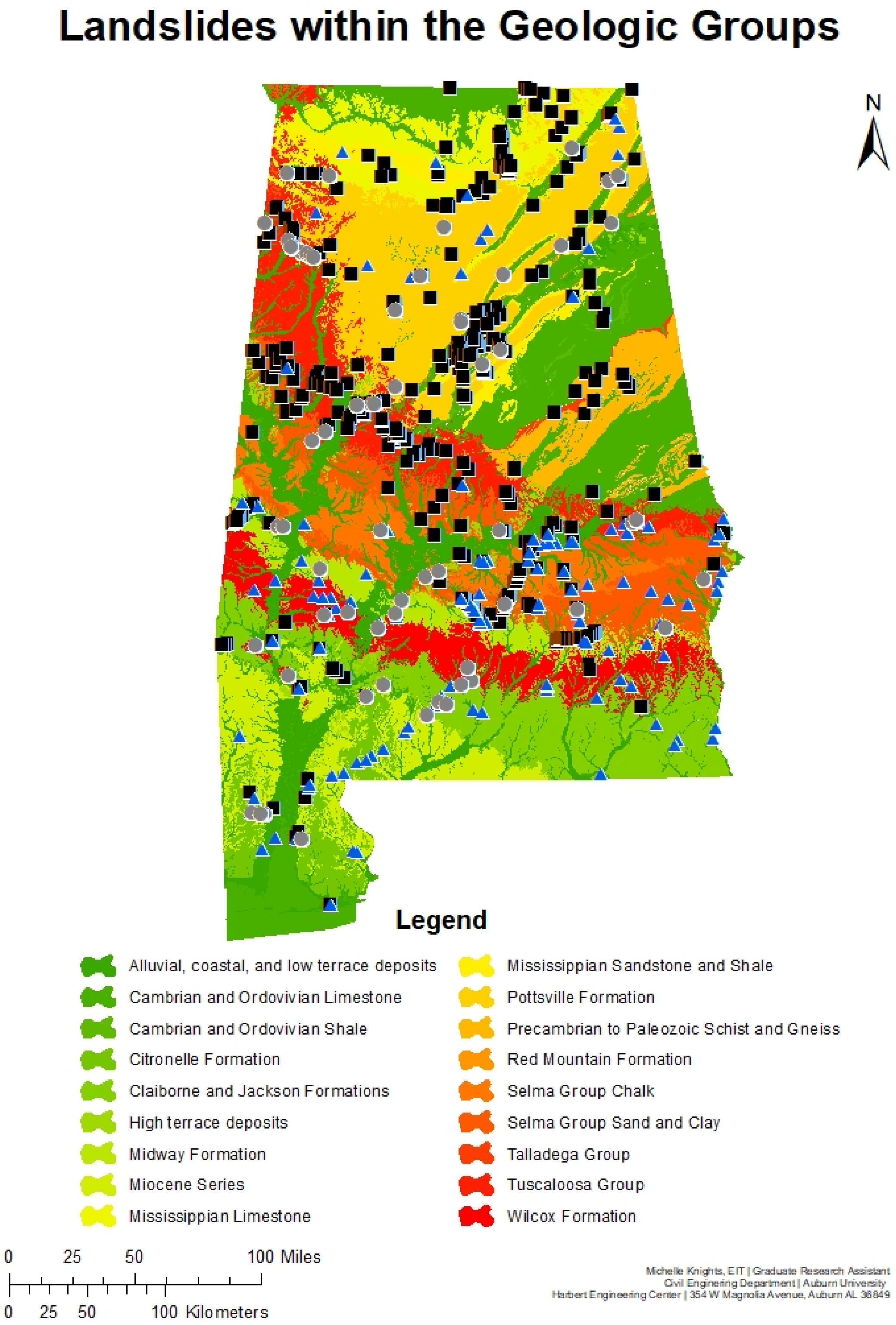
Landslides within the Geologic Groups

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Figure 4-6. Landslide Locations in Relation to the Geologic Groups of Alabama

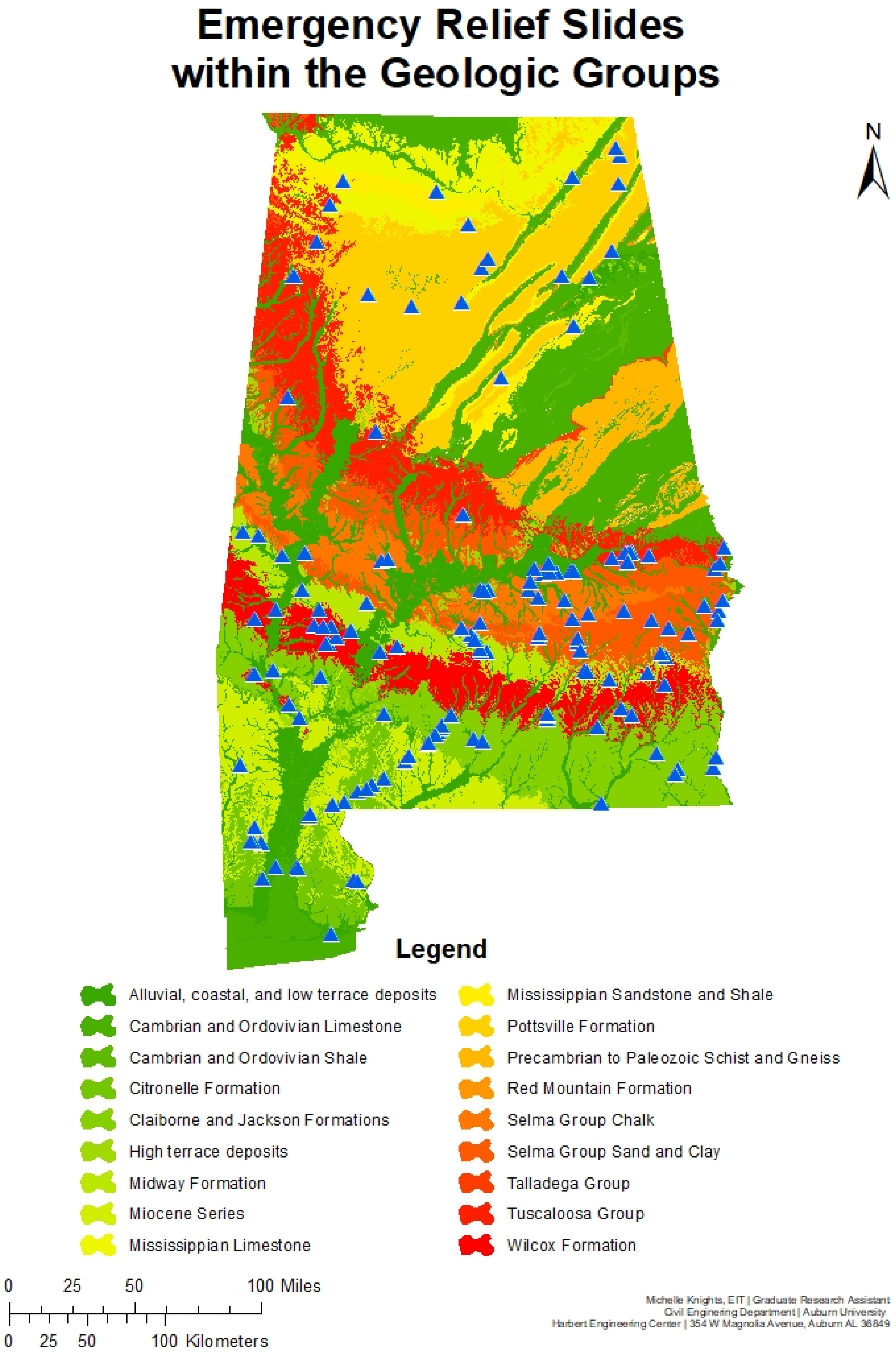


Figure 4-7. Emergency Relief Slides within the Geologic Groups (Dicken et al. 2017)

4.3.2 Weather at Failure

The weather at failure was examined for the landslides in the Slide Spread databases to determine if it could be used as a proxy for the failure mechanism. The weather data, which was collected within Slide Spread as well as extracted from external data sources, was used to determine trends between the geology of the region and the volume of rainfall due to heavy precipitation events. Many slides within the landslide reports database did not have enough information to identify the specific weather at the time of failure. Approximately half of the slopes within the landslide reports database (46 slides) described the weather at or near the time of failure—all of which reported rain. The reports generally did not provide details about the precipitation (e.g., volume of rainfall, or duration of storm). In addition, the historical landslides database did not give the time of the failure. Therefore, the weather at or near the time of failure could not be determined.

The emergency relief slides database offers a clearer picture of the weather at failure, as each slide has been attributed to a specific weather event. The breakdown of slides in the database by the initiating event is shown in Figure 4-8. Each of the events represents periods of intense rainfall. The weather events associated with the emergency relief slides were examined to determine the estimated rainfall within each region after the storm events, comparing the results to the landslide locations (Figure 4-7). Cumulative rainfall plots for the storms occurring between 2011 and 2015 were obtained for the NWS. Figure 4-9 through Figure 4-13 give an estimation of the rain throughout the state as well as illustrates the locations of the landslides resulting from the storm. The figures were used to compare the locations of landslides to the estimated amount of rainfall during storm events, accounting for the miles of roadway within each rainfall region and the geologies in which the failures occurred. Table 4-7 summarized the rainfall data.

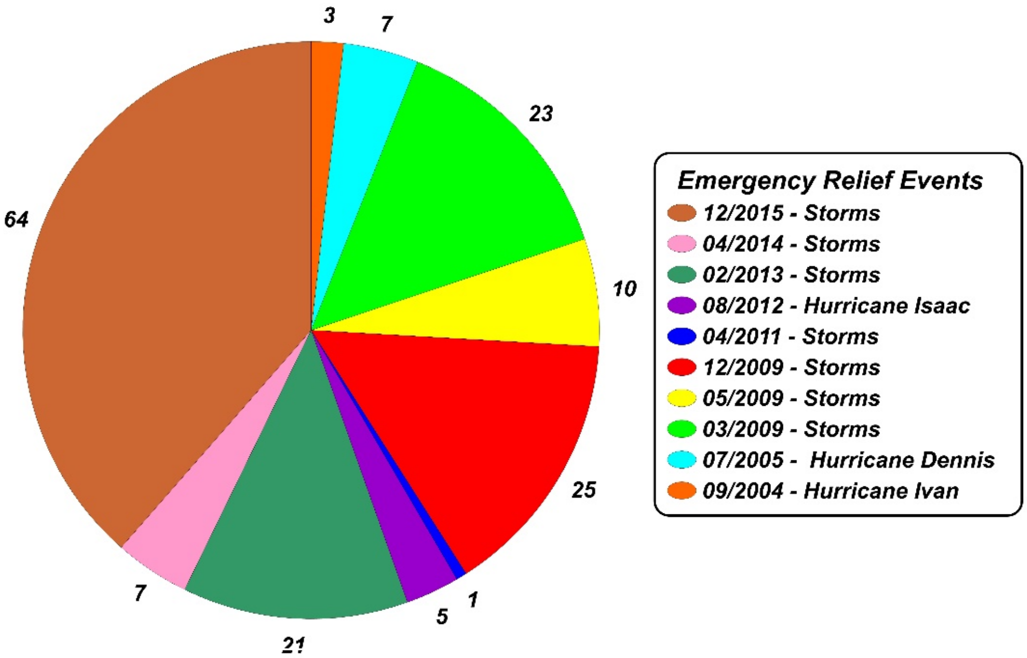


Figure 4-8. Distribution of Emergency Relief slides by event.

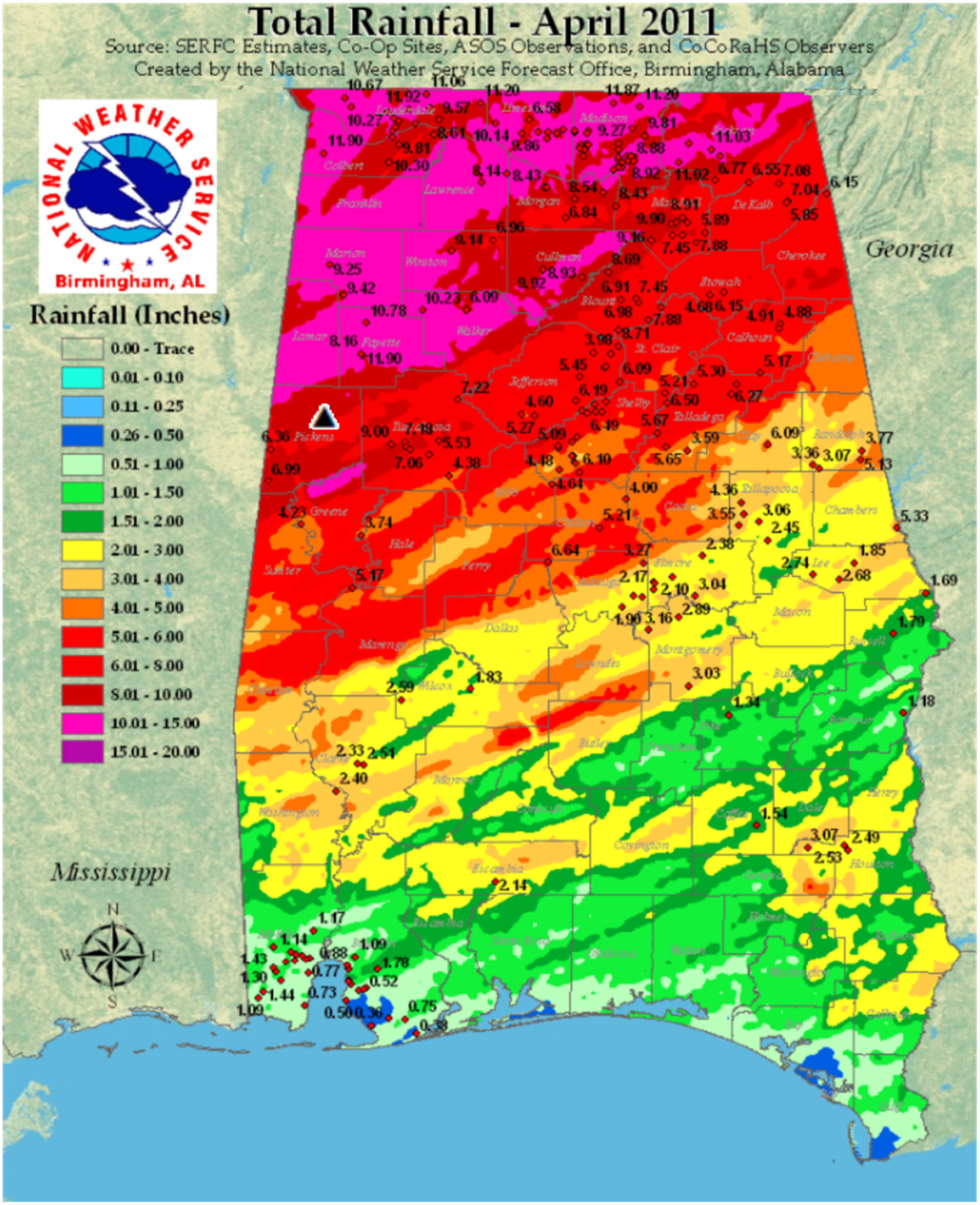


Figure 4-9. Landslides and inches of rainfall resulting from April 2011 storm (National Weather Service 2017).

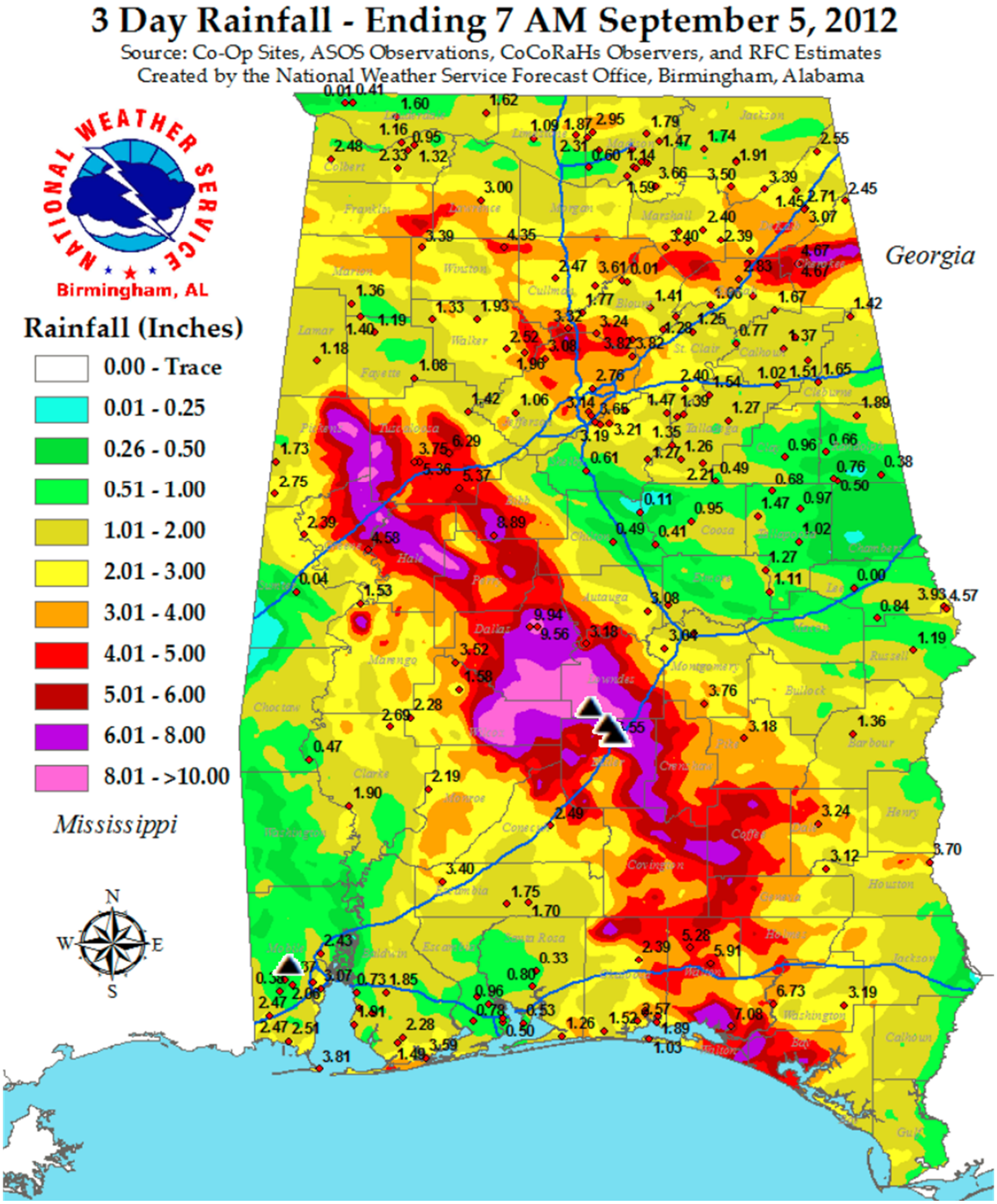


Figure 4-10. Landslides and inches of rainfall resulting from Hurricane Isaac, September 2012 (National Weather Service 2017).

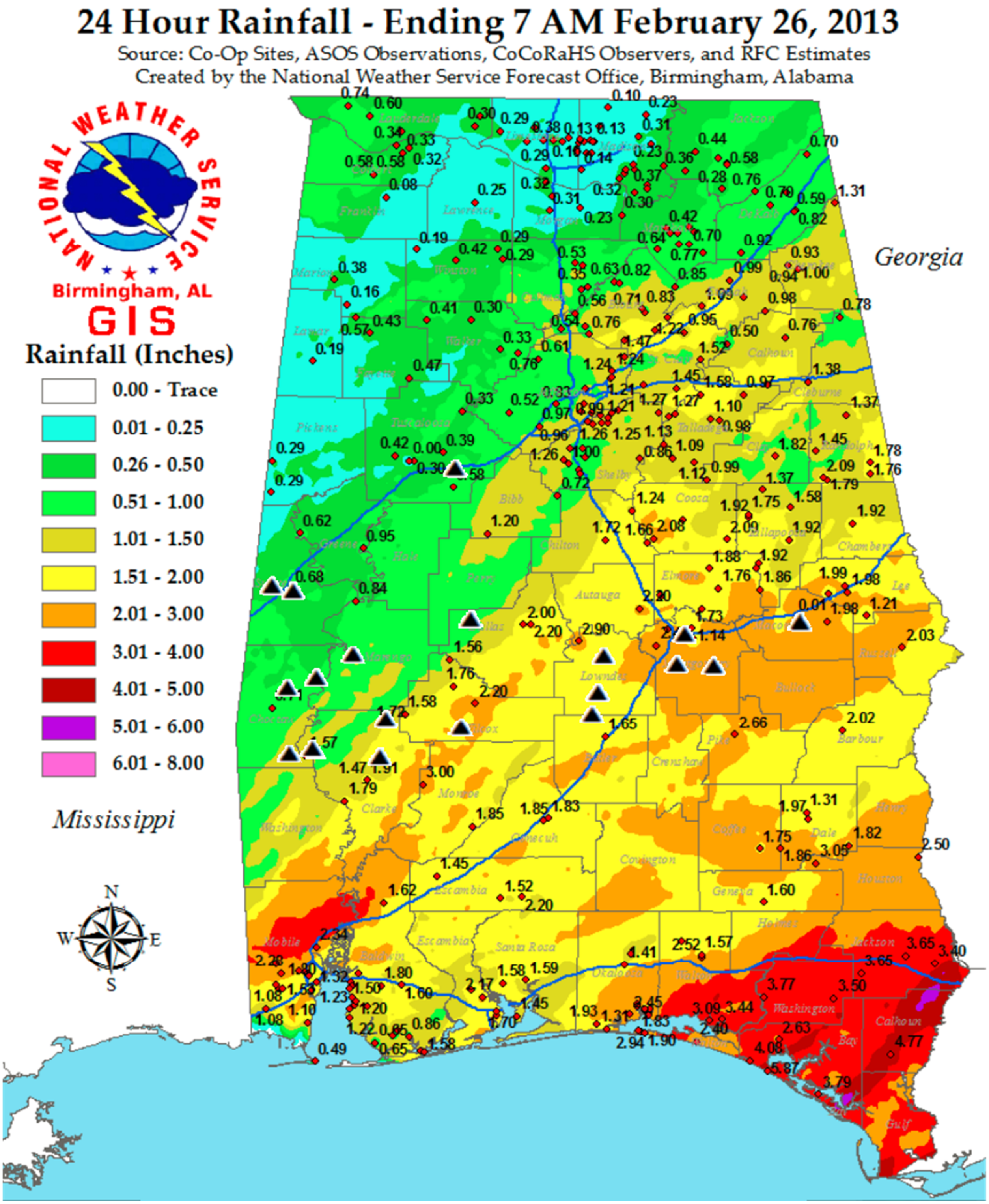


Figure 4-11. Landslides and inches of rainfall resulting from February 2013 storm (National Weather Service 2017).

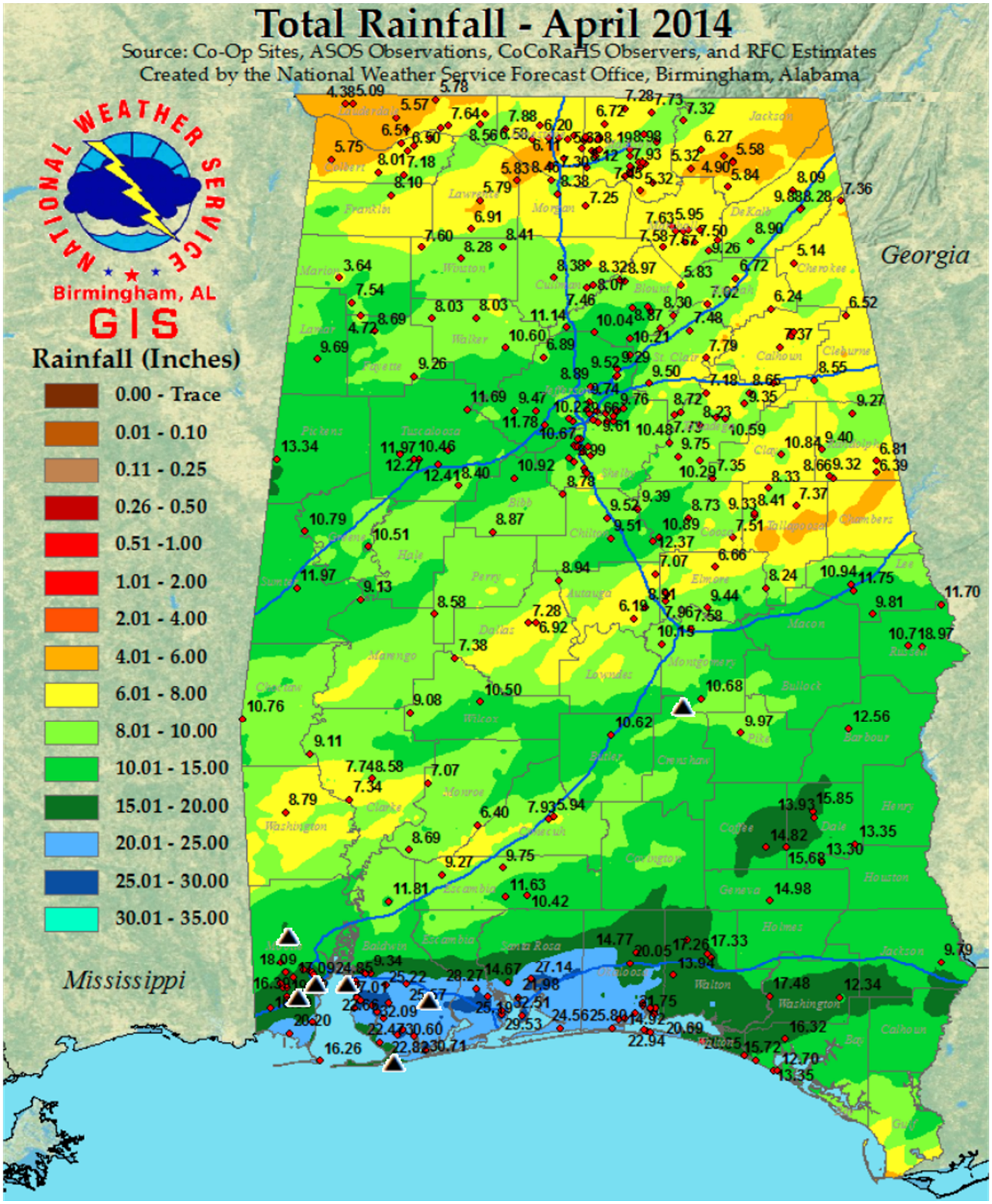


Figure 4-12. Landslides and inches of rainfall resulting from April 2014 storm (National Weather Service 2017).

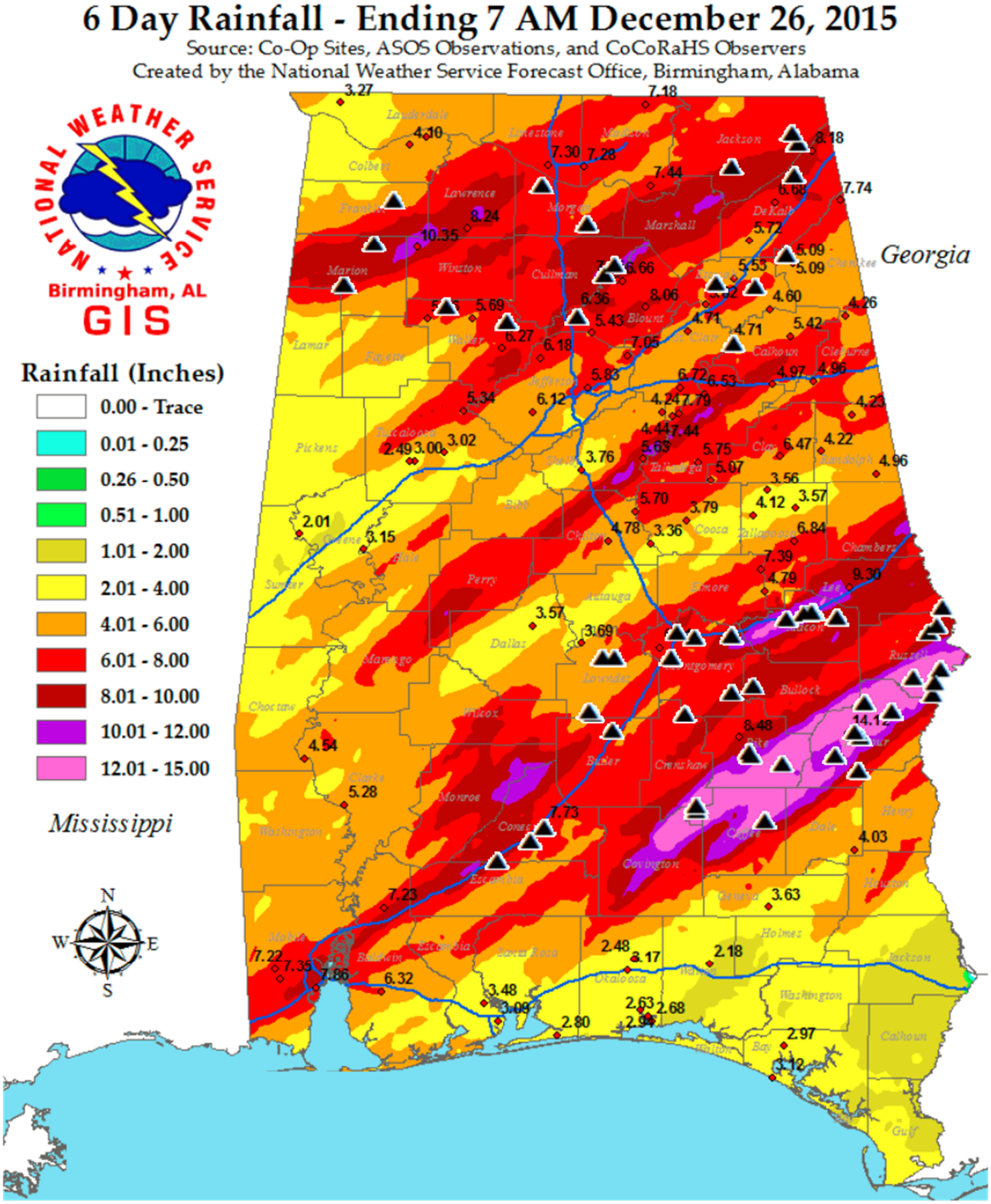


Figure 4-13. Landslides and inches of rainfall resulting from December 2015 storm (National Weather Service 2017).

Table 4-7. Estimated Rainfall near Time of Failure of Emergency Relief Slides Occurring between 2011 and 2015 (Dicken et al. 2017, NWS 2017)

Rain (inches)	Total (Years 2011 – 2015)	Year				
		2011	2012	2013	2014	2015
0.00-0.25	0	0	0	0	0	0
0.26-0.50	2	0	0	2	0	0
0.51-1.00	6	0	1	5	0	0
1.01-1.5	4	0	0	4	0	0
1.51-2.00	6	0	0	6	0	0
2.01-3.00	4	0	0	4	0	0
3.01-4.00	0	0	0	0	0	0
4.01-6.00	8	0	0	0	0	8
6.01-8.00	21	0	2	0	0	19
8.01-10.00	15	1	1	0	0	13
10.01-15.01	26	0	0	0	2	24
15.01-20.00	4	0	0	0	4	0
20.01-25.00	1	0	0	0	1	0

The number of slides in each rainfall region were divided by the miles of roadway exposed to that amount of precipitation, normalizing the value, to determine the relationship between rainfall exposure and the number of slides per 1000 miles (Table 4-8). The results showed the number of slides per 1000 miles generally increased with precipitation, displaying the impact of the rainfall on the stability of the slope. There are several exceptions to this trend in Table 4-7. These exceptions to the trend could be related to the geology in the area, particularly susceptible slopes failing at lower than expected rainfall, or rainfall occurring in areas with good storm water management systems in place. For example, a low frequency of slides was observed within the Mississippian Limestone (1 slide) and the Cambrian and Ordovician Limestone (3 slides) despite the large amount of rainfall in these areas. This is likely due to the strength of rock dominating the region which makes it less susceptible to rainfall-induced failures.

Table 4-8. Number of Failure of Emergency Relief Slides occurring per 1000 Miles between 2011 and 2015 within each Rainfall Region (Dicken et al. 2017, NWS 2017)

Rain (inches)	Year				
	2011	2012	2013	2014	2015
0.00-0.25	-	0	0	-	-
0.26-0.50	-	0	1.102	-	-
0.51-1.00	0	0.517	1.961	-	-
1.01-1.5	0	0	1.579	-	-
1.51-2.00	0	0	1.585	-	-
2.01-3.00	0	0	2.065	-	0
3.01-4.00	0	0	0	-	0
4.01-6.00	0	0	-	0	1.732
6.01-8.00	0	4.576	-	0	3.748
8.01-10.00	0.770	10.342	-	0	5.818
10.01-15.01	0	-	-	0.378	30.948
15.01-20.00	-	-	-	9.023	0
20.01-25.00	-	-	-	3.743	0

The rainfall analysis may be skewed due to the impact of the December 2015 storm, which consisted of approximately 66 percent of the slides (64 slides of the total 97 occurring between 2011 and 2015). This may have influenced the trends observed within the geologic groups, as the slides (with the exception of slides within rock formations) generally occurred in regions experiencing higher rainfall. In the future, this bias may be combated with the inclusion of addition slides.

4.3.3 Roadways Adjacent to Landslides

The roadways adjacent to the landslide were provided for each slide within the Slide Spread database. However, the Historical Landslide Database does not contain roadway information. The roadways adjacent to the historical slides were determined using the program ArcGIS, via the spatial analysis tools Buffer and Clip. The tools were used to create a perimeter around each historical landslide with a 100 foot radius, identifying each roadway which intersected the created region. The value of the radius was determined by examining the distance between landslides and the adjacent roadways, while attempting to eliminate the likelihood of assigning one landslide to multiple roadways, as well as exclude the slides which are not adjacent to state roadways. The procedure may have eliminated landslides adjacent to roadways from the analysis. However, the method was conducted to reduce the challenges of analyzing landslide sites unrelated to the Alabama highway network, while also lowering the likelihood of identifying numerous roadways for any given landslide site.

This thesis spatially correlated the locations of the historical landslides with present locations of the state highway and interstate network. The method determined each roadway which intersected the created region, identifying 221 historical landslides adjacent to the current orientation of the roadway systems (approximately 48% of the total number). Assuming the orientation of the roads have remained relatively constant, approximately 50 percent of the landslides are located along the roadways or in close proximity to the roadway. However, the landslide sites which were not adjacent to a state roadway may be located along county roads or minor roads not included in the state highway network.

This data, along with the roadways identified using Slide Spread, were used to determine the highways experiencing the largest number of slope failures. The roadways with multiple names where combined using information available in Google Maps. Landslides were found to have occurred along at least 96 roadways within Alabama. Table 4-9 presents the number of landslides along the roadways experiencing at least two percent of the total number of slides within the three databases.

The largest total number of landslides and the largest number of historical landslides were seen along US-31. In contrast, the largest number of Slide Spread landslides were located along I-65. The trends between the historical slides and adjacent roadways have some uncertainty due to both the spatial correlation tool used and the possibility that roadway alignment may have changed since the landslides were recorded. As failure dates were not included with the historical landslides it was not possible to determine roadway alignments at the time of failure.

Table 4-9. Number of Landslides along Alabama Roadways

Roadway	**Number of Landslides**		
	Total	**Historical Landslides Database**	**Slide Spread Databases**
US-31	36	29	7
I-65	30	9	22
SR-6	28	23	7
SR-21	25	17	8
SR-8	22	6	16
I-85	22	2	17
I-59	18	11	7
SR-9	14	6	8
SR-12	14	7	7
I-22	12	0	12
SR-69	12	4	8
SR-10	12	6	6
SR-2	10	5	5

4.3.4 Past landslides

Landslides are likely to occur at or near the location of past, or previously occurring, landslides due to either a weakened slip surface within the slope or a regional failure mechanism (e.g., Duncan et al. 2014). Therefore, Slide Spread collects information on the presence of past landslides at or adjacent to current slide locations, noting the cause of the previous failure(s) and documenting the repairs. Approximately half of the landslide reports (41 landslides) mentioned the presence of previous failures in the area. The other half did not provide enough information to determine whether there was no history of previous landslides or if that history was unknown.

The past failures occurring at landslide sites were not provided within all the reports examined for this study. Therefore, an additional spatial analysis for the landslides within all three databases was conducted to identify past landslides within 1000 feet, highlighting regions experiencing multiple landslide failures within short distances. The 1000-foot distance was chosen to account for the uncertainty of the landslide locations and the length of the landslides. The results of the analysis provide an estimation of slides occurring at or near the sites of pervious failures.

The analysis was conducted using the ArcGIS buffer tool to develop a 1000-foot perimeter (or polygon) around each landslide point. The number of landslides located within the perimeter were then counted. The results showed a total of 143 slides occurring within 1000 feet of another landslide. The number of slides included 21 of the 41 landslides previously determined to have occurred near a past slide through the data available in Slide Spread. Therefore, a total of 163 slides were estimated to have occurred at or near a pervious landslide failure, making up 23.1% of the slides within the three databases. These landslides consisted of 65 historical landslides, 35 emergency relief slides, and 63 landslide reports slides. These results show that more the three-quarters of the landslide reports occurred in areas near other slides.

The results indicate landslides along previously failing sites may be a hazard to Alabama highway. However, the analysis assumed the landslides were 1000 feet in length or shorter. This broad search range was employed to account for the uncertainty in the landslide locations, as well as the uncertainty of the length of the slides. In addition, the analysis assumed the adjacent past landslides were recorded within one of the 3 databases, eliminating slides undergoing maintenance repairs for which a formal report was not written. Data collection may be improved by requiring the geographical coordinates of the slides, eliminating the uncertainties developed through changes in the road alignment when only the mile post is provided. In addition, the length of a slide along the roadway should be recorded within the report (e.g., ALDOT slope stability report, and/or DDIRs) as well as within the Slide Spread database. This will allow the search radius to be specified for each slide, lowering the number of unrelated slides being identified through this method. The site investigation of each landslide should indicate the history of the site. This record would document any known failures previously occurring near the failed slope—stating whether the site has or has not experienced recorded failures in the past.

4.3.5 Adjacent Structures

The structures adjacent to failed slopes were recorded for the landslide reports database within Slide Spread. Data was gathered on natural structures—such as waterways and wooded regions, as well as manmade constructions such as utilities, culverts, and bridges. Forty of the 83 landslides had adjacent structures that were discussed in the landslide reports, many of which had more than one adjacent structure listed. The results (Figure 4-14) show that over 50% of the slides in the landslide report database occurred near a culvert, drain or flowing waterway.

The culverts adjacent to emergency relief slides were recorded within Slide Spread—however additional structures were not included within the database due to the availability of information. Therefore, the emergency relief slides were excluded from the initial analysis of the total number and type of structures adjacent to landslides.

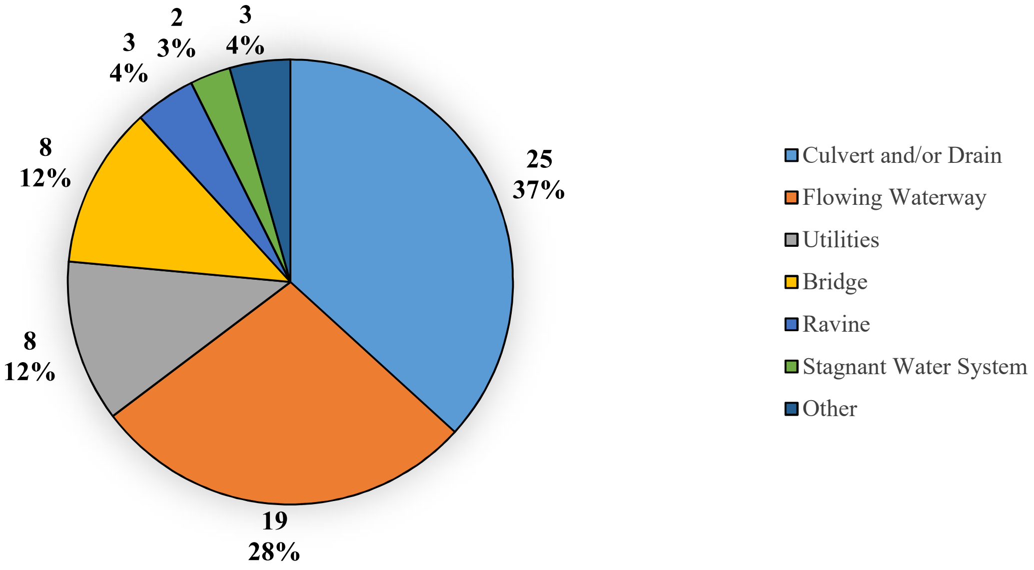


Figure 4-14. Number and Type of Structures Located Adjacent to Landslide Report Slides

The slides adjacent to culverts were analyzed in more detail to determine the state of the culvert at the time of failure. Culverts were classified as either damaged, blocked or undamaged (Table 4-10) within both the landslide reports database and the emergency relief slides database. Most of the failures near culverts were classified as shallow failures with most landslides occurring near undamaged culverts categorized as erosion failures and most slides near damaged culverts classified as shallow failures within the fill material. This trend between culvert location and landslides deserves further study to determine the cause of the slides, examining maintenance frequency and conducted repairs within the region, along with the environmental factors or designs which may influence failures.

Table 4-10. Total Number of landslides by failure classification for landslide sites located at or near culverts.

Failure Type	Total Number of landslides
Undamaged Culvert	24
Damaged Culverts	21
Unknown	1
Total	46

4.3.6 Failure Location along the Roadway

The location of the slope failure along the roadway was categorized within Slide Spread using two descriptors: the slope type (e.g., fill section, cut section, or cut and fill section) and the slope location along the roadway (e.g., front slope, back slope, or front and back slope). The descriptors were used to provide details regarding the design of the failed slopes—indicating whether the failure occurred within borrow material (fill section) or native soil (cut section). This data was spatially correlated to the geology at the landslide site—to determine trends between the location of the slope failure along the roadway and the geology.

Trends in the location of slope failure along the roadway may be an indication of the geologic formations more prone to failures in either the fill or cut sections. Fill sections generally consist of borrow materials taken from cut sections in the same area and so are likely representative of the geologic formation in which they are located. The location of the slope along the roadway in which the failure occurred may highlight trends between failure within the fill and cut sections and the geologic formation of the region.

The slope type (e.g., fill section, and/or cut section) was provided within 72 of the 82 landslide reports. However, the slope type is not generally given within the DDIRs—provided for only 26 of the 165 slides with the Emergency Relief Slides database. Therefore, the analysis was conducted for only failures recorded with the landslide reports database. The results, presented in Table 4-11, give the number of landslides within each slope type. The results did not provide a clear trend between landslide type and geologic group. The Tuscaloosa Group (8.5% of landslide report slides) and Pottsville Formation (7.3% of landslide report slides) experienced the largest number of landslides within the cut sections. Whereas, the Wilcox Group (8.5% of landslide report slides), Cambrian and Ordovician Limestone group (7.3% of landslide report slides), and Midway Formation (7.3% of landslide report slides) had the greatest number of slides within the fill sections. The number of slides examined may have affected the results—as each category within the geologic groups contained seven or less slides.

Table 4-11. Failure Types of the Landslide Report Slides

Slope Type	**Number of Landslides**	**Percentage of landslides (%)**
Cut	21	25.6
Fill	36	44.0
Cut and Fill	14	17.0
Unknown	11	13.4
Total	82	100

The analysis was expanded to include the location of the slope failure along the roadway (e.g., front slope, back slope, or front and back slope), which was available for both the landslide reports database and the emergency relief slides database. The location of the failure along the road provides a generalization, or approximation, of slides occurring within fill sections or cut sections. The front slope, or the slope with a negative grade when moving away from the centerline of the roadway, generally coincides with an embankment or fill section. Whereas, a back slope—or slope with a positive grade when moving away from the centerline of the roadway—generally indicates a cut section. Figure 4-15 provides a diagram of a roadway with the front slope and back slopes labeled.

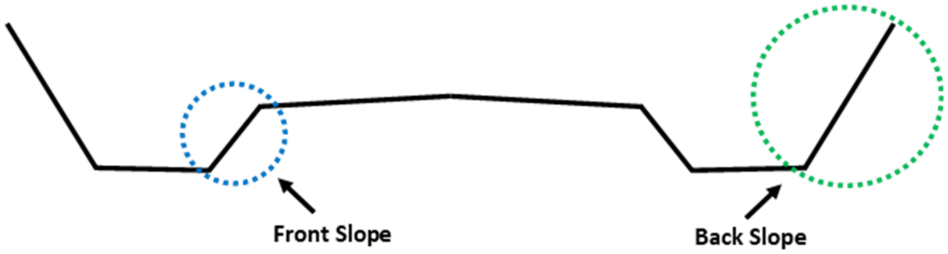


Figure 4-15. Location of the Front Slope and Back Slope along a Roadway

The location of failure along the slope was analyzed for both the emergency relief slides and the landslide reports slides. The results, summarized in Table 4-12, show the total number of front slope, back slope, and front slope and back slope failures with the Slide Spread databases. The majority of landslides (approximately 68 percent) occurred within the front slope alone the roadway, indicating a failure trend within fill sections. Whereas approximately 22 percent of failures occurred within the back slope, predominately composed of cut sections. The percentage of failures within the front slope closely agrees with the percentage of failures within the fill sections, indicating the trends made between the front slopes and fill sections were likely correct.

Table 4-12. Number of Front Slope and Back Slope failures along Alabama Highways

Failure Location along the Roadway	**Number of Landslides**			**Total Percentage (%)**
	Landslide Reports Slides	**Emergency Relief Slides**	**Total**	
Front Slope	47	117	164	66
Back Slope	23	26	49	20
Front Slope and Back Slope	0	6	6	2
Unknown	12	16	28	11

4.3.7 Slope Ratio

The slope ratio, or the change in horizontal distance to the change in vertical distance up a slope, was provided for 55 of the 82 slides within the landslide reports database. 17 of the 55 slides, or approximately 31% of the slides, occurred along slopes with slope ratios greater than 3:1 (H:V), illustrated in Figure 4-16. These failures, which occurred in relatively flat slopes, were compared to the failure category and geologic groups in which the failures were located (Table 4-13 and Table 4-14, respectively). 10 of the 17 failures were classified as shallow failure (one of which was also determined to be a translational failure at an interface). The geologic units with the most failures in this category tend to have higher plasticity clays, which are prone to softening.

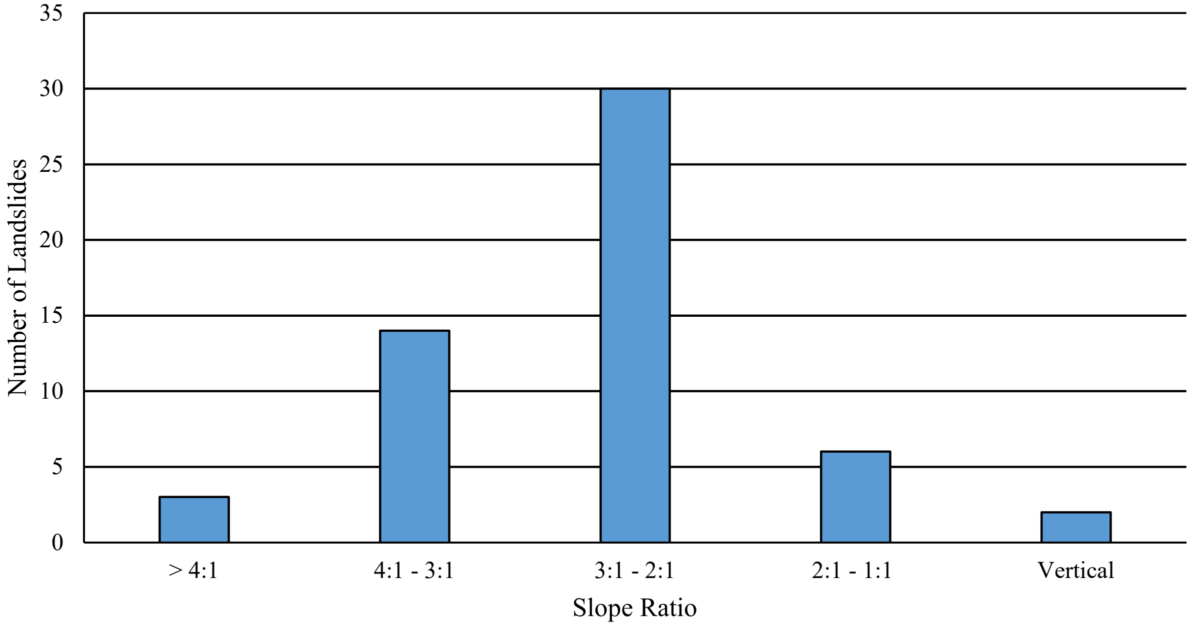


Figure 4-16. Slope Ratio Verse Landslide Failures

Table 4-13. Failure Category of Slides Occurring within Slopes with Slope Ratios Larger than 3:1 (H:V)

Failure Category	Number of Slides
Deep failure in calcareous clay	2
Shallow failure in cut slope	3
Shallow failure in fill section	6
Shallow failure in native soil	1
Translation failure at interface	3
Other	1
Unknown	2

Table 4-14. Geology Group of Slides Occurring within Slopes with Slope Ratios Larger than 3:1 (H:V)

Geologic Group	Number of Slides
Alluvial, coastal, and low terrace deposits	1
Claiborne and Jackson Formations	2
Pottsville Formation	1
Selma Group Chalk	1
Selma Group Sand and Clay	3
Tuscaloosa Group	4
Wilcox Formation	5

4.4 Landslide Susceptibility Map

The landslide susceptibility map, shown in Figure 4-17 and Figure 4-18, was developed for the GSA to portray the likelihood of a landslide event occurring within a region based on the rock strength and slope steepness of the given area. The system employed a rating matrix (Figure 2-1), assigning a landslide hazard score for each raster cell based on the effective cohesion and friction angle of the rock within the region, as well as the slope angle at that the given location. The matrix, described in section 2.6, was developed using an overlay analysis—assigning raster cell values based on the impact of the attribute on slope stability. The map was compared to the locations of historical landslides (Rheams et al. 1982), the annual average rainfall across Alabama, as well as a map of the potential seismic amplification throughout the state.

The landslide susceptibility map of Alabama was compared to the locations of the historical landslides and the Slide Spread landslides. The landslide locations were plotted on the landslide susceptibility map (Figure 4-17 and Figure 4-18). The regions determined to consist of the highest landslide potential were located near the northern third of the state, largely residing in Pottsville Formation, Tuscaloosa Group, and Cambrian and Ordovician Limestone, as well as within the alluvial, coastal and low terrace deposits geologic group. Whereas, the regions determined to have the lowest landslide potential were located along the western border, northern border, and lower third of the state—generally falling within the Piedmont physiographic province, Mississippian Limestone, Selma Chalk Group, and Tallahatta Formation (within the Claiborne and Jackson Formation), respectively.

The landslide susceptibility map generally agreed with the locations of the historical landslides (see section *4.3 Geology at Landslide Sites*)—showing large landslide potential in the Pottsville Formation (60 slides), Cambrian and Ordovician Limestone (28 slides), and Tuscaloosa group (82 slides). In addition, the historical landslide locations supported the regions experiencing low landslide potential, having very few slope failures within the Piedmont province (13 slides). However, numerous landslides occurred within the Selma Chalk Group, Claiborne and Jackson Formation, and Tuscaloosa Group despite their apparently low susceptibility. The disagreement in results deserves further study.

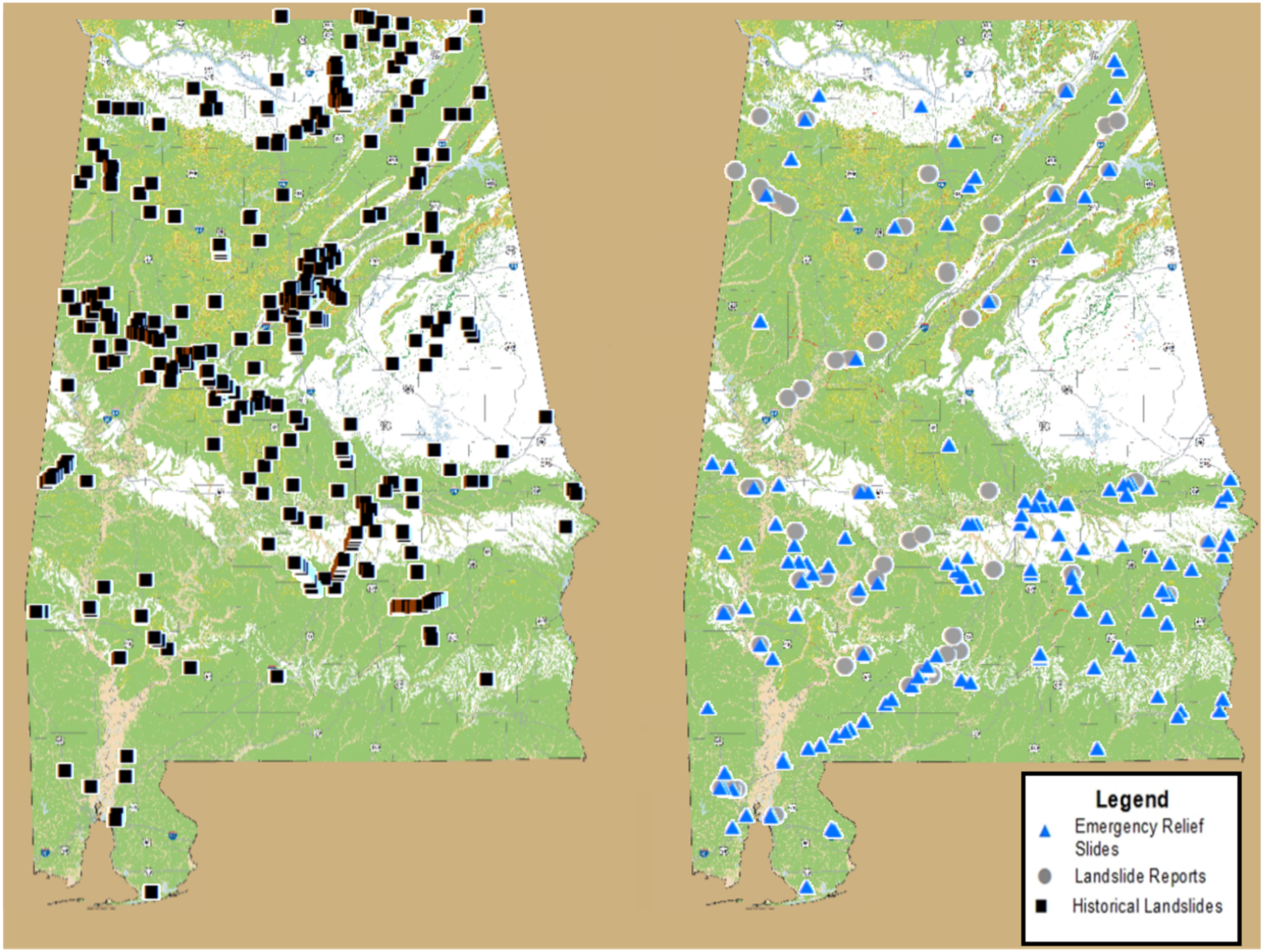


Figure 4-17. Landslide susceptibility map of Alabama and the locations of the historical landslides and Slide Spread database landslides (Ebersole et al. 2011, Rheams et al. 1982)

4.5 Common Failure Categories

Slide Spread was used to determine common failure categories for both the landslide reports and the emergency relief databases. The categories were established based on common failure descriptions and failure classifications provided within the landslide reports and DDIRs, and/or determined through the interpretation of photographs, physical descriptions of the site, and/or computer analyses of the slope failures conducted by ALDOT engineers. The categories differ for the landslide reports database and the emergency relief slides database due to the amount of information provided within the two report types—the landslide reports generally providing detailed analyses and descriptions of the slope failure, and the DDIRs generally providing brief slope failure/repair statements and images of the slides.

The landslide reports database consists of ten categories, defined in Table 4-15. The groups generalize failures based on the location of the sliding surface (e.g., fill or cut section, and/or shallow or deep failure), and/or by a unique identifier (e.g., crack, or rockfall). The emergency relief database separates landslides based on five categories, defined in Table 4-16—distinguishing the slides based on the type (or shape) of failure (e.g., erosion, rotation, translation, or rockfall). The categories will be used to form similarities between the landslide data collected within Slide Spread, as well as spatial trends between the landslides and additional databases—such as regional geology.

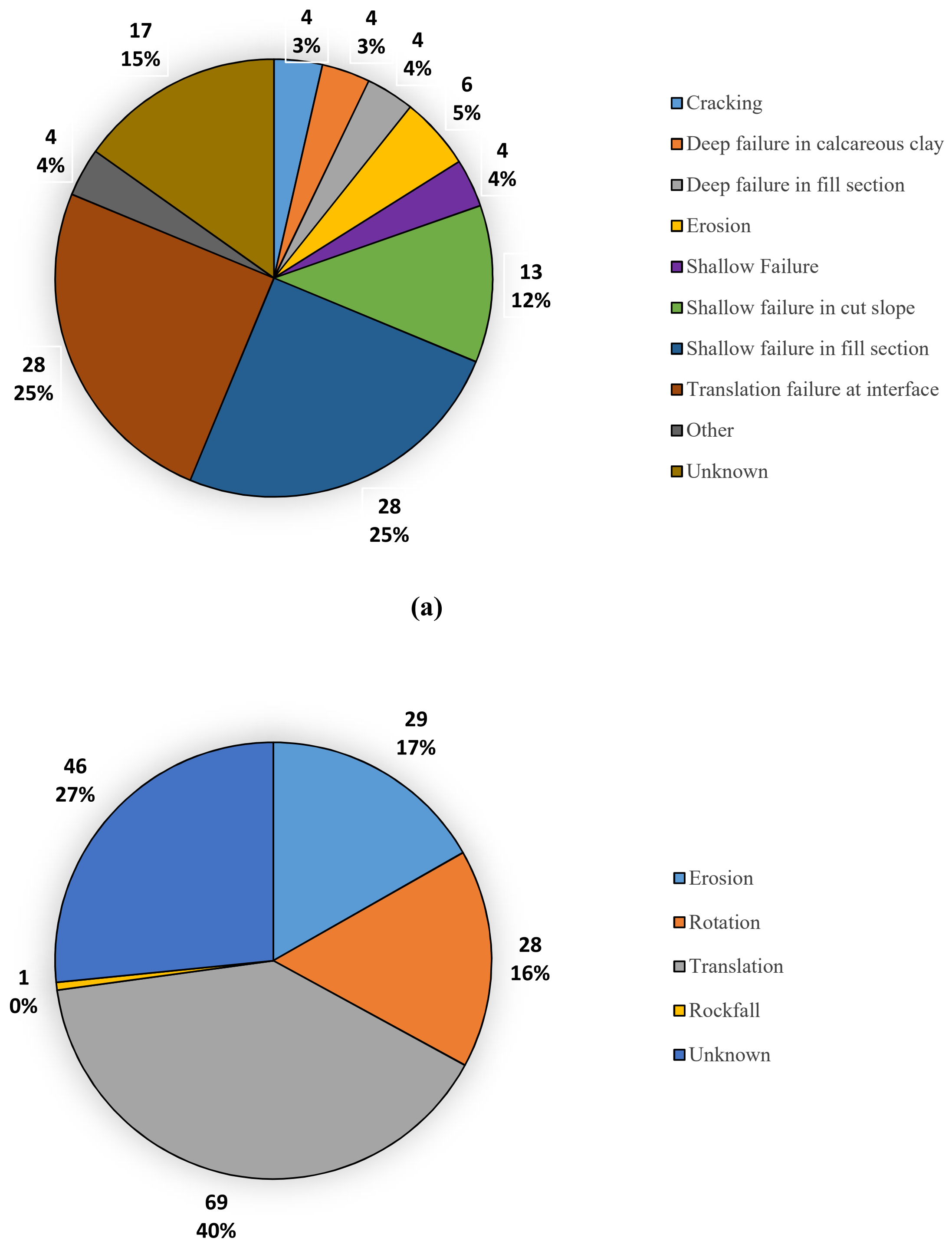
The number of landslides within each failure category is presented in Figure 4-19 (a) and (b). The charts represent the number of times the failure categories appear within the database, allowing landslides to be counted more than once if it experienced multiple failure types. For example, a site with a shallow landslide occurring within a fill section and cracked pavement will be represented in both the “Shallow Failure in Fill Section” and “Crack” categories, increasing the total number of failures recorded in the figure. The Figure 4-18 (a) shows the majority of landslides within the landslide reports database consists of shallow failures within the fill section (28 slides) and translation failures (28 slides) at an interface. Approximately 45 percent of landslides within the landslide report database (51 slides—shallow failure in fill, shallow failure in cut, shallow failure, and erosion) were shallow failures, whereas approximately 7 percent of landslides (8 slides) were deep failures. In addition, Figure 4-19 (b) shows the majority of DDIR landslides consist of translation failures (69 slides), making up approximately 40 percent of the database. The location of the landslides, portrayed in Figure 4-19 and Figure 4-20, are displayed based on the failure categories assigned to each slide.

Table 4-15. Landslide Reports Database Failure Categories along Alabama Highways

Failure Category	Description
Crack	A failure consisting of cracks in the pavement and/or soil.
Deep Failure in Calcareous Clay	A failure that extends deeper than the toe of the slope, located within marine clays (which are generally within the coastal plain physiographic province).
Deep Failure in Fill Section	A failure that extends deeper than the toe of the slope, located within fill material.
Erosion	A shallow failure occurring due to the wearing away of the top layer or layers by surface water or runoff.
Shallow Failure	A shallow slope failure occurs within the upper soil layers, located near the face of the slope. The failure does not extend deeper than the toe of the slope, nor beyond the toe of the slope. The category was assigned to landslides occurring in unknown soils, where the slope type (fill or cut) could not be distinguished
Shallow Failure in Cut Slope	A failure located within the upper soil layers in a cut section, consisting of native soils.
Shallow Failure in Fill Slope	A failure located within the upper soil layers in a fill section, consisting of fill soils.
Translation Failure at Interface	A failure along a weak or slick interface with a planar slip surface.
Other	Other contains several failure categories which did not fit into the above groupings, and contained a total 1 failure within each group. This includes deep failures in native soil, rockfalls in cut sections, and shallow failure in native soil. A deep failure in native soil consists of a failure surface which extends deeper than the toe of the slope, located within native soils. The shallow failure in native soil occurred in a fill section. However, the sliding surface was located below the fill, in the native soil.
Unknown	The slides were not able to be confidently categorized into one of the above categories using the information provided within the landslide report.

Table 4-16. Emergency Relief Database Failure Categories along Alabama Highways

Failure Category	Description
Erosion Failure	A shallow failure occurring due to the wearing away of the top layer or layers by surface water or runoff.
Rotational Failure	A failure occurring along a circular sliding surface
Translational Failure	A failure along a weak or slick interface with a planar slip surface.
Rockfall	A failure within a cut rock slope, consisting of fallen rock.
Unknown	The landslides were not able to be confidently categorized into one the above categories using the information provided within the DDIR report.



(a)

(b)

Figure 4-18. Landslide Category Distribution of Slides in (a) the Landslide Reports Database and (b) the Emergency Relief Database.

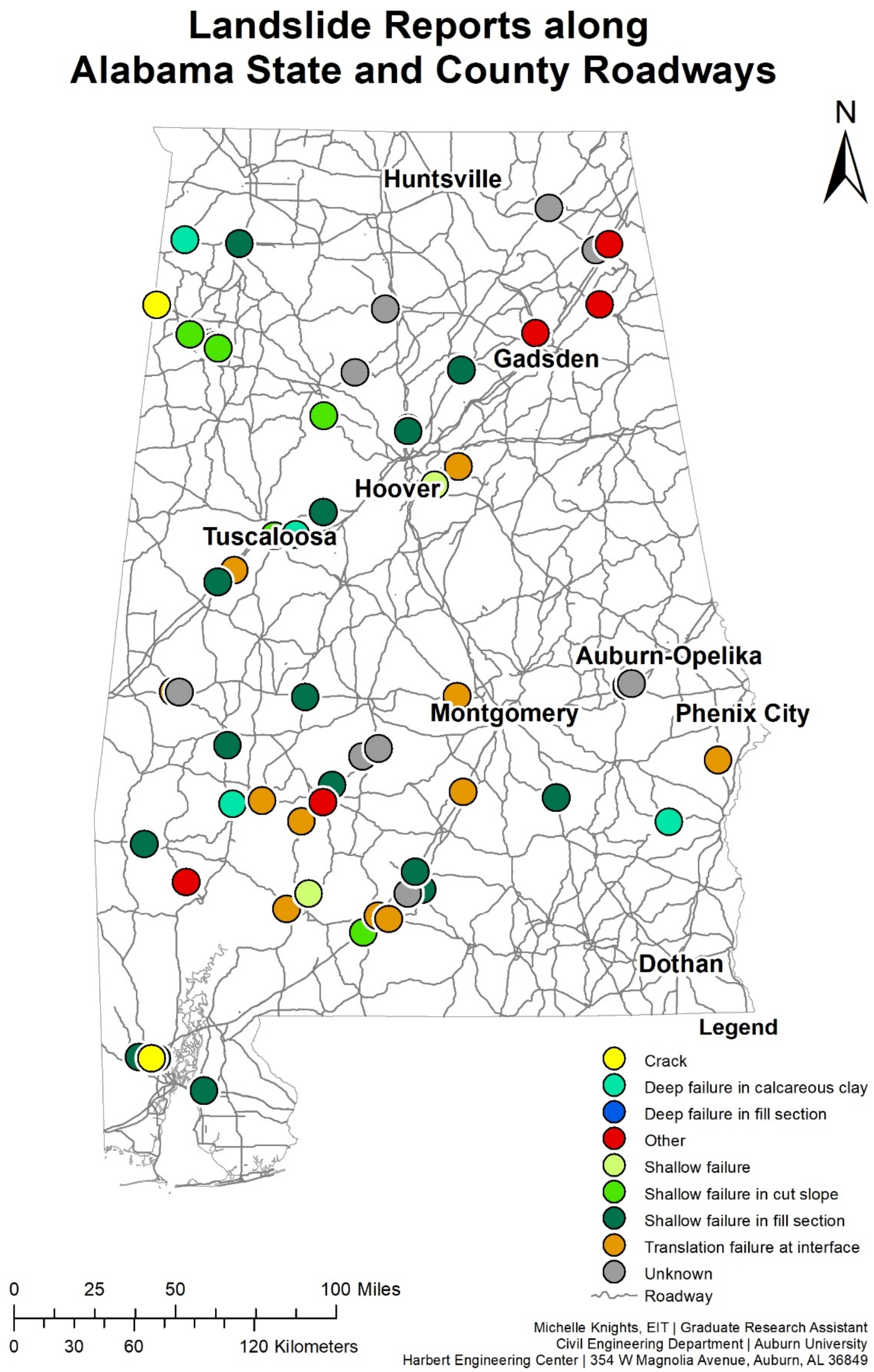


Figure 4-19. Map of Landslide Reports Failure Category Distribution.

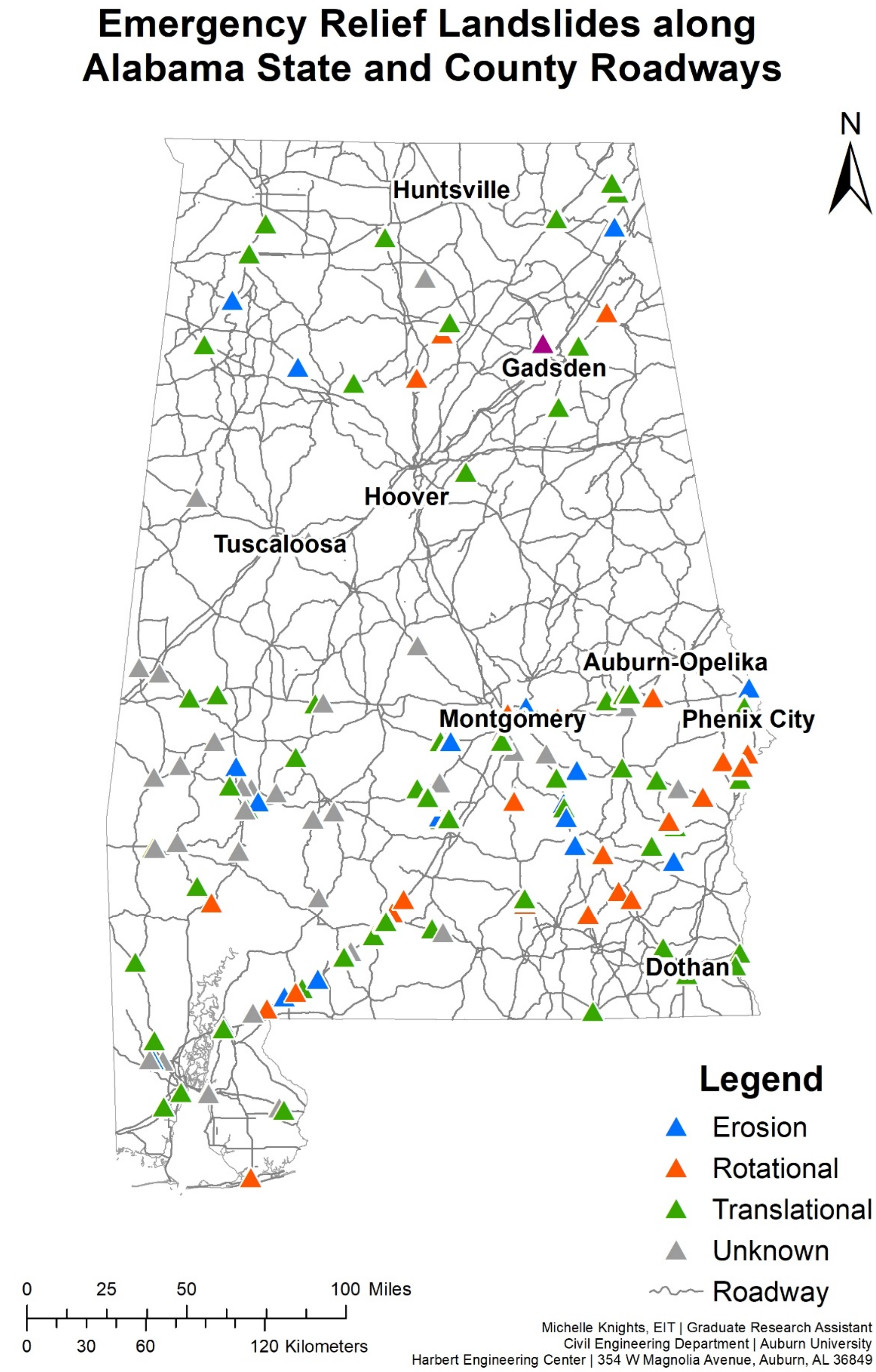


Figure 4-20. Map of Emergency Relief Failure Category Distribution.

4.6 Summary and Conclusions

This chapter analyzed the data collected within the historical landslide database, the emergency relief slides database, and the landslides reports database. These three databases were used to determine independent trends between the landslides and external data (regional geology, storm precipitation, and Alabama highway network), as well as similarities between the material and physical attributes of landslides, using the methods employed by Aydilek et al. (2013). The information provided within Slide Spread was used to develop slope failure categories—classifying slides through the failure type. The analysis may be improved through the collection of data pertaining to additional landslide sites, as well as improved data collection methods.

Three external data sets were employed to determine the relationships between landslides and geology and precipitation: geologic groups, NWS rainfall plots, and the Alabama highway network. The length of roadway was determined within each geologic group to compare the effect of geology and effect of exposure on the number of slides within a geologic unit. The study found the geologic groups impacted the probability of slides occurring within a region. The one-way Chi square test found the Tuscaloosa Group, Midway Group, and Selma Group Chalk have a higher likelihood of landslide events along roadways, based on a uniform distribution of landslides per mile of highway within each group. Whereas, the Mississippian Limestone and Cambrian and Ordovician Limestone were less likely to experience a landslide event.

The NWS rainfall pots where used to examine the number of slides occurring per 1000 miles of highway within each rainfall region. The results showed the number of slides within a region generally increased with increased precipitation. However, few landslides occurred within the Mississippian Limestone, and the Cambrian and Ordovician Limestone—despite the amount of rainfall—further supporting the impact of geology on the number of slides.

The data collected within the Slide Spread databases was used to identify common trends between similar slides—examining past failures, landslide location along the slope, and slope ratio. The past failures were estimated to have occurred at 25% of the landslide locations. The results may indicate regions of weaker soil near the joints, or boundaries, of geologic groups, leading to increase the number of slides within a geologic formation. However, this estimation assumed that adjacent slides were located within 1000 feet of the current landslide—accounting for the accuracy of the map and the slide coordinates. More research needs to be conducted to determine the impact of past slides along Alabama highways. This may be accomplished through the inclusion of landslide site history within the landslide reports, aiding in the collection of past landslide data.

In addition, the majority of landslides within the Slide Spread database (approximately 61%) occurred within the front slope, indicating a failure trend within fill sections. This observation was supported by the data available on failures within cut and/or fill slopes. The results indicated borrow soils have a larger likelihood of failing. This may be due to construction methods (such as compaction) or design (such as drainage or slope ratio).

The most common structures near landslides adjacent to highways were culverts and/or drains, and flowing water systems. The majority of slides located near culverts were classified as shallow failures. The condition of the culvert (i.e. damaged or undamaged) had little effect on the number of slides. Future studies are recommended to determine the cause of the slides, examining maintenance frequency and conducted repairs within the region, along with the environmental factors or designs which may influence failures.

Failure categories, or classifications, were determined for slides within the emergency relief database and the landslides reports. The majority of slides within the Landslide Reports database were shallow failures—consisting of failures within the fill and cut sections, as well as failures due to erosion. The most common failure type within the emergency relief database was translational failures. Translational failures may be due to soil layers located within the slope, leading to perch water tables and slickened slip surfaces. More research needs to be conducted on the cause of the failures within the two categories.

CHAPTER 5: DEVELOPMENT OF ROADSIDE LANDSLIDE HAZARD PRIORITIZATION SYSTEM FOR ALABAMA HIGHWAYS

5.1 Introduction

This chapter describes the development and implementation of the Landslide Hazard Prioritization System (LHPS) prototype for Alabama. The LHPS was based on the design of landslide hazard systems employed by other state transportation agencies (reviewed in Chapter 2), while selecting assessment categories specifically affecting Alabama highways and accounting for the data available for analysis. This chapter describes the hazard and risk assessment component of the SSMSs for Alabama, based on the systems employed by other state transportation departments. The descriptions summarize the objectives of the LHPS, the system framework, and the recorded data. A preliminary study was conducted using landslide data collected from state Detailed Damage Inspection Reports (DDIR), or emergency landslide reports. The results are presented and analyzed.

5.2 Alabama Landslide and Traffic Data

The data used in the development of the LHPS for Alabama were collected from two sources: Slide Spread, and the Alabama Traffic Data (ATD) database. These systems collect information on landslides and AADT, respectively—providing a broad range of information which may be used to determine the risk factor scores at a given site. The following sections summarize the data available within each source, detailing the information used within the LHPS.

5.2.1 Alabama Traffic Data (ATD)

The traffic data use for this study was obtained from the ATD (Maintenance Bureau of the Alabama Department of Transportation 2018) map, a traffic monitoring tool used and maintained by the Maintenance Bureau of ALDOT (Maintenance Bureau of the Alabama Department of Transportation 2018). This database contains the AADT along most state and federal roads within Alabama—providing values based on the location of the given site and year of interest between 2006 and 2016 (Maintenance Bureau of the Alabama Department of Transportation 2018). The ATD is open to the public and may be found at the following address: https://aldotgis.dot.state.al.us/atd/default.aspx.

The geographic coordinates from Slide Spread were used to collect the AADT along roadways affected by landslides. The data was collected for state and federal roadways between the years 2006 and 2016. The database did not include the AADT of roadways prior to 2006 or after 2016, therefore this information was excluded from the analysis. The ATD did not provide the AADT for the county roads within the Slide Spread databases.

5.3 The Alabama Landslide Hazard Prioritization System (LHPS)

The Alabama LHPS was developed to aid in the prioritization of landslide remediation—assisting ALDOT with the allocation of funds and resources through the identification and ranking of landslide sites based on the hazard to the roadway and the traveling public. The system was developed based on the above review of implemented hazard ranking systems and available data, altered to fit the purpose of the project. The risk factors were chosen based on the systems employed by other state transportation agencies (Calvin et al. 2009, Pensomboon et al. 2007, ODOT 2001), while accounting for the limited data pertaining to landslides and roadway impact.

The risk factors analyzed within the LHPS include the AADT, impact on traffic, repair cost, and roadway impact. The AADT was collected as an indicator of the number of potential vehicles being affected by the landslide, with a higher value indicating a larger risk to motorist safety. Therefore, the hazard score increases with rising AADT values. The traffic impact score depends on the number of lanes open to motorists, indicating a shoulder, lane, or road closure. The values may vary based on the number of lanes along the highway, availability of on-site detours, and/or distance to off-site detours—increasing the hazard score with growing traffic disruption. The repair cost consisted of the predicted or actual value for the recommended repair for the site. The category is scored based on the numerical value. A higher cost is assumed to be associated with more severe or substantial slides—leading to either increased risk due to slide severity or period of time a vehicle is within the zone of failure, resulting in a higher hazard level. The roadway impact indicates the damage to the roadway. The rating scores are separated by the location of the damage as well as the extent of damage (i.e. a crack in pavement, or the collapse of the lane). The roadway impact hazard score is therefore dependent on the extent of damage to the roadway.

The reviewed hazard ranking systems all include information on the history of the sites, collecting data on both the accident history and maintenance frequency. The inclusion of these factors was explored; however, there was insufficient data within the crash inventory of Alabama as well as the state and federal landslide reports. The accident history within the reviewed prioritization systems is collected either through the number of collisions occurring as a result of the landslide being analyzed, or the highest severity of collisions due to landslides near the site over the past 10 years (i.e. no crashes, property damage only, injury, or fatality) (Calvin et al. 2009, Pensomboon 2007, ODOT 2001, Pierson et al. 1990). The systems require the analysis to only include collisions resulting from landslide debris (Calvin et al. 2009, Pensomboon 2007, ODOT 2001, Pierson et al. 1990), excluding other crash events from the scoring system. The Critical Analysis Reporting Environment (CARE), a crash database containing data from collision reports of 12 states—including Alabama (*CARE 10.1.0.19* 2016)—was reviewed in order to identify crashes caused by landslides. Data from crashes occurring between 2006 and 2015 was reviewed, but there was not enough information in the database to identify crashes that were specifically caused by landslides. Including data from crashes that were not caused by landslides would lead to a bias database. Therefore, the crash data was excluded from this analysis.

The maintenance frequency and/or annual maintenance cost indicates the number of slope failures at the given site (Calvin et al. 2009, Pensomboon 2007, ODOT 2001, Pierson et al. 1990). The higher values indicate more persistent movement, and therefore the hazard value increases, along with maintenance urgency (Calvin et al. 2009). The landslide reports collected in Slide Spread do not consistently provide information on past slides at or adjacent to the current landslide site. If a past slide is noted, the frequency and/or repair costs are not generally provided. In addition, the annual maintenance cost is not included in the database. Therefore, the maintenance frequency was not included in the LHPS.

5.3.1 Hazard Score

The LHPS scoring guidelines were determined through the analysis of categorical and numerical data within Slide Spread and the ATD through the identification the common classification groupings. Table 5-1 gives the outline of the LHPS matrix rating system, providing scoring values based on the conditions of the landslide sites. The category values within each scoring group were determined using data collected within Slide Spread. The categorical data (i.e. impact on traffic and roadway impact) values were taken directly from Slide Spread, which collects data on the landslides impact. The numerical intervals were determined using the AADT and repair cost data from Slide Spread, collected for the case study. The values were then categorized using the geometric interval classification method (ESRI 2017). This data classification method is generally used for continuous data—defining breaks in the data using a geometrical series and creating ranges with approximately the same number of points to minimize variance within the intervals (ESRI 2017). The geometric interval classification method used data from all the landslides within the Slide Spread database with applicable information (i.e. recorded repair cost, and/or available AADT) in order to develop representative rankings, which specifically accounted for the landslides along Alabama highways.

Table 5-1. Landslide Hazard Prioritization System Ranking Matrix

Risk Factor	**Weight (Points)**			
	3	**9**	**27**	**81**
AADT	< 2,500	2,500 – 10,000	10,000 – 35,000	> 35,000
Impact on Traffic	No Impact	Traffic Control	Lane Closure	Road Closed, Offsite Detour
Repair Cost*	< 23,000	23,000 – 98,000	98,000 – 433,000	> 433,000
Roadway Impact	No Impact	Shoulder Damage	Lane Damage	Multiple Lanes Damaged

*Repair cost converted to 2015 dollars using the CPI Inflation Calculator developed by Bureau of Labor Statistic of United States Department of Labor (Bureau of Labor Statistics United States Department of Labor 2018).

The scoring scale of each risk factor follows the convention of hazard rating systems employed by other state transportation agencies (Calvin et al. 2009, Pensomboon 2007, ODOT 2001, Pierson et al. 1990)—using an exponential rating system with defined breaks (i.e. 3, 9, 27, and 81) to create an obvious distinction between hazard levels. However, the scale consists of continuous values between 1 and 100. The breaks in values, depicted in Table 5-1, are used to aid in the completion of the form. Values ranging from 1 to 100 may be selected, with higher values indicting greater severity and/or impact to the roadway and/or motorists. Pierson et al. (1990)

recommended the use of experience and judgement to complete the form, selecting values ranging from 1 to 100, rather than selecting the base values provided.

5.4 Case Study: Landslides Occurring due to December 2015 Storm

The analysis in Chapter 4 found that the majority of landslides within Slide Spread resulted from above average rainfall or elevated groundwater levels. All 165 emergency landslides occurred due to storm events. In addition, 77 landslide report slides (approximately 75% of the landslide report database) were due to high groundwater levels, moisture fluctuation, or surface water. Therefore, a case study was conducted to determine the hazard ranking scores of the slides resulting from the December 2015 storm, occurring between December 20th and December 26th. 3 landslides occurring along county roads were excluded from the analysis, as the AADT for the adjacent roadways were not publically available. The rainfall event was equivalent to a 100-year or 200-year storm (Thomas et al. 2017)—producing 2 to 15 inches of rainfall (Thomas et al. 2017), and resulting in at least 61 landslides located in both the northern third and southern third of Alabama.

The 61 landslides were evaluated using the LHPS, determining the hazard score for each risk factor. This score can be used to rank the landslide sites, providing a prioritized list of landslides to undergo repairs. Figure 5-1 provides a histogram of the analysis results, depicting the number of landslides within each risk factor scoring interval. The majority of landslides had risk factor hazard score values between 3 and 18 for the AADT, impact on traffic, and/or roadway impact. Whereas, the repair cost score peaked in the 18 to 54 interval.

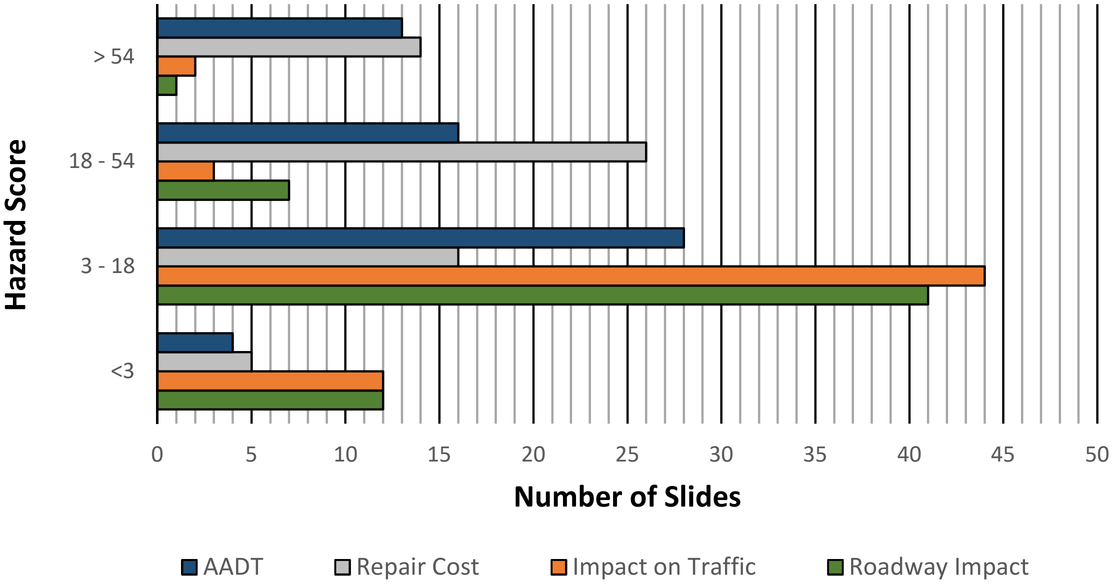


Figure 5-1. Risk factor scores for DDIR 2015 slides

The total hazard scores for each slide were used to create the overall hazard ranking categories, shown in Table 5-2. The categories were determined using the geometric interval classification method, creating ranges with approximately the same number of landslides, minimizing the hazard score variance within each category (ESRI 2017). These hazard categories are specific to the landslides analyzed in this project, and therefore will need to be adjusted as new landslides are entered into the system.

Table 5-2. Overall Hazard Ranking Categories.

Overall Hazard Ranking	**Low**	**Medium Low**	**Medium High**	**High**
Overall Hazard Score	≤ 38	39 - 68	69 – 115	> 115

The overall hazard distribution is given in Figure 5-2—depicting the locations and hazard scores of the landslides, as well as the precipitation throughout Alabama. The majority of the slides occurred in the geological groups of the Pottsville Formation, the Selma Group Sand, and the Selma Group Chalk (defined in Appendix D). However, this was likely due to the rainfall within the region, rather than the geologic properties of the soil alone. These areas experienced between 4 and 15 inches of rainfall, supporting the observation that above average rainfall is a significant contributing factor for landslides in Alabama. However, the majority of high hazard slides are located within regions experiencing 6 to 15 inches of rain, rather than the regions experiencing the greatest amounts of precipitation. This may be due to less hazard slides—such as shallow erosion—or less susceptible soils within the regions. However, more research should be conducted on the risk factors included within this analysis, as the results may indicate a need to adjust the risk factors collected through this process.

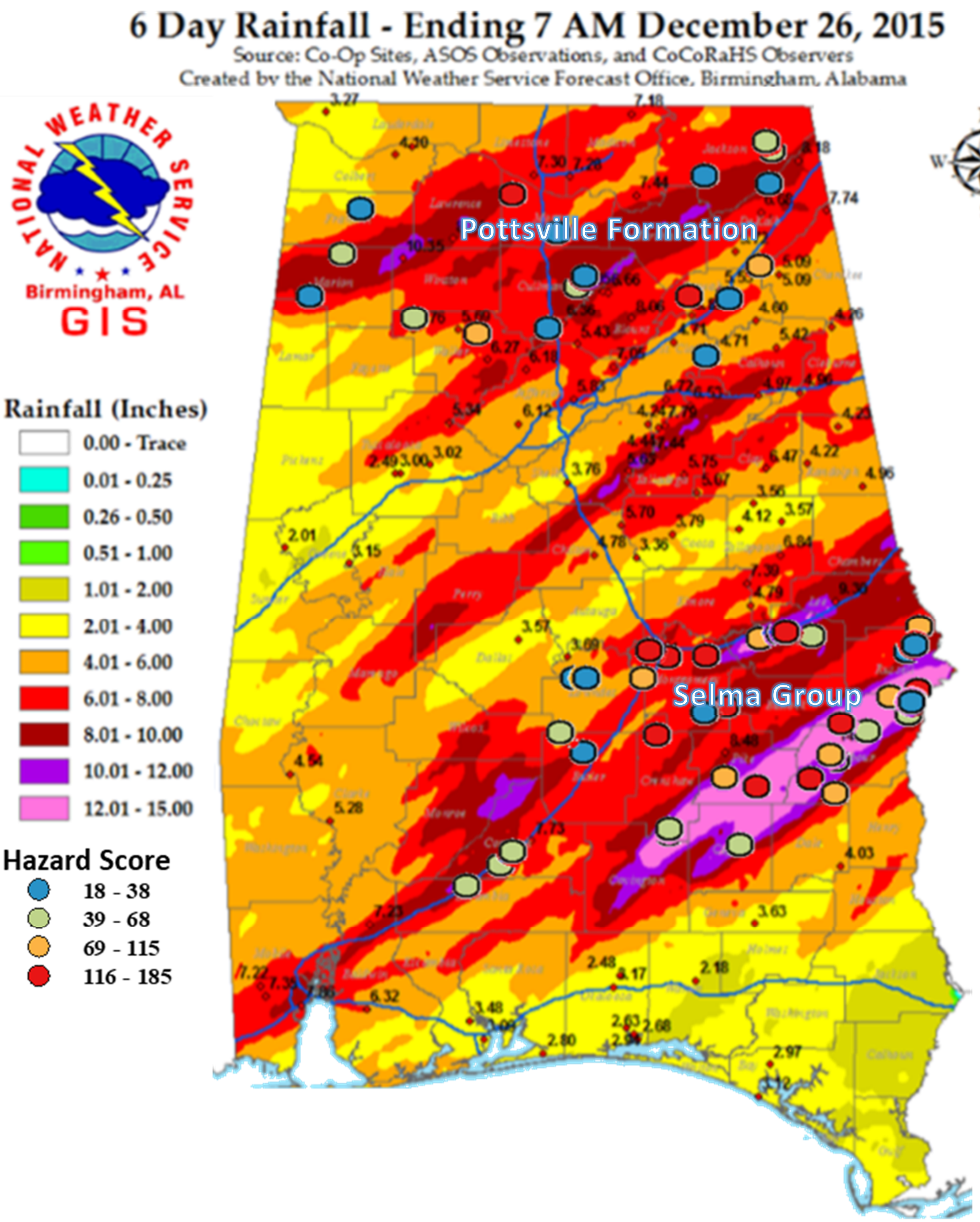


Figure 5-2. December 2015 rainfall event and resulting landslides (National Weather Service 2017)

Figure 5-3 summarizes the average hazard scores per county. Morgan, Bullock, Etowah, and Macon Counties were determined to have the highest average overall landslide hazard scores, indicating these areas were greatly affected by the storm. This is supported by Figure 5-2, showing these counties experienced an estimated 6 to 15 inches of rainfall over the 6 day period. In particular, I-85 was the roadway most affected the landslides, experiencing 3 medium-high hazard slides in Montgomery County and 8 high hazard slides in Macon County.

The slides were also compared using the individual risk factors. Montgomery and Macon Counties had highest recorded AADT scores, indicating high volumes of traffic which may lead to significant road delays in the event of a landslide. Etowah, Walker, and Barbour Counties experienced the largest roadway impact—likely leading to traffic delays due to traffic control, lane closures, or on-site detours resulting from future repairs efforts. Cherokee and Etowah County had the highest average impact on traffic—likely experiencing traffic delays due to the implemented traffic control, lane and/or road closure. Morgan and Bullock Counties were allotted the most repair funding and therefore had the highest repair cost risk factor.

The results show that the repair cost had a larger effect than some of the other factors on the overall hazard scores, possibly leading to bias results. This may indicate a need for more risk factors to be added to the LHPS—as the current factors may be missing valuable information on the impact of landslides on the roadways—or the results may support the need for the implementation of this program—showing funds may be allocated more effectively.

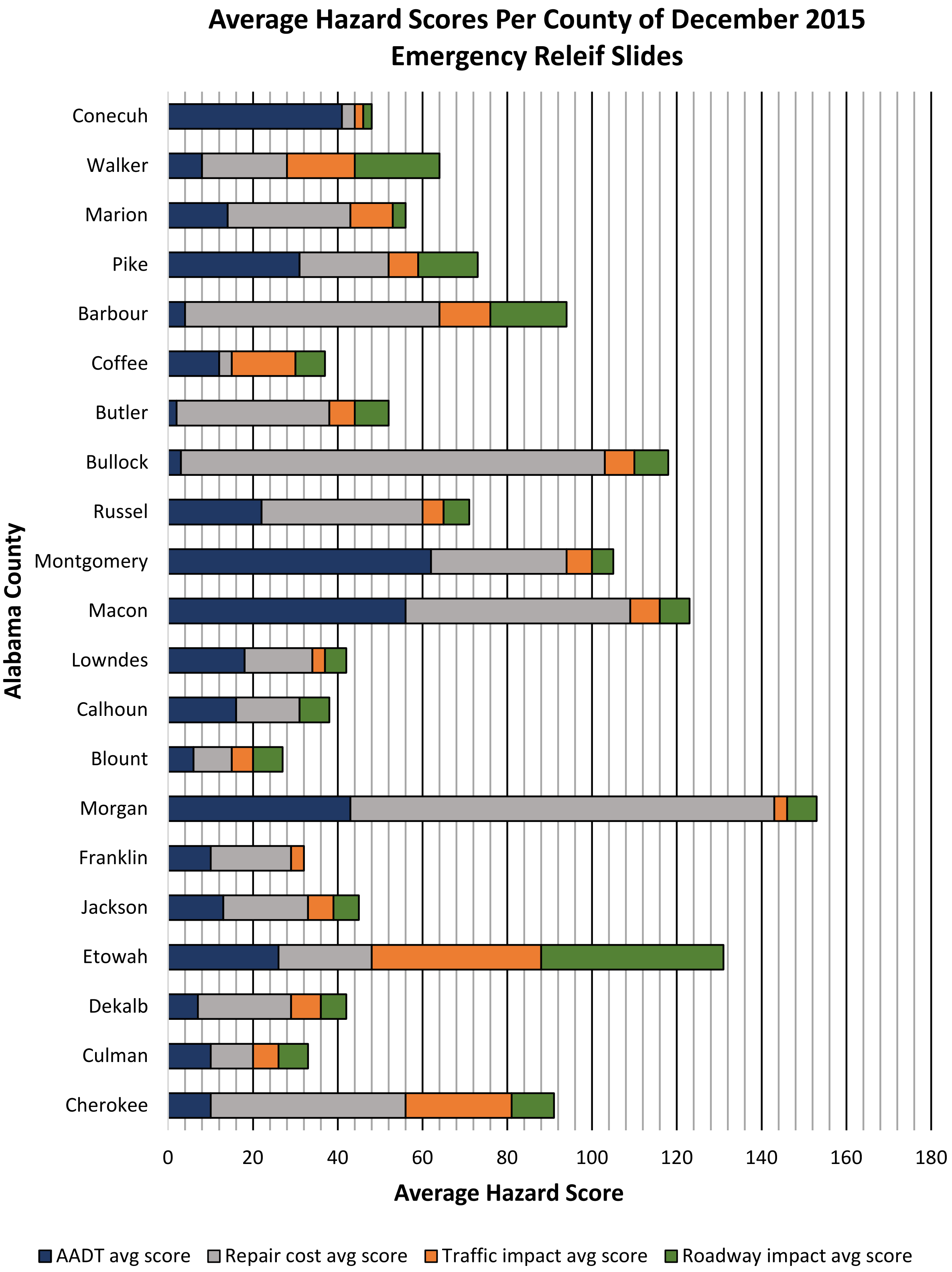


Figure 5-3. Average overall landslide hazard scores per county experiencing landslides.

5.4.1 Future Improvements

The LHPS, largely based on four implemented programs, does not currently consider accident history, maintenance frequency, length of roadway impact, or precipitation. Consequently, the LHPS overlooks the effect of vehicle damage and motorist injury/fatalities, the yearly cost to maintain the roadway, the number miles of the roadway affected, and the effects of a tropical climate—possibly leading to lower hazard ratings than the scores assigned through other systems. Futures studies should include crash, maintenance frequency, landslide length, and precipitation data.

The collision data may be obtained through the further examination of current vehicle accident databases (i.e. the Alabama Safety Portal, or the Alabama Law Enforcement Agency Crash Reports) or the implementation of traffic studies at landslide locations. Currently, CARE does not provide enough information to identify crashes due to landslides. However, the CARE database may be used to select police crash reports through the use of the filter tool. The narratives of the selected police reports may then be reviewed to identify crashes resulting from landslides. Maintenance frequency data and landslide length may be requested from ALDOT.

Water is a large contributing factor for landslides with at least 243 landslides within the Slide Spread database being attributed to rainfall events, high groundwater elevation, or erosion from surface water. This indicates the need to account for rainfall events within the LHPS—addressing the tropical climate through the analysis of the resilience of the slopes to storms, as well as the cost to improve stability. This may be accomplished obtaining precipitation data from the National Weather Service.

5.5 Conclusions

This study was conducted to develop a landslide hazard safety prioritization system to function as the asset management component of the SSMS for Alabama. The prioritization system addresses the landslide impact on the roadway, as well as functions as the first step in a cost-benefit analysis. The LHPS ranks landslides based on risk factor parameters. These risk factors include the AADT of the roadway, the repair cost of the landslide, the traffic impact, and the roadway impact. These parameters were used to determine an overall hazard rank for slides occurring due to the December 2015 rain storm. The system determined Morgan, Bullock, Etowah and Macon Counties had the highest hazard score ratings, and I-85 was the roadway most affected by the landslides. However, more research must be conducted before the recommendations are made for repairs.

It is recommended the LHPS be expanded to include accident history, maintenance frequency, length of roadway impact, and precipitation. The addition of the above risk factors may enhance the ability of the LHPS by accounting for motorist risk, the life-cycle cost of the roadway, the impacted area, and the topical climate—thereby, forming a comprehensive hazard prioritization system, enhancing the accuracy of the hazard scoring system. The implementation of the enhanced asset management system may aid in the prioritization of resources (i.e. funding, expertise, and equipment), assisting ALDOT in the remediation and mitigation of landslides.

CHAPTER 6: CONCLUSIONS

6.1 Summary

Landslides along highways pose a significant challenge for state and federal transportation agencies. Slope Stability Management Systems (SSMSs) have been developed and implemented by multiple state transportation departments to manage landslide hazards through the collection of slope and landslide attributes. The goal of these systems is to collect and organize landslide data, as well as prioritize remediation and mitigation resources for hazardous slopes along state highways. This thesis presented development of two components of a SSMS for Alabama—a landslide collection system and database called Slide Spread, and a hazard ranking system called the Landslide Hazard Prioritization System (LHPS). These systems were used to aid in the identification of common failure categories along Alabama highways, recognition of regions of higher landslide risk, and development of the framework for a future repair prioritization system.

Slide Spread was developed based on the SSMSs implemented by other U.S. state transportation agencies. Therefore, the system followed their data collection methods—collecting information on the location of the site, the regional geology, site stratigraphy, failure descriptions, historical failures and/or repairs, slope geometry, vegetation, recommended repairs, and failure category. The methods employed by these systems, as well as the data collected, were altered based on the needs of Alabama and the advice of ALDOT engineers. Therefore, Slide Spread consists of two data collection UserForms and two databases, accounting for the differing levels of details provide within the ALDOT landslide reports and the Detailed Damage Inspection Reports (DDIRs).

The data collected within Slide Spread consisted of varying levels of details which resulted in numerous data gaps. Therefore, the method employed by Aydilek et al. (2013) was implemented throughout the analysis. The method analyzed attributes independently, and compared the results to the landslide susceptibility map developed by the Geologic Survey of Alabama (GSA). The analysis used data from Slide Spread and a database of historical failures (Rheams et al. 1982). The landslide analysis highlighted regions experiencing larger numbers of landslides, as well as displayed slope attributes which may influence the likelihood of a landslide event. The results are summarized below.

- The Tuscaloosa Group, Midway Group, and Selma Group Chalk had a higher likelihood of landslide events along roadways. Whereas, the Mississippian Limestone and Cambrian and Ordovician Limestone were less likely to experience a landslide event. Few historical landslides and no landslides within the Slide Spread databases occurred within the Piedmont Upland. These results were generally supported by the number of slides found in each unit, as well as the landslide susceptibility map developed by the GSA.
- 25% of the landslides analyzed occurred within 1000 feet of converging geologic groups. This may indicate regions of weaker soil near the joints, or boundaries, of geologic groups which may increase the number of slides within a geologic formation. More research needs to be conducted on the impact of geologic boundaries.
- The rainfall analysis illustrated the number of slides within a region generally increased with increasing precipitation.
- Few emergency relief slides occurred in regions consisting of limestone. This trend is likely attributed to being located within rock formations, as the precipitation leads to little or no impact to the driving forces and resisting forces within the rock dominated slopes.

However, the limestone dominated formations have a large number of historical landslides. This may be due to a variety of factors, including data collection practices and initiating events which triggered the slides.

- An estimated 39.5% of landslides within the 3 databases occurred at or adjacent to a past failure. However, this value was based on broad approximations, due to the accuracy of the landslide locations and the available information on the length and history of the landslide sites. Further research should be conducted on the present of past failures are more information is collected within Slide Spread.
- The majority of landslides occurred within the front slope, indicating a failure trend within fill sections. This observation was supported by the data available on failures within cut and/or fill slopes, which consisted of approximately 44 percent of slides occurring within fill sections and approximately 25 percent of slides occurring within the cut sections.
- The most common structures located near landslides adjacent to Alabama highways were culverts and/or drains, and flowing water systems. These structures were located at approximately 30 percent and 23 percent of slides within the landslide reports database, respectively. The majority of slides located near culverts were classified as shallow failures.

The information provided within Slide Spread was also used to develop slope failure categories—classifying slides by the failure type, displaying common modes of slope failure throughout the Alabama highway system. The analysis of the failure categories found the majority of slides within the Landslide Reports database were shallow failures. These slides consisted of failures within the fill and cut sections, as well as failures due to erosion. The most common failure type within the emergency relief database was translational failures. These failures—likely triggered by to rainfall events—are affected by the geology of region (both the geologic formation and the convergence of two or more formations), proximity to past landslides, and/or culverts located at the site.

The LHPS is a landslide rating and ranking system consisting of a hazard ranking matrix used to determine the impact of a landslide on the adjacent roadway and the traveling public based on risk factor parameters (the AADT of the roadway, the repair cost of the landslide, the traffic impact, and the roadway impact). The system was developed using the data provided within the Emergency Relief Slides database, following the procedures and framework of other landslide hazard prioritization systems developed by other U.S. state transportation agencies—creating a ranking system based on the distribution values for the AADT, traffic impact, repair cost, and roadway impact. The LHPS thereby assists in the prioritization of landslide repairs through the evaluation of a landslide hazard impact score. The following summarizes the analysis results of the LHPS.

The risk factor parameters were used to determine an overall hazard rank for the Emergency Relief Slides which occurred due to the December 2015 rain storm. The system determined Morgan, Bullock, Etowah and Macon Counties had the highest hazard score ratings, and I-85 was the roadway most affected by the landslides. The system does not currently consider the accident history along the roadway, maintenance frequency, length of roadway impact, or precipitation. This thesis developed the framework of the LHPS. However, future studies should include crash data, maintenance frequency, landslide length, and precipitation data. Therefore, more research must be conducted repair recommendations are provided.

6.2 Recommendations for Future Improvements

6.2.1 Slide Spread

Slide Spread and the LHPS were developed based on the data collection systems and hazard prioritization matrixes of SSMSs employed by other U.S. state transportation agencies. The systems utilized data collected from state and federal landslide reports to develop and populate landslide databases which may be used to aid in the creation of common remediation methods, and the allocation of state funding. The systems developed in this research are continuous projects and will require addition data, alterations, and further analysis in order to reach the full potential of the program. However, this paper developed the framework of the system and provided data analysis which may be currently employed in the development of landslide remediation methods.

Slide Spread collected landslide data for landslide events occurring between the years 1990 and 2015, providing a large inventory of 247 landslides. However, the information provided within the landslide reports varied greatly—with some landslide reports containing one page memorandums while other files included detailed site descriptions, field exploration data, original site plans, repair plans, data analysis, etc. Slide Spread was developed to account for the diversity of the landslide reports; however, as Slide Spread is implemented into ALDOT procedures, the database should be populated during the site investigation and analysis process—rather than filled in retroactively. This will help identify attributes that may otherwise be overlooked, as well as provide an indication of whether the value of a given attribute is unknown or not present at the site. The procedure will increase the amount of data collected within the databases, aiding in the future analysis of landslides along Alabama highways.

6.2.2 Landslide Hazard Prioritization System (LHPS)

The LHPS does not currently collect data on the accident history, maintenance frequency, length of roadway impact, or precipitation. Therefore, the system does not account for the effect of vehicle damage and motorist injury/fatalities, the yearly cost to maintain the roadway, the number miles of the roadway affected, and the effects of a tropical climate—possibly leading to lower hazard ratings than the scores assigned through other hazard ranking systems.

The data was excluded due to the availability of information. The Critical Analysis Reporting Environment (CARE) does not provide enough information to identify crashes due to landslides. However, the CARE database may be used to select police crash reports. The narratives of the selected police reports may then be reviewed to identify crashes resulting from landslides. Maintenance frequency data and landslide length may be requested from ALDOT, and/or should be added to the landslide reports. The date of failure and weather at or near time of failure should be noted within the landslide reports and within Slide Spread, providing enough information to determine the precipitation at the landslide site—accounting for the tropical climate. Using the data collected from the above methods, the LHPS matrix should be adjusted to include crash, maintenance frequency, landslide length, and precipitation data.

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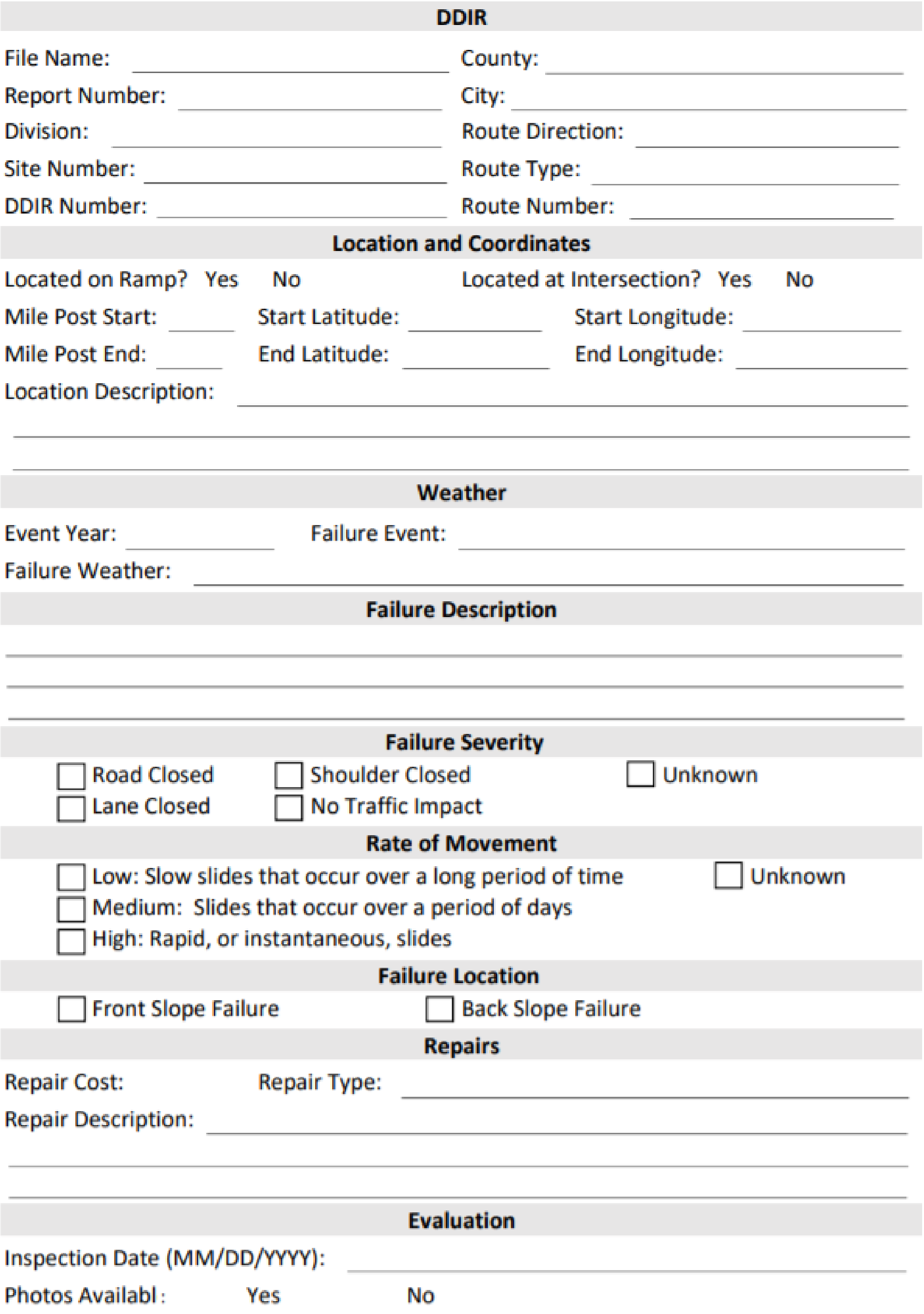
APPENDIX A: DDIR FIELD FAILURE SHEET



DDIR

File Name: ____________________ County: ____________________

Report Number: ____________________ City: ____________________

Division: ____________________ Route Direction: ____________________

Site Number: ____________________ Route Type: ____________________

DDIR Number: ____________________ Route Number: ____________________

Location and Coordinates

Located on Ramp? Yes No Located at Intersection? Yes No

Mile Post Start: ______ Start Latitude: __________ Start Longitude: __________

Mile Post End: ______ End Latitude: __________ End Longitude: __________

Location Description: ____

Weather

Event Year: __________ Failure Event: ____________________

Failure Weather: ____

Failure Description

Failure Severity

☐ Road Closed ☐ Shoulder Closed ☐ Unknown
☐ Lane Closed ☐ No Traffic Impact

Rate of Movement

☐ Low: Slow slides that occur over a long period of time ☐ Unknown
☐ Medium: Slides that occur over a period of days
☐ High: Rapid, or instantaneous, slides

Failure Location

☐ Front Slope Failure ☐ Back Slope Failure

Repairs

Repair Cost: Repair Type: ____________________

Repair Description: ____

Evaluation

Inspection Date (MM/DD/YYYY): ____________________

Photos Available: Yes No

Failure Surface

Select the failure surface that most closely resembles the failure.

☐ Deep, Rotational Failure

☐ Shallow, Crest Failure

☐ Shallow, Slope Failure

☐ Translational Failure (planar failure surface)

☐ Shallow, Toe Failure

☐ Erosion of the slope face

☐ Rockfall or topple

Slide Sketch

Please draw a sketch of the slide and any important features.
Examples: Wet spots, cracks, utilities, etc.

Additional Comments

APPENDIX B: SLIDE SPREAD INSTRUCTION MANUAL

LANDSLIDE REPORTS DATABASE

Appendix B.1 Introduction

The following is an instruction manual for the for the Landslide Reports Database collection system within Slide Spread. The system uses a UserForm developed within Microsoft excel. The purpose of the Landslide Reports UserForm is to aid in the input and organization of data collected from landslide reports. It was designed as a multi-user system, providing consistent output data that may be used in conjunction with ArcGIS for spatial analysis. This guide provides definitions of terms, procedures for data input, and examples of data input. The guide should be used as reference when feeding data into the Landslide UserForm, insuring the data is consistent and comprehensive. The guide is divided into sections based on the page, or tab, on the UserForm. The page title is listed in bold print. The subheading are the labels associated with each data entry box. Next to the subheading a definition or explanation is provided, followed by examples (including an in-test quote, and a suggested data entry).

Appendix B.2 Landslide Reports Database Instructions

Appendix B.2.1 Road

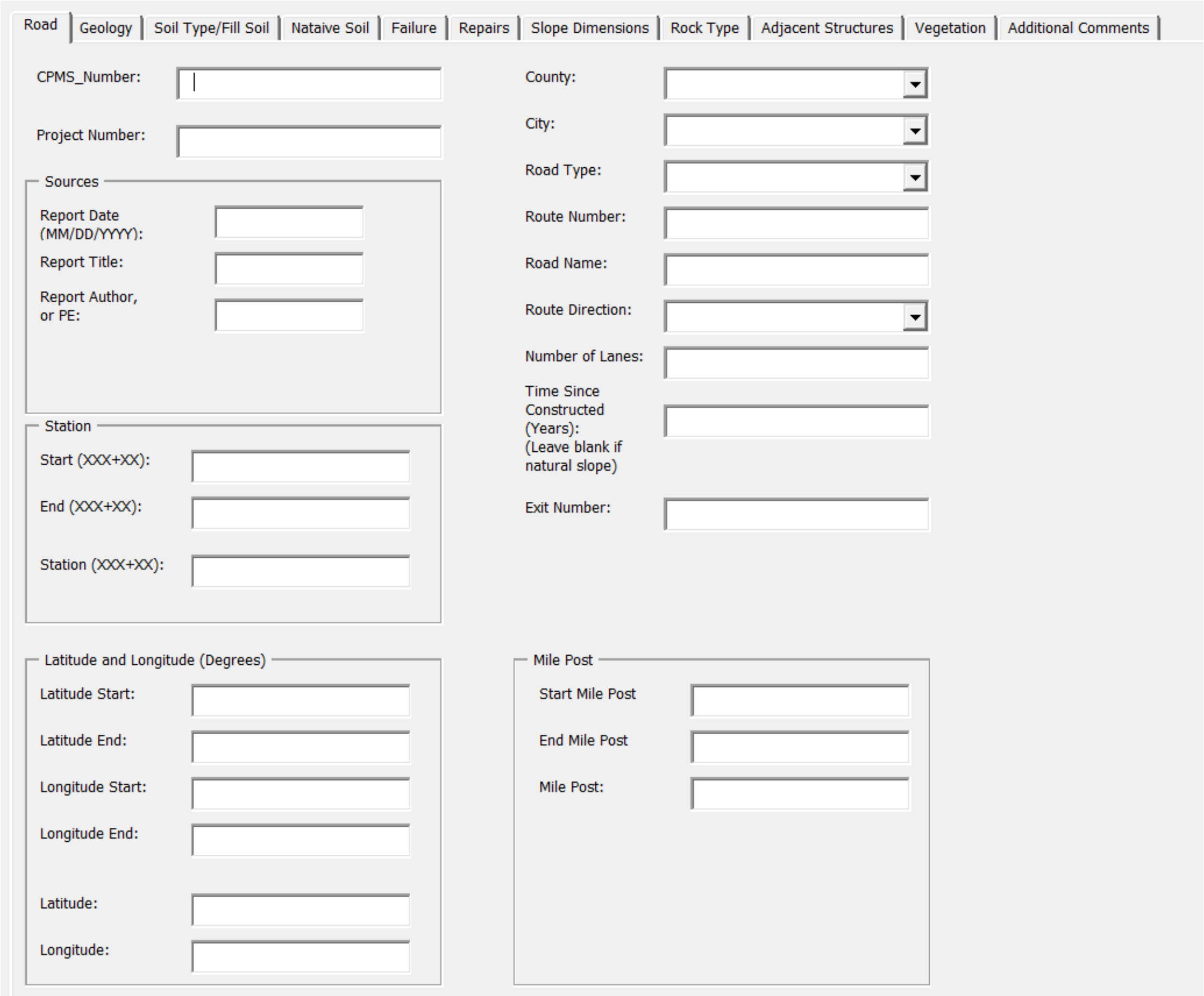


Figure B-1. Landslide Report UserForm—Road Tab

<u>CPMS Number:</u> Comprehensive Project Management System (CPMS) is an organization system that controls access to various applications within ALDOT. The number is used to search for reports and landslide locations on geogis.caps.ua.edu. The CPMS Number will not appear on landslide reports, but can be added to the database at a later time.

Examples:

CPMS Numbers	100060563	1000466679	100054082

<u>Project Number:</u> The project number is an indexing value attached to the project. The project number may be identified by the phrases "ALDOT Project No.", "Project

No.", or "Project." If two or more project numbers are provided, the response should only include the ALDOT Project Number.

Examples:

Project Number:	ST-037-I59-002	APD-0004 (515)	NH-0035 (527)

Sources:

Report Date: Provides the date the report was published. This is generally provided on the title page or in the letter heading. The format of the date should be as followed: MM/DD/YYYY

Report Title: The report title is given on the cover page of the report. Examples include "Slide Correction", "Landslide Correction Report", or "Slope Evaluation and Recommendation."

Report Author, or PE: The report author is provided in the letter heading of the report. Type the name as First-Name Last-Name, Title. For example: James D. Brown, PE or Kaye Chancellor Davis, PE.

Examples:

Report Data	02/22/2016	12/12/2000	10/01/2009
Report Title	Landslide Correction Report for SR-13 at MP 93.7	Landslide on SB Should of US-231	Slide Investigation of SR-69 at MP 8
Report Author	Kaye C. Davis, PE	Larry Lockett	B.E. Cox, Jr., PE

County: Choose the county where the landslide occurred from the drop down list. If the county is not listed, type the county into the drop down menu text box (the country does not need to be listed in the drop down menu). If the landslide occurs in two or more counties, type the counties separated by a comma.

Examples:

County	Autauga	Mobile, Baldwin	Perry, Hale, Bibb

City: Choose city where the landslide occurred from the drop down list. If the city is not listed, type the city into the drop down menu text box (the city does not need to be listed in the drop down menu). If the landslide occurs in two or more cities, type the cities separated by a comma.

Examples:

City	Auburn, Opelika	Mobile	Adamsville

Road Type: Roads are classified as Interstate (I), State Road (SR) or Country Road (CR). Choose the road type classification from the drop down menu. If the road type is not listed, type the road type into the drop down menu text box (the road type does not need to be listed in the drop down menu).

Example:

Road Type	**CR**	**SR**	**SR**

Route Number: Roads are assigned a road type classification and route number. Type in the route number into the text box. The text box will not accept non-integer values.

Examples:

Route Number	23	35	247

Road Name: In addition to the road classification and route number, the road may have name. Type the road name into the text box.

Examples:

Road Name	Southwest 13th Street	Southwest Archer Road	Corridor V

Route Direction: The route direction refers to the direction of traffic on the side of the road with the failure. The traffic may be moving south bound (SB), north bound (NB), west bound (WB), or east bound (EB). If there are failures on both sides of the road way (for example, north bound and south bound) separate the slides into two or more rows in the UserForm, filling out the new form for each slide.

Examples:

Route Direction	SB	EB	NB

Station: The station refers to the roadway station the landslide is near. Roadway stations are horizontal measurements along a project. One station is equal to 100 feet. Stations are writing in the form XXX+XX, for example 0+00, 100+28, or 38+02.

The station values may be given as a point, or a range. If multiple station ranges or point values are given, separate the slides into multiple data points.

Station Start (XXX+XX): If the projects stations are given as a range of values, the start station is the first station in the range.

Station End (XXX+XX): If the projects stations are given as a range of values, the end station is the last station in the range.

Station (XXX+XX): If the station is given as a signal value, type the value is this text box.

Examples:

Station	Station Start: 50+00 Station End: 79+00	Station: 76+00	Station: 117+25

Latitude and Longitude (degrees): The latitude and longitude of the slide may be listed is as a range or as a point. The values may be given if degrees, minutes, seconds, or as decimal degrees. If the value is given in degrees, minutes, and seconds it must be converted into decimal degrees before being imputed.

If multiple latitude/longitude ranges or point values are given, separate the slides into multiple data points.

Latitude Start: If the project's latitude values are given as a range of values, the Latitude Start is the first latitude value in the range.

Latitude End: If the project's latitude values are given as a range of values, the Latitude End is the last latitude value in the range.

Longitude Start: If the project's longitude values are given as a range of values, the Longitude Start is the first longitude value in the range.

Longitude End: If the project's longitude values are given as a range of values, the Longitude End is the last longitude value in the range.

Latitude: If the Latitude is given as a signal value, type the value is this text box.

Longitude: If the Longitude is given as a signal value, type the value is this text box.

Examples:

Type-in UserForm:	Latitude: 32.219556 Longitude: -87.769806

Mile Post: The mile post is a marker indicating the distance along a road. The mile post may be listed as a range or as a point.

If multiple latitude/longitude ranges or point values are given, separate the slides into multiple data points.

Start Mile Post: If the project's mile posts are given in a range, the Start Mile Post is the first mile post listed in the range.

End Mile Post: If the project's mile posts are given in a range, the End Mile Post is the last mile post listed in the range.

Mile Post: If the mile post is given as a signal value, type the value in this textbox.

Examples:

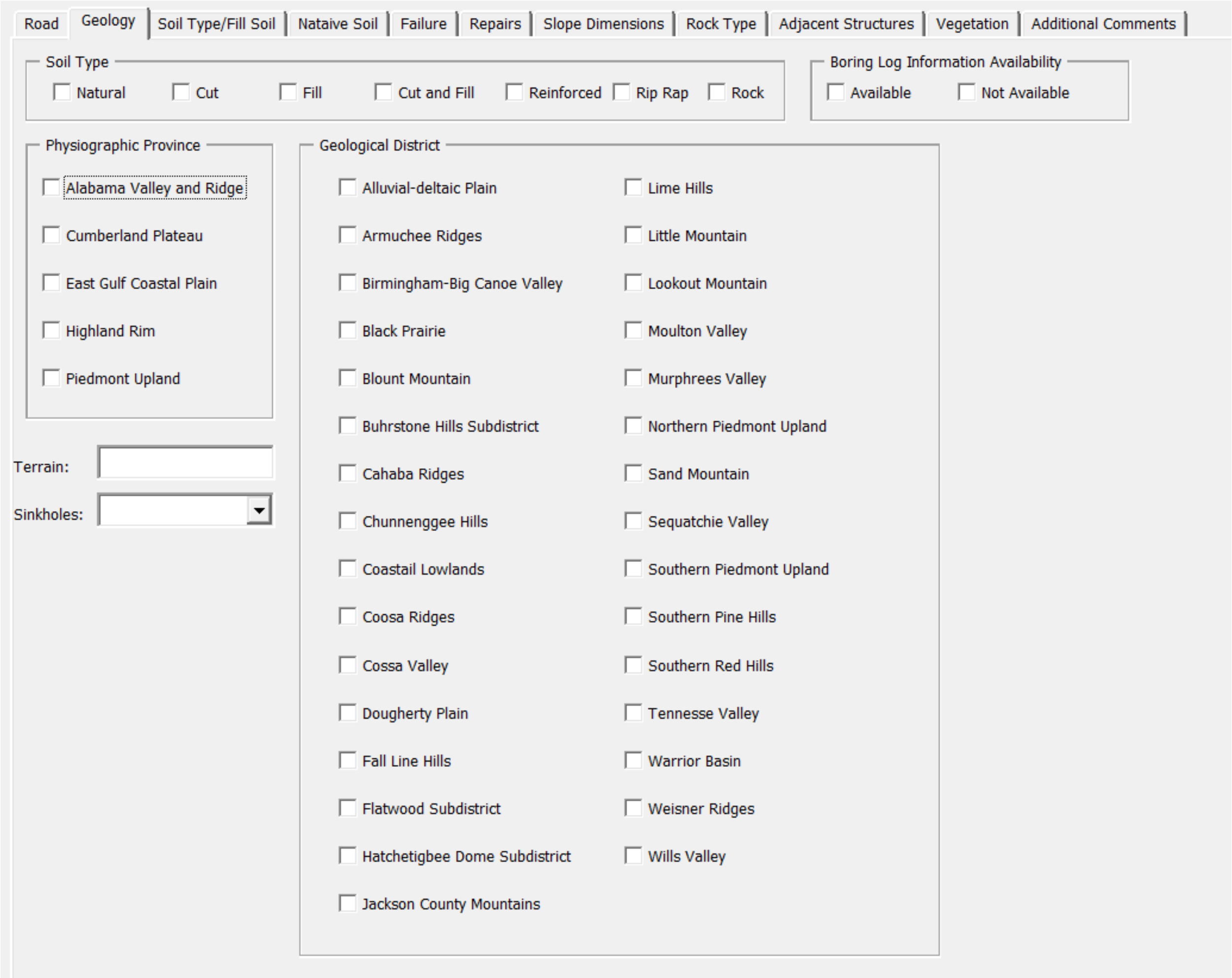
Mile Post	Mile Post: 49.2	Separate the slopes into 8 analyses: 1) Mile Post Start: 0.0 Mile Post End: 26.0 2) Mile Post: 1.1 3) Mile Post: 15.8 4) Mile Post: 17.4 5) Mile Post: 21.1 6) Mile Post: 23.2 7) Mile Post: 24.8 8) Mile Post: 26.0

Exit Number: If the landslide is near an exit, or on an exit ramp, list the exit number.

Examples:

Exit Number	134

Appendix B.2.2 Geology



Soil Type

☐ Natural ☐ Cut ☐ Fill ☐ Cut and Fill ☐ Reinforced ☐ Rip Rap ☐ Rock

Boring Log Information Availability

☐ Available ☐ Not Available

Physiographic Province

☐ Alabama Valley and Ridge
☐ Cumberland Plateau
☐ East Gulf Coastal Plain
☐ Highland Rim
☐ Piedmont Upland

Terrain:

Sinkholes:

Geological District

☐ Alluvial-deltaic Plain
☐ Armuchee Ridges
☐ Birmingham-Big Canoe Valley
☐ Black Prairie
☐ Blount Mountain
☐ Buhrstone Hills Subdistrict
☐ Cahaba Ridges
☐ Chunnenggee Hills
☐ Coastail Lowlands
☐ Coosa Ridges
☐ Cossa Valley
☐ Dougherty Plain
☐ Fall Line Hills
☐ Flatwood Subdistrict
☐ Hatchetigbee Dome Subdistrict
☐ Jackson County Mountains
☐ Lime Hills
☐ Little Mountain
☐ Lookout Mountain
☐ Moulton Valley
☐ Murphrees Valley
☐ Northern Piedmont Upland
☐ Sand Mountain
☐ Sequatchie Valley
☐ Southern Piedmont Upland
☐ Southern Pine Hills
☐ Southern Red Hills
☐ Tennesse Valley
☐ Warrior Basin
☐ Weisner Ridges
☐ Wills Valley

Figure B-2. Landslide Report UserForm—Geology Tab

Soil Type: The soil type identifies if the slope is natural, fill, cut, cut and fill, reinforced, contains a Riprap layer, and/or is a rock slope. 0 to 7 options may be selected. If the slope is cut and fill, do not select the “cut” and “fill” options. Reinforced slopes may include a facing, geotextiles, anchors, buttresses, or other forms of reinforcement.

Boring Log Information Available: Mark the availability of the boring logs in the UserForm. If the boring logs are included in the report or supporting documentation, check “Available”, if the boring logs are not included check “Not Available.”

Physiographic Province: A physiographic province is a geographic region with similar physical features, subsurface rock type, or structural elements. The 5 physiographic provinces in Alabama are listed as options. 0 to 5 provinces may be selected. Additional provinces may not be inputted. The physiographic province name may not exactly match the names given in the UserForm. However, choose the option closest to the name given in the report.

Examples:

Physiographic Province	Cumberland Plateau	Alabama Valley and Ridge	East Gulf Coastal Plain

Geological District: A geological district, or geological unit, is an area of rock of identifiable origin and relative age that can be easily mapped and has recognizable characteristics. Each physiographic province consists of geological units. 0 to 31 districts may be selected. Additional provinces may not be inputted. The physiographic province name may not exactly match the names given on the UserForm, however choose the option that is closest to the name given in the report.

Example:

Geological District	Lookout Mountain	Birmingham-Big Canoe Valley	Fall Line Hills

Terrain: The terrain describes a stretch of land with regard to its physical features. The terrain may be described as rolling, mountainous, flat, etc. Use a one word description.

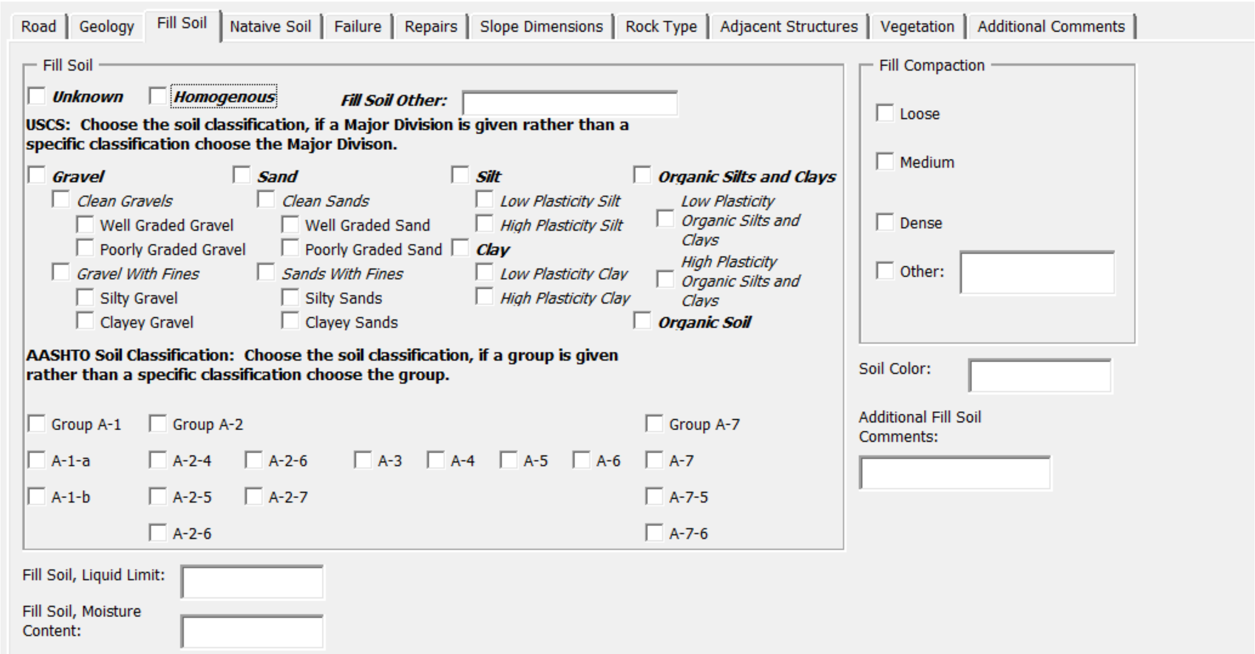
Example:

Terrain	Hilly	Flat	Lowland

Sinkholes: A sinkhole is a ground cavity due to water erosion. The drop down menu includes the following options.

- “Yes”: there is a sinkhole at or near the failure site
- “No”: there is no recorded or seen sinkhole at the site
- “Susceptible, none seen”: the rock formation or surrounding area is susceptible to sinkholes, however none have been recorded or seen.

Appendix B.2.3 Fill Soil



Road | Geology | Fill Soil | Nataive Soil | Failure | Repairs | Slope Dimensions | Rock Type | Adjacent Structures | Vegetation | Additional Comments

Fill Soil

☐ ***Unknown*** ☐ ***Homogenous*** ***Fill Soil Other:***

USCS: Choose the soil classification, if a Major Division is given rather than a specific classification choose the Major Divison.

☐ ***Gravel***
  ☐ *Clean Gravels*
    ☐ Well Graded Gravel
    ☐ Poorly Graded Gravel
  ☐ *Gravel With Fines*
    ☐ Silty Gravel
    ☐ Clayey Gravel

☐ ***Sand***
  ☐ *Clean Sands*
    ☐ Well Graded Sand
    ☐ Poorly Graded Sand
  ☐ *Sands With Fines*
    ☐ Silty Sands
    ☐ Clayey Sands

☐ ***Silt***
  ☐ *Low Plasticity Silt*
  ☐ *High Plasticity Silt*

☐ ***Clay***
  ☐ *Low Plasticity Clay*
  ☐ *High Plasticity Clay*

☐ ***Organic Silts and Clays***
  ☐ *Low Plasticity Organic Silts and Clays*
  ☐ *High Plasticity Organic Silts and Clays*

☐ ***Organic Soil***

AASHTO Soil Classification: Choose the soil classification, if a group is given rather than a specific classification choose the group.

☐ Group A-1 ☐ Group A-2 ☐ Group A-7

☐ A-1-a ☐ A-2-4 ☐ A-2-6 ☐ A-3 ☐ A-4 ☐ A-5 ☐ A-6 ☐ A-7

☐ A-1-b ☐ A-2-5 ☐ A-2-7 ☐ A-7-5

☐ A-2-6 ☐ A-7-6

Fill Soil, Liquid Limit:

Fill Soil, Moisture Content:

Fill Compaction

☐ Loose

☐ Medium

☐ Dense

☐ Other:

Soil Color:

Additional Fill Soil Comments:

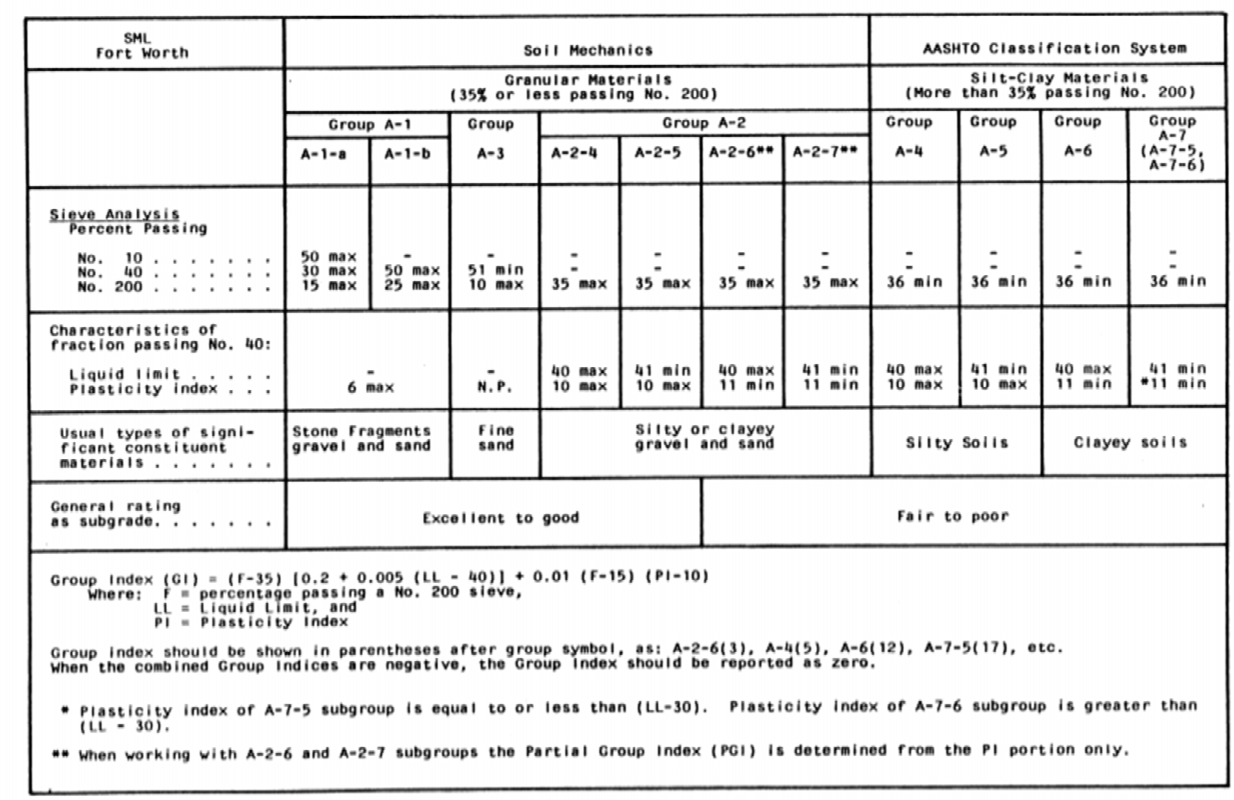
Figure B-3. Landslide Report UserForm—Fill Soil Tab

<u>Fill Soil</u>: The fill soil refers to the soil moved to the slope site from a borrow site, or excavation. The soil is separated into two classification systems—the American Association of State Highway and Transportation (AASHTO) Soil Classification System, and the Unified Soil Classification System (USCS).

The AASHTO Soil Classification System classifies soil by group and/or subgroup. Figure B-4 gives a chart summarizing the AASHTO Soil Classification System.

The USCS classifies soil into division with letter symbols. Figure B-5 gives a chart summarizing the USCS.

If the soil is unknown or homogenous, check the box correlating to the respective option. If the soil type is not listed, fill in the “Fill Soil Other” textbox with the soil type listed in the report. The user may select as many options as necessary to accurately describe the soil.



SML Fort Worth	Soil Mechanics								AASHTO Classification System			
	Granular Materials (35% or less passing No. 200)								Silt-Clay Materials (More than 35% passing No. 200)			
	Group A-1		Group A-3	Group A-2					Group A-4	Group A-5	Group A-6	Group A-7 (A-7-5, A-7-6)
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6**	A-2-7**					
Sieve Analysis Percent Passing												
No. 10	50 max	-	-	-	-	-	-		-	-	-	-
No. 40	30 max	50 max	51 min	-	-	-	-		-	-	-	-
No. 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max		36 min	36 min	36 min	36 min
Characteristics of fraction passing No. 40:												
Liquid limit	-		-	40 max	41 min	40 max	41 min		40 max	41 min	40 max	41 min
Plasticity index . . .	6 max		N.P.	10 max	10 max	11 min	11 min		10 max	10 max	11 min	*11 min
Usual types of significant constituent materials	Stone Fragments gravel and sand		Fine sand	Silty or clayey gravel and sand					Silty Soils		Clayey soils	
General rating as subgrade.	Excellent to good					Fair to poor						

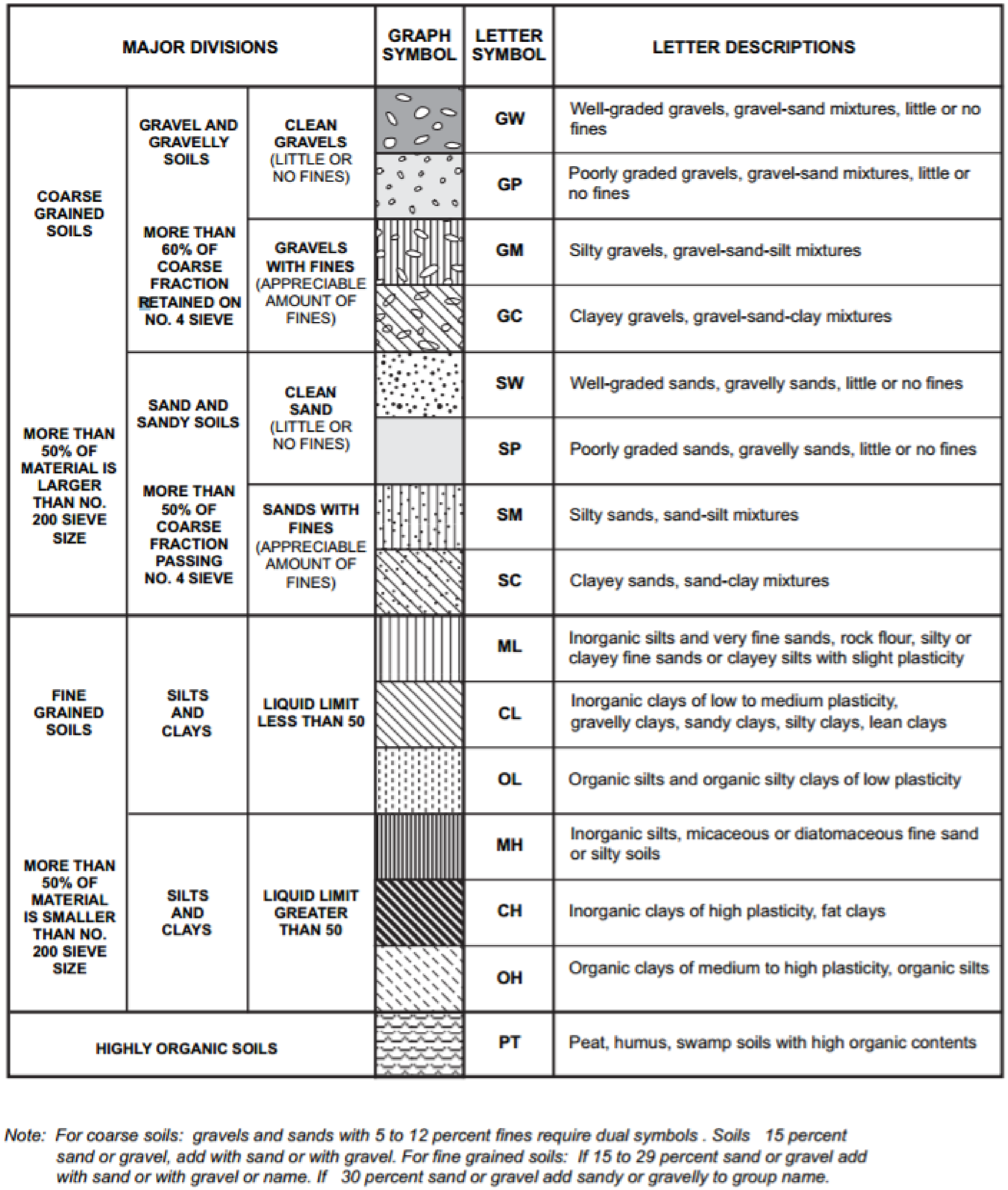
Group Index (GI) = (F-35) [0.2 + 0.005 (LL - 40)] + 0.01 (F-15) (PI-10)
Where: F = percentage passing a No. 200 sieve,
LL = Liquid Limit, and
PI = Plasticity Index

Group Index should be shown in parentheses after group symbol, as: A-2-6(3), A-4(5), A-6(12), A-7-5(17), etc.
When the combined Group Indices are negative, the Group Index should be reported as zero.

* Plasticity index of A-7-5 subgroup is equal to or less than (LL-30). Plasticity index of A-7-6 subgroup is greater than (LL - 30).

** When working with A-2-6 and A-2-7 subgroups the Partial Group Index (PGI) is determined from the PI portion only.

Figure B-4. AASHTO Soil Classification Chart. "Soil Mechanics Level I." (1987): 12. Natural Resources Conservation Service. Web. 7 Feb. 2017.



MAJOR DIVISIONS			GRAPH SYMBOL	LETTER SYMBOL	LETTER DESCRIPTIONS
COARSE GRAINED SOILS MORE THAN 50% OF MATERIAL IS LARGER THAN NO. 200 SIEVE SIZE	GRAVEL AND GRAVELLY SOILS MORE THAN 60% OF COARSE FRACTION RETAINED ON NO. 4 SIEVE	CLEAN GRAVELS (LITTLE OR NO FINES)	▨	GW	Well-graded gravels, gravel-sand mixtures, little or no fines
			▨	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
		GRAVELS WITH FINES (APPRECIABLE AMOUNT OF FINES)	▨	GM	Silty gravels, gravel-sand-silt mixtures
			▨	GC	Clayey gravels, gravel-sand-clay mixtures
	SAND AND SANDY SOILS MORE THAN 50% OF COARSE FRACTION PASSING NO. 4 SIEVE	CLEAN SAND (LITTLE OR NO FINES)	▨	SW	Well-graded sands, gravelly sands, little or no fines
			▨	SP	Poorly graded sands, gravelly sands, little or no fines
		SANDS WITH FINES (APPRECIABLE AMOUNT OF FINES)	▨	SM	Silty sands, sand-silt mixtures
			▨	SC	Clayey sands, sand-clay mixtures
FINE GRAINED SOILS MORE THAN 50% OF MATERIAL IS SMALLER THAN NO. 200 SIEVE SIZE	SILTS AND CLAYS	LIQUID LIMIT LESS THAN 50	▨	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
			▨	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			▨	OL	Organic silts and organic silty clays of low plasticity
	SILTS AND CLAYS	LIQUID LIMIT GREATER THAN 50	▨	MH	Inorganic silts, micaceous or diatomaceous fine sand or silty soils
			▨	CH	Inorganic clays of high plasticity, fat clays
			▨	OH	Organic clays of medium to high plasticity, organic silts
HIGHLY ORGANIC SOILS			▨	PT	Peat, humus, swamp soils with high organic contents

Note: For coarse soils: gravels and sands with 5 to 12 percent fines require dual symbols . Soils 15 percent sand or gravel, add with sand or with gravel. For fine grained soils: If 15 to 29 percent sand or gravel add with sand or with gravel or name. If 30 percent sand or gravel add sandy or gravelly to group name.

Figure B-5. Unified Soil Classification System. UNIFIED SOIL CLASSIFICATION SYSTEM (1952): 1. Web. 7 Feb. 2017.

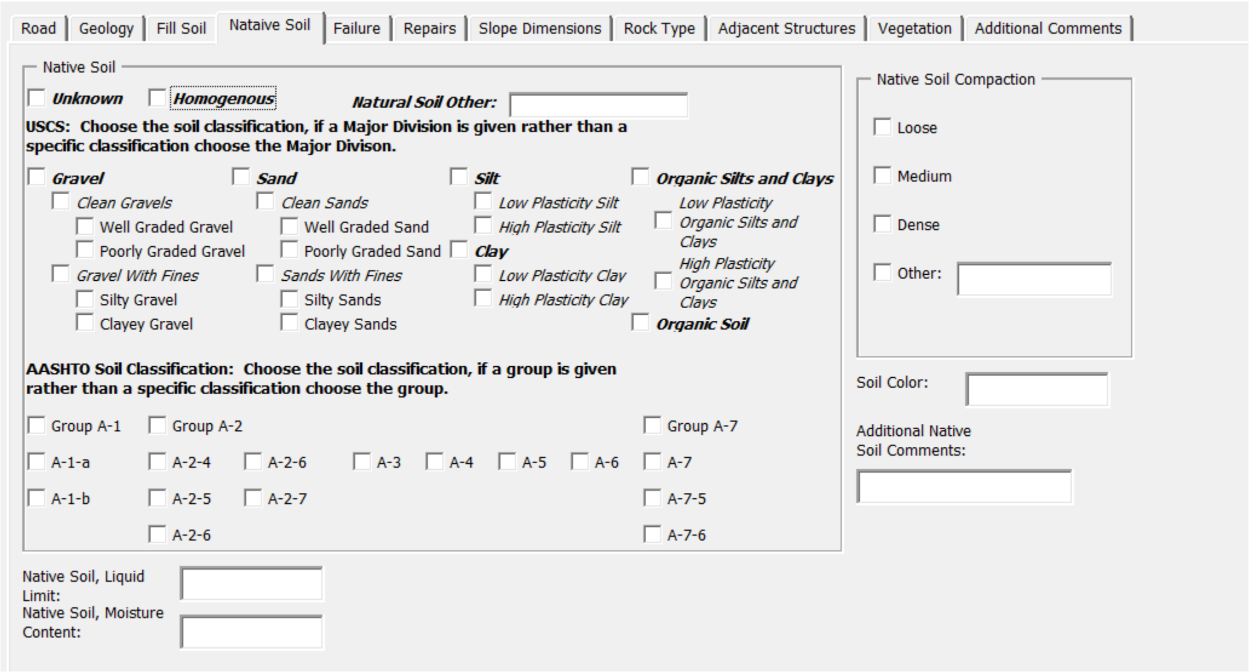
<u>Fill soil, Liquid Limit:</u> The liquid limit is the moisture content at which soil begins behaving like a liquid and begins to flow.

Fill Soil, Moisture Content: The moisture content is a ratio of mass of water to the mass of solids in the sample. The value should be expressed as a percentage.

Compaction: The soil may be classified as loose, medium, or dense. Indicate the compaction by checking one or more of the boxes within the compaction frame. If the compaction does not fit in any category check other and provide an explanation in the textbox.

Additional Fill Soil Comments: Place any addition information about the soil in the text box. The information should be additional data that may affect the soil stability, however do not fit in any other categories given. Information should be presented in short phrases, separated by commas.

Appendix B.2.4 Natural Soil



Native Soil

☐ ***Unknown*** ☐ ***Homogenous*** ***Natural Soil Other:***

USCS: Choose the soil classification, if a Major Division is given rather than a specific classification choose the Major Divison.

- ☐ ***Gravel***
  - ☐ *Clean Gravels*
    - ☐ Well Graded Gravel
    - ☐ Poorly Graded Gravel
  - ☐ *Gravel With Fines*
    - ☐ Silty Gravel
    - ☐ Clayey Gravel
- ☐ ***Sand***
  - ☐ *Clean Sands*
    - ☐ Well Graded Sand
    - ☐ Poorly Graded Sand
  - ☐ *Sands With Fines*
    - ☐ Silty Sands
    - ☐ Clayey Sands
- ☐ ***Silt***
  - ☐ *Low Plasticity Silt*
  - ☐ *High Plasticity Silt*
- ☐ ***Clay***
  - ☐ *Low Plasticity Clay*
  - ☐ *High Plasticity Clay*
- ☐ ***Organic Silts and Clays***
  - ☐ *Low Plasticity Organic Silts and Clays*
  - ☐ *High Plasticity Organic Silts and Clays*
- ☐ ***Organic Soil***

AASHTO Soil Classification: Choose the soil classification, if a group is given rather than a specific classification choose the group.

☐ Group A-1 ☐ Group A-2 ☐ Group A-7

☐ A-1-a ☐ A-2-4 ☐ A-2-6 ☐ A-3 ☐ A-4 ☐ A-5 ☐ A-6 ☐ A-7

☐ A-1-b ☐ A-2-5 ☐ A-2-7 ☐ A-7-5

☐ A-2-6 ☐ A-7-6

Native Soil, Liquid Limit:

Native Soil, Moisture Content:

Native Soil Compaction

☐ Loose

☐ Medium

☐ Dense

☐ Other:

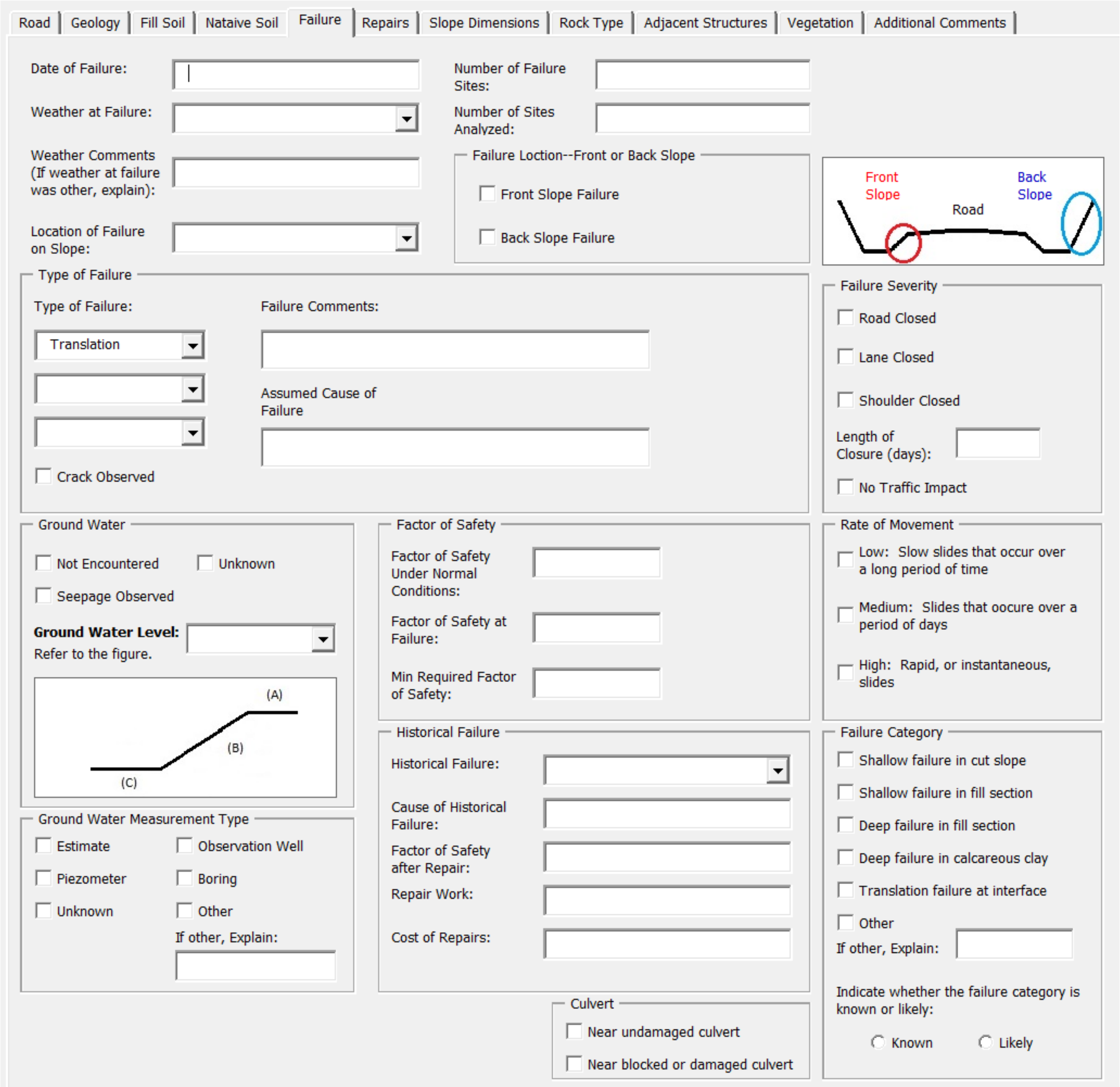
Soil Color:

Additional Native Soil Comments:

Figure B-6. Landslide Report UserForm—Native Soil Tab

Natural Soil: Natural soil refers to the soil that was originally located at the site without the interference of humans. The soil is classified by the AASHTO Soil Classification System and/or USCS. See the Fill Soil section above for an explanation of the methods.

Appendix B.2.5 Failure



Date of Failure:

Weather at Failure:

Weather Comments (If weather at failure was other, explain):

Location of Failure on Slope:

Number of Failure Sites:

Number of Sites Analyzed:

Failure Loction--Front or Back Slope

☐ Front Slope Failure

☐ Back Slope Failure

Type of Failure

Type of Failure: Translation

Failure Comments:

Assumed Cause of Failure

☐ Crack Observed

Failure Severity

☐ Road Closed

☐ Lane Closed

☐ Shoulder Closed

Length of Closure (days):

☐ No Traffic Impact

Ground Water

☐ Not Encountered ☐ Unknown

☐ Seepage Observed

Ground Water Level:

Refer to the figure.

Factor of Safety

Factor of Safety Under Normal Conditions:

Factor of Safety at Failure:

Min Required Factor of Safety:

Rate of Movement

☐ Low: Slow slides that occur over a long period of time

☐ Medium: Slides that oocure over a period of days

☐ High: Rapid, or instantaneous, slides

Ground Water Measurement Type

☐ Estimate ☐ Observation Well

☐ Piezometer ☐ Boring

☐ Unknown ☐ Other

If other, Explain:

Historical Failure

Historical Failure:

Cause of Historical Failure:

Factor of Safety after Repair:

Repair Work:

Cost of Repairs:

Failure Category

☐ Shallow failure in cut slope

☐ Shallow failure in fill section

☐ Deep failure in fill section

☐ Deep failure in calcareous clay

☐ Translation failure at interface

☐ Other

If other, Explain:

Indicate whether the failure category is known or likely:

○ Known ○ Likely

Culvert

☐ Near undamaged culvert

☐ Near blocked or damaged culvert

Figure B-7. Landslide Report UserForm—Failure Tab

<u>Date of Failure</u>: The date of failure should be provided in the format MM/DD/YYYY. If a range is give, the dates should be separated with a dash (MM/DD/YYYY-MM/DD/YYYY) to indicated a range of dates, or a comma denoting the failure took place on non-consecutive days (MM/DD/YYYY, MM/DD/YYYY)

If the day is not provided in the report the date should be denoted in the format MONTH YYYY. If the month and day are not recorded the date should be denoted as the season and year (winter YYYY) or year (YYYY).

Example:

Date of Failure	December 2015	Spring 2001	02/27/1999

Number of Failure Sites: The number of failure sites at the location may vary. If there are multiple failures in the same location, presumably occurring due to the same reason, they may all be included in the same report. Type the number of failure sites analyzed in the report as an integer.

Weather at Failure: The weather at failure may be listed in the report. If the weather at failure is other, type the weather condition into the Weather Comments textbox.

Number of Sites Analyzed: The number of failure sites analyzed in the report may vary. Indicate the number of failure locations in the report analyses. Write the value as an integer. If multiple sites are being analyzed in 1 report, create 1 data point for the group and 1 data point for each individual slide.

Location of Failure on Slope: The location of the failure may be indicated in the report. For example, the failure may be at the toe, in the fill material, or in the layer of riprap. The drop down menu provides 2 common locations on the slope, however additional answers may be typed into the text box.

Failure Location—Front or Back Slope: Refer to the picture provided in the UserForm and Figure B-8. Check whether the failure was located on the front slope, and or back slope. As you walk off the road, you shall walk down the front slope, and up the back slope.

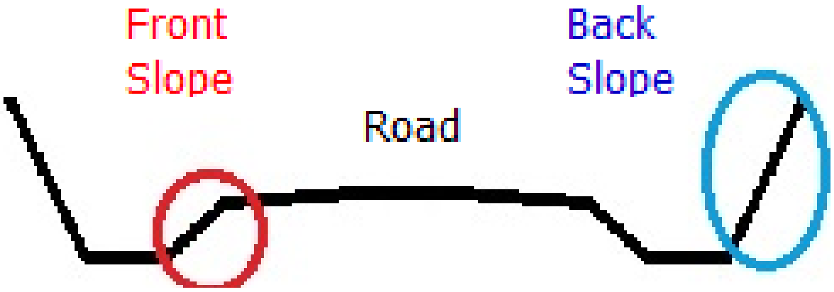


Figure B-8. Front Slope and Back Slope.

Type of Failure: The “Type of Failure” frame has 3 dependent drop down menus. The first drop down menu contains the type of failure—erosion, rotational, translation, compound, or other. The second and third drop down menus contain additional descriptions such as location along the slope or shape.
The second and third drop down menus are dependent on the first drop down menu. Therefore, the options may change. For example, the second and third menus may be blank depending on the input of the first drop down menu.

Failure Severity: Failure severity indicates whether the failure was catastrophic—occurring over a short period of time—or not catastrophic—occurring over a long period of time.

A catastrophic slide may occur over one day, were as a non-catastrophic slide may occur over a period of years. Non-catastrophic slides may be undergoing soil creep.

<u>Failure Comments</u>: If any additional information/data is provided about the failure that does not fit in the other categories place it here.

<u>Assumed Cause of Failure:</u> Type the assumed cause of failure into the text box. Use a short phrase.

<u>Crack Observed</u>: If a crack is observed, check the box next to the caption.

<u>Ground Water</u>: The ground water can be described as "Not Encountered", "Unknown", "Seepage Observed", or by water level. The ground water level values are given in a dropdown menu, the value should be estimated to the nearest option—top of the slope, failure surface, or toe (ground surface).

<u>Water Measurement Type</u>: The water measurement type describes the measurement method used to find the ground water level. Indicate if the ground water level was an estimate or if the source of the information is unknown.

<u>Factor of Safety</u>: The factor of safety of the slope is separated into 3 categories. All of the factors of safeties must be given as numerical values (X.XX).

<u>Factor of Safety under Normal Conditions</u>: This is the F.S. of the slope before its failure conditions

<u>Factor of Safety at Failure</u>: The F.S. at Failure is generally back calculated in the reports. The value will be less than 1.

<u>Minimum Required Factor of Safety</u>: The Minimum required F.S. is the F.S. required by the codes and policies of the designers.

<u>Historical Failure:</u>

<u>Historical Failure</u>: If a failure has occurred at or near the site in the past it must be indicated by selecting "Yes" in the dropdown menu.

<u>Cause of Historical Failure</u>: If the cause of the historical failure is given, provide a short phrase that explains it.

<u>Factor of Safety after Repair work:</u> This is the F.S. after the historic repair was made on the slope.

<u>Repair work:</u> If the report provides information on the repair work of historical failures, type it here. Keep responses short. Separate causes by commas.

<u>Failure Category</u>: The failure category groups slides based on the location and description of failure. Table B.1 provides a description of each category found using Slide Spread. If slides do not fall within one of the below categories, more may be added by selecting other, and providing a short description. The use then indicates if the

failure category was explicitly noted in the report (selecting “Known”) or if the failure category was inferred by the user (selecting “Likely”).

Table B-1. Current Failure Categories Defined for the Landslide Reports Database in Slide Spread

Failure Category	Description
Crack	A failure consisting of cracks in the pavement and/or soil.
Deep Failure in Calcareous Clay	A failure that extends deeper than the toe of the slope, located within marine clays (which are generally within the coastal plain physiographic province).
Deep Failure in Fill Section	A failure that extends deeper than the toe of the slope, located within fill material.
Erosion	A shallow failure occurring due to the wearing away of the top layer or layers by surface water or runoff.
Shallow Failure	A shallow slope failure occurs within the upper soil layers, located near the face of the slope. The failure does not extend deeper than the toe of the slope, nor beyond the toe of the slope. The category was assigned to landslides occurring in unknown soils, where the landslides could not be distinguished between failures in cut sections (native soils) or fill soils.
Shallow Failure in Cut Slope	A failure located within the upper soil layers in a cut section, consisting of native soils.
Shallow Failure in Fill Slope	A failure located within the upper soil layers in a fill section, consisting of fill soils.
Translation Failure at Interface	A failure along a weak or slick interface with a planar slip surface.
Other	Other contains several failure categories which did not fit into the above groupings, and contained a total 1 failure within each group. This includes deep failures in native soil, rockfalls in cut sections, and shallow failure in native soil. A deep failure in native soil consists of a failure surface which extends deeper than the toe of the slope, located within native soils. The shallow failure in native soil occurred in a fill section. However, the sliding surface was located below the fill, in the native soil.
Unknown	The landslides were not able to be confidently categorized into one the above categories using the information provided within the landslide report.

Culvert: The culvert section indicates whether the slide occurred at or adjacent to a damaged or undamaged culvert. If a culvert was not present, this is left blank.

Appendix B.2.6 Repairs

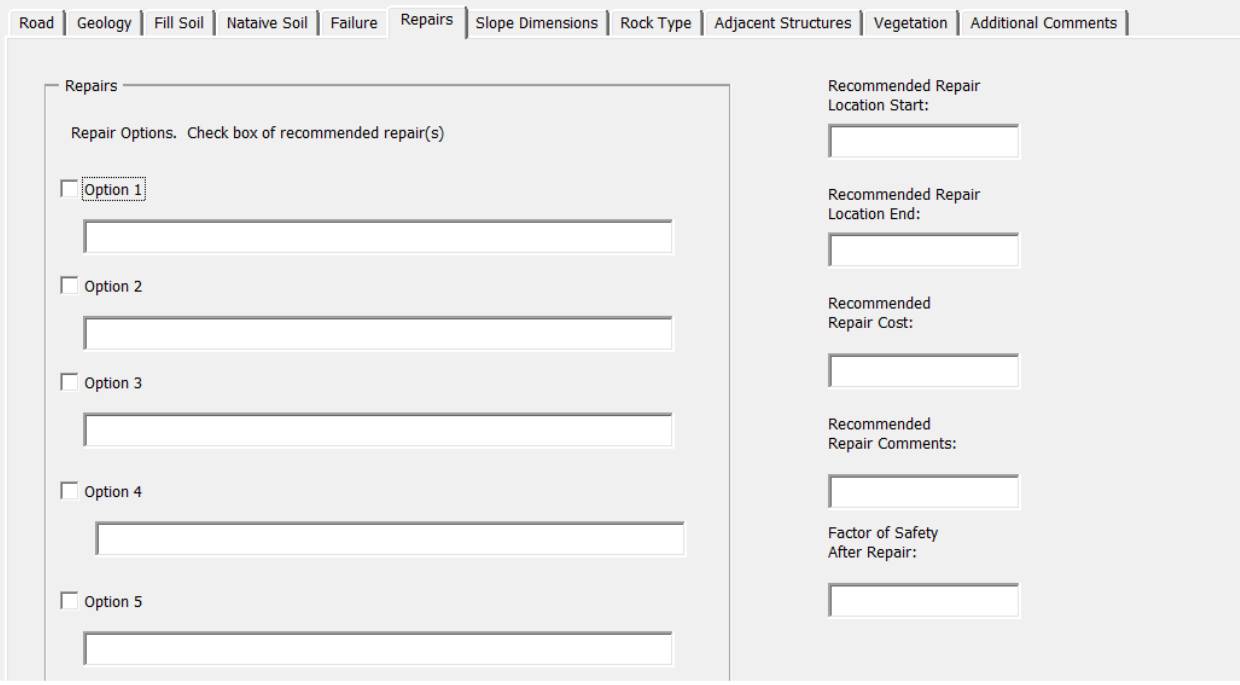


Figure B-9. Landslide Report UserForm—Repairs Tab

<u>Repairs</u>: Slope failure reports provide a section for recommended repairs. The repair sections will have several options and generally one or two recommendations. In the text boxes, list the general repair options—for example “Buttress” or “Drain”—and check the box of the recommended, or most recommended, repair.

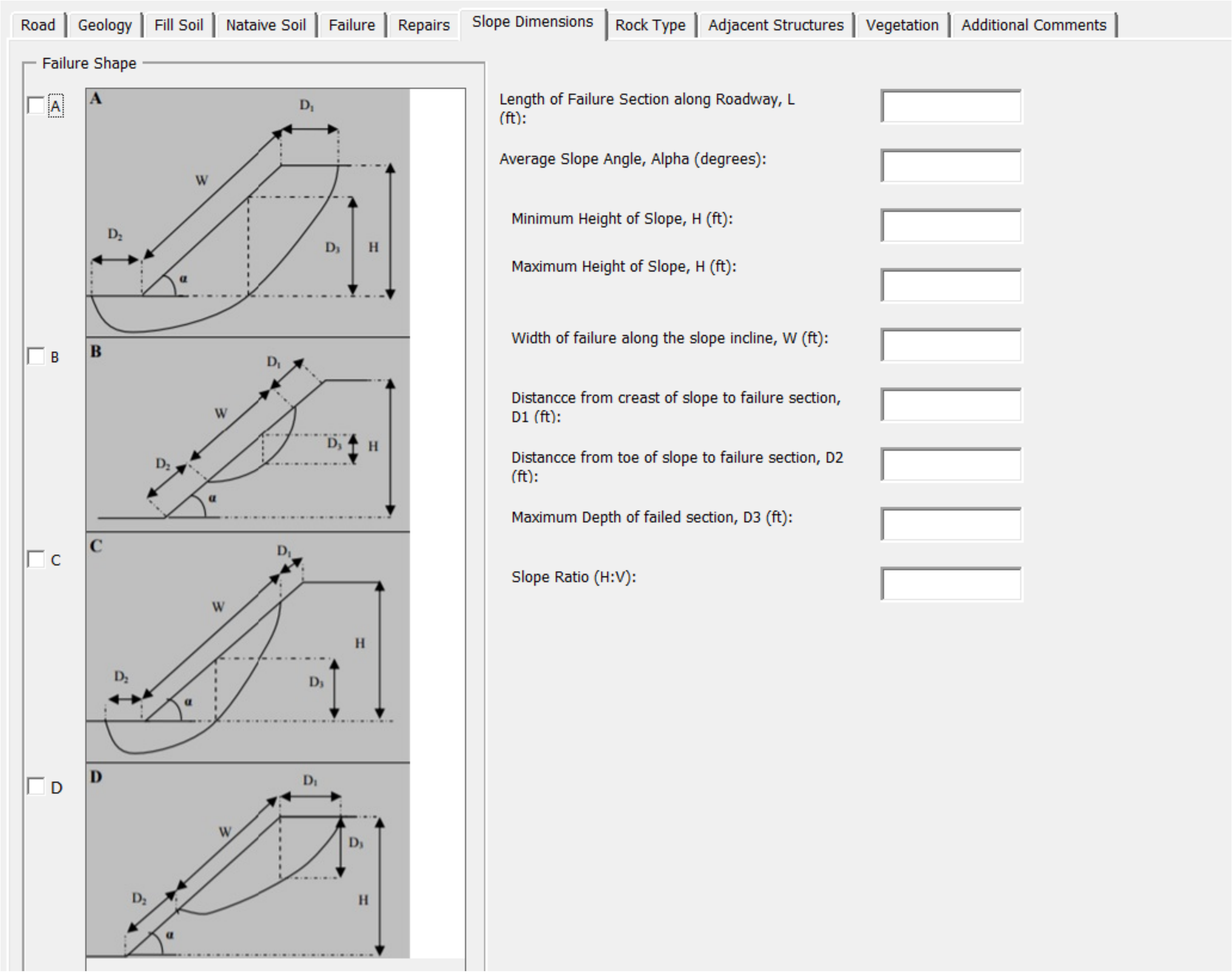
<u>Recommended Repair Location:</u>

<u>Recommended Repair Location Start:</u> The repair recommendations will give a start and end location for the repairs to take place. The location may be given as a station, mile post, coordinate, or exit number. Place the first value in the range in this text box, formatted as either a station (XXX+XX), mile post (MP XXX), coordinate point in decimal degrees (latitude, longitude), or exit number (EXIT XXX).

<u>Recommended Repair Location End:</u> The repair recommendations will give a start and end location for the repairs to take place. The location may be given as a station, mile post, coordinate, or exit number. Place the last value in the range in this text box, formatted as either a station (XXX+XX), mile post (MP XXX), coordinate point in decimal degrees (latitude, longitude), or exit number (EXIT XXX).

<u>Recommended Repair Comments</u>: If there is any addition information about the recommended road repairs that does not have a designated location place it here.

Appendix A.2.7 Slope Dimensions



Failure Shape

☐ A

☐ B

☐ C

☐ D

Length of Failure Section along Roadway, L (ft):

Average Slope Angle, Alpha (degrees):

Minimum Height of Slope, H (ft):

Maximum Height of Slope, H (ft):

Width of failure along the slope incline, W (ft):

Distancce from creast of slope to failure section, D1 (ft):

Distancce from toe of slope to failure section, D2 (ft):

Maximum Depth of failed section, D3 (ft):

Slope Ratio (H:V):

Figure B-10. Landslide Report UserForm—Slope Dimensions Tab

Many of the slope dimensions are giving directly in the reports. However, figures, images, and charts may provide the information. Many of the values may be determined by using the cross-sections provided in the reports.

Failure Shape: If the failure surface is described in detail or illustrated in the report, choose from one of the 4 slope failure profiles that most matches the landside site. The 4 profiles provided are shown in Figure B-10. Failure Profiles:

(A) Deep failure stating in the slope crest
(B) Shallow failure starting and ending in the slope face
(C) Deep failure stating in the slope face
(D) Shallow failure starting in the slope crest

Length of Failure Section along Roadway, L (ft): The length of the failure section along the road way is the length of failure parallel to the road. The value must be recorded in feet.

Average Slope Angle, Alpha (degrees): The average slope angle is the acute angle between the slope surface and the horizontal. The value must be given in degrees.

Height of Slope: The height of the slope is generally given as a range of values—for example, 25-30 feet. To include the entire range, the minimum value in the range will be placed in the Minimum Height of slope, H (ft) text box and the larger value in the range will be placed in the Maximum Height of Slope, H (ft) textbox.

Width of Failure along the Slope's Incline, W (ft): The width of the failure (W) is the failure distance along the incline. The width must be given in feet.

Distance form Crest of Slope to Failure Section, D_1 (ft): D_1 is the distance between the failure section and the crest.

Distance from Toe of Slope to Failure Section, D_2 (ft): D_2 is the distance between the failure section and the toe of the slope.

Maximum Depth of Failed Section, D_3 (ft): D_3 is the maximum depth of the failure section in relation to the slopes surface. The measurement is taken vertically from the original slope surface to the failure surface.

Slope Ratio (H:V): The slope ratio is the ratio of the horizontal projection of the slope to the vertical projection of the slope. The value must be written in the form H:V, horizontal length to vertical length. The value is illustrated in Figure B-11.

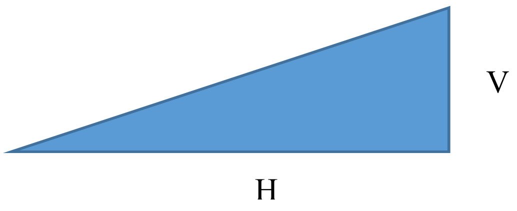
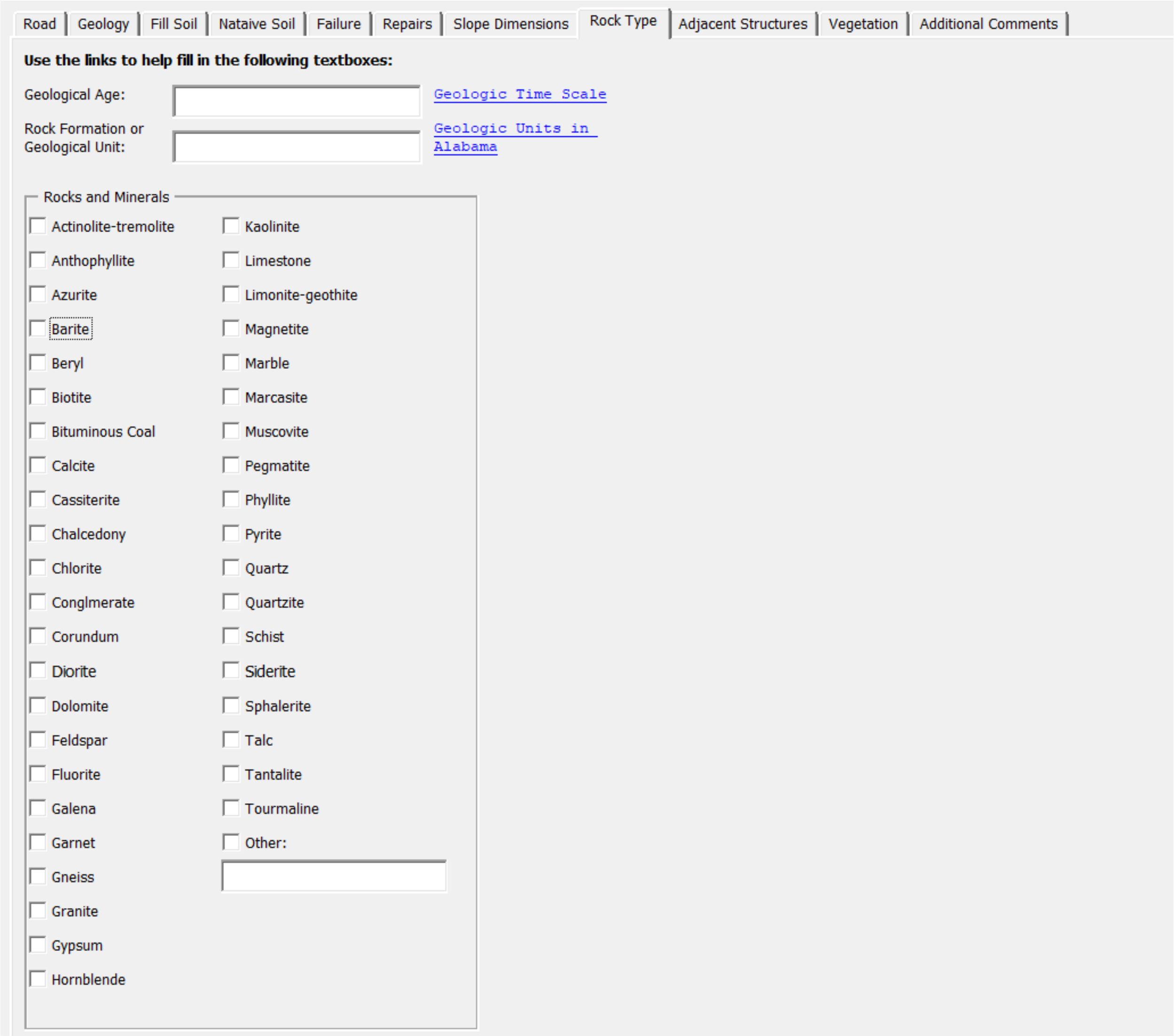


Figure B-11. Slope Ratio, H:V

Appendix B.2.8 Rock Type



Road | Geology | Fill Soil | Nataive Soil | Failure | Repairs | Slope Dimensions | Rock Type | Adjacent Structures | Vegetation | Additional Comments

Use the links to help fill in the following textboxes:

Geological Age: ______ Geologic Time Scale

Rock Formation or Geological Unit: ______ Geologic Units in Alabama

Rocks and Minerals

☐ Actinolite-tremolite
☐ Anthophyllite
☐ Azurite
☐ Barite
☐ Beryl
☐ Biotite
☐ Bituminous Coal
☐ Calcite
☐ Cassiterite
☐ Chalcedony
☐ Chlorite
☐ Conglmerate
☐ Corundum
☐ Diorite
☐ Dolomite
☐ Feldspar
☐ Fluorite
☐ Galena
☐ Garnet
☐ Gneiss
☐ Granite
☐ Gypsum
☐ Hornblende
☐ Kaolinite
☐ Limestone
☐ Limonite-geothite
☐ Magnetite
☐ Marble
☐ Marcasite
☐ Muscovite
☐ Pegmatite
☐ Phyllite
☐ Pyrite
☐ Quartz
☐ Quartzite
☐ Schist
☐ Siderite
☐ Sphalerite
☐ Talc
☐ Tantalite
☐ Tourmaline
☐ Other: ______

Figure B-12. Landslide Report UserForm—Rock Type Tab

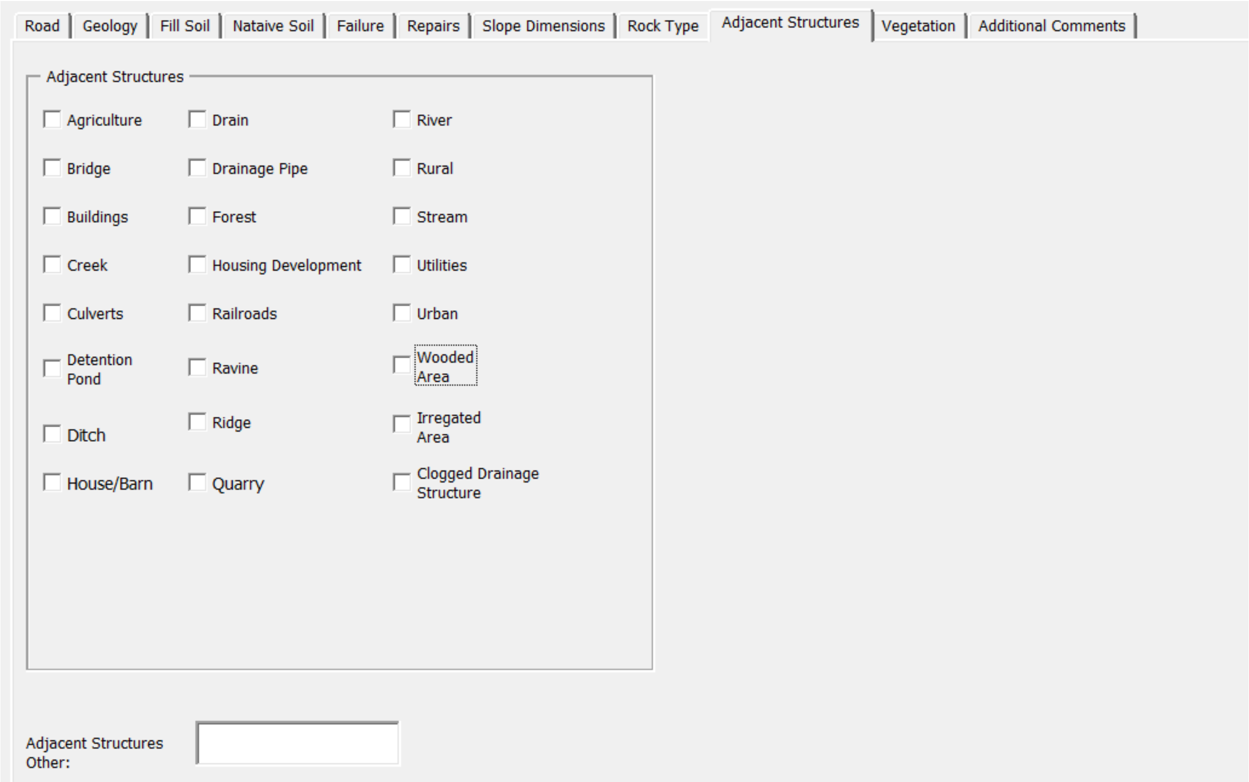
<u>Geological Age</u>: The geological age refers to the geologic time scale. Many rock formations are formed during a particular time period, affecting the properties of the rock. A hyperlink reference is given to provide the geologic time scale.

<u>Rock Formation</u>: Rock formations are classified by similar rock characteristics. There are numerous rock formations in Alabama. The link next to the textbox contains all of the names of each rock formation in Alabama and description.

<u>Rock and Minerals</u>: The common rocks and minerals found in Alabama are giving in the frame. Additional rock types and mineral types are found in Alabama. If a report gives a rock type not listed, fill in the "Other" textbox with the information. Typically, the report will describe the common rock in each formation. Rather than

providing typical rock types for each formation, only provide information that was explicitly found at the site, for example through boring logs.

Appendix B.2.9 Adjacent Structures



Adjacent Structures

☐ Agriculture
☐ Bridge
☐ Buildings
☐ Creek
☐ Culverts
☐ Detention Pond
☐ Ditch
☐ House/Barn
☐ Drain
☐ Drainage Pipe
☐ Forest
☐ Housing Development
☐ Railroads
☐ Ravine
☐ Ridge
☐ Quarry
☐ River
☐ Rural
☐ Stream
☐ Utilities
☐ Urban
☐ Wooded Area
☐ Irregated Area
☐ Clogged Drainage Structure

Adjacent Structures Other:

Figure B-13. Landslide Report UserForm—Adjacent Structures Tab

<u>Adjacent Structures</u>: The adjacent structures include structures, landforms, and utilities that may be located near a roadway. Check the boxes of the adjacent structures near the landslide. If any adjacent objects are not included, provide it in the "Adjacent Structures Other" textbox.

Appendix B.2.10 Vegetation

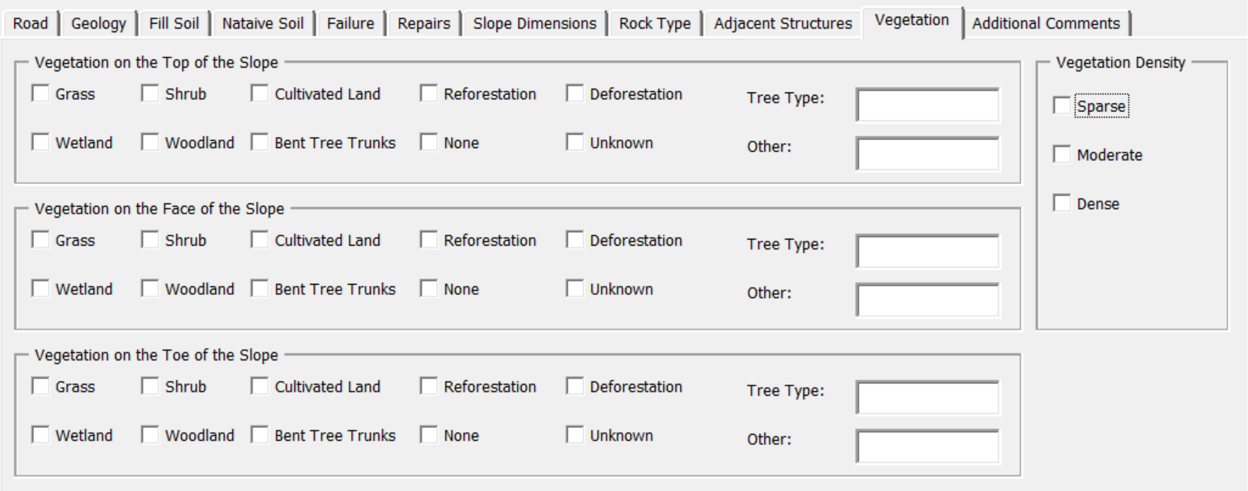
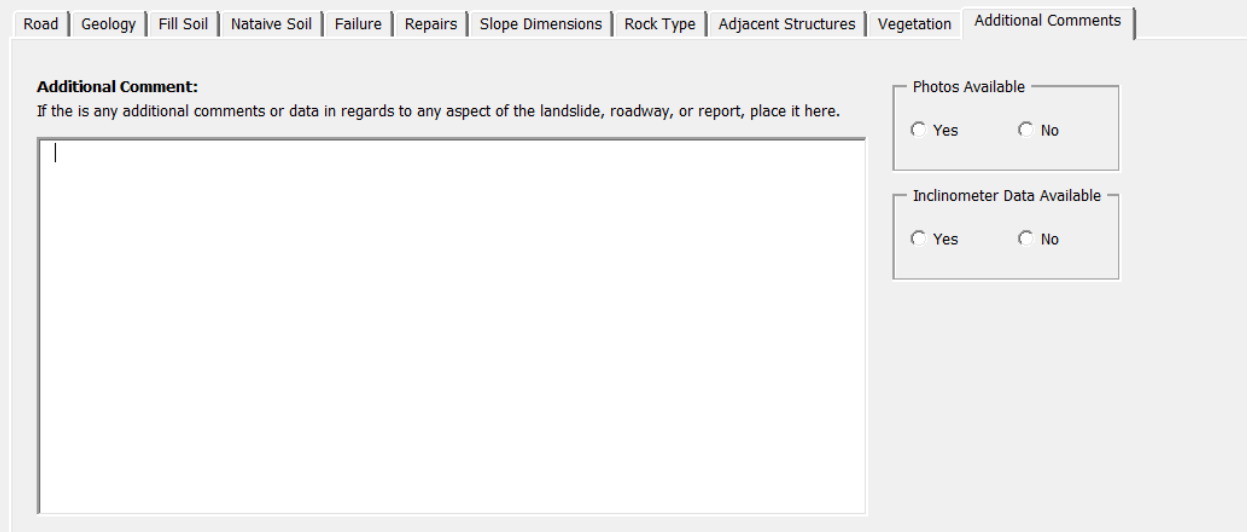


Figure B-14. Landslide Report UserForm—Vegetation Tab

Vegetation may be located on the top (crest), face (slope), or toe (ground surface) of the slope. The vegetation may be a factor in slope failure, or may be helping protect against slope failure. Indicate the vegetation along the 3 areas of the slope. If none is listed, mark unknown. If vegetation is present, mark the density of the vegetation—sparse (very little), moderate, or dense.

Appendix B.2.11 Additional Comments



Additional Comment:

If the is any additional comments or data in regards to any aspect of the landslide, roadway, or report, place it here.

Figure B-15. Landslide Report UserForm—Additional Comments Tab

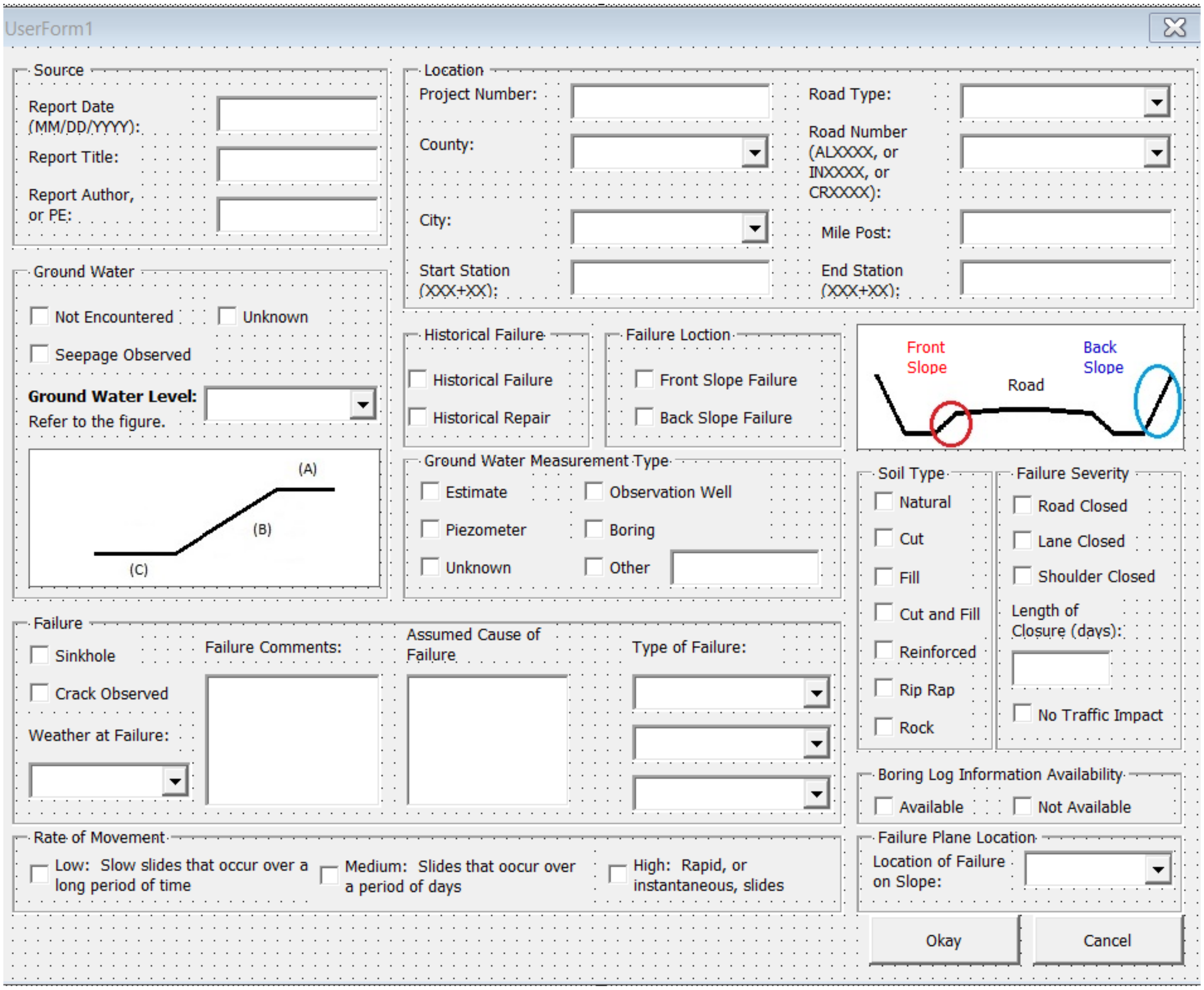
Additional Comments: If there is any additional data that the user wants to input, but does not have a desired location on the form please place it here.

APPENDIX C: SLIDE SPREAD INSTRUCTION MANUAL

EMERGENCY RELIEF SLIDES DATABASE

Appendix C.1 Introduction

The following is an instruction manual for the for the Emergency Relief Slides Database collection system within Slide Spread. The system uses a UserForm developed within Microsoft excel. The purpose of the Emergency Relief Slides UserForm is to aid in the input and organization of data collected from landslide reports. It was designed as a multi-user system, providing consistent output data that may be used in conjunction with ArcGIS for spatial analysis. This guide provides definitions of terms, procedures for data input, and examples of data input. The guide should be used as reference when feeding data into the Emergency Relief Slides UserForm, insuring the data is consistent and comprehensive. The guide is divided into sections based on the frame (e.g., data grouping), on the UserForm. The frame title is listed in bold print. The subheading are the labels associated with each data entry box. Next to the subheading a definition or explanation is provided, followed by examples.


UserForm1

Source
Report Date (MM/DD/YYYY):
Report Title:
Report Author, or PE:

Location
Project Number:
County:
City:
Start Station (XXX+XX):
Road Type:
Road Number (ALXXXX, or INXXXX, or CRXXXX):
Mile Post:
End Station (XXX+XX):

Ground Water
☐ Not Encountered ☐ Unknown
☐ Seepage Observed
Ground Water Level:
Refer to the figure.

Historical Failure
☐ Historical Failure
☐ Historical Repair

Failure Loction
☐ Front Slope Failure
☐ Back Slope Failure

Ground Water Measurement Type
☐ Estimate ☐ Observation Well
☐ Piezometer ☐ Boring
☐ Unknown ☐ Other

Soil Type
☐ Natural
☐ Cut
☐ Fill
☐ Cut and Fill
☐ Reinforced
☐ Rip Rap
☐ Rock

Failure Severity
☐ Road Closed
☐ Lane Closed
☐ Shoulder Closed
Length of Closure (days):
☐ No Traffic Impact

Failure
☐ Sinkhole
☐ Crack Observed
Weather at Failure:
Failure Comments:
Assumed Cause of Failure
Type of Failure:

Boring Log Information Availability
☐ Available ☐ Not Available

Rate of Movement
☐ Low: Slow slides that occur over a long period of time
☐ Medium: Slides that oocur over a period of days
☐ High: Rapid, or instantaneous, slides

Failure Plane Location
Location of Failure on Slope:

Figure C-1. Emergency Relief Slides UserForm

Appendix C.2 Landslide Reports Database Instructions

Appendix C.2.1 Source

Sources:

Report Date: Provides the date the report was published. This is generally provided on the title page or in the letter heading. The format of the date should be as followed: MM/DD/YYYY

Report Title: The report title is given on the cover page of the report. Examples include "Slide Correction", "Landslide Correction Report", or "Slope Evaluation and Recommendation."

Report Author, or PE: The report author is provided in the letter heading of the report. Type the name as First-Name Last-Name, Title. For example: James D. Brown, PE or Kaye Chancellor Davis, PE.

Appendix C.2.2 Location

Project Number: The project number is an indexing value attached to the project. The project number may be identified by the phrases "ALDOT Project No.", "Project No.", or "Project." If two or more project numbers are provided, the response should only include the ALDOT Project Number.

Examples:

Project Number:	ST-037-I59-002	APD-0004 (515)	NH-0035 (527)

County: Choose the county where the landslide occurred from the drop down list. If the county is not listed, type the county into the drop down menu text box (the country does not need to be listed in the drop down menu). If the landslide occurs in two or more counties, type the counties separated by a comma.

Examples:

County	Autauga	Mobile, Baldwin	Perry, Hale, Bibb

City: Choose city where the landslide occurred from the drop down list. If the city is not listed, type the city into the drop down menu text box (the city does not need to be listed in the drop down menu). If the landslide occurs in two or more cities, type the cities separated by a comma.

Examples:

City	Auburn, Opelika	Mobile	Adamsville

Station: The station refers to the roadway station the landslide is near. Roadway stations are horizontal measurements along a project. One station is equal to 100 feet. Stations are writing in the form XXX+XX, for example 0+00, 100+28, or 38+02. The station values may be given as a point, or a range. If multiple station ranges or point values are given, separate the slides into multiple data points.

Station Start (XXX+XX): If the projects stations are given as a range of values, the start station is the first station in the range.

Station End (XXX+XX): If the projects stations are given as a range of values, the end station is the last station in the range.

Station (XXX+XX): If the station is given as a signal value, type the value is this text box.

Examples:

Station	Station Start: 50+00 Station End: 79+00	Station: 76+00	Station: 117+25

Road Type: Roads are classified as Interstate (I), State Road (SR) or Country Road (CR). Choose the road type classification from the drop down menu. If the road type is not listed, type the road type into the drop down menu text box (the road type does not need to be listed in the drop down menu).

Example:

Road Type	**CR**	**SR**	**SR**

Road Number: Roads are assigned a road type classification and route number. Type in the route number into the text box. The text box will not accept non-integer values.

Examples:

Route Number	23	35	247

Mile Post: The mile post is a marker indicating the distance along a road. The mile post may be listed as a range or as a point.

If multiple latitude/longitude ranges or point values are given, separate the slides into multiple data points.

Start Mile Post: If the project's mile posts are given in a range, the Start Mile Post is the first mile post listed in the range.

End Mile Post: If the project's mile posts are given in a range, the End Mile Post is the last mile post listed in the range.

Mile Post: If the mile post is given as a signal value, type the value in this textbox.

Examples:

Mile Post	Mile Post: 49.2	Separate the slopes into 8 analyses: 9) Mile Post Start: 0.0 Mile Post End: 26.0 10) Mile Post: 1.1 11) Mile Post: 15.8 12) Mile Post: 17.4 13) Mile Post: 21.1 14) Mile Post: 23.2 15) Mile Post: 24.8 16) Mile Post: 26.0

Appendix C.2.3 Ground Water

Ground Water: The ground water can be described as "Not Encountered", "Unknown", "Seepage Observed", or by water level. The ground water level values are given in a dropdown menu, the value should be estimated to the nearest option—top of the slope, failure surface, or toe (ground surface).

Appendix C.2.4 Historical Failure

Historical Failure: A historical failure, or a previous failure occurring at or adjacent to the current landslide site may be noted within the report or previous reports at the given location. If a historical failure is known to have occurred at the landslide site, the user should check the box next to "Historical Failure." If a repair was implemented at the site for a previous failure, the user should also check the box next to "Historical Repair."

Appendix C.2.5 Failure Location

Failure Location: The front slope and back slope refer to the picture provided in the UserForm and Figure C-2. Check whether the failure was located on the front slope, and/or back slope along the roadway. As you walk off the road, you will walk down the front slope, and up the back slope.

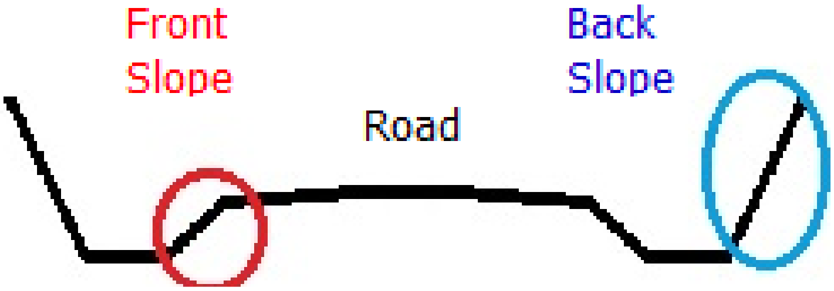


Figure C-2. Front Slope and Back Slope.

Appendix C.2.6 Groundwater Measurement

Ground Water Measurement Type: The water measurement type describes the measurement method used to find the ground water level. Indicate if the ground water level was an estimate or if the source of the information is unknown.

Appendix C.2.7 Soil Type

Soil Type: The soil type identifies if the slope is natural, fill, cut, cut and fill, reinforced, contains a Riprap layer, and/or is a rock slope. 0 to 7 options may be selected. If the slope is cut and fill, do not select the "cut" and "fill" options. Reinforced slopes may include a facing, geotextiles, anchors, buttresses, or other forms of reinforcement.

Appendix C.2.8 Failure Severity

Failure Severity: The failure severity indicates the impact of the slope failure on the surrounding structure, adjacent highway, and traveling public. The failure severity is recorded by noting the effect of the road and traffic—recording the whether there has been a shoulder, lane, or road closure, as well as noting the number of days in which the closure occurs, as well as whether the traffic has been impacted.

Appendix C.2.9 Failure

Sinkholes: A sinkhole is a ground cavity due to water erosion. The drop down menu includes the following options.

- "Yes": there is a sinkhole at or near the failure site
- "No": there is no recorded or seen sinkhole at the site
- "Susceptible, none seen": the rock formation or surrounding area is susceptible to sinkholes, however none have been recorded or seen.

Crack Observed: If a crack is observed, check the box next to the caption.

Weather at Failure: The weather at failure may be listed in the report. If the weather at failure is other, type the weather condition into the Weather Comments textbox.

Failure Comments: If any additional information/data is provided about the failure that does not fit in the other categories place it here.

Assumed Cause of Failure: Type the assumed cause of failure into the text box. Use a short phrase.

Type of Failure: The "Type of Failure" frame has 3 dependent drop down menus. The first drop down menu contains the type of failure—erosion, rotational, translation, compound, or other. The second and third drop down menus contain additional descriptions such as location along the slope or shape.

The second and third drop down menus are dependent on the first drop down menu. Therefore, the options may change. For example, the second and third menus may be blank depending on the input of the first drop down menu.

Appendix C.2.10 Boring Log Availability

Boring Log Information Available: Mark the availability of the boring logs in the UserForm. If the boring logs are included in the report or supporting documentation, check "Available", if the boring logs are not included check "Not Available."

Appendix C.2.11 Rate of Movement

Rate of Movement: The rate of movement indicates rate at which the failure occurs. The rate of movement may be low (occurring over a long period of time, such as several years), medium (occurring over a period of days), or high (occurring at a rapid or instantons rate).

Appendix C.2.12 Failure Plane Location

Failure Plane Location: The failure plane location gives the location of the failure along the slope, for example the toe of the slope. The user may use the drop down menu to select locations programed into the UserForm, or type a new location category based on the data provided within the DDIR.

APPENDIX D: GEOLOGIC FORMATION GROUPINGS (DICKEN ET AL. 2017)

Category	Unit	Age	Rock Type	Description
Alluvial, Coastal, and low terrace deposits	Alluvial, Coastal, and low terrace deposits	Holocene	• Alluvium • Beach Sand	• Alluvial, Coastal, and low terrace deposits
Claiborne and Jackson Formations	Tallahatta Formation	Eocene	• Claystone • Clay or mud	• Claiborne Group • Light-greenish gray siliceous claystone • Thin layers of fossiliferous clay, sandy clay and glauconitic sand and sandstone • White to light-greenish-gray fine to course sand and fine gravel
	Gosport Sand and Lisbon Formation	Eocene	• Sand • Clay or mud	• Fossiliferous, glauconitic, quartz sand • Lenses of greenish-gray clay
	Jackson Group	Eocene	• Sand • Clay or mud	• Jackson Group • Yazoo Clay and Crystal River and Moodys Branch Formations
	Lisbon Formation	Eocene	• Sand • Clay or mud	• Claiborne Group • Fossiliferous, glauconitic quartz sand • Greenish-gray clay
	Residuum	Eocene-Oligocene	• Residuum • Clay or mud	• Claiborne/Jackson Group

				• Whit to reddish-orange mottled sandy clay and residual clay • Layers of gravelly medium to coarse sand, fossiliferous chert and limestone boulders and limonitic sand masses
Citronelle Formation	Citronelle Formation	Pleistocene-Pliocene	• Sand • Clay or mud	• Moderate-reddish-brown deeply weathered fine to very coarse quartz sand and mottled lenticular beds of clay and clayed gravel
High Terrace Deposits	High terrace deposits	Pleistocene	• Terrace	• Varicolored lenticular beds of poorly sorted sand, ferruginous sand, silt, clay, and gravelly sand
Cambrian and Ordovician Limestone	Nashville and Stone River Groups	Ordovician	• Limestone • Bentonite	• Medium to dark gray fossiliferous limestone • Yellowish-gray laminated silty limestone
	Little Oak Limestone	Ordovician	• Limestone • Mudstone	• Dark-gray medium to thick-bedded fossiliferous, argillaceous to silty limestone containing chert nodules
	Knox Group	Ordovician-Cambrian	• Dolostone (dolomite) • Limestone	•
	Copper Ridge Dolomite	Cambrian	• Dolostone (dolomite) • Chert	• Thick bedded siliceous dolomite
	Chepultepec and Copper Ridge Dolomites	Ordovician-Cambrian	• Dolostone (dolomite) • Limestone	• Light-gray to dark-gray dolomite and interbedded light-gray limestone • Abundant chert
	Ketona Dolomite	Cambrian	• Dolostone (dolomite)	• Light to medium gray thick bedded coarsely crystalline dolomite

	Shady Dolomite	Cambrian	• Dolostone (dolomite) • Chert	• Bluish-gray or pale-yellowish-gray thick bedded siliceous dolomite
	Conasauga Formation	Cambrian	• Limestone • Shale	• Medium-bluish-gray fine-grained, argillaceous limestone and interbedded dark-gray shale
	Chickamauga Limestone	Ordovician	• Limestone • Conglomerate	• Medium to dark-gray fossiliferous limestone
	Chilhowee Group	Cambrian	• Conglomerate • Mudstone	• Light to medium-gray arkose, arkosic conglomerate • Mudstone
	Oligocene Series	Oligocene	• Limestone • Clay or mud	• Paynes Hammock Sand • Chickasawhay Limestone • Bucatunna Clay Member • Marianna Limestone • Red Bluff Clay • Bumpnose Limestone
	Newala Limestone	Ordovician	• Limestone • Dolostone (dolomite)	• Light to dark-gray thick-bedded micritic and peloidal limestone and minor dolomite
	Ordovician System	Ordovician	• Limestone • Shale	• Elkmont Formation • Leiper Limestone • Inman Formation • Nashville Group • Stones River group
Cambrian and Ordovician Shale	Athens Shale	Ordovician	• Black Shale • Limestone	• Black gratoltic shale • Interbedded dark-gray limestone
	Greensport Formation	Ordovician	• Shale • Mudstone	• Greensport Formation

	Rome Formation	Cambrian	• Mudstone • Shale	• Interbedded mudstone, shale, siltstone, and sandstone • Limestone and dolomite • Quartzose sandstone near top
	Sequatchie Formation	Ordovician	• Shale • Mudstone	• Grayish-red, grayish-green and yellowish gray calcareous shale and calcareout mudstone • Interbedded fossiliferous limestone • Medium-gray to moderate-red partly sandy and glauconitic • Bioclastic limestone
Midway Group	Porters Creek Formation	Paleocene	• Clay or mud • Sand	• Midway Group • Dark-gray plastic clay, with glauconitic shell marl at the top • Light-greenish-gray calcareous, micaceous, clayey fine to medium sand, medium-gray sandy, calcareous clay, light to gray thin bedded partly clayey, fossiliferous limestone
	Naheola Formation	Paleocene	• Sand • Clay or mud	• Midway Group • Coal Bluff Marl Member: glauconitic sand, thin-bedded silty clay, and sandy fossiliferous marl • Oak Hill Member: Laminated silt, clay, and fine sand
	Clayton Formation	Paleocene	• Silt • Clay or mud	• Midway Group • Upper part: White to yellowish-gray argillaceous limestone • Lower part: medium-gray fossiliferous calcareous silt, glauconitic sand and thin beds of sandy limestone and calcareous sandstone

Miocene Series	Miocene Series	Miocene	• Sand • Clay or mud	• Yellow-range think bedded to massive fine to course sand, gravelly sand, clay and sandy clay
Mississippian Limestone	Tuscumbia Limestone	Mississippian	• Limestone • Chert	• Light-gray limestone • Fine to course grained bioclastic crinomidal limestone common • Light-gray chert modules and concretions
	Bangor Limestone	Mississippian	• Limestone • Mudstone	• Medium-gray bioclastic and oolitic limestone
	Monteagle Limestone	Mississippian	• Limestone	• Fragmental and oolitic limestone, light-gray • Fine-grained, brownish-gray limestone
Mississippian Sandstone and Shale	Hartselle Sandstone	Mississippian	• Sandstone • Shale	• Light thick bedded quartzose sandstone • Interbeds of dark-gray shale
	Pride Mountain Formation	Mississippian	• Shale • Limestone	• Medium to dark-gray shale
	Parkwood and Pennington Formation	Pennsylvanian-Mississippian	• Shale • Sandstone	• Interbedded medium to dark-gray shale and light to medium-gray sandstone
	Parkwood Formation	Pennsylvanian-Mississippian	• Shale • Sandstone	• Interbedded medium to dark-gray shale and light to medium-gray sandstone
	Floyd Shale	Mississippian	• Shale • Sandstone	• Dark-gray shale • Thin beds of sandstone, limestone and chert
	Pennington Formation	Mississippian	• Shale • Limestone	• Medium-gray shale containing interbedded limestone, dolomite, argillaceous sandstone, dusty-red and grayish-olive mudstone, and minor shaly coal

	Parkwood Formation and Floyd Shale	Pennsylvanian-Mississippian	• Shale • Sandstone	• Parkwood Formation • Interbedded medium to dark-gray shale to light to medium-gray sandstone • Floyd Shale
Pottsville Formation	Pottsville Formation	Pennsylvanian	• Sandstone • Conglomerate	• Light-gray thin to thick-bedded quartzose sandstone and conglomerate containing interbedded dark-gray shale, siltstone, and coal
	Pottsville Formation (lower part)	Pennsylvanian	• Sandstone • Shale	• Light-gray pebbly quartzose sandstone, interbedded dark-gray shale, siltstone, and thin discontinuous coal
	Pottsville Formation (lower part)	Pennsylvanian	• Shale • Siltstone	• Light-gray pebbly quartzose sandstone, interbedded dark-gray shale, siltstone, and thin discontinuous coal
	Pottsville Formation (upper part)	Pennsylvanian	• Shale • Siltstone	• Interbedded dark-gray shale, siltstone, medium-gray sandstone, and coal • Razhurg Sandstone Member • Camp Branch Sandstone Member • Lick Creek Sandstone Member • Bremen Sandstone Member
Selma Group Chalk	Demopolis Chalk	Cretaceous	• Carbonate • Mixed Clastic/Carbonate	• Selma Group • Light-gray to medium-light-gray • Brittle chalk overlain by fossiliferous chalky marl, clayey chalk and calcareous clay
	Mooreville Chalk	Cretaceous	• Carbonate • Mixed Clastic/Carbonate	• Selma Group • Yellowish-gray to olive-gray • Fossiliferous clayey chalk and chalky marl

	Prairie Bluff Chalk	Upper Cretaceous	• Carbonate • Clay or mud	• Selma Group • Light-gray to light-bluish-gray firm sandy, fossiliferous brittle chalk and grayish-black silty sandy calcareous glauconitic, fossiliferous clay • Semi-indurated beds of sandy, clayey limestone
Selma Group Sand and Clay	Blufftown Formation	Cretaceous	• Sand • Mixed Clastic/Carbonate	• Selma Group • Glauconitic calcareous fine sand, micaceous clay and marl, fossiliferous clay, gray calcareous fossiliferous sand stone, and carbonaceous clay and silt • Lower part: gravelly sand, glauconitic sand, calcareous clay, and sandy clay • Upper part: Calcareous sand clay and micaceous silty fine sand with thin layer of limestone and sandstone
	Cusseta Sand Member of the Ripley Formation	Cretaceous	• Sand • Clay or mud	• Selma Group • Cross-bedded, medium to coarse sand • Glauconitic, fossiliferous find sand • Dark-gray fossiliferous, micaceous, carbonaceous clay
	Ripley Formation	Cretaceous	• Sand • Clay or mud	• Selma Group • Light-gray to pale-olive micaceous, glauconitic, fossiliferous fine sand • Sandy calcareous clay • Thin indurated beds of fossiliferous sandstone
	Providence Sand	Cretaceous	• Sand • Clay or mud	• Selma Group • Upper part: cross-bedded fine of coarse sand and white, dark-gray/pale-red-purple clay • Lower part: dark-gray laminated to thin-bedded silty clay and micaceous, carbonaceous, fossiliferous fine sand

	Eutaw Formation	Cretaceous	- Sand - Clay or mud	- Grayish-green sand - Glauconitic, micaceous - Interbedded with gray laminated clays
Tuscaloosa Group	Gordo Formation	Cretaceous	- Sand - Clay or mud	- Tuscaloosa Group - Beds of cross-bedded sand, gravely sand, and lenticulars - Lower part gravelly sand
	Tuscaloosa Group	Cretaceous	- Sand - Clay or mud	- Tuscaloosa Group - Light-gray to moderate-reddish-orange clayey, gravelly fine to very coarse sand - Mottled sandy clay - Local wood and leaf beds - Thin beds of indurated sandstone
	Coker Formation	Cretaceous	- Sand - Clay or mud	- Light-colored micaceous fine to medium sand, cross-bedded sand, varicolored micaceous clay, and gravel beds
Wilcox Group	Nanafalia Formation	Paleocene	- Clay or mud - Claystone	- Wilcox group - Gramphian Hills Member: medium-gray clay, claystone, sandy fossiliferous clay and fine sand - Gravel Creek Sand Member: Pale-yellowish-orange to reddish-brown micaceous cross-bedded fine to very coarse sand
	Tuscahoma Sand	Paleocene	- Silty - Clay or mud	- Wilcox Group - Light-gray to light-olive gray laminate and thin-bedded carbonaceous silt and clay interbedded with fine sand - Thin lignite beds - Lower part: beds of fossiliferous, glauconitic fine quartz sand, gravel and clay pebbles

	Hatchetigbee Formation	Eocene	- Clay or mud - Silt	- Wilcox Group - Light to dark-gray laminated carbonaceous clay, silt and fine sand, and cross-bedded glauconitic sand - Upper part: thin beds of fossiliferous marly glauconitic sand and sandstone - Base: bed of glauconitic calcareous sand with fossils sandstone concretions
Precambrian to Paleozoic Schist and Gneiss	Auburn Gneiss	Precambrian to Paleozoic	- Felsic gneiss - Mica schist - Pegmatite	- Biotite-oligoclase gneiss intermixed with muscovite-biotite schist
	Hackneyville Schist	Precambrian to Paleozoic	- Schist - Quartzite	- Medium to coarse-grained quartz-plagioclase, almandine, kyanite, biotite-muscovite schist, graphite-muscovite-quartz schist and quartzite containing biotite
	Higgins Ferry Group	Precambrian to Paleozoic	- Felsic gneiss - Mica Schist	- Layered biotite-feldspar-quartz gneiss, sericite-feldspar-muscovite schist, biotite, garnet-muscovite schist, and biotite-garnet feldspathic gneiss
	Hillabee Greenstone	Paleozoic	- Greenstone - Phyllite	- Pale-green to light olive brown greenstone interbedded with mafic phyllite
	Mad Indian Group	Precambrian to Paleozoic	- Felsic gneiss - Schist	- Feldspathic biotite gneiss - Muscovite-biotite-garnet schist - Kyanite and sillimantite
	Ketchepedrakee Amphibolite	Precambrian to Paleozoic	- Amphibolite - Schist	- Layered to massive amphibolite mixed with zone of chlorite actinolite schist
	Poe Bridge Mountain Group	Precambrian to Paleozoic	- Mica Schist - Gneiss	- Course to fine-grained feldspatic graphite schist, stauroltie, kayanite, sillimanite-muscovite, biotite schist, garnet-biotite-muscovite schist, and gneiss

	Wedowee Group	Precambrian to Paleozoic	• Schist • Phyllite	• Cragford Phyllite • Cutnose gneiss
	Mitchell Dam Amphibolite	Precambrian to Paleozoic	• Amphibolite	• Dark-green to black thin-layere to massive hornblende-actinolite amphibolite
	Tallassee Metaquartzite	Precambrian to Paleozoic	• Quartzite • Meta-conglomerate	• Medium to fine-grained quartzite and metaconglomerate and thin beds of graphitic quartz schists
	Elkahatchee Quartz Diorite Gneiss	Precambrian to Paleozoic	• Orthogneiss	• Mesocratic to melanocratic, shared quartz diorite gneiss
	Waverly Gneiss	Precambrian to Paleozoic	• Mafic Gneiss • Amphilbolite	• Feldspatic biotite-hornblende gneiss with layers of amphibolite, calc-silicate rock, garnet quartzite, muscovite schist
Talladega Group	Jemison Chert and Chulafinnee Schist	Silurian – Devonian	• Schist • Phyllite	• Matachert and light to dark greenish gray fine to medium grained fissile quartz –sericite-chlorite phyllite and schist
	Lay Dam Formation	Silurian – Devonian	• Phyllite • Metasedimentary	• Interbedded dark-green phyllite, medium-gray to light-brown and black metasilstone, dark-green feldspathic metagraywackes, and light-gray and dark-gray arkosic quartzite and metaconglomerate
Red Mountain	Red Mountain Formation	Silurian	• Sandstone • Shale	• Interbedded yellowish-gray to moderate-red sandstone, siltstone and shale • Greenish-gray to moderate-red fossiliferous partly silty and sandy limestone