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Research Report

EVALUATION OF LANDSLIDES ALONG ALABAMA HIGHWAYS

Submitted to

The Alabama Department of Transportation

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16. Abstract

Slope stability management systems (SSMSs) have been developed by multiple state transportation agencies to assess landslides adjacent to highways and aide in the effective allocation of resources for slope and/or roadway repairs. 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 to motorists. This report reviews the landslide database component of SSMSs employed by other state transportation agencies. The descriptions of each SMSS detail the analysis purpose, database framework, and recorded data, which were all used in the design of the database and data collection system for the proposed SSMS for the Alabama Department of Transportation (ALDOT). The data collection system and landslide inventory of the proposed system are described, including the database structure, data sources and collected attributes. Preliminary observations from the database are discussed.

The information from the landslide database is used to identify possible remediation measures that would be effective for stabilizing slopes along Alabama highways. This is accomplished by selecting multiple case histories from the landslide database which can then be analyzed to identify possible remediation techniques that can address the failure mechanism at that site. Some case histories where shallow slope failures have been caused by rutting from mowing activities along slopes are also included. A simple prioritizing scheme is suggested to allow the different remediation techniques to be compared and the optimal technique to be selected. Recommendations are provided regarding the most promising remediation techniques and areas where changes could be made to design or operations to improve slope stability along highways. Topics related to this study that could benefit from future research are also identified.

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ABSTRACT

Slope stability management systems (SSMSs) have been developed by multiple state transportation agencies to assess landslides adjacent to highways and aide in the effective allocation of resources for slope and/or roadway repairs. 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 to motorists. This report reviews the landslide database component of SSMSs employed by other state transportation agencies. The descriptions of each SMSS detail the analysis purpose, database framework, and recorded data, which were all used in the design of the database and data collection system for the proposed SSMS for the Alabama Department of Transportation (ALDOT). The data collection system and landslide inventory of the proposed system are described, including the database structure, data sources and collected attributes. Preliminary observations from the database are discussed.

The information from the landslide database is used to identify possible remediation measures that would be effective for stabilizing slopes along Alabama highways. This is accomplished by selecting multiple case histories from the landslide database which can then be analyzed to identify possible remediation techniques that can address the failure mechanism at that site. Some case histories where shallow slope failures have been caused by rutting from mowing activities along slopes are also included. A simple prioritizing scheme is suggested to allow the different remediation techniques to be compared and the optimal technique to be selected. Recommendations are provided regarding the most promising remediation techniques and areas where changes could be made to design or operations to improve slope stability along highways. Topics related to this study that could benefit from future research are also identified.

TABLE OF CONTENTS

List of Tables vi

List of Figures vii

Chapter 1: Introduction 1

1.1 Background 1

1.2 Project Objectives 4

1.3 Research Approach 4

1.4 Report Organization 4

Chapter 2: Literature Review 6

2.1 Introduction 6

2.2 Slope Stability Problems along Highways 6

2.3 Categories of Landslides 6

2.4 Slope Stability Management Systems 10

2.5 Data Collection Systems 11

2.6 Landslide Hazard Prioritization Systems 15

2.7 Remediation of Slope Failures along Highways 15

Chapter 3: Development of the Landslide Database 26

3.1 Introduction 26

3.2 Database Development 26

3.3 Data Sources 28

3.4 Landslide Reports 31

3.5 Emergency Relief Slides 31

3.6 Database Limitations 33

3.7 Surface Erosion from Mowing Activities 33

Chapter 4: Analysis of the Landslide Database 36

4.1 Introduction 36

4.2 Geology at Landslide Sites 37

4.3 Effects of Rainfall on Failure Patterns 41

4.4 Failure Location along the Roadway 44

4.5 Past landslides 44

4.6 Adjacent Structures 45

4.7 Landslide Categories 46

4.8 Summary 48

Chapter 5: Methods to address landslides 49

5.1 Introduction 49

5.2 Landslide Case Histories 49

5.3 Prioritizing Remediation Options 53

5.4 Options for Mowing-related Failures 54

5.5 Recommendations for New Slopes 55

Chapter 6: Conclusions and Recommendations 57

6.1 Summary 57

6.2 Conclusions 58

6.3 Recommendations for Implementation 60

6.4 Future Studies 61

References 63

Appendix A: Example Reporting Form for Landslides 69

List of Tables

Table 2-1. Comparison of landslide attributes collected in various SSMSs (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon 2007)..................... 14

Table 3-1. Comparison of landslide attributes collected in various SSMSs (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon 2007)..................... 28

Table 3-2. Data Collection for ALDOT Landslide Database. 30

Table 3-3. Locations of mowing-related rutting and surface erosion on slopes (Hodnett, J. personal communication, February 2019)... 35

Table 4-1. Number of landslides in each database sorted by geologic group. The list is ordered by the total number of landslides in a group... 40

Table 4-2. Number of emergency relief slides occurring per 160 km (100 miles) of highway within each rainfall range (rainfall totals from NWS 2017) 43

Table 4-3. Number of Front Slope and Back Slope failures along Alabama Highways 44

Table 5-1. Summary table for the selected landslide case histories 50

Table 5-2. Remediation options (alphabetical order) for the case histories listed in Table 5-1. .. 51

List of Figures

Figure 1-1. Different types of landslide movements observed along Alabama highways including: (a) an earth rotational landslide (b) an earth translational landslide, (c) a surface erosion (creep) failure (d) a rock fall. 1

Figure 2-1. Diagram of a rotational landslide (USGS 2004). 7

Figure 2-2. Diagram of a translational landslide (USGS 2004) 8

Figure 2-3. Diagram of a rock fall (USGS 2004). 8

Figure 2-4. Diagram of a rock topple (USGS 2004). 9

Figure 2-5. Shallow slope failures caused by rutting from mowing activities along Highway 69 near mile post 137.7 (photo provided by Jacob Hodnett, ALDOT). 10

Figure 2-6. Diagram of a flow landslide (USGS 2004). 10

Figure 2-7. Example of benching for a back slope (Caltrans 2018). 17

Figure 2-8. Application of lightweight fill for a roadway embankment (Aabøe et al. 2019). 18

Figure 2-9. Typical rock buttress used to control unstable slopes (Schuster and Krizek 1978). 18

Figure 2-10. A counterberm providing weight at toe of embankment. (Abramson et al. 2002). 19

Figure 2-11. Cross-section of a berm showing a shear key (Schuster and Krizek 1978). 19

Figure 2-12. Stabilization of shallow slope failures using recycled plastic pins (Loehr et al. 2000). 21

Figure 2-13. Main application of soil nailing (Abramson et al. 2002). 22

Figure 2-14. Example of slope stabilization using micropiles (FHWA 2005). 23

Figure 2-15. Stabilization of slope with MSE. (Tarawneh et al. 2017). 24

Figure 2-16. Forces on slope with vegetation (Abramson et al. 2002). 25

Figure 3-2**.** Data model for the ALDOT landslide database**.** Each box shows a tab within the model which group together similar attributes of both the roadway and the slide. 29

Figure 3-3. Landslides along state and county highways**.** Multiple slides may be located at the same latitude and longitude coordinates and are shown using a single marker................ 32

Figure 3-4. Definition of front slope and back slope along a typical highway cross-section....... 32

Figure 3-5. Rutting along the face of a slope due to mowing activities (photo provided by Jacob Hodnett, ALDOT).. 34

Figure 3-6. Shallow slope failures caused by rutting from mowing activities along Highway 69 near mile post 137.7 (photo provided by Jacob Hodnett, ALDOT). 35

Figure 4-1. Landslide locations within each physiographic section of Alabama (physiographic regions from data provided by the University of Alabama, Department of Geography). 38

Figure 4-2. Landslide locations compared with the geologic units of Alabama (geologic map simplified from Tew 2006). 39

Figure 4-3. Distribution of emergency relief slides by event. The number in parenthesis indicates the number of landslides attributed to that event. 42

Figure 4-4. Number and Type of Structures Located Adjacent to Landslide Report Slides. 46

Figure 4-5. Landslide categories for the landslide reports within the database. 47

Figure 4-6. Landslide categories for the emergency relief slides within the database. 47

CHAPTER 1: INTRODUCTION

1.1 Background

Landslides along roadways (e.g., Figure 1-1) 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.

Figure 1-1. Different types of landslide movements observed along Alabama highways including: (a) an earth rotational landslide (b) an earth translational landslide, (c) a surface erosion (creep) failure (d) a rock fall.

Several landslide databases have been developed throughout the world to collect and provide data on landslide hazards and conduct risk assessments, which aid remediation and mitigation efforts, and land planning. Rosser et al. (2017) estimated 46 countries have instituted landslide databases. In particular, the United States has 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 and Van Vickle 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 and Van Vickle 1993).

Other examples of national databases include the United Kingdom (Foster et al. 2012), Switzerland (Hilker et al. 2009), Italy (Trigila et al. 2010), Poland (Mrozek et al. 2013), New Zealand (Rosser et al. 2017), Australia (Mazengarb et al. 2010) Hong Kong (Dai and Lee 2002), and Ireland (GSI 2019). The purpose of these databases is to gather information about landslides to assess natural hazard areas and develop mitigation measures for high risk areas. These databases collect attributes of the landslide, including site location, type of failure, failure cause, material type and geometry of the landslide. This information can then be used for regional level assessments of landslide hazard. These national level databases are not specifically focused on highways and therefore do not commonly collect information on the impacts of the landslide to adjacent roadways. This has led many transportation agencies to develop their own focused databases.

The United States Federal Highway Administration (FHWA) recommended 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 18 state transportation agencies within the U.S. have developed state specific slope stability management systems (SSMSs) for 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, Hoppe and Whitehouse 2006, Maerz et al. 2004, NYSDOT 2007, ORDOT 2001, Pack et al. 2002, Pack et al. 2007, Pensomboon 2007, Pierson et al. 2005, Pratt 2014, Rose 2005). SSMSs improve the documentation, study, and remediation process for landslides and rockfalls, specifically along highways, by tracking unstable slopes and repairs to form comprehensive statewide landslide inventories.

The purpose of state specific SSMSs is to aid in the identification of common slope failure mechanisms in the region, identification of high landslide risk areas, and implementation of remediation or mitigation methods based on a landslide hazard rating system. This is 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 report documents the preliminary development of a SSMS for ALDOT. The data collection system and database were created to aid in the identification, tracking, and analysis of the effects of slope failures on highways, while accounting for the available data within ALDOT landslide reports. The components were developed based on the implemented SSMSs of Alaska (Calvin et al. 2009), Maryland (Aydilek et al. 2013), Ohio (Pensomboon 2007), Oregon (ORDOT 2001, Pierson et al. 2005, Burns et al. 2014), and Washington State (Badger et al. 2013). These systems were chosen as models due to the inclusion of a slope failure inventory focused on failures in earth materials (defined as fine-grained engineering soils dominated by clay to sand-size fractions after Varnes 1978), rather than or in addition to a rockfall and/or debris slide database.

This report reviews the landslide database component of SSMSs employed by other state transportation agencies, focusing on landslides occurring within soil slopes. In this report, the term soil is used to refer to engineering soil (unconsolidated or poorly cemented agglomerate of minerals, organic materials and sediments) and rock is used to refer to bedrock (hard or firm rock that was intact before movement) following the definitions by Varnes (1978). The descriptions of previous studies detail the analysis purpose, database framework, and recorded data, which were all used in the design of the database and data collection system for the proposed SSMS. The data collection system and landslide inventory of the proposed system are described, including the database structure, data sources and collected attributes. Preliminary observations from the database are discussed. Further analysis of this database will aid in identifying correlations between individual landslides and determining common landslide failure mechanisms along Alabama highways.

The information from the landslide database is used to identify possible remediation measures that would be effective for stabilizing slopes along Alabama highways. This is accomplished by selecting multiple case histories from the landslide database which can then be analyzed to identify possible remediation techniques that can address the failure mechanism at that site. A simple prioritizing scheme is suggested to allow the different remediation techniques to be compared and the optimal technique to be selected. Recommendations are provided regarding the most promising remediation techniques and areas where changes could be made to design or operations to improve slope stability along highways. Topics related to this study that could benefit from future research are also identified.

1.2 Project Objectives

The primary goal of this project is to provide ALDOT engineers and geologists with information on common causes of landslides along Alabama highways, which can then be used to design effective and efficient remediation measures. Specific objectives include:

1. Develop a database of recent landslides along Alabama highways including information on the location, geometry and timing of the failure along with the site stratigraphy and selected repair method.
2. Identify correlations between similar landslides in the database through examination of likely failure mechanisms and geologic conditions at the site.
3. Select possible remediation or intervention strategies that may be effective and cost-efficient for specific types of landslides or landslide-prone soils.

1.3 Research Approach

The following tasks were performed to accomplish the research objectives of this project:

- Task 1 involved the development of a database of recent landslides from across the state with a focus on landslides occurring in soil.
- Task 2 consisted of identifying common failure mechanisms within the landslide database.
- Task 3 selected case histories that were representative of larger trends within the landslide database for further analysis.
- Task 4 identified remediation alternatives that could be applied to the selected case histories.

1.4 Report Organization

Chapter 2 contains a literature review with information about causes and categories of landslides, slope stability management systems used by other state DOTs, and remediation techniques for unstable slopes. Chapter 3 summarizes the development of the landslide database, which was the primary focus of this research. Chapter 3 also discusses some case histories where shallow slope failures have been caused by rutting from mowing activities along slopes. Chapter 4 identifies several important trends among the landslides contained in the database, which are then used to select representative case histories in Chapter 5. Chapter 5 summarizes the selected case histories and possible remediation alternatives for each. Chapter 6 contains the project summary, conclusions, and recommendations for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Landslides along highways are a significant problem for transportation officials. This chapter reviews important literature concerning landslides along highways. The causes of landslides are briefly discussed in Section 2.2. Section 2.3 summarizes different categories of landslides identified in this study. Sections 2.4 and 2.5 review slope stability management systems and corresponding data collection systems used for previously developed landslide databases. Section 2.6 discusses landslide hazard prioritization systems employed by other state DOTs and Section 2.7 provides background information on remediation options for landslides.

2.2 Slope Stability Problems along Highways

A landslide, defined as "the movement of a mass of rock, debris or earth down a slope" (Cruden and Varnes 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.

2.3 Categories of Landslides

Various classification systems have been developed to describe landslide movements. These systems are useful as they allow landslides to be grouped together for analysis and the patterns of movement can help distinguish between different failure mechanisms. Understanding the patterns of movement can also help to identify remediation measures that are likely to be able to effectively stabilize the landslide. The landslide classification system used in this report follows Varnes (1978). Six main categories of landslides are used for this study: rotational slides, translational slides, falls, topples, surface erosion (creep), and flows. These categories were selected as they are considered most applicable to landslides along Alabama highways. Each of these categories is described briefly below based on the classifications provided by Varnes (1978).

2.3.1 Rotational Slide

A rotational slide is defined as a failure that occurs on a well-defined, curved failure surface (Figure 2-1). Blocks of failed material can rotate and can at times be seen to tilt backwards towards the slopes. Deep rotational slides are commonly associated with failures in relatively thick fine-grained materials, while shallow rotational slides can be observed in materials which are subject to softening due to moisture fluctuations over time.

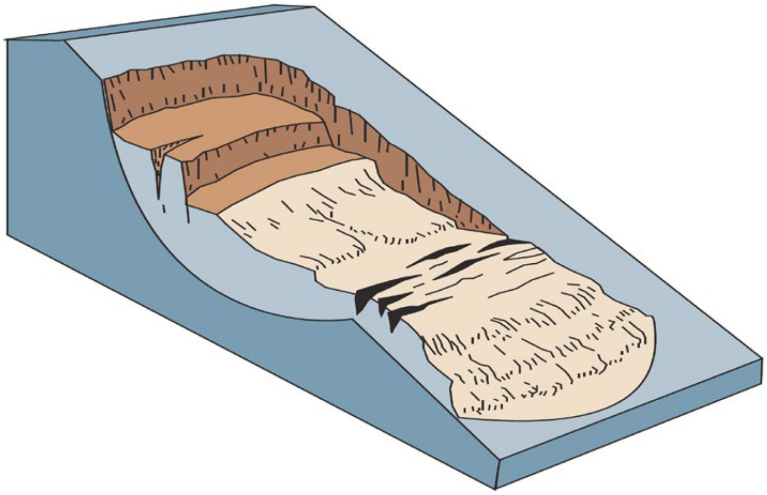


Figure 2-1. Diagram of a rotational landslide (USGS 2004).

2.3.2 Translational Slide

The failure mass in a translational landslide moves out, or down and outward, along a relatively flat surface with little rotation or backward tilting (Figure 2-2). These failures commonly occur when a plane of weak material exists within the slope. This could be due to softening of the soil along an interface (e.g., softened clay at a sand interface), sliding along a bedding plane (e.g., failures occurring in shale), or reactivation of a previous shear plane.

2.3.3 Fall

During a fall failure, pieces of rock or earth, or both, quickly detach from steep slopes or cliffs and collect near the base of the slope (Figure 2-3). These generally occur at cliffs or very steep slopes and are often caused by mechanical weathering or the intact material. The current study focused on failures in soil and so few falls were observed in the current database.

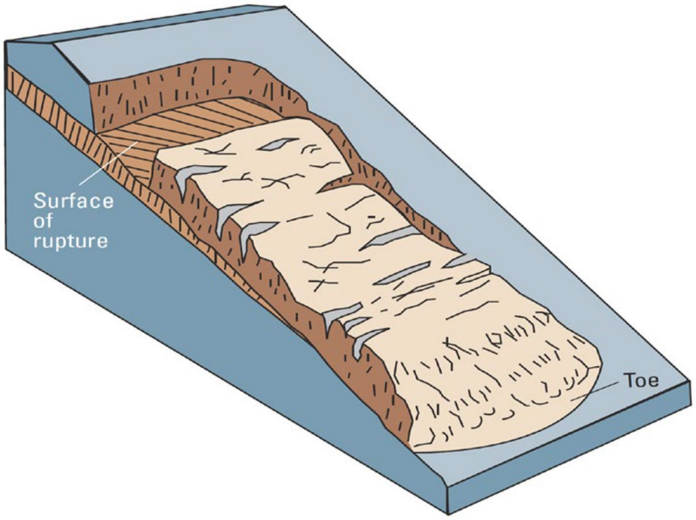


Figure 2-2. Diagram of a translational landslide (USGS 2004).

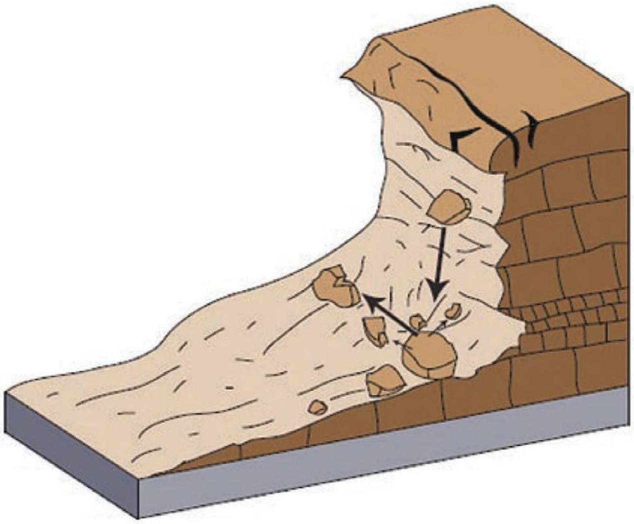


Figure 2-3. Diagram of a rock fall (USGS 2004).

2.3.4 Topple

A topple failure occurs when a mass of soil or rock rotates out from the intact material (tilting) around an axis (or point) near the base of the block (Figure 2-4). Topples are often caused by forces applied from adjacent units or water collecting in cracks in the material. Topples most commonly occur at vertical faces and often results in the formation of debris or a debris cone at the base of the slope; this pile is called a talus cone. No topples were recorded in the current database.

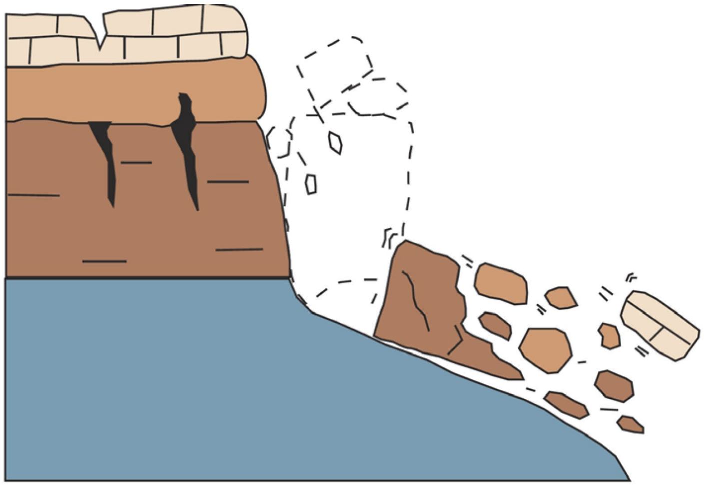


Figure 2-4. Diagram of a rock topple (USGS 2004).

2.3.5 Surface Erosion

Surface erosion failures are not specifically included in Varnes (1978) classification system, but would most likely fit within the creep category. Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. These landslides can have various causes, but the most common observed along Alabama highways is erosion of the surface material. This type of failure occurs when the upper few inches to foot of soil is eroded by moving water leaving an area of bare soil behind (Figure 2-5). This failure may be initiated by rutting on the slope caused by vehicle traffic such as mowing. This type of failure is discussed further in Section 3.7.

2.3.6 Flow

Flows are landslides that involve the movement of material down a slope in the form of a fluid. The failed mass does not usually have a well-defined structure, which helps distinguish it from a translational or rotational slide. Flows generally occur in saturated conditions and may be triggered by heavy rain. No instances of flow landslides were observed in the current database.

Figure 2-5. Shallow slope failures caused by rutting from mowing activities along Highway 69 near mile post 137.7 (photo provided by Jacob Hodnett, ALDOT).

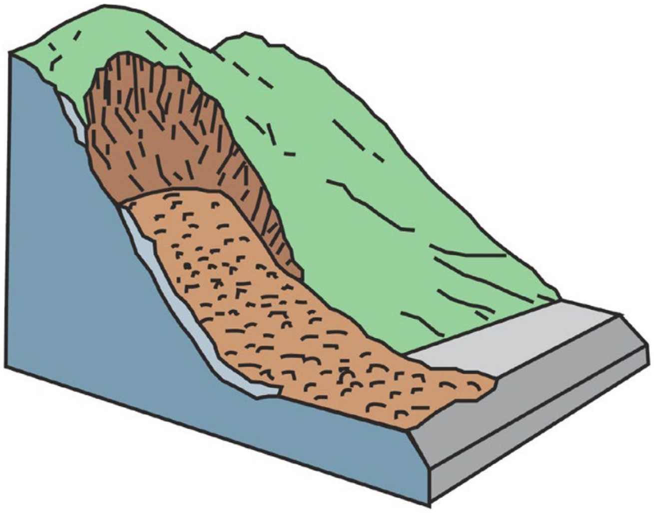


Figure 2-6. Diagram of a flow landslide (USGS 2004).

2.4 Slope Stability Management Systems

Specialized SSMSs evaluate landslide hazards through the collection of physical and material attributes of the landslide, along with historical data. This information is used to create ranking systems, or risk management systems, that 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 that can determine mitigation regions based on the probability of future failures (Pack et al. 2007). The Washington State Department of Transportation (WSDOT) developed and implemented the Unstable Slope Management System (USMS) for both rockfall and soil slides (Badger et al. 2013). 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.

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, Hoppe and Whitehouse 2006, Maerz et al. 2004, NYSDOT 2007, OHDOT 2001, Pack et al. 2002, Pack et al. 2007, Pensomboon 2007, Pierson et al. 2005, Pratt 2014, Rose 2005). 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 includes maintaining the functionality of slopes over the life-cycle of the adjacent roadways, while reducing costs and traffic disruptions (Thompson et al. 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. 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 et al. 2016).

2.5 Data Collection Systems

SSMSs collect and retrieve information on hazardous and/or failed slopes to aid in the analysis of landslide locations. The following section summarizes the data collection component of the SSMSs implemented by five state transportation departments— Alaska (AKDOT, Calvin et al. 2009), Maryland (MDOT, Aydilek et al. 2013), Ohio (OHDOT, Pensomboon 2007), Oregon (ORDOT, Burns et al. 2014), and Washington State (WSDOT, Badger et al. 2013). The systems were chosen because they all include a database of slides in earth materials 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 generally use standardized forms completed in the field and/or computer databases with Graphical User Interfaces (GUIs) to collect data. The standardized forms are meant to be completed by the maintenance crew and/or engineers who investigate the landslide and collect detailed information on site observations and field investigations. These personnel may or may not have training in landslide identification or geology, which can lead to varying quality of data. The information is then input into a database program (e.g., Microsoft Access or 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 choice 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. Many of the databases are integrated with GIS software to allow access to multiple users and provide a platform for spatial analysis.

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 varied between the SSMSs reviewed (

Table 2-1). For example, ORDOT and WSDOT focus largely on the roadway and motorist impacts of a landslide. AKDOT developed a slope stability asset management system to prioritize remediations based on cost-benefit analyses conducted at each 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 are collected on the past maintenance and repair costs as well as the effect of the failure on traffic and vehicle safety. In addition to a database, MDOT developed a landslide prediction model and so data collection focuses on physical features that may be used to predict vulnerable regions along state highways, including weather events, slope geometry, and failure causes.

Table 2-1. Comparison of landslide attributes collected in various SSMSs (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon 2007)

Attributes	AKDOT	MDOT	OHDOT	ORDOT	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/Horizonal Displacement	X				
Weather Preceding/at Failure		X	X		

Most systems collect data on the location of the site, previous landslides and/or repairs at or adjacent to the failure site, impact to the 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. This variation is largely due to the objective of each individual system.

2.6 Landslide Hazard Prioritization 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 2014, Hopkins et al. 2003, Maerz et al. 2004, Pierson et al. 2005, NYSDOT 2007, Pensomboon 2007, ORDOT 2001, Burns et al. 2017, Rose 2005, Pack et al. 2002, Eliassen et al. 2007, Eliassen et al. 2015, Hoppe and 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 assign a level of priority for landslide mitigation or remediation. Many 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). 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. The creation of a landslide hazard prioritization systems for ALDOT is beyond the scope of the current study.

2.7 Remediation of Slope Failures along Highways

Various slope repair methods are used to stabilize landslides. While designing a suitable remediation, engineers need to consider several factors, such as technical constraints, site constraints, environmental constraints, and budget availability. However, changes in these factors may lead to the loss of stability and subsequent slope failures. Therefore, the causes of a slope failure should be identified prior to any design of a stabilization (Abramson et al. 2002). The slope stabilization is generally a design process of increasing resistance to movement and decreasing the driving forces on the slope. Excavating unstable materials and draining ponded water from the potential failure area are two common methods to stabilize the slope by reducing driving forces. Five stabilization methods are commonly used to increase the resisting forces, including subsurface drainage, reinforcement, excavation of weak soils, construction of retaining structures or supports, and ground improvement. The following sections provide a brief description of some stabilization methods that can be used for improving slope stability. Additional discussion on approaches to slope stabilization are provided by Abramson et al. (2002) and Duncan et al. (2014).

2.7.1 Unloading:

Unloading is used to stabilize slopes by reducing the driving forces of the potential failure zone. This can include both excavation of surcharge material and excavation and replacement with lightweight fill (Hossain et al. 2017). The most common method of unloading for stabilization of existing slopes is excavation, while lightweight fill materials are usually used for embankment construction to reduce the driving forces on the foundation layers.

(1) Excavation

Excavation is a common method to improve slope stability by reduction of driving forces (Hossain et al. 2017). Removal of the upper portion of the slope, unstable materials, flattening the slope and benching are considered effective approaches to excavation. The disadvantage of excavation is the costs associated with ensuring the safety of workers and equipment during the excavation process, deposal of excavated materials and right-of-way costs. However, compared with other stabilization methods, the cost of excavation is relatively low. Removal of the head of slope failure is often used for existing failures, leading to reduction of driving forces and improving the stability of the slope (Abramson et al. 2002). Drainage should be considered as well when designing an excavation in order to increase the effective stress and the soil strength.

Flattening failed slopes is a very common repair technique and is often considered at the beginning of a remediation study. Driving forces will be reduced by flattening the slope and the critical failure surface would be pushed deeper into the slope, where firmer soil may be encountered. Benching slopes is an alternative to flattening an entire slope and works by separating a single tall slope into several shorter ones. A typical benching pattern is shown in Figure 2-7. Benching leads to higher initial construction costs due to larger excavation quantities, but will result in lower maintenance costs (Abramson et al. 2002). Surface erosion can also be controlled using this method.

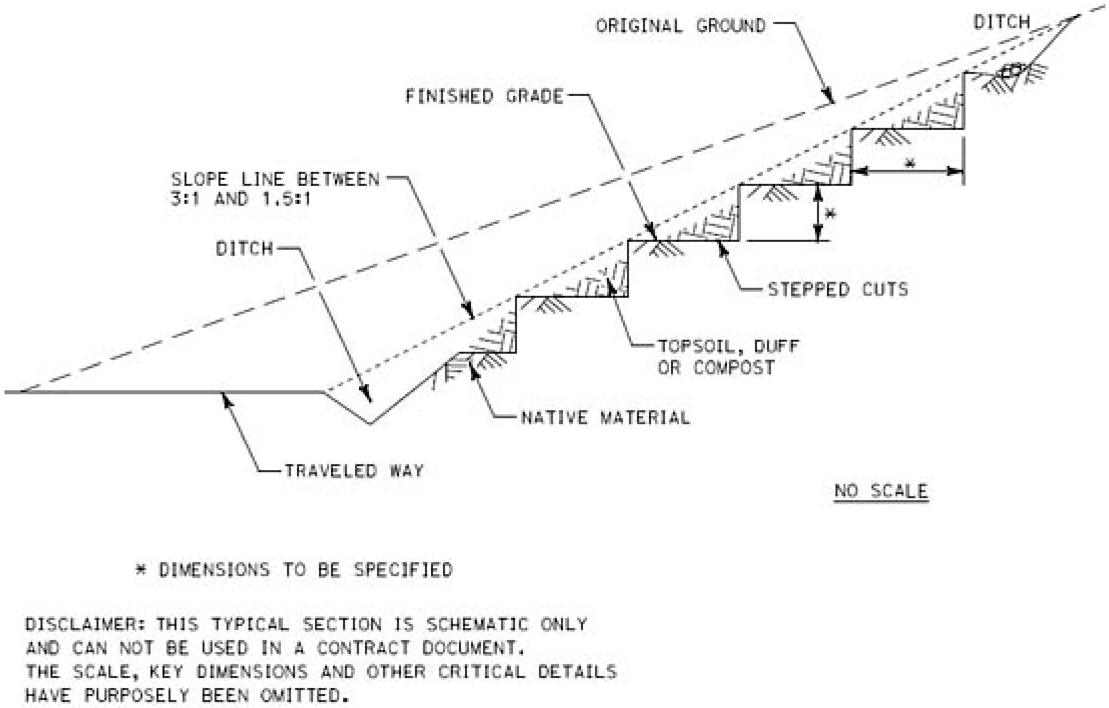


Figure 2-7. Example of benching for a back slope (Caltrans 2018).

(2) Lightweight Fill

The stability of a slope can be increased by using lightweight fill to reduce driving forces on the failure surface (Hossain et al. 2017). Current options for lightweight fill includes slag, encapsulated sawdust, expanded shale, cinders, shredded rubber tires, polystyrene foam and others. The material selection is often determine by cost and availability in the area of the failure. Drains can be installed together in order to prevent possible floating of lightweight fill by buoyant forces from high groundwater levels. Figure 2-8 shows application of lightweight fill.

2.7.2 Buttressing:

Buttressing is used to offset or counter the driving forces on a slope by applying external forces (Duncan et al. 2014) which results in the increase of resisting forces. There are many different options for buttress material. These include soil and rock fill, counterberms, shear keys, mechanically stabilized embankments (MSE) and pneusol (tiresoil). Some of these are described in further detail below.

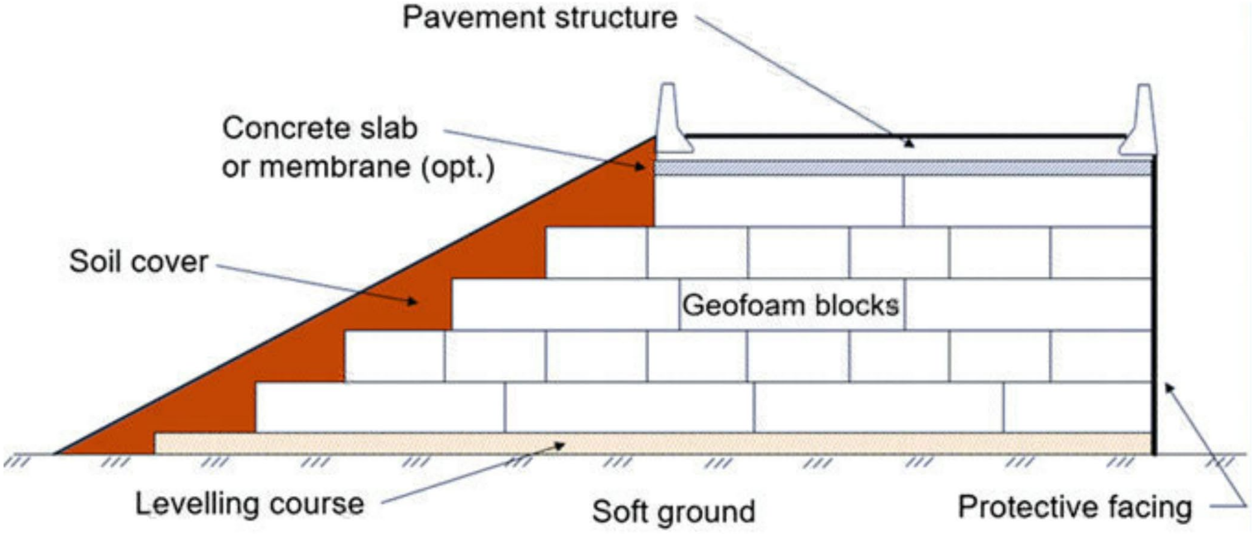


Figure 2-8. Application of lightweight fill for a roadway embankment (Aabøe et al. 2019).

(1) Soil and rock fill

Sufficient dead load weight can be provided at the toe of unstable slope by placing soil and rock fill to prevent soil movement (Figure 2-9). The material for the buttress can often be obtained locally and the construction process is fairly straightforward making rock or soil buttresses popular options for slope repair. Rock buttresses can also be covered with topsoil and vegetation to improve the aesthetics for the traveling public (Caltrans 2018).

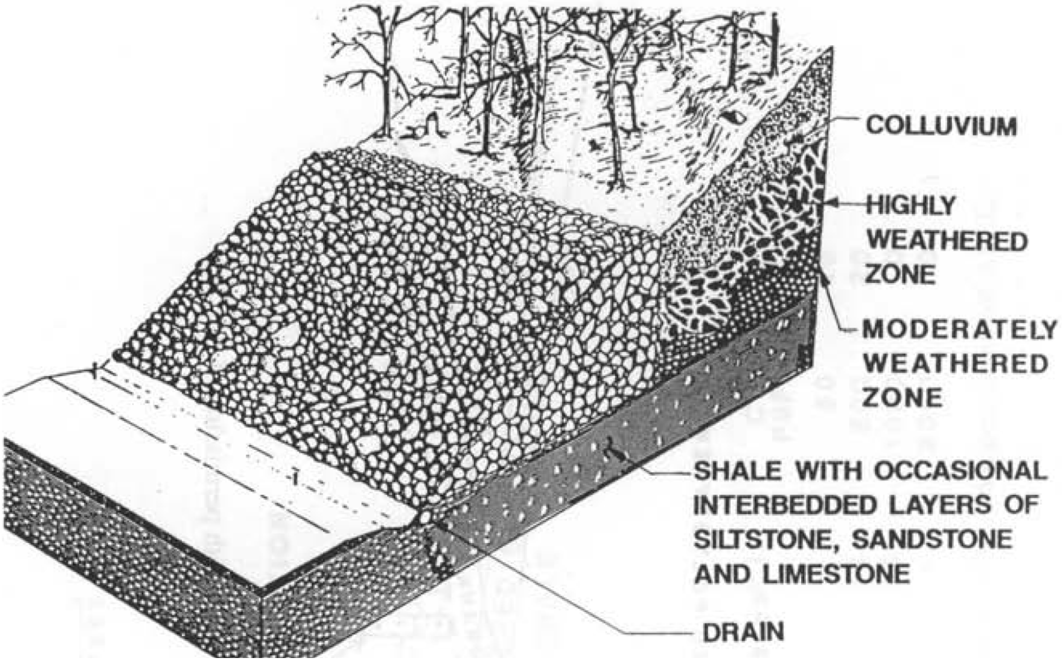


Figure 2-9. Typical rock buttress used to control unstable slopes (Schuster and Krizek 1978).

(2) Counterberms

Higher shear strength can be achieved below the toe of an unstable slope by using counterberms to apply additional weight at the slope toe (Abramson et al. 2002). This technique is especially useful to stabilize embankments on soft soils. The presence of the counterberm will drive the failure surface deeper increasing both the length of the failure surface and providing a resisting moment against movement. Figure 2-10 shows the counterberm that providing weight at toe of embankment.

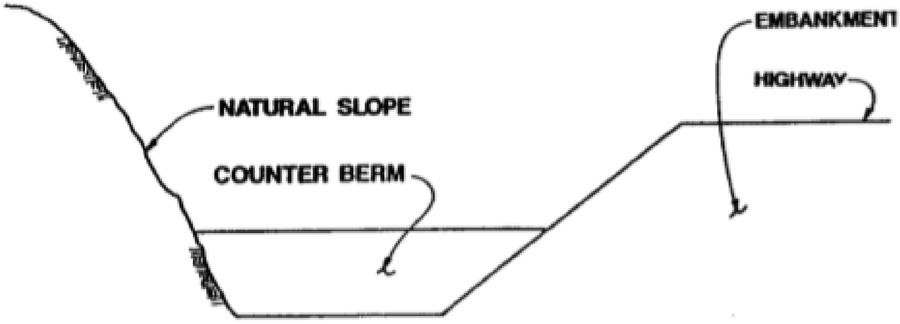


Figure 2-10. A counterberm providing weight at toe of embankment. (Abramson et al. 2002).

(3) Shear keys

A shear key can be added to a counterberm or rock or soil buttress to increase the stability. The shear key ties the berm into a deeper stable layer and therefore forces the critical failure surface into the deeper stronger layer. This method is recommended for the slope where a relatively thin layer of soft soil exists over a stronger layer. The method can be used to inexpensively add additional resistance to a design. Figure 2-11 shows a berm with an added shear key.

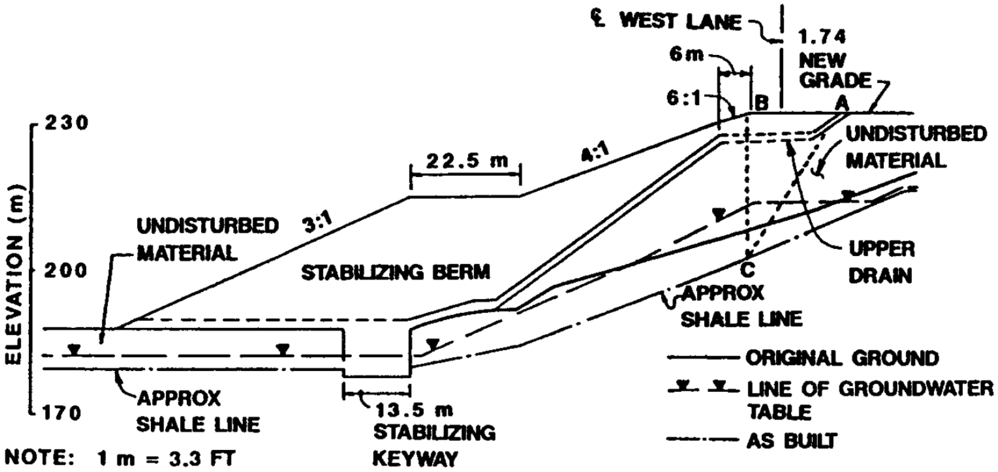


Figure 2-11. Cross-section of a berm showing a shear key (Schuster and Krizek 1978).

2.7.3 Drainage

Drainage is one of the most important techniques used for stabilizing slope failure or potential slip zone (Duncan et al. 2014). Surface drainage can prevent slope erosion and ponding of water that can lead to destabilizing hydrostatic forces. Subsurface drainage can be used to reduce pore pressures within the slope, increasing the effective stress and therefore the soil strength. A disadvantage of relying only on drainage for stabilization is that the effectiveness of the drains may decrease over time due to clogging or damage. Ensuring that drainage features are working can be a significant maintenance burden. Despite this drainage is an essential part of many remediation designs.

(1) Surface drainage

Proper surface drainage is critical to ensuring stability of slopes. Surface runoff should be carried away from the slope in order to reduce the flow across the face of the slope and prevent ponding at the top of the slope. Water should also be moved away from the toe of the slope to avoid saturating this area which can lead to failures. Permanent surface drainage systems often include swales or concrete channels combined with typical storm drain systems. Temporary remedial measures can include sandbags to divert water runoff away from the failure zone, sealing cracks with a surface coating by shotcrete, lean concrete or bitumen, and covering the ground surface temporarily with plastic sheets to reduce infiltration and the risk of movement during construction activities.

(2) Subsurface drainage

Subsurface drainage should be considered to stabilize the slope when the failure surface passing below the ground water table. Many types of subsurface drainage options are available including drain blankets, trenches, cut-off drains, horizontal drains, relief wells, and drainage tunnels. While subsurface drains do increase maintenance requirements, not considering these methods can lead to less cost-efficient remediation designs.

2.7.4 Reinforcement

Reinforcement is used to increase slope stability by increasing the resisting forces. The most common techniques for adding reinforcement include soil nailing, plastic or metal pins, drilled shafts, micropiles, anchors, stone columns, and reinforced soil slopes using geosynthetics (Abramson et al. 2002). Some of these techniques are discussed in more detail below.

(1) Recycled plastic pins

Recycled plastic pins (RPPs) are a type of pin manufactured from post-consumer waste plastic and can be used to stabilize slopes with shallow (< 10 feet deep) failures (Figure 2-12). The pins themselves are low cost and are resistant to moisture, corrosion, rot and insects (Hossain et al. 2017). The spacing, length and strength of the RPPs must be specified to ensure adequate reinforcement is being provided. The properties of RPPs varies since they are made from recycled plastics, it is highly recommended that commercially produced RPPs are selected as structural elements and reinforced with glass/wooden fibers (Hossain et al. 2017). The spacing of the pins usually varies from 2 to 5 feet depending on the location within the slope.

One significant benefit of using RPPs is that the installation can be accomplished using DOT personnel and equipment rather than specialty contractors (Loehr et al. 2000). This installation is often accomplished using hydraulic hammers mounted to excavators or percussion hammers mounted to drill rigs.

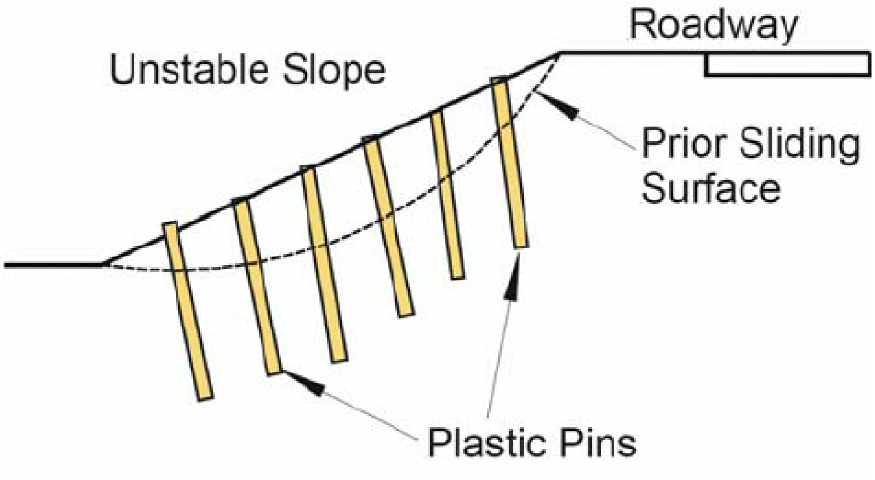


Figure 2-12. Stabilization of shallow slope failures using recycled plastic pins (Loehr et al. 2000).

(2) Soil nailing

Soil nailing is performed by placing long slender bars through an unstable soil mass into the stable material behind or underneath it (Figure 2-13). The bars act as a passive reinforcing member and provide resistance as the soil attempts to move. Soil nailing is a very common slope stabilization technique and has been used successfully as both permanent and temporary stabilization at multiple sites in Alabama. The installation of soil nails is often performed by a specialty contractor. Design guidance for soil nail walls is provided by FHWA (2003).

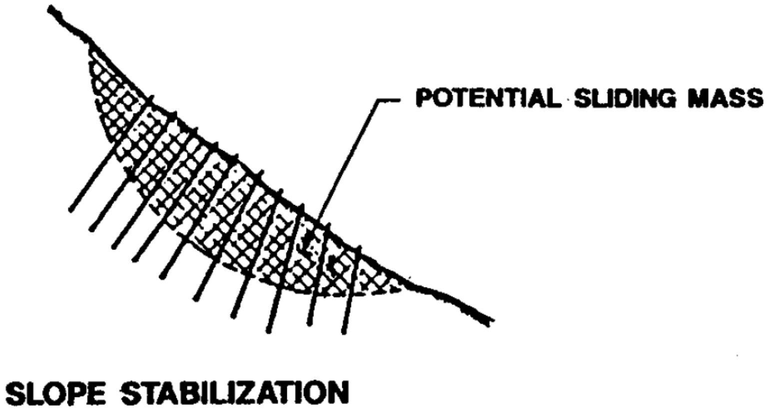


Figure 2-13. Main application of soil nailing (Abramson et al. 2002).

(3) Drilled Shafts and Micropiles

Drilled shafts (FHWA 2010) and micropiles (FHWA 2005) can be used to increase the resisting force of slopes. Both drilled shafts and micropiles are drilled through the unstable soil mass into a stable layer below. Some of the load from the unstable mass is then transferred through the structural response of the shaft or micropile (Figure 2-14). Drilled shafts and micropiles essentially serve as soil dowels and generate resistance as the soil attempts to move past the structural members (Loehr and Brown 2008). Micropiles were previously used to stabilize a landslide along U.S. 43 near Littleville, AL (Brown and Chancellor 1997). Drilled shafts and micropiles are typically installed by a specialty foundation drilling contractor.

(4) Geosynthetics

Geosynthetics can be used in a variety of ways to increase slope stability by adding reinforcement (Duncan et al. 2014). Layering geosynthetics within the soil can greatly increase its strength allowing for even very steep slopes to remain stable. Geosynthetics can be placed in layers within embankments to provide increased stability. Geogrids are commonly used for slope stability applications as they allow drainage while providing significant tensile strength. Day (1996) discusses using geogrids to repair shallow slope failures. Cellular confining systems are another option for stabilizing surficial failures and consist of a honeycomb pattern of geosynthetic material that can be filled with soil or rock (Caltrans 2006). These systems are effective at reducing erosion while vegetation is becoming established.

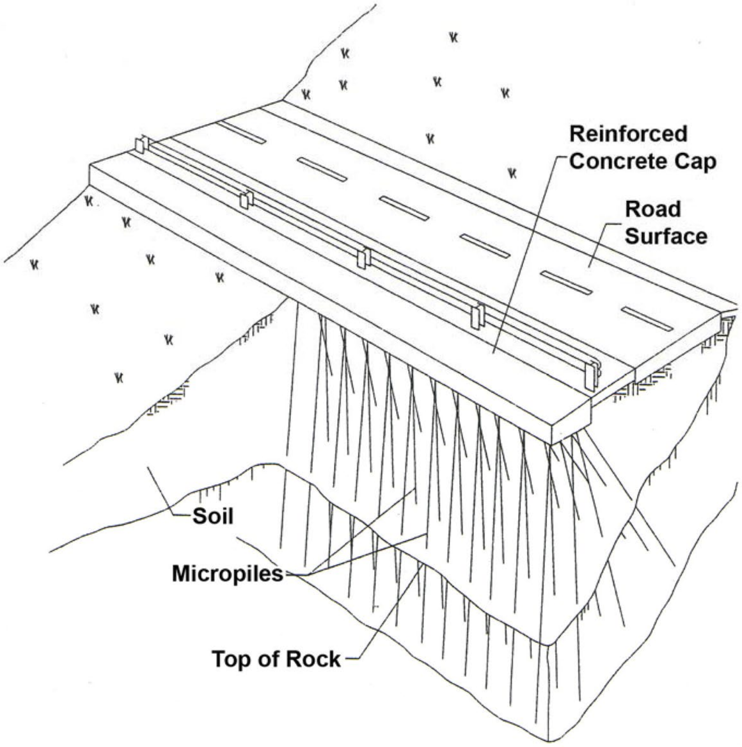


Figure 2-14. Example of slope stabilization using micropiles (FHWA 2005).

2.7.5 Retaining walls

Retaining walls are commonly used for slope stabilization when a cut or fill is required, and no adequate right-of-way can be provided for flattening the slope. The presence of a properly designed retaining wall will improve the slope stability by increasing the resisting forces. Sufficient stability will be obtained if the wall is deep enough, and critical surface will pass around the wall (Abramson et al. 2002). The retaining wall must be designed to resist overturning moments, sliding forces at or below their base, internal shear forces and bending stresses while functioning as a stabilizing mass. Global stability calculations must be performed to ensure the wall is large enough to provide adequate stability. Many different types of retaining walls are available (Abramson et al. 2002).

One type of retaining wall is a mechanically stabilized earth (MSE) wall which is constructed by reinforcing a backfill soil and thin metallic strips, metallic mesh or a geosynthetic mesh (FHWA 2009). This approach creates a mass of reinforced soil that is capable of supporting the lateral loads from the unstable slope. MSE slope must be designed for internal and external stability, as previously discussed. Reinforcement should be sized and spaced in order to not fail in tension stress when design with internal stability. Same external design requirement should be met for external stability. It must resist forces causing overturn, sliding at or below the base and global instability. Figure 2-15 shows the stabilization of slope with MSE.

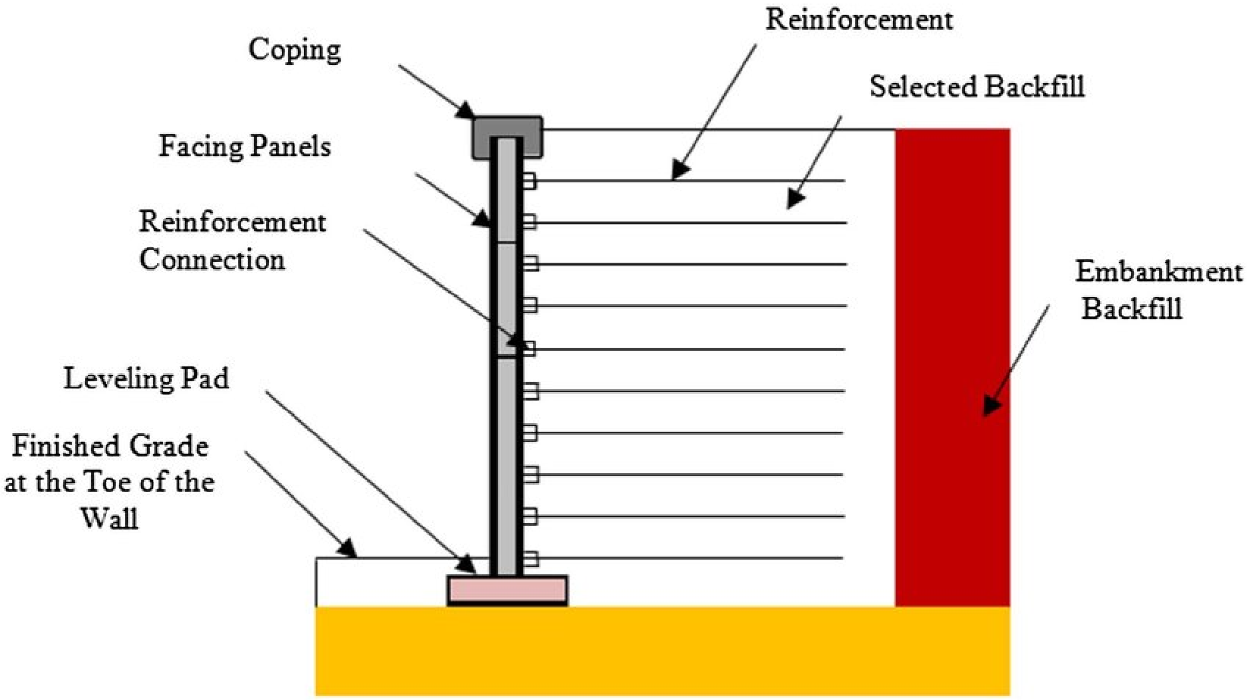


Figure 2-15. Stabilization of slope with MSE. (Tarawneh et al. 2017).

2.7.6 *Vegetation*

Stabilizing slopes with vegetation is a natural method to reinforce soil with plant roots. Grass, shrubs, and trees are commonly used for vegetation on slopes. The roots of the plants can stabilize the soil surface and the leaves and stems can intercept heavy rainfall and slow the runoff velocity of water on the slope. This can increase the strength of the shallow soil and help control erosion. An example of vegetation to stabilize potential slide is shown in Figure 2-16. Vegetation can also be combined with other stabilization techniques such as benching, drainage and geosynthetic reinforcement to create a more robust repair solution. Vegetation is often more economical than structural solutions, and no complex equipment and installation is required. Issues with using vegetation as a stabilization technique include a shallow depth of reinforcement, difficulty in controlling the growth of the plants, and maintenance and watering requirements.

These effects can mitigated by properly selecting plants for the soils and climate at the site of the failure (Norris et al. 2008).

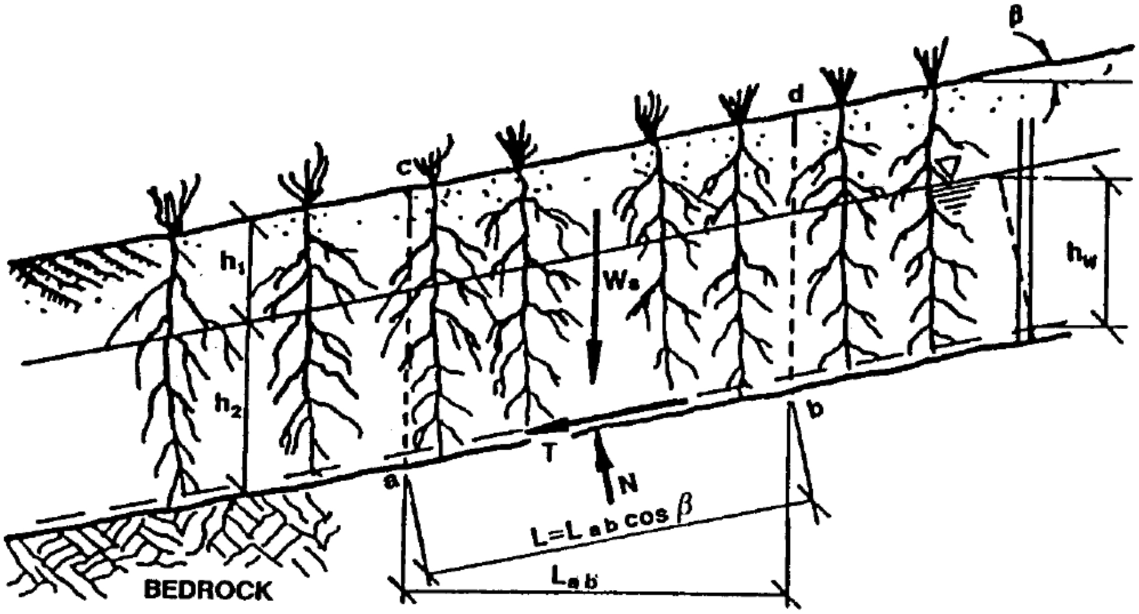


Figure 2-16. Forces on slope with vegetation (Abramson et al. 2002).

Some types of plants are intrinsically better suited than others for specific stabilization objectives (Norris et al. 2008). Grasses for example grow very fast, are less susceptible to damage and form a dense protective ground cover, but often have very shallow root systems. Shrubs are often more useful for stabilizing slopes than trees, as they are easier to control and maintain and pose a minimal hazard to the traveling public, but still provide relatively deep root systems. Regardless of the type of vegetation selected, native plants and grasses should be used due to the adaptability to local climate.

2.7.7 Ground improvement

Some slope stability issues can be addressed through ground improvement techniques such as grouting and lime stabilization (Duncan et al. 2014). The goal of these techniques is to increase the strength of the soil in-situ by either altering the chemistry of clayey soils (lime) or adding cement to the soil (grouting). While this can be an effective and low cost technique, it can be difficult to control the areas of improvement and to quantify the amount of improvement in properties in the field. It can also take time for the improvements to occur which may or may not be acceptable depending on the situation.

CHAPTER 3: DEVELOPMENT OF THE LANDSLIDE DATABASE

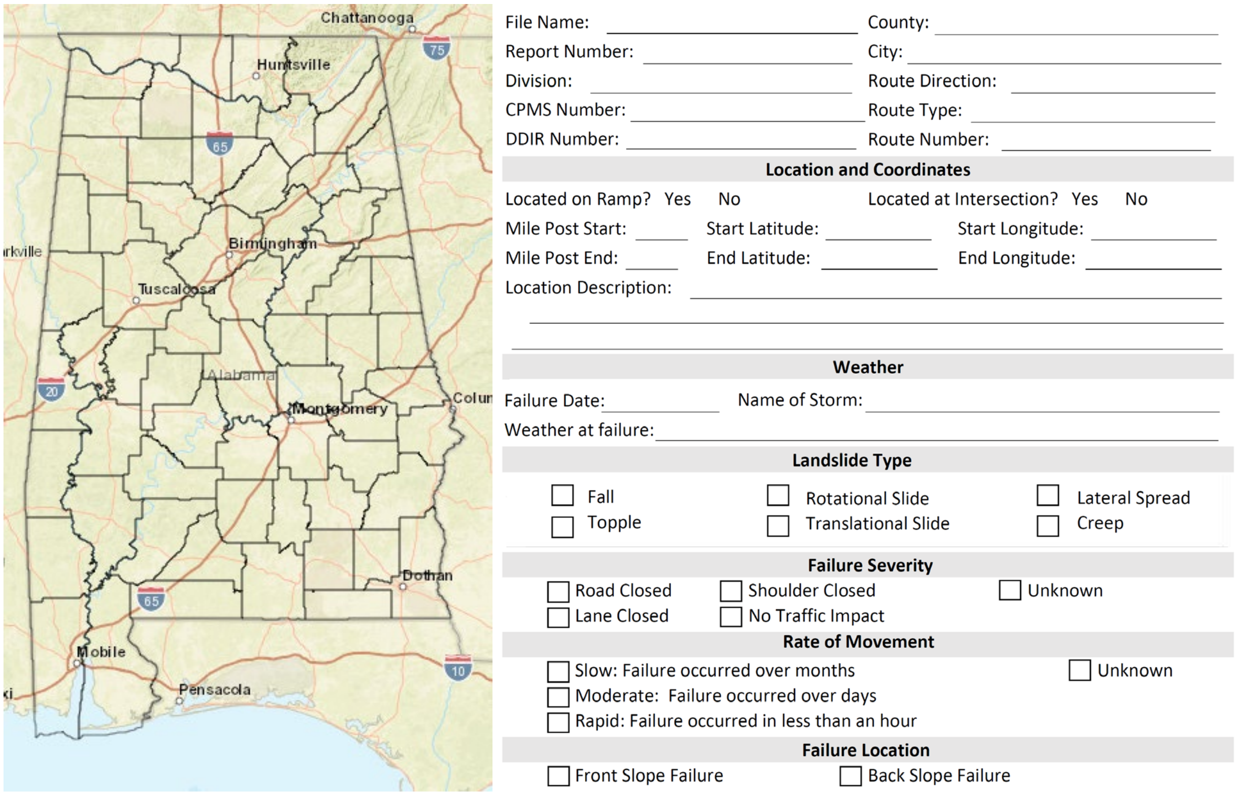
3.1 Introduction

As part of this study, a landslide data entry system and database were developed for ALDOT. The goal of the system was 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). The proposed system follows the practices of the five SSMSs reviewed previously with modifications based on the needs of ALDOT. The system developed in this study largely follows Slope Failure Investigation Management System created by MDOT because the goal of the MDOT system was similar to the current study. That goal was to collect physical attributes of landslides that may be used to predict vulnerable regions along state highways, as opposed to other systems that focused more on traffic or maintenance impacts. The system was designed to be an accessible landslide inventory compatible with ArcGIS software (ESRI 2016) to allow data to be updated, queried, and displayed easily. Data were collected from ALDOT reports on landslides, which had various levels of detail. This required a flexible data structure to be able to combine information from sources with different levels of detail.

3.2 Database Development

Table 3-1 compares the data collection system developed for ALDOT to the previously reviewed data collection systems. The data selected for collection were chosen based on the review of similar landslide collection systems and advise from ALDOT engineers and geologists. Nine attributes collected within other SSMSs were excluded from the current system. The effects of freeze/thaw cycles were not included as this is not a significant concern in Alabama’s climate. The current system also does not include a landslide hazard prioritization system (or asset management system), so information about 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 this study. Information on maintenance frequency/cost and probability of additional movement would be useful, but this information is not currently collected by ALDOT for slope failures and so was not available for inclusion in the database.

The original data collection system for this study used a GUI, or a user form, developed using Microsoft Excel and Visual Basic for Applications (VBA) and is described by Knights (2018). Auburn University researchers entered information into the database using user forms to help ensure information was collected uniformly from different users. Validation routines were written to ensure that the data entered could subsequently be used for spatial analysis within ArcGIS (ESRI 2016). This initial version of the database was then integrated into the existing web-based geotechnical database management system used by ALDOT (GeoGIS). GeoGIS uses a Microsoft Structured Query Language (SQL) database to store the landslide information and a web-based ArcGIS server to display the data. Details of GeoGIS are discussed by Graettinger et al. (2011). Future users will directly enter landslide information into the GeoGIS system using an online user form (e.g., Figure 3-1). The system is currently only available to ALDOT personnel, consultants and Auburn University researchers, but future iterations of the database may consider adding a citizen science component to allow the public to report landslides similar to the systems used by British Geological Survey and USGS (e.g., Baum et al. 2014).



File Name: ______________ County: ______________
Report Number: ______________ City: ______________
Division: ______________ Route Direction: ______________
CPMS 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

Failure Date: ______ Name of Storm: ______________
Weather at failure: ______________

Landslide Type

☐ Fall ☐ Rotational Slide ☐ Lateral Spread
☐ Topple ☐ Translational Slide ☐ Creep

Failure Severity

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

Rate of Movement

☐ Slow: Failure occurred over months ☐ Unknown
☐ Moderate: Failure occurred over days
☐ Rapid: Failure occurred in less than an hour

Failure Location

☐ Front Slope Failure ☐ Back Slope Failure

Figure 3-1. Example of web-based user interface for entering landslides in the GeoGIS database system.

Table 3-1. Comparison of landslide attributes collected in various SSMSs (Aydilek et al. 2013, Badger et al. 2013, Calvin et al. 2009, OHDOT 2001, Pensomboon 2007)

Attributes	AKDOT	MDOT	OHDOT	ORDOT	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/Horizonal 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, attribute collected within the database were not available

3.3 Data Sources

Two main sources of information about landslides along Alabama highways were identified: landslide reports and Detailed Damage Inspection Reports (DDIRs). Landslide reports are written by a geologist or a geotechnical engineer to document the characterization and analysis of a landslide. These reports document observations from the site and results for site investigations and slope stability analyses (if performed). They may also include information on recommended repairs, but as they are written during the investigation phase, no information is included on the actual repair or associated costs. Landslide reports are typically only written for larger slides and only after movement has occurred, so information on exact timing of the failure is difficult to determine. DDIRs are completed for emergency relief slides where repair assistance is requested from the FHWA due to a federally declared disaster. The DDIRs contain significantly less information than the landslide reports– often only a location, photos of the failure, and a description of the repair method and repair cost. While the DDIRs contain significantly less information about each slide, the reports are tied to a specific initiating event (i.e., a federally declared disaster, such as a hurricane) and a complete inventory of slides is available for each event.

Knights (2018) originally developed two databases to deal with the different levels of detail in each of the data sources, but the information has been combined into a single database in this study (Figure 3-2). The current database collects information on the location of the landslide, the soil conditions, the weather around the time of failure, the landslide type (following Varnes 1978), measurements of the landslide geometry, repairs, and effects of the landslide on the roadway. If available, information is also collected on the rate of movement, groundwater, subsurface conditions, previous landslides in the area, vegetation, and availability of additional data (i.e., photos, instrumentation, borings, and laboratory tests). These attributes are further described in Table 3-2.

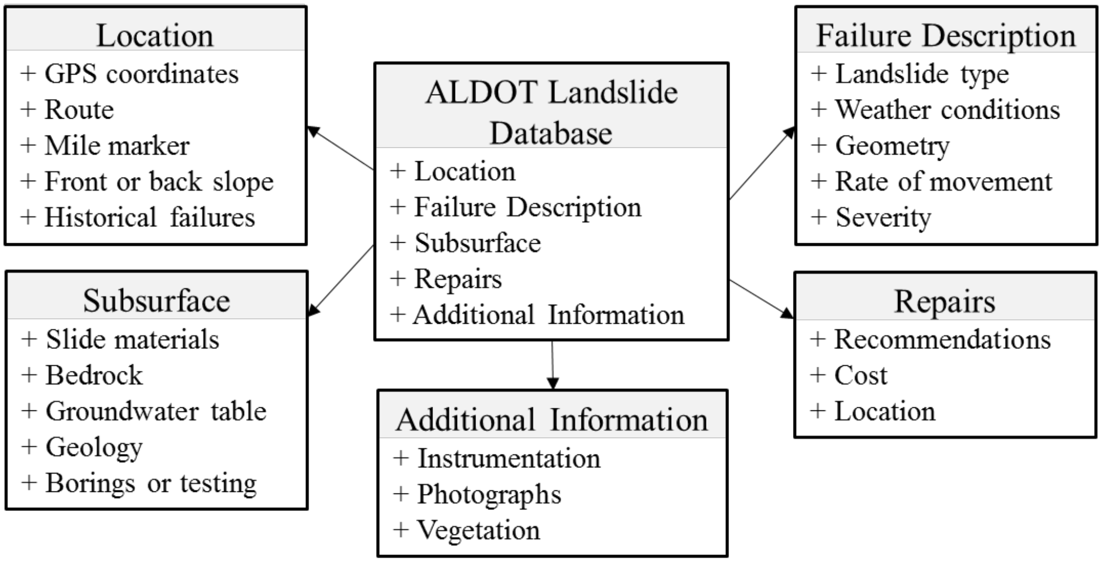


Figure 3-2**.** Data model for the ALDOT landslide database**.** Each box shows a tab within the model which group together similar attributes of both the roadway and the slide.

Additional information about each landslide beyond those listed in Table 3-2 can be gathered using other sources of geospatial information. For example, the regional surface geology can be obtained through correlation with digital geologic maps (e.g., Tew 2006). This is very useful for emergency relief landslides where no geologic information was provided in the original DDIRs. The database attempted to collect information on the weather around the time of failure to distinguish failures that can be attributed to a specific weather event, but the user is not asked to describe antecedent rainfall that may have occurred leading up to the failure. Antecedent rainfall does play an important role in slope stability (e.g., Rahardjo et al. 2001), but this information is not commonly available in ALDOT reports. Information on historical weather can be gathered from external sources (e.g., the National Weather Service in the United States) if needed for analyses.

Table 3-2. Data Collection for ALDOT Landslide Database.

Data Collection	Definition
Source	Cites the report used in the data analysis.
Location	Collects information on the location of the landslide—such as the county, city, roadway, direction of traffic, and site coordinates. The failure site location may also be denoted by the station number, mile marker, and/or exit number. The location of the failure in relation to the roadway (e.g., the front slope or back slope as shown in Figure 3-4) is also collected.
Failure Description	Collects general failure information such as the date of the failure, landslide type (according to Varnes 1978), weather conditions around the time of the failure, and measurements of the geometry of the landslide. Presence of sinkholes or cracks near the landslide are also noted.
Rate of movement	Indicates whether the failure occurred over a period of months, weeks, days or hours or if the rate of movement is unknown. The landslide velocity classes proposed by Curden and Varnes (1996) are used to classify the rate of movement.
Failure severity	Indicates the effect of the slope failure on the roadway and traffic. The severity may be a shoulder, lane, or road closure. Estimates of displacements are also collected.
Groundwater	Indicates the depth of the groundwater table and the method used to measure this depth (e.g., piezometers, in-situ testing, geophysical methods, assumed, etc.).
Subsurface profile	A general description of the material involved in the landslide. Earth materials are described using the Unified Soil Classification System (ASTM 2017). Rock materials, including bedrock, are described according to their geologic unit. Any borings or laboratory tests should be noted.
Geology	The geology of the slope is recorded, if available in the report. If not, the geology of the region is recorded using the physiographic province (a geographical region with similar physical features), and/or regional geological unit (an area of soil/rock with similar characteristics).
Repairs	Collects the list of repair options—indicating the recommend method, repair location and estimated repair cost. This information can be updated by the user after the repair is complete.
Adjacent Structures	Information is collected on adjacent structures, such as utilities, culverts, bridges, etc.
Additional Information	Availability of additional data (i.e., photos, instrumentation, and eyewitness accounts) is noted. A description of the vegetation along the slope can be provided. The user can also enter comments about the landslide.

3.4 Landslide Reports

The first data source for this study was landslide reports collected from ALDOT archives. A focus was placed on documenting landslides that had occurred within the past 10 years; however, all available reports were collected and the report dates ranged 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 a distance along a highway alignment (referred to as a mile marker), which were converted to latitude and longitude using a GIS-based conversion tool developed by ALDOT. These locations were then checked manually using the maps provided in the report. Slides where an exact location could not be determined were excluded from the database. The location of the landslide along the road section was also noted (Figure 3-4). Landslides were classified as occurring in either the front slope (slope with a negative grade when moving away from the centerline of the roadway) or back slope (slope with a positive grade when moving away from the centerline of the roadway). Repair costs were not available for most of the landslide reports as the reports are often completed separately from construction.

3.5 Emergency Relief Slides

The reports described above do 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. The maintenance repairs could not easily be tracked using available information, but emergency repairs where federal funds were requested were documented using DDIRs, as previously discussed. The emergency relief slides were included in the database described above, but the DDIRs had significantly less information than the landslide reports and so many of the attributes were unknown for these landslides. The emergency relief slides contributed an additional 165 slides to the database, resulting from 10 weather events between 2004 and 2015. The total repair cost for these slides was $30.4 million. The locations of the emergency relief slides are shown in Figure 3-3.

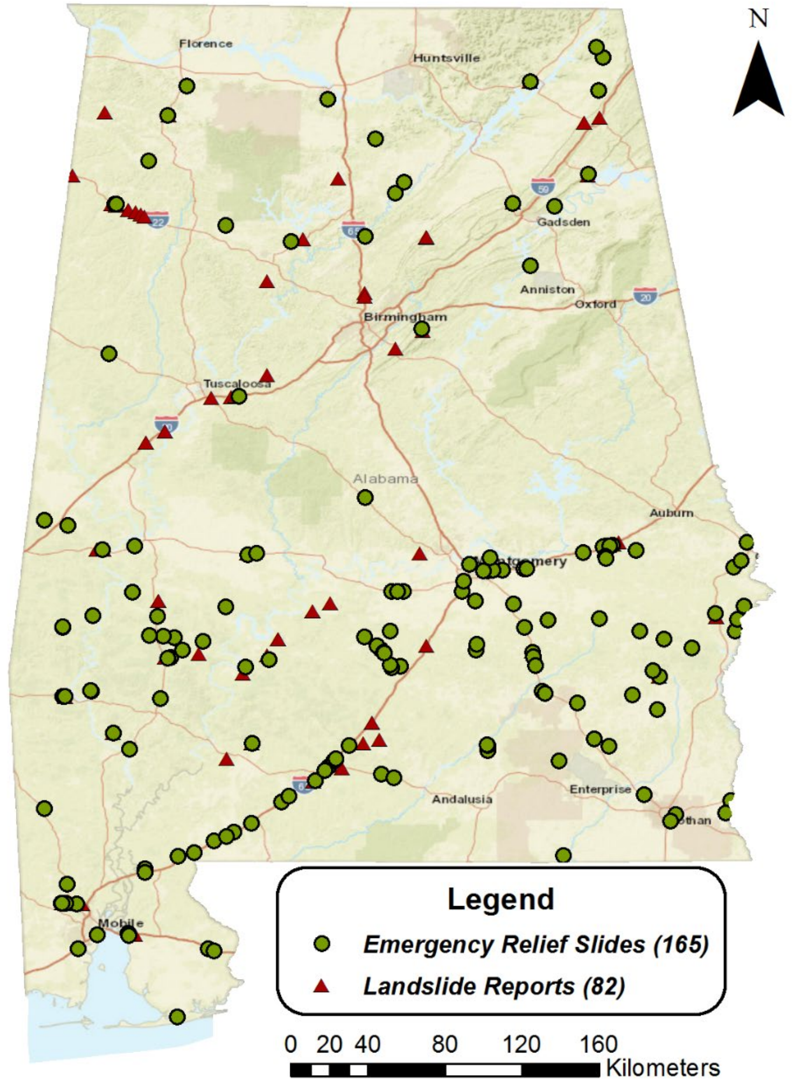


Figure 3-3. Landslides along state and county highways**.** Multiple slides may be located at the same latitude and longitude coordinates and are shown using a single marker.

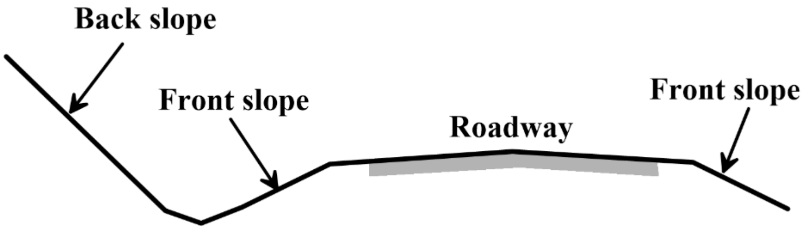


Figure 3-4. Definition of front slope and back slope along a typical highway cross-section.

3.6 Database Limitations

The current database contains data on approximately 250 landslides that have occurred over the past 28 years. These do not represent all of the landslides occurring along Alabama roadways during this period. The emergency relief slides are relatively complete back to 2004, but no data were available for prior years. In addition, many other landslides are known to have occurred, but were either not documented using the two types of reports collected for this study or the reports were not available during the data collection phase. Additional landslides will be added to the database as the reports are located. The reports that were available did not contain the same level of detail or capture the same categories of data across all reports. This has resulted in varying levels of recorded information for each slide, likely affecting the analysis results presented in the next chapter. To address this, the database 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. This should lead to a more complete and consistent data set in the future. Future updates to the database can also consider using public input, social media postings, or news articles to identify landslide locations that may not be documented using formal ALDOT reports. This approach may help develop a more complete picture of where landslides are occurring, even though the technical details on each landslide may not be available.

Reported landslide locations may not be equally 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. Landslides also 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. These factors may have affected the collected data leading to a possible spatial and/or temporal bias in the observed trends within the database.

3.7 Surface Erosion from Mowing Activities

A significant source of slope stability problems not covered by the current database is the erosion of slopes due to rutting on the slope face. This rutting is often caused by mowing operations (Figure 3-5). The rutting itself is not considered to be a slope failure, but the ruts remove vegetation and provide areas for water to pool which can lead to surficial failures during subsequent rain events (Figure 3-6). If left unrepaired, these surficial failures may lead to larger stability problems. These types of surface erosion failures are not reported to the Materials and Tests Bureau or FHWA and so were not included in the reports collected for the database described in the previous sections. Repairs of these failures are typically handled by local maintenance forces and commonly involve cleaning failed material out of ditches or other drainage structures and possibly placing top soil to fill in the eroded area. These repairs are often considered part of "ditching activities", which can also include repairs to drainage features, constructing a new driveway or entrance onto a state route, and beaver dam removal. While it is not possible to track the exact amount of money spent on repairing surface erosion failures, ALDOT spent more than $13.7 million on ditching activities between 2014 and 2018. Surface erosion from slopes likely represents a significant portion of these repair costs.

Figure 3-5. Rutting along the face of a slope due to mowing activities (photo provided by Jacob Hodnett, ALDOT).

Figure 3-6. Shallow slope failures caused by rutting from mowing activities along Highway 69 near mile post 137.7 (photo provided by Jacob Hodnett, ALDOT).

A second set of case histories documenting slope damage from mowing activities was identified through discussions with Howard Peavy and Jacob Hodnett, agronomists in the Maintenance Bureau. They were able to provide locations for nine areas around the state where slopes had been damaged due to mowing activities leading to rutting and erosion of the slope face (Table 3-3). This problem can be observed in many more parts of the state, but the locations in this table have been attributed specifically to mowing related activities. Possible options for remediating this type of failure are discussed in Section 5.4.

Table 3-3. Locations of mowing-related rutting and surface erosion on slopes (Hodnett, J. personal communication, February 2019)

Locations of mowing-induced rutting and slope failures
I-65 North – Damage occurring in the median north of exit 161
I-65 North – Surface erosion near mile marker 78
I-65 South – Rutting near mile marker 268.5
AL-43 – Deep rutting near mile marker 204.5
AL-69 – Surface erosion near mile marker 137.7
AL-293 – Rutting in the drainage ditch between I-85 and AL-110
I-22 – Mowing-related damage to slopes between mile marker 80.4 and 74.5
US-82 Centerville Bypass – Mowing-related damage to slopes between mile marker 88.4 and 83.8
US-280 - Mowing-related damage to slopes between mile marker 99.8 and 86.5

CHAPTER 4: ANALYSIS OF THE LANDSLIDE DATABASE

4.1 Introduction

The database of landslides along Alabama highways has been analyzed to identify common features and select appropriate remediation options for future landslides. One of the challenges in analyzing the database stems from inconsistent details provided for each of the landslides due to the varying levels of detail provided within individual landslide reports. The retroactive data collection method employed for this study led to inconsistent data levels and gaps in available information. The variation of available information was also encountered by Aydilek et al. (2013) in the examination of landslides along Maryland highways. In their study, Aydilek et al. (2013) short-listed physical parameters based on the advice and experience of MDOT engineers. 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 within the data. The analysis presented herein follows the process implemented by Aydilek et al. (2013) and examines each landslide attribute separately. The analysis does not account for the combined effects of the influencing parameters (e.g., the combined effects of geology and precipitation). The trends presented are based on the information provided within the reports and therefore may have been influenced by any spatial or temporal bias within the database.

In order to determine factors that are making landslides more of less likely to occur, a corridor landslide susceptibility analysis could also be performed (e.g., Saha et al. 2005, Blais-Stevens et al. 2012). These analyses are based on qualitative or quantitative methodologies to provide information or predict the behavior of areas that present a higher risk of landslide activity (Saha et al. 2005), in order to determine the landslide hazard along a particular roadway. Corridor analyses have not been performed as part of this study and so it is not possible to distinguish which specific factors are causing landslides to be more or less likely to occur. This remains an important area for future work, but information in the current database can be used to identify trends in the collected data and to identify regions where more landslides are being observed. This information can be used to locate areas where further study, such as a corridor analysis is needed.

The authors examined possible correlations between the number of landslides and the geology of the region, the proximity to other landslides (e.g., landslide density), the weather at failure, and the presence of previous landslides at or adjacent to the site of the current landslide. The authors also examined relationships between landslides and their physical attributes, including the failure pattern, adjacent structures, slope height, and slope ratio. This report discusses results for five areas in which trends were identified (geology, rainfall at failure, location along the roadway, adjacent structures or landslides, and failure category). Results for the other factors discussed above are presented by Knights (2018).

4.2 Geology at Landslide Sites

The landslide locations were mapped in relation to both the physiographic provinces (Neilson 2007) and geologic units (Tew 2006). The physiographic provinces are regions characterized by similar physiographical attributes and correspond to areas with distinct features and/or landforms. Figure 4-1 displays the landslide locations in relation to the physiographic provinces of Alabama. Landslides occurred in four of the five physiographic provinces, with the vast majority occurring the coastal plain and Cumberland Plateau regions. No landslides were identified within the Piedmont Upland, which is composed primarily of metamorphic bedrock and residual soils (Neilson 2007), despite the presence of a major interstate (I-85) in this region. The lack of reported landslides in this region could be due to either reduced susceptibility or because they have not been recorded for some reason.

The geology of the landslides sites were further examined by spatially correlating the landslide locations with the geologic units of Alabama to determine the number of slides within each geologic formation (Figure 4-2). Only landslides along state highways were included in this analysis, which meant eight of the landslide reports that were located along county roads were not considered. Failures occurring in native materials (within cut sections) and occurring in borrow materials (within fill sections) were analyzed together as it is common practice to gather borrow materials for the fill sections from nearby cut sections. Therefore, the geologic formation of the region is commonly representative of the fill materials. The number of landslides in each unit was normalized by the length of highway in each unit (

Table 4-1). This was done to determine if more landslides were occurring in a geologic group due to either a higher landslide susceptibility, or a higher landslide exposure rate (i.e., a longer length of the highway within the geologic group).

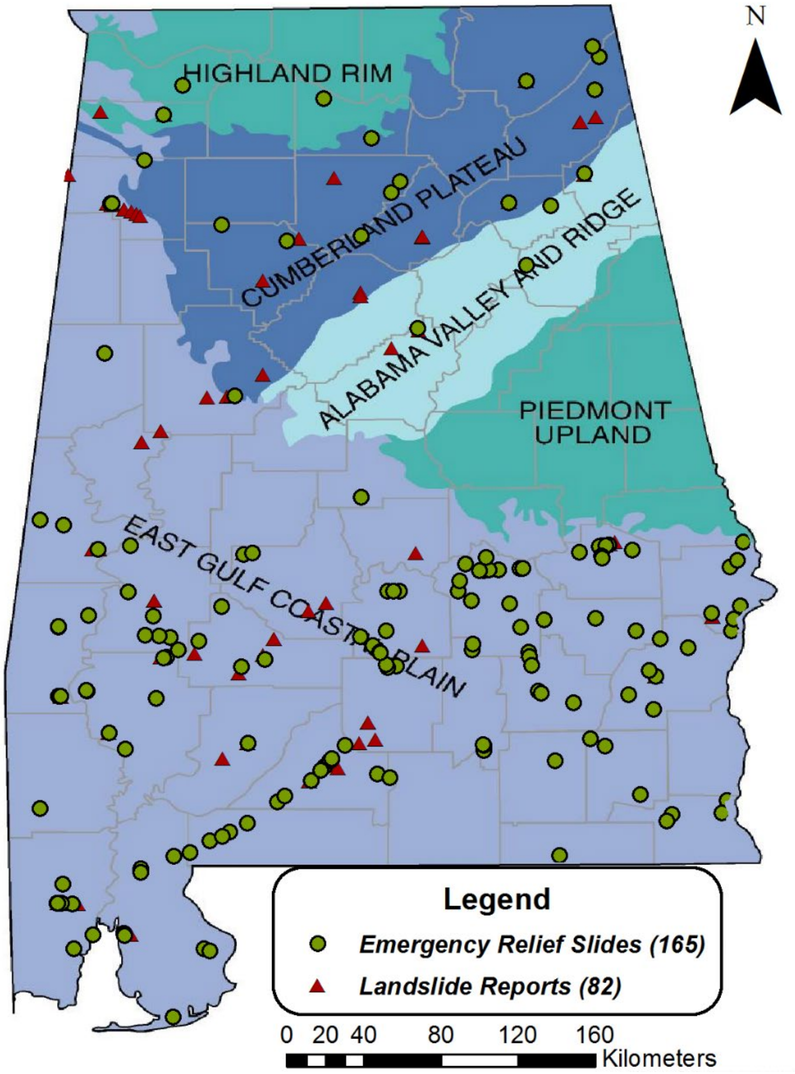


Figure 4-1. Landslide locations within each physiographic section of Alabama (physiographic regions from data provided by the University of Alabama, Department of Geography).

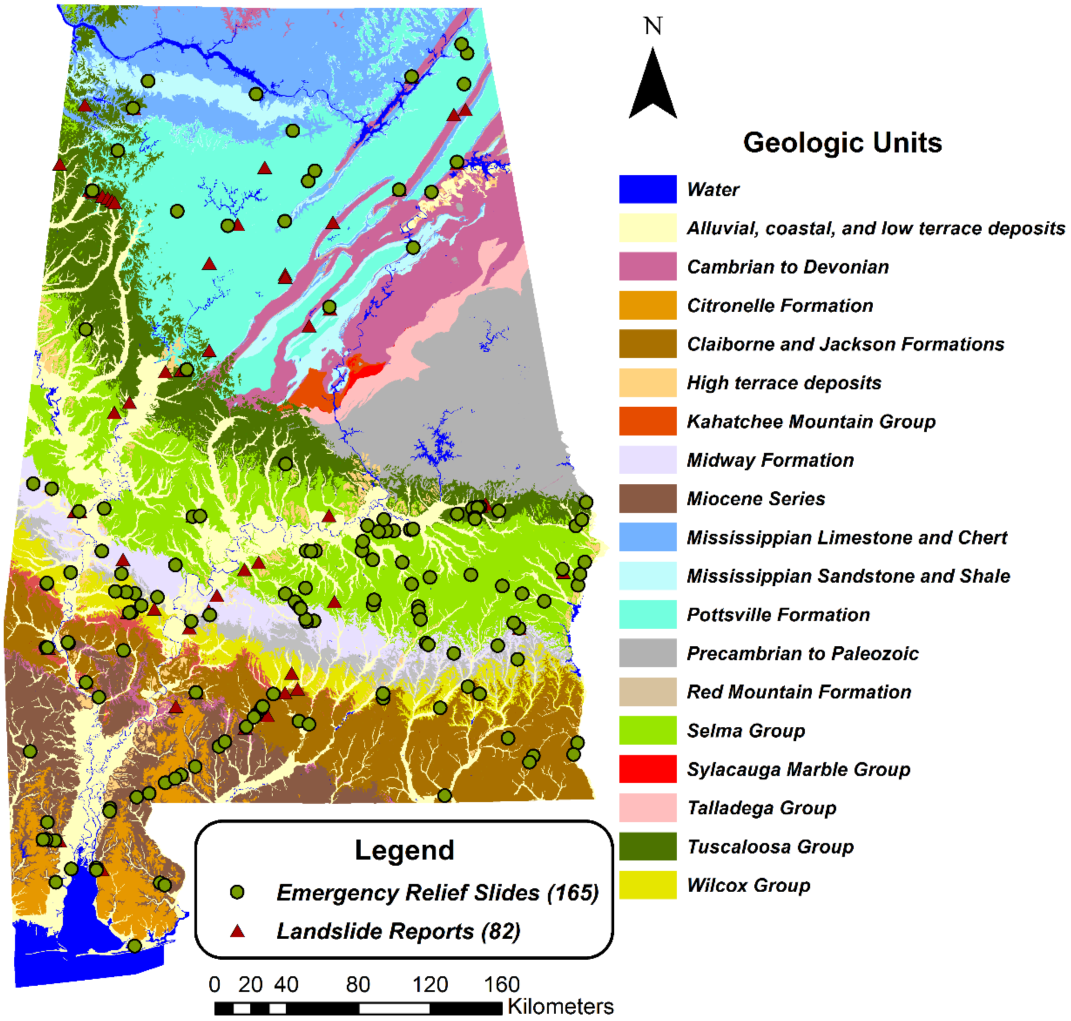


Figure 4-2. Landslide locations compared with the geologic units of Alabama (geologic map simplified from Tew 2006).

Table 4-1. Number of landslides in each database sorted by geologic group. The list is ordered by the total number of landslides in a group

Geological Group	Number of Landslides		Number of Landslides Per 160 km (100 miles) of Highway	
	Emergency Relief Slides	**Landslide Reports**	**Emergency Relief Slides**	**Landslide Reports**
Alluvial, coastal, and low terrace deposits	35	9	2	0.5
Midway Group	26	7	6	1.6
Pottsville Formation	13	13	0.7	0.7
Claiborne and Jackson Formation	21	4	1.6	0.3
Selma Group Sand and Clay	15	6	2	0.8
Tuscaloosa Group	8	13	0.7	1.1
Selma Group Chalk	16	2	2.7	0.3
Wilcox Group	14	8	2.3	1.3
High Terrace Deposits	6	1	1.9	0.3
Miocene Series	0	5	0	1.1
Citronelle Formation	4	0	0.8	0
Mississippian Sandstone and Shale	3	1	0.6	0.2
Mississippian Limestone	1	1	0.1	0.1

Table 4-1 shows the number of landslides within each geologic group (for groups with at least one landslide) along with the number of landslides per 160 km (100 miles) of highway within that unit. The results show that the units with the most landslides per unit length are the Midway, Selma and Wilcox groups. These units are primarily composed of high plasticity clays and interlayered sand and clay deposits. Few slides were observed in the limestone groups, but it should be noted that data on rockfalls was not gathered as part of the current study, which was focused on identifying remediation options for landslides in earth materials. A significant number of emergency relief slides were observed in areas categorized as alluvial, coastal and low terrace deposits. These deposits are often found in close proximity to water and may contain a variety of soil types depending on which area of the state they are located. It should also be noted that the distribution of emergency relief slides is influenced by the amount of rainfall from the corresponding storm, which will skew the distribution of landslides. The effect of rainfall is discussed in the next section.

4.3 Effects of Rainfall on Failure Patterns

Rainfall is often a contributing factor to landslides and understanding the effects of rainfall requires examining the weather both at the time of the failure and in the days or weeks leading up to the failure (Rahardjo et al. 2001). Many of the landslide reports did not include information on the weather at the time of failure or a failure date, which could be used to determine the weather from historical databases. The emergency relief database offers a clearer picture of the weather conditions leading up to failure, as each slide has been attributed to a specific weather event (Figure 4-3). Each of the events in this database was a federally declared disaster due to periods of intense rainfall. Cumulative rainfall plots for the events occurring between 2011 and 2015 were obtained from the National Weather Service (NWS 2017). These 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 (

Table 4-2) and the geologic groups in which the failures occurred.

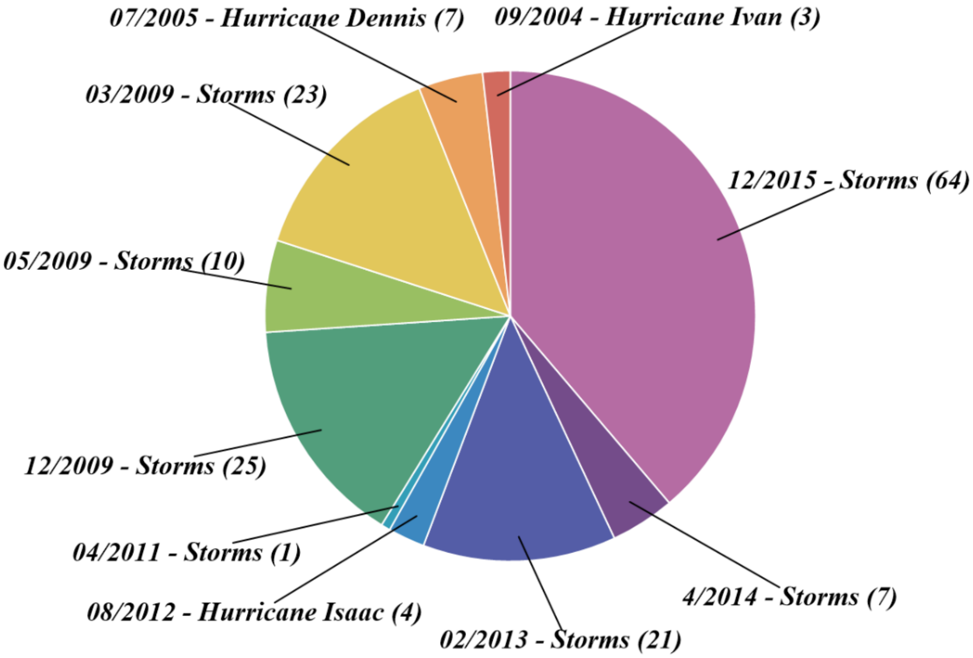


Figure 4-3. Distribution of emergency relief slides by event. The number in parenthesis indicates the number of landslides attributed to that event.

Table 4-2. Number of emergency relief slides occurring per 160 km (100 miles) of highway within each rainfall range (rainfall totals from NWS 2017)

Rain (inches)	Year				
	2011	2012	2013	2014	2015
0.00-0.25	-	0	0	-	-
0.26-0.50	-	0	0.11	-	-
0.51-1.00	0	0.05	0.20	-	-
1.01-1.5	0	0	0.16	-	-
1.51-2.00	0	0	0.16	-	-
2.01-3.00	0	0	0.21	-	0
3.01-4.00	0	0	0	-	0
4.01-6.00	0	0	-	0	0.17
6.01-8.00	0	0.46	-	0	0.38
8.01-10.00	0.08	1.03	-	0	0.58
10.01-15.01	0	-	-	0.04	3.10
15.01-20.00	-	-	-	0.90	0
20.01-25.00	-	-	-	0.37	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 160 km (100 miles) (

Table 4-2). The number of slides per 160 km (100 miles) generally increased with precipitation, displaying the impact of the rainfall on the stability of the slope. There are several exceptions to this trend. For example, a lower frequency of slides was observed within geologic units containing primarily limestone despite the large amount of rainfall in these areas. Developing correlations between geologic group and the amount of rainfall to cause failure would be useful to create a predictive model for rainfall-induced landslides in Alabama.

4.4 Failure Location along the Roadway

The database was further analyzed to try to identify the percentage of landslides occurring in either cut or fill sections. Many reports did not explicitly state whether the failure occurred in a cut or fill section and so the location of the landslide along the roadway (Figure 3-4) was used instead (e.g., front slope, back slope, or front and back slope). The front slope generally coincides with an embankment or fill section. Whereas, a back slope generally indicates a cut section.

The location of failure along the slope was analyzed for both the emergency relief slides and the landslide reports slides. The total number of failures occurring in either the front slope or the back slope (or both) are shown in Table 4-3. The results show that the majority of landslides (approximately 66 percent) occurred within the front slope of the roadway. Approximately 20 percent of failures occurred within the back slope, which is predominately composed of cut sections. This indicates that the majority of failures are occurring within fill sections rather than cut sections. These failures may have occurred within borrow materials or within native materials beneath the roadway.

Table 4-3. 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

4.5 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, the database collects information on the presence of past landslides at or adjacent to current slide locations. 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 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 a total of 98 slides were estimated to have occurred at or near a pervious landslide failure, making up 40% of the slides within the database. These landslides included 35 emergency relief slides, and 63 landslide reports slides. These results show that more the 75% of the landslide reports occurred in areas near other slides.

4.6 Adjacent Structures

The structures adjacent to failed slopes were recorded for the landslide reports. 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 82 landslides had adjacent structures that were discussed in the landslide reports, many of which had more than one adjacent structure listed. The results (Figure 4-4) show that approximately 65% of the slides in the landslide report database occurred near a culvert, drain or flowing waterway. This is an important result as it suggests that the issues with drainage structures may be contributing to failures.

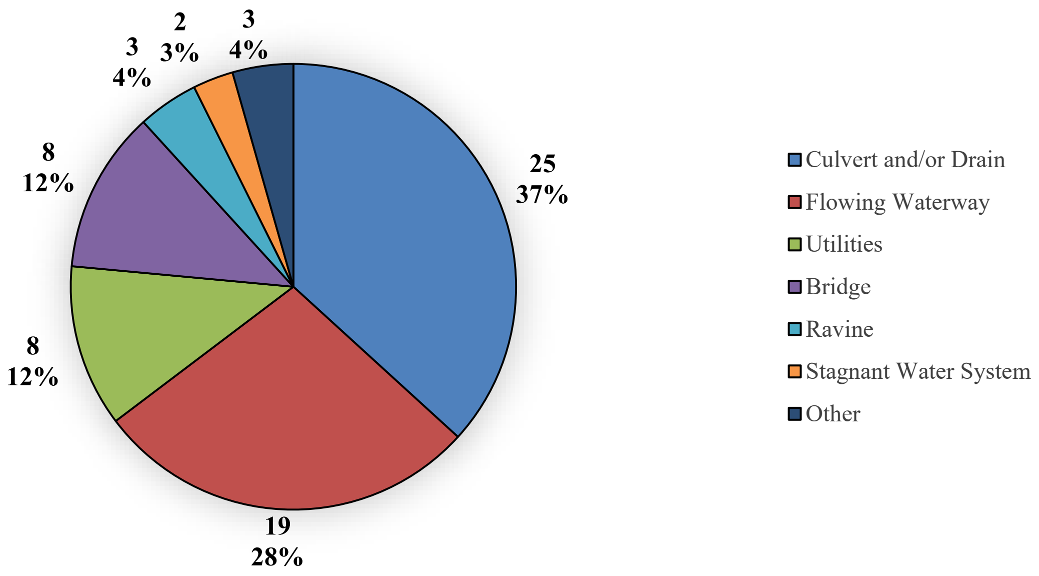


Figure 4-4. Number and Type of Structures Located Adjacent to Landslide Report Slides.

4.7 Landslide Categories

The database was used to determine common failure categories for both the landslide reports and the emergency relief landslides. The categories were established based on failure descriptions 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 classifications generally followed the guidelines provided by Varnes (1978), as described in Section 2.3. The rotational landslides for the landslide reports were further divided into shallow and deep. This distinction was not made for the emergency relief landslides as not enough information was usually available to identify the depth of the failure surface. More than 25% of the DDIRs did not have enough information to accurately assign a failure category to the landslide.

The number of landslides within each failure category is presented in Figure 4-5 and Figure 4-6. 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. Figure 4-5 shows the majority of landslides within the landslide reports database are classified as either shallow rotational failures (40%) or translation failures (25%). Figure 4-6 shows the majority of the emergency relief landslides were classified as either translational (40%) or erosion failures (17%). The increase in erosion-related failures within the emergency relief slides is expected as these slides are driven by heavy rain which can overwhelm drainage structures.

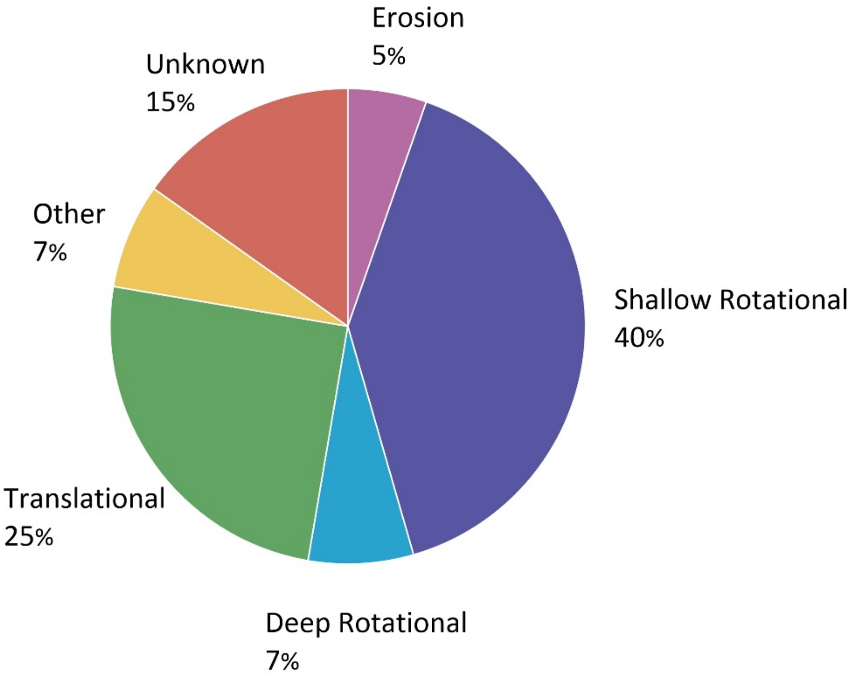


Figure 4-5. Landslide categories for the landslide reports within the database.

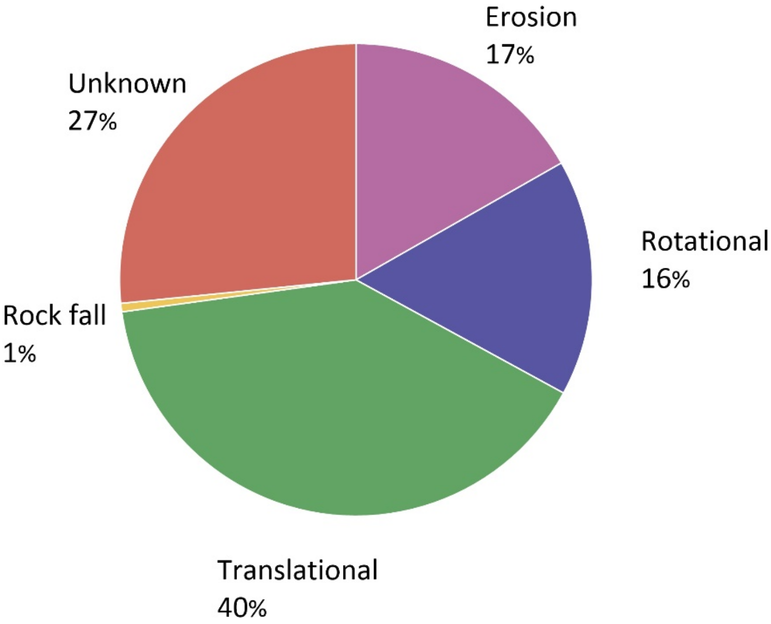


Figure 4-6. Landslide categories for the emergency relief slides within the database.

4.8 Summary

The previous sections have highlighted some important trends present within the current landslide database. These trends have shown that a large number of the failures are occurring in fill sections and many of these failures are shallow. This likely suggests issues with compaction or material selection near the edge of embankment sections where quality control may be less stringent. Approximately 40% of the failures in the database occurred at the same location or within 1000 feet of a previously recorded landslide. Slides occurring this close together could have similar failure mechanisms and a more regional approach may be needed to fully address the underlying issues. Nearly two-thirds of the landslide reports indicated that failures were occurring near culvert, drain or flowing waterway.

Translational failures (failures with a planar rather than circular failure surface) make up 40% of the emergency relief slides and 25% of the landslide reports. These failures often occur when a weak plane develops within the slope, such as a pre-existing shear plane, an interface between two materials, or when shear bands form after softening. Analyzing these failures accurately requires using a non-circular failure surface within the selected slope stability program. Remediating translational failures requires identifying the plane of sliding and arresting the movement on this plane. Options for remediations will be discussed in the next chapter.

The analyses of the database have also shown more landslides are being reported in three geologic groups (Midway, Selma and Wilcox groups) than would be expected based on the length of highway within these groups. These geologic groups are primarily made up of high plasticity clays and interlayered sands and clays. One important concern in these materials is the potential for the materials to reach a fully softened strength after shearing, which may be significantly lower than the intact or peak strength of the material.

CHAPTER 5: METHODS TO ADDRESS LANDSLIDES

5.1 Introduction

The previous chapter outlined several trends within the landslide database, which have highlighted factors that may be making landslides more likely to occur. Possible remediation alternatives for these factors were identified through the analysis of selected case histories from the landslide database described in Chapter 3. In addition to the landslides captured within the database, surface erosion has been cited as a significant problem along Alabama highways with one of the contributing factors being rutting from mowing activities. Mowing-related failures are not typically documented in the form of a report and are instead repaired by local district forces as part of their normal maintenance duties. Exact cost estimates for these repairs are unknown. Recommendations for addressing the mowing-related surface failures are discussed in Section 5.4. Recommendations for the design of new slopes in order to decrease the likelihood of future failures are also discussed in Section 5.5.

5.2 Landslide Case Histories

Twelve case histories have been selected from the landslides database in order to identify remediation alternatives that may address the observed failure mechanisms. The case histories were selected based on several factors, including landslide density in the area, geologic unit, primary failure mechanism, and the weather of the failure. Information on each case history was collected from landslide reports, DDIRs, and the other reports provided by ALDOT. Each case history was then analyzed using the slope stability software, *Slide* from Rocscience. Details of the case histories and the slope stability analyses are provided by Xuan (2019).

Table 5-1 shows the relevant details for each of the selected case histories, including the failure category, availability of information (photos, borings and lab tests), and a description of the critical layer for the failure. After collecting all of the relevant information each case history was analyzed to identify remediation options which could address the underlying cause of the failure. The remediation options considered in this study were described in Section 2.7. Possible remediation options were selected for each case history, which would likely be able to address the underlying causes of failure. Many of these options would be used in combination with one another. These remediation options are listed in Table 5-2. Details of the selection of the remediation options along with examples of the design approach for each of the main remediations are presented by Xuan (2019).

Table 5-1. Summary table for the selected landslide case histories

#	Name	Type					Photos	Borings	Lab tests	Failure description
		Deep	Shallow	Rotational	Translational	Erosion				
1	99-405-690-000-513		✓	✓			✓	✓	✓	Failure in fat clay fill located above a culvert
2	99-707-690-000-601	✓			✓		X	✓	X	Failure in native elastic silt underlying embankment
3	99-708-069-000-001	✓		✓			X	✓	X	Embankment failure due to high ground water from infiltration and damaged CMP
4	99-708-690-000-901		✓	✓			✓	✓	✓	Failure in sandy clay embankment due to perched water table
5	ER-8910(937)	✓			✓		✓	✓	✓	Failure along a zone of softened clay overlying chalk layer
6	ERPR-9010(980)		✓	✓			✓	✓	✓	Failure along weak zone overlying stiff calcareous clay
7	ERPR-8960(921)	✓			✓		X	✓	X	Failure along a zone of softened clay overlying chalk layer
8	NH-0004(522)		✓	✓		✓	X	✓	✓	Shallow failures in primarily cut sections
9	IM-1065(413)	✓			✓		✓	✓	X	Failure in a soft silty clay fill section near drainage ditch
10	NHF-7571(600)		✓			✓	✓	✓	✓	Shallow erosion failures along edge of newly constructed embankment
11	ST-037-159-002		✓		✓		✓	✓	✓	Failure due to poorly compacted fill
12	ST-069-000-015	✓			✓		X	✓	✓	Failure along clay/shale layers

Table 5-2. Remediation options (alphabetical order) for the case histories listed in Table 5-1.

#	Remediation Options					
	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
1	Pins	Remove and replace failed material	Retaining wall	Rock buttress	Vegetative Cover	
2	Drainage	Drilled shaft or micropiles	Rock buttress	Shear Key	Soil nail wall	
3	Counterberm	Drainage	Removal and replacement with geosynthetic reinforced soil			
4	Drainage	Flatten slope	Pins	Rock buttress	Vegetative Cover	
5	Anchors	Drainage	Drilled shaft or micropiles	Rock buttress	Shear key	Soil nail wall
6	Anchors	Drainage	Flatten slope	Rock buttress	Shear key	
7	Anchors	Drainage	Drilled shaft or micropiles	Rock buttress	Shear key	Soil nail wall
8	Benching slope	Drainage	Pins	Rock buttress	Vegetative cover	
9	Drainage	Remove and replace clay fill	Rock buttress	Shear key		
10	Benching slope	Drainage	Pins	Riprap blanket	Vegetative cover	
11	Excavate and replace material	Flatten slope	Soil improvement	Soil nail wall		
12	Anchors	Retaining wall	Shear key	Soil improvement		

Based on the analyses, several remediation options can be identified which would be useful for multiple of the case histories. These include the use of pins and vegetative covers for shallow failures and the use of shear keys and micropiles or drilled shafts for deep failures. Few if any of the reports examined considered these options and so they represent possible expansions of the current remediation options typically considered for landslide repairs. Each of these options is briefly discussed below.

Pins (e.g., recycled plastic pins, RPPs) are effective for stabilizing shallow slope failures in both cut and fill sections. These pins increase the resisting forces with the slide and can effectively stop movements when the failure surface is less than 10 feet deep. The RPPs can be installed by DOT personnel with standard construction equipment and so can reduce the reliance on specialty contractors. Designs could also likely be standardized based on the type of failure and slope geometry to allow repairs to be made quickly with minimal site-specific engineering. This is a promising area for future research. This stabilization method has been used effectively in multiple states (Hossain et al. 2017) and is a promising technology for ALDOT to consider for future repairs.

Vegetative covers can be used to reduce the likelihood of erosion related failures on steep slopes. Vegetative covers are often a combination of vegetation and some sort of reinforcement, such as cellular confinement systems or Flexamat, to provide additional resistance to shallow soil layers. These covers can reduce erosion, control infiltration and prevent shallow failures. An additional benefit of vegetative covers is that they can be installed rather quickly by ALDOT forces. These types of repairs are also a promising option for repairing mowing-related failures as discussed in Section 5.4.

Shear keys are a common component of buttress systems and involve excavating a section of the buttress down to an underlying stable layer in order to increase the available resistance. Rock buttresses are the most common repair option selected in the examined case histories, but most of these buttresses extended only down to the assumed failure surface. Keying these buttresses into a lower stiffer layer can increase the capacity and may allow the size of the buttress to be reduced. It will also add an additional level of protection should the slide reactivate in the future at a lower elevation.

For deep translational failures, sliding often occurs on a weakened plane. It may not be practical to remove enough material to construct a berm at these sites and anchors or soil nails may not be able to reach stable layers beneath the failure surface. In these situations, drilled shafts or micropiles may be a good option for stabilizing the slope. These repairs are expensive and so would only be considered on larger slides, but the reduced right-of-way needs and lack of future maintenance concerns may make these attractive options compared to large buttresses. The use of both micropiles and drilled shafts is well-established for slope repairs (Loehr and Brown 2008).

5.3 Prioritizing Remediation Options

The previous section has outlined several remediation options that could be considered for each of the case histories identified. Many of these remediation options would likely be used in combination with each other, but it may also be desirable to select the most effective option. In addition to ensuring that the remediation can address the underlying failure mechanism, it is important to consider the total construction time required for the selected option, the amount of labor required, the availability of necessary equipment, maintenance requirements for the repair, and total cost. Balancing these requirements can be difficult unless a formal process is used to compare the remediations.

One option for prioritizing remediation options would be to assign a score to each alternative in the five categories discussed above. A simple scoring system would be to assign a score from 1 to 5 to each category with 1 representing the least desirable score and 5 representing the most desirable. As this ranking is performed on a project by project basis, the absolute value of the score is less important than the relative scores between the remediations being examined. The scores can then be summed (using weights to increase the importance of a specific factor if desired) and the remediation with the highest score would represent the optimum solution for that particular project. This prioritization scheme was used by Xuan (2019) to rank the remediation options for the case histories in Table 5-2.

In addition to prioritizing remediation options at a single site, it may become necessary to rank sites in order to efficiently allocate resource. This could be accomplished through the development of a landslide hazard ranking and prioritization systems (Calvin et al. 2009, Pratt 2014, Hopkins et al. 2003, Maerz et al. 2004, Pierson et al. 2005, NYSDOT 2007, Pensomboon 2007, ORDOT 2001, Burns et al. 2017, Rose 2005, Pack et al. 2002, Eliassen et al. 2007, Eliassen et al. 2015, Hoppe and Whitehouse 2006, Badger et al. 2013, Douglas et al. 2013). While the information gathered for this study would be useful for developing such a system, this was beyond the scope of the current project. Future research could develop such a system for ALDOT to assist with allocating resources for maintaining and repairing slides.

5.4 Options for Mowing-related Failures

Nine additional mowing related case histories were identified (Table 3-3). The remediation options described above have not specifically addressed surface erosion due to mowing-related rutting. These types of failures have not commonly been discussed in the literature and so less information is available on possible remediations. The most effective solution to remediating these types of failures would be to prevent the rutting from occurring in the first place. From discussions with ALDOT personnel, it seems that the rutting is likely due to mowing when the slopes are too wet, using equipment that is too heavy, mowing too often, and not using turf tires on tractors. The effect of reduced mowing frequency is being examined through a pilot vegetation management program at three of the sites listed in Table 3-3: I-22 between mile marker 80.4 and mile marker 74.5, US-82 between mile marker 88.4 and mile marker 83.8, and US-280 between mile marker 99.8 and mile marker 86.5. The results of this pilot study should provide good data for the effects of reducing mowing frequency on the stability of these slopes. Allowing the grass to grow longer will also likely lead to deeper root systems that will help stabilize the soil against future erosion.

For sites where surface erosion has already developed, it is unlikely that these eroded areas will heal themselves without some sort of repair measure. The best option for repairing these areas is likely a combination of shallow reinforcement and vegetation. The goal of the reinforcement is to stabilize the soil until the roots from the vegetation grow deep enough to provide some stability. The reinforcement can be provided by erosion control products, such as cellular confinement systems or anchored wire meshes (Caltrans 2006). Current ALDOT vegetation practices mostly involve placing grass seed, but other types of vegetation with deeper root systems could also be considered. Woody plants and shrubs can be an especially good choice for slope stabilization as they are easier to control and maintain than trees, but provide a deeper stronger root system than grasses (Norris et al. 2008). This is an area which deserves further study to identify which types of plants may provide the best stability, while also being easy to maintain and visually appealing for the traveling public.

5.5 Recommendations for New Slopes

While the current project is focused on remediating landslides it is also important to consider how the trends observed in the landslide database may affect design of new slopes. In this respect several recommendations can be made for designing new slopes:

1. Tall, steep slopes can be designed to be initially stable, but pose significant maintenance challenges as they are difficult to mow and are likely to experience surface erosion as water flows quickly across the face of the slope. Benching slopes can allow for tall slopes to be constructed without some of these issues as the benches provide a break in the water flow and reduce the size of the individual slope faces that must be mowed.
2. Many geologic units within the state have clayey soils within them that are susceptible to strength loss. This strength loss can cause these materials to reach a fully softened strength, which may be significantly lower than the intact strength measured using in-situ or lab tests. This potential for strength loss should be considered in design to ensure that slopes will remain stable even if the material softens. These materials should not be used as fill materials for embankments without considering the potential for shallow failures to develop due to moisture fluctuation.
3. Many of the observed failures occurring in fill sections were shallow, indicating problems with the material placed near the edge of the embankment. For many of the case histories, this material was clay which is susceptible to drainage problems and softening with repeated cycles of wetting and drying. As these materials are often outside of the travel area of the roadway, they may not be subject to the same material and compaction specifications. While this may not affect the initial stability of the embankment, it could lead to longer term problems as these materials may have lower strengths than designed. Placement of low plasticity and granular soils near the edge of embankments may help reduce the likelihood of these shallow failures.
4. Future slope designs may consider including vegetation as part of the design process. Different types of vegetation can be selected for different locations along the slope to provide the maximum benefit in terms of stability, erosion control, and infiltration. This vegetation design process would likely need to be a collaborative effort between design, construction, operations and maintenance personnel to ensure that the selected vegetation plan meets the needs of each of these areas.

5. Many of the case histories examined relied on Standard Penetration Test (SPT) results to estimate soil strengths. This may work well for granular soils, but the SPT can be unreliable for estimating the strength of clayey soils and does not have the ability to estimate softened strengths for clays that may be susceptible to strength loss. Supplementing SPT results with cone penetration test (CPT) data or vane shear test results when fine-grained soils are expected may help provide more reliable strength estimates.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Landslides along highways pose a significant challenge for state and federal transportation agencies. These challenges include direct repair costs, and indirect costs associated with traffic delays and road closures. SSMSs have been developed and implemented by multiple state transportation departments to manage landslide hazards through the collection of slope and landslide attributes. These systems often consist of a data collection system, GIS database, and hazard prioritization system. The goal of these systems is to collect information on the landslide site and adjacent roadway, analyze the data to form spatial and non-spatial correlations, and prioritize remediation and mitigation along hazardous slopes near state highways.

This report described the development of a landslide data collection system and database, which has been used to collect and analyze landslide data for slides along Alabama highways. The current database contains approximately 250 landslides that have occurred over the past 30 years. The system has been integrated into the existing web-based geotechnical database management system used by ALDOT (GeoGIS, Graettinger et al. 2011). Future users will directly enter landslide information into the GeoGIS system using an online user form. The landslide database can then be searched, plotted against other geotechnical data, or downloaded to be analyzed in an external GIS program.

The landslide database developed in this study has several important limitations. The first of these is that the current database is not representative of all of the landslides occurring along Alabama roadways during the past 30 years. The data were collected from available reports, but many landslides are not documented using the reports collected in this study (e.g., those repaired by maintenance crews or in non-federal emergencies). The completeness of the data also varies between the slides based on the information that was available in the reports. To address this, the database has been designed to be routinely updated after its implementation within ALDOT. Landslide report locations also 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 by the visibility of landslides from the roadway. The database may also have a spatial and/or temporal bias due to non-uniform reporting and possible delays between when a failure occurred and when it was reported. While additional work on landslides along Alabama highways remains to be done, the information provided in this study has identified some regions where landslides are both more and less likely to occur. This information can allow ALDOT to better allocate resources and identify areas where further study is needed to explore causes of landslides.

A second set of case histories was collected to document effects of mowing activities on surface erosion on slopes. This damage appears to be occurring when mowing activities cause ruts on the slope face, which remove vegetation and provide areas for water to pool that can lead to surficial failures during subsequent rain events. These types of surface erosion failures are not currently being tracked by ALDOT as repairs of these failures are typically handled by local district forces as part of their normal maintenance duties. These repairs are often considered part of "ditching activities," which can also include repairs to drainage features, constructing a new driveway or entrance onto a state route, and beaver dam removal. While it is not possible to track the exact amount of money spent on repairing surface erosion failures, ALDOT spent more than \$13.7 million on ditching activities between 2014 and 2018. Surface erosion from slopes likely represents a significant portion of these ditching costs.

The landslides collected as part of the database were analyzed to identify common trends, which may offer insight into failure mechanisms. Patterns were examined in terms of geologic group, distance to other landslides, adjacent structures, rainfall leading up to failure, location along roadway, and landslide category. These patterns were then used to select case histories, which could be analyzed in detail to identify applicable remediation measures for different types of landslides. Several remediation options were identified which could be applicable to multiple landslides. A simple prioritization scheme was developed that can be used to rank these options for future landslides.

6.2 Conclusions

Preliminary analysis of the database has shown more landslides are being reported in three geologic groups (Midway, Selma and Wilcox groups) than would be expected based on the length of highway within these groups. These geologic groups are primarily made up of high plasticity clays and interlayered sands and clays. Analyses have also shown that nearly two-thirds of the reported failures in the database occurred within the front slope area of the roadway, which usually indicates an embankment or fill section. The majority of these reported failures were shallow which may indicate issues with material selection or compaction near the edge of the embankments. Failures in the front slope area of the roadway could also be caused by failure within the native materials beneath the fill sections. Additional work is needed to identify the different failure mechanisms that are contributing to this large number of slides.

The emergency relief slides (landslides where repair assistance is requested from the FHWA due to a federally declared disaster) in the current database all occurred after periods of extended and/or heavy rainfall. This rainfall may contribute to slope failures through the reduction in matric suction or increases in pore pressure within the slope, ponding of water in cracks or at the top of a slope, or increases in the height of the water table within the slope (e.g., Duncan et al. 2014). Heavy rainfall can also lead to surface erosion, which may cause shallow failures. The slides within the emergency relief database were analyzed to determine how the distribution of landslides was affected by rainfall quantity. Data from the NWS (2017) were used to determine both the number of slides and length of highway miles within each rainfall range. The results showed that the number of slides generally increased with increasing rainfall after normalizing for the number of highway miles in each category. Exceptions to this trend occurred within the limestone units in the north part of the state, which experienced very heavy rainfall in some of the storms, but had few landslides.

After reviewing the 21 selected landslide case histories (12 from the landslide database and 9 from the mowing-related failures), several remediation options were identified which were not commonly considered in the original landslide reports, but would have likely been useful in several of the case histories. These include the use of recycled plastic pins and vegetative covers (combining vegetation with shallow reinforcement) for shallow failures and the use of shear keys and micropiles or drilled shafts for deep failures. Further details on each of these are discussed in Sections 2.7 and 5.2. The vegetative covers are believed to be especially useful for repairing surface erosion failures caused by drainage issues or rutting on the slopes.

Rutting on slopes due to mowing activity appears to be a significant source of damage to slopes along Alabama highways that is not currently being tracked. Possible explanations for the observed rutting include mowing when the slopes are too wet, using equipment that is too heavy for the slope, mowing too often, and not using turf tires on tractors. The effect of reduced mowing frequency is being examined through a pilot vegetation management program at three sites with a history of mowing-related problems, which should provide good data for the effects of reducing mowing frequency on the stability of these slopes. Allowing the grass to grow longer will also likely lead to deeper root systems that will help stabilize the soil against future erosion. For sites where surface erosion has developed, it is unlikely that these eroded areas will heal themselves without some sort of repair. The best option for repairing these areas is likely a combination of reinforcement and vegetation. Woody plants and shrubs can be an especially good choice for slope stabilization as they are easier to control and maintain than trees, but provide a deeper, stronger root system than grasses (Norris et al. 2008). This is an area that deserves further study to identify which types of plants may provide the best stability, while also being easy to maintain and visually appealing for the traveling public.

6.3 Recommendations for Implementation

The primary objective of the current study was to develop a landslide database that would allow ALDOT engineers and geologists to identify common causes of failure and select remediation options to address these failures. The database developed through this study has accomplished this objective, but it will only be useful in the future if it continues to be updated as new landslides are reported. The database is currently being implemented as a layer in the GeoGIS system used by ALDOT to facilitate this updating. The number of attributes collected for future landslides has been reduced in order to focus on the most important features identified in this study, but additional attributes can be added in the future if ALDOT engineers or geologists require additional information. Updating the database can become the final step in completing a landslide report to ensure that the information is entered in a timely manner.

A large number of landslides are documented using DDIRs when requesting emergency relief funds from FHWA. The standard DDIR forms do not typically contain sufficient information to identify possible movement patterns or likely causes of failure. To alleviate this, an additional form has been developed (Appendix A) to document emergency relief slides. This form should be able to be completed by whoever is submitting the DDIR and will collect enough information to enter the landslide into the GeoGIS landslide layer. It is not likely that all of the information will be collected for each landslide, but using this form will increase the likelihood of the important information being recorded.

Small landslides occurring along Alabama highways are commonly repaired by local crews by cleaning out ditches when they become filled with failed material or placing topsoil or rock to repair damaged areas on the slopes. Costs for these repair efforts are being recorded along with many other types of repairs, but they are not recorded specifically as landslide repair so it is not possible to know how much funding is being spent on these repairs or where in the state they are occurring. Better tracking of these repairs would allow engineers and geologists to identify where these small failures are occurring and possibly intervene before they turn into large failures that may require extensive repairs. As a first step to tracking these repairs, it is recommended that any slope repair performed by ALDOT be reported to the Materials and Tests Bureau including both the location and photos of the site before and after repairs are made. A longer term solution would be to develop a database for completed landslide repairs that could track costs and allow effectiveness of the repairs to be checked over time.

Many of the observed failures occurring in fill sections were shallow, indicating problems with surface drainage and/or the strength of the material placed near the edge of the embankment. Within the selected case histories, the materials in fill sections that experienced failures were often clayey soils, which are prone to drainage problems and potential strength loss. As these materials are often outside of the travel area of the roadway, they may not be subject to the same material and compaction specifications as the rest of the embankment. This may lead to placement of fill materials with lower strengths than designed, leading to future failures and repair costs. It is recommended that specifications for the materials placed near the edges of the embankments be examined to determine if improvements can be made to reduce the number of shallow failures occurring in fill sections.

Ensuring the stability of slopes along highways is often considered a geotechnical concern, but it really requires input from multiple disciplines. When designing new slopes or significant repairs input should be provided from design, operations, construction and maintenance personnel to ensure that the selected design meets the needs of each of these areas. This is especially true for maintenance personnel who will be responsible for mowing the slopes and clearing the drainage features. Discussions between these different areas may identify changes that can be made early in the design to reduce costs associated with maintenance and repairs later.

6.4 Future Studies

As the database developed in this study is updated, it will be useful to reexamine the trends to see if any changes occur over time. Trends within the database could also be examined to identify additional correlations, such as cross-correlations between geologic group and the amount of rainfall to cause failure. These relationships would be useful to create a predictive model for rainfall-induced landslides in Alabama. The information in the database could also be used to develop a landslide hazard ranking and prioritization systems to assist with allocating resources for maintaining and repairing slides. Work on these topics is beyond the scope of the current study, but would represent important topics for future research.

Designing vegetation programs with slope stability in mind could be an effective and cost efficient way to prevent future slope failures. Plants could be selected and combined with geosynthetics to provide shallow reinforcement and reduce the likelihood of erosion. Increasing the use of shrubs and other woody vegetation would also reduce the areas that must be mowed potentially reducing maintenance costs. Further research is need to identify plants that would be suitable for the various areas of Alabama, while providing maximum root reinforcement and minimal maintenance costs. Methods to quantify the effects of the plants on the stability of the slope would also need to be developed and implemented.

Several remediation options have been identified in this study that could be considered for future slope repairs. Among these the most promising are recycled plastic pins, vegetative covers, shear keys, and micropiles or drilled shafts. Pilot studies could be performed on one or more of these techniques to develop design guidance for ALDOT and demonstrate the effectiveness of the technique. These studies should also include a monitoring program to ensure the repair is performing as expected.

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APPENDIX A: EXAMPLE REPORTING FORM FOR LANDSLIDES

Landslide Reporting Form Report or CPMS #:

Completed By: ______________________ Inspection Date: ___________

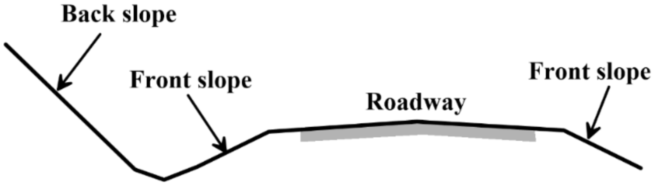
Location

Route Number: ______ Milepost: ____ Direction: ☐ North ☐ South ☐ East ☐ West

County: _____________ Latitude: _ _ . _ _ _ _ _ _° Longitude: _ _ . _ _ _ _ _ _°

Location along roadway:

☐ Front Slope ☐ Back Slope



Failure Description

Landslide Type: ☐ Rotational ☐ Translational ☐ Surface Erosion

See definitions on next page ☐ Fall ☐ Topple ☐ Flow

Slide Material: ○ Earth (predominantly sand and/or clay)
Select best description
○ Debris (20 – 80% of particles are larger than 1 inch)
○ Rock (intact before movement occurred)

Length of slide (ft, parallel to road): ____________ Slope Ratio: ____ H : _____ V

When did the failure occur? Month: ________ Day: _____ Year: _________

Impacts: ☐ Shoulder Closed ☐ Lane Closed ☐ Road Closed ☐ No Traffic Impact

Additional Information

Nearby Structures: ☐ Bridge ☐ Retaining wall ☐ Culvert ☐ Buried Utilities

Other:

Vegetation on Slope: ☐ Grass ☐ Brush ☐ Trees ☐ None

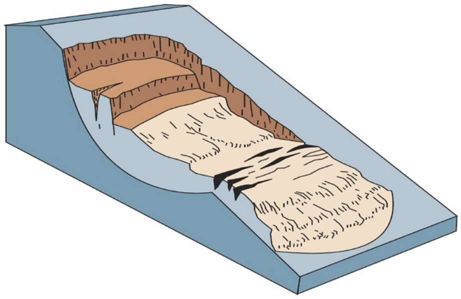
Are there any previously repaired slope failures within 500 feet? ○ Yes ○ No

Is there rutting from vehicle tires on nearby slopes? ○ Yes ○ No

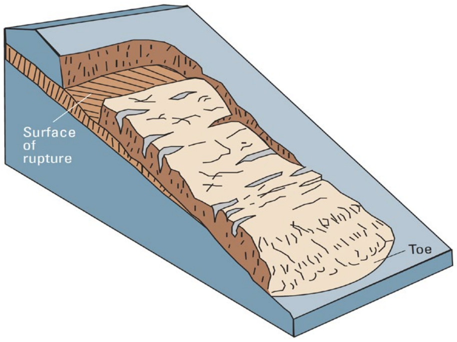
Comments:

Definitions for Landslide Types:

Rotational Slide: Failure occurs on a well-defined curved failure surface. Blocks of failed material can rotate and can at times be seen to tilt backwards towards the slope.

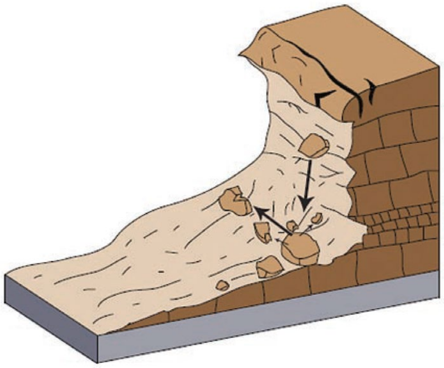


Translational Slide: The mass in a translational landslide moves out, or down and outward, along a relatively flat surface with little rotation or backward tilting.

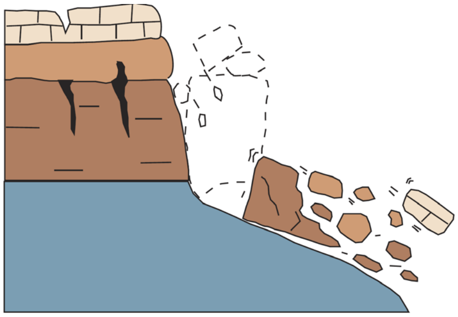


Surface Erosion: The upper few inches to foot of soil is eroded by moving water leaving an area of bare soil behind.

Fall: Pieces of rock or earth, or both, quickly detach from steep slopes or cliffs and collect near the base of the slope.



Topple: A mass of soil or rock rotates out from the intact material (tilting) around an axis (or point) near the base of the block.



Flow: Flows are landslides that involve the movement of material down a slope in the form of a fluid. The failed mass does not usually have a well-defined structure.