ABSTRACT

Title of Document: **SOIL SLOPE FAILURE INVESTIGATION MANAGEMENT SYSTEM.**

Raghav Sarathy Ramanathan, Master of Science, 2012.

Directed By: Professor Ahmet H. Aydilek, Department of Civil and Environmental Engineering.

Highway slopes are exposed to environmental and climatic conditions, such as deforestation, cycles of freezing and thawing weather, heavy storms etc. Over time these climatic conditions can influence slope stability in combination with other factors such as geological formations, slope angle and groundwater conditions. These factors contribute towards causing slope failures that are hazards to highway structures and the traveling public. Consequently, it is crucial to have a soil slope failure investigation management system to track, record, evaluate, analyze and review the soil slope failure data and soil slope remediation data so that cost effective and statistically efficient remedial plans may be developed. This paper presents the framework for developing such a system for The State of Maryland, using a GIS database and a collective overlay of maps to indicate potentially unstable highway slopes through spatial and statistical analysis.

SOIL SLOPE FAILURE INVESTIGATION MANAGEMENT SYSTEM.

By

Raghav Sarathy Ramanathan.

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Advisory Committee:
Professor Ahmet H. Aydilek, Chair
Professor Sherif M. Aggour
Professor Burak F. Tanyu

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CHAPTER 1

INTRODUCTION

Highway slopes are exposed to environmental and climatic conditions, such as cycles of freezing and thawing weather, heavy storms etc. Over time these climatic conditions can influence slope stability in combination with other factors such as geological formations, slope angle and type of slope vegetation. These factors contribute towards causing slope failures that are hazards to highway structures and the traveling public. The Federal Highway Administration (FHWA) has strongly suggested to all States that a landslide and rock slope inventory be developed so cost estimates and, eventually, remedial plans may be developed (Hopkins et al., 2001).

The focus now is on developing an early warning system, using a Geographic Information System (GIS) database and a collective overlay of maps that enables highway engineers to predict soil slides or slope failures in advance. The GIS database records and stores information about previous slope failures such as type and mode of failure, location of failure, slope gradient, slope vegetation, drainage type and remediation methodology. The collective overlay of maps consists of (i) Statewide state of nature maps that include geological formation maps, land cover data, highway slope failure inventory and elevation data, (ii) derivative maps that include data layers derived from the state of nature maps, e.g. Slope angle map, Storm event precipitation map, drainage section map. The system should also allocate weights to all these factors based on the extent of their influence over slope stability and slope failure history.

Movement of soil mass along slopes can now be assessed by incorporating statistical analysis of data collected on the slopes into the assessment system. Many GIS based slope instability assessment systems use different methods to analyze the data collected. Each assessment system may have different sets of parameters or ranking/weightage scheme, as they may be defined for different landscapes. Such a self sustaining system that analyzes the stability of slopes is called as slope stability management system (SMS) (Lee et al., 2006).

Different soil types and slope characteristics have varied levels of impact on parameters involved in analyzing stability of slopes. Although, it seems that many failures occur in highly plastic soils used in embankment construction; various soil slope instability mechanisms, such as surficial failure and rotational failures, have also been observed. Consequently, it is crucial to have a soil slope failure investigation management system to track, record, evaluate, analyze and review the soil slope failure and remediation data. This will provide data to evaluate the causes of soil slope failures and provide design, construction, and maintenance recommendations to minimize the potential of soil slope failures and repair.

The primary objectives of this study were (i) gathering and evaluation of historical data on soil slope failures in the State of Maryland and developing the necessary protocols to incorporate that information into a GIS database, (ii) developing a database structure containing information relating to soil slope failures, and (iii) creating a quantitative model for predicting the probability of failure for highway slopes in the State of Maryland and translating the model output into color coded vulnerability maps.

Currently, the State Highway Administration (SHA) of Maryland does not have a database or management system in place to evaluate and identify the details of highway slope failures, or track the remediation methods and costs. Hence, the immediate need to gather relevant information regarding current and previous highway slope failures is paramount to sustain an efficient SMS. Once all the relevant information relating to the slope failures is documented on site with the aid of adequate tools such as site survey sheets, handheld Global Positioning System

(GPS) devices and other site investigation apparatus, the data must be cataloged and stored in a comprehensive yet user friendly database. This enables faster retrieval of required information at any given time in the future. With this system of recording and storing information in a computerized format setup, the process of evaluating and analyzing data stored becomes a less complicated task with the database being significantly populated.

CHAPTER 2

2.1 INTRODUCTION

SMS are early-warning systems that help formulate land-utilization regulations for minimizing the loss of life and property damage. The Office of Materials and Technology (OMT) has recognized a need to implement an electronic soil slope failure investigation management system to better track, record, evaluate, analyze and review the soil slope failure data and soil slope remediation data on Maryland SHA roadways. Over the years, many soil slope failures have occurred on or near SHA roadways. Figure 2.1 shows a collage of the different types of slope failures that have occurred in the state of Maryland. These soil slope failures have had a negative impact on the public safety and highway safety and cost SHA millions and thousands of dollars. For instance, the repair of the soil slope failure at MD 24 N/B from CSX Bridge to US 40 Connector caused SHA approximately $1.5 million.

Most of the current research focuses on developing an early warning system, using a GIS database and a collection of spatial data that enables prediction of soil slides or slope failures in advance. Such a system should have information on the various factors that influence slope stability and can be grouped into six categories: (i) Slope failure inventory data, (ii) information on geological formations, (iii) slope material and characteristics information, (iv) local topographic information such as slope height and slope angle, (v) remediation and maintenance information and (vi) weather condition information and data on other extraneous phenomenon

The SHA currently does not have a database or management system in place to evaluate and identify the details of these failures, or track the remediation methods and costs. Popescu (1994) has listed a variety of ground conditions that may be conducive for slope instability such as highly plastic soils used in embankment construction, weak and collapsible material, contrast in permeability and stiffness within the fill material, e.g. stiff, dense material over plastic material. Popescu (2002) has also listed several natural geomorphologic processes and man-made physical processes that have a direct impact on soil mass movement in slopes (Table 2.1). The occurrence of these ground conditions and physiological processes individually or in combination can trigger different soil slope instability mechanisms, such as surficial erosion, rotational or transitional failures, rockfalls, slides, spread and debris flow (Cruden and Varnes, 1996). Figure 2.2 shows the different type of soil slope instability mechanisms. Consequently, it is crucial to have a soil slope failure investigation management system to track, record, evaluate, analyze and review the soil slope failure data and soil slope remediation data. This will provide data to evaluate the causes of soil slope failures and provide design, construction, and maintenance recommendations to minimize the potential of soil slope failures and repair.

While many publications discuss in depth on how to categorize slope failures into different hazard levels based on impact and consequences of failure (Pierson et. al, 1990; ODOT, 2001; UDOT, 2001; OHDOT, 2007; NYSDOT, 2007), few address issues regarding prioritizing remediation response towards these failed slopes. This research project has listed out vital factors that should be considered while deliberating upon the type of remediation technique that might be effective for each slope failure and also addresses prioritizing resource and budget allocations for these remediation projects. With this asset management and decision support tool, the SHA of Maryland will be able decide which slope failures would require immediate repair, thereby prioritizing and optimizing their remediation response to slope failures.

2.2 BACKGROUND

Different soil types and slope characteristics will have varied levels of impact on parameters involved in analyzing stability of slopes. Hence there are many SMSs currently in use in many parts of the world. According to Rose (2005), as of 2005 ten states and four countries have adopted slope stability management programs to help identify unstable slopes for remediation. The following pages will discuss in detail, various slope management programs developed by different Departments of Transportation (DOTs) that are used in slope stability assessment.

As discussed above, different SMSs have different methods of ranking and analysis. However data analysis methods used by SMSs are broadly classified into three types (Glade et al., 2005): (i) Expert analysis or heuristic analysis, (ii) statistical analysis of historic events, and (iii) mechanical approach.

Heuristic or expert evaluation analysis makes use of past experience of experts who sets guidelines to analyze slope failures based on evolution of ground movements and failure modes and mechanisms that control the occurrence of such phenomenon. Even though the method is commonly used, it is a very subjective approach towards determining potentially unstable slopes and is the most widely used method up to the present (Glade et al., 2005).

Statistical analysis makes use of regression functions and distribution curves to predict slope failure based on data collected from site or from the laboratory. It overcomes the insufficiencies inherent in the heuristic or experience based approach. Most of these models are created using GIS software by the use of probabilistic analysis by linearizing variables that are considered to affect slope stability (Hansen, 1984).

Mechanical analysis involves calculating a stability coefficient, i.e. Factor of Safety from specific 1D, 2D or even 3D slope stability models. The choice of the model depends on the data availability of the various input parameters (Cruden and Fell, 2001).

Various SMS have been developed and each system is unique in its own particular way, i.e. it may differ in the type of modeling technique used, or differ in reliability models used etc. But all these SMS have the following components, which are vital for any such assessment model:

a) Data collection and verification system

b) GIS database management system

c) Index maps

d) Statistical or deterministic model

e) Validation of model

The first two components are complementary and used together. A data collection system needs to be integrated with a GIS database, thus making it easy for retrieval, manipulation and review. Also this integration of the two components creates a data mine that is compatible with all mapping software, thus enabling projection of the data onto maps.

Figure 2.3 shows the proposed framework for developing the slope stability management system; based on the Unstable Slope Management Systems adopted by different states across the USA which have more or less a similar framework for the rating system. The SMS currently in use by other states were used as a benchmark or platform for selection of rating criterion and field classification of failures and other such input parameters.

Most of the unstable Slope Management Systems are based on the Rockfall Hazard Rating system (RHRS) developed by the Oregon Dept. of Transportation (ODOT). This system was proposed by Pierson et al. (1990) with the intent of proactive rockfall site identification and prioritization. The project was funded by the Federal Highway Administration (FHWA) and ten other states.

The FHWA has developed a Rockfall Database Management Program (RDMP) specifically for the RHRS. The program has a standalone database that does not require any supporting software, which offers the advantage of allowing rapid transfer of information (Pierson et al., 1990). A total of 3000 slope were inventoried, and subjectively classified into categories A, B and C. Where A and B categories consists of rock slopes that have a higher probability of failure and may have severe consequences in the case of failures and are further classified based on a ranking system developed by the TDOT. Category C consists of slopes that are weathered by erosion and hence neglected. Categories A and B are further investigated and rated using field sheets and an exponential scoring system with a base of 3.

Tennessee DOT has developed GIS application for the management of landslides along the Tennessee highways. This application includes the development of a statewide landslide database and the production of 31 thematic maps accessible via the Internet. Essential information pertaining to a landslide include: (i) attribute data e.g. type of slide, surficial geology, remedial actions taken, and associated costs, (ii) temporal data e.g. as dates of landslide activity and remedial actions, and (iii) spatial data e.g. geographic location of the landslide, site special geological conditions and nearby related features. The GIS landslide database is linked with the above-mentioned attribute, temporal and spatial data, in an geodatabase for cataloguing, visualizing and managing landslides along the State Routes and Interstate Highways (Rose, 2005).

Kentucky Transportation Cabinet (KyTC) together with the University of Kentucky has also carried out similar type of work. The database developed by KyTC consists of rock slope, landslide and soil and rock engineering data for risk management of landslides and rock slopes. More than 10,000 rock slopes were examined and were rated using the RHRS. The ratings provide a priority list of sites which require immediate remedial or mitigation measures. A geotechnical database was created using Oracle database software which stored rock slope and landslide attributes along with location information and site photographs. The rock slope and landslide segments of the geotechnical database establish a program for allocating funding for remediation of slopes that are identified as high risk (Hopkins, et al., 2001).

The Washington State Department of Transportation (WSDOT) has developed the Unstable Slope Management System (USMS) since 1993, which can be used for both rock-falls and landslides. Both slope condition and economic assessment were incorporated in the strategy for managing slopes. The information used for assessing slope conditions included the location of slope, whether the slope is on left or right of centerline, type of instabilities and frequency of slope failure. Economic assessment includes the estimation of annual maintenance cost associated with mitigating the unstable slope (Lowell et al., 2002).

The Ohio Department of Transportation uses the Geological Hazard Management System (GHMS) to manage geological hazards data and activities related to planning, design, construction, and maintenance. The geological hazards include abandoned underground mines, karsts, and shoreline erosion. In 2007, a landslide hazard rating system was developed for the Ohio DOT and incorporated into the GHMS (Liang, 2007). This system evaluates six landslide risk factors that potentially impact the safety and operation of a roadway and adjacent highway structures. Each of the risk factors is rated using a scoring system similar to ODOT. The numerical scores of 3, 9, 27 and 81 represent the increasing hazard of each factor.

The Alaska Dept. of Transportation (AKDOT) has a three step procedure to rate slopes. The first step involves preliminary rating of slopes into three categories: A (high probability of failure), B (moderate probability of failure) and C (low probability of failure). The second step is the slope hazard assessment. In this step, the slopes categorized into A and B receive a detailed assessment based on the Hazard Score calculated from the information obtained through field visit. The final step is the slope risk assessment. Here the slopes are assessed based on the severity of hazard calculated from the previous step, maintenance frequency and annual maintenance cost (Huang et al., 2009).

The SMS developed in Taiwan is built on a well designed Management Information Systems (MIS). The information stored in the MIS can be displayed using the functionalities of GIS. Then the influence of various factors on landslides is assessed. The SMS is capable of accepting more than one format of input. Also, maintenance and monitoring information of slopes is given priority in the frame work. All data collected is thoroughly and meticulously classified and indexed into different databases. Hence, this SMS has 4 different databases based on the categories of data collected. . It also allows for cross-database search process. The search engine can search for records with either administrative regions or data types as queries (Lee, et al., 2006).

In summary, all the SMS discussed above despite using quantitative analysis in calculating hazard indices for rating unstable slopes, have an inherent factor of subjectivity linked with the analysis. Table 2.2 lists some of the DOTs that have adopted SMSs and the number of slopes analyzed in respective studies. Table 2.3 highlights the pros and cons of the various SMS adopted by different state agencies in the USA. Most of the survey forms used by the DOTs to record failure information require the engineer on site to make expert judgments regarding slope failure characteristics and attributes. This might lead to over compensated hazard rating of relatively less hazardous slopes. It is this inherent drawback in the reviewed programs that is attempted to be addressed while developing the SMS for the State of Maryland.

2.3 SMS COMPONENTS

One of the crucial issues in GIS-based hazard assessment is the availability of suitable input data, which remain fundamentally inadequate in quantity and quality for the intended task (Huabin, et al., 2005). Since the GIS database is a central source for majority of information relating to slope failure data it is vital to review data collection procedures followed in the field for identifying the source of errors and uncertainty in site investigation techniques.

Virtually all the instability factors collected in the field or derived in laboratory are affected by inaccuracies or errors whose magnitude cannot readily be estimated or controlled during the subsequent phase of data analysis or modeling (Carrara et al., 1995). Thus, it is important to preserve and maintain homogeneity throughout the process of data collection in the field. For this purpose, it is essential to have a systematic method of approach towards data collection and this requirement was satisfied by developing a slope failure field sheet which is discussed in detail in the latter part of the chapter.

Two fundamental rules must be observed when creating a database (Leroi, 1997): the information must be homogeneous, i.e., it must have the same work scale and the same geographic projection system, and the database must be organized into basic monothematic layers, each of which contains homogeneous data (Carrara et al., 1999).

A rough outline of tasks involved in developing the database system maybe listed as follows (Pierson et al., 1990):

Preliminary data collection: All slope failures reported to the SHA office are visited by field engineers in person, and necessary data regarding these slope failures is collected using the failure field sheet.

Database population: All the data recorded using the failure field sheet is keyed into the database using a simple Graphic User Interface (GUI).

Design recommendation and cost estimate: Design recommendations and cost estimations are based on factors such as Highway classification, Ratio of maintenance cost to repair cost and Frequency of maintenance and related projects.

Annual review and update: An annual report is prepared on the efficiency of the system in place and based on feedback from the report and engineers using the system necessary changes and updates are made to ensure enhanced performance of system.

There are four primary components of the SMS developed for the State of Maryland. They are: (i) MS Access database, (ii) Failure field sheet and remediation response categorization, (iii) eGIS slope failure content, and (iv) Failure density mapping. The first 3 components will be discussed in detail in the following pages of this chapter and the final component will be discussed in the latter part of this document.

2.3.1 MS Access database

The database for the SMS was developed using MS Access and consists of 8 different tables. The first step taken towards developing the database was to decide on an efficient data-structure. Figure 2.4 shows the relationship tree of the database. The fields in each of the tables were arranged and grouped so that fields relevant to that particular table remained together. Each table represented similar fields that contributed to a particular aspect of slope stability management. Each table consists of a unique field that is assigned the role of a primary key, which enables the user or the software to uniquely identify any particular record. Each of these primary keys form links between the tables, thus making it easy to access information from more than one particular table at the same time.

As shown in Figure 2.4, the primary key for each table is the Project ID field which is an auto-generated number by the software for each particular record. The data structure is such that there is one primary table to which all other tables are linked (Figure 2.4). This enhances data management tasks such as creating new records, editing and deleting existing records. The 8 tables constituting the database are listed as follows:

I. Failure type and location information table

II. Dimensions of failure table

III. Cause of failure information

IV. Failure impact table

V. Slope materials information table

VI. Slope characteristics table

VII. Remediation information table

VIII. Vegetation information table

Failure type and location information is the primary table, to which all other tables are linked. This table, as the name suggests, records and stores information relating to the location and type of failure. Information relating to location constitutes GPS coordinates, Northing and Easting values, Mile point information, Route number and name. Failure type information constitutes information about the mechanism of failure and weather conditions before failure, Project description provided for each case by the SHA, Contract # and FMIS# and other identity related information; which is the reason this table is assigned the role as the primary table.

The dimensions of different aspects of the slope failure such as apparent depth of failure, scarp depth and width, distance of failure surface from original slope crown and toe, slope angle and slope height are recorded in the dimensions of failure table. These data are collected for different modes of failure. The cause of failure information table consists of information relating to natural or human activities that contributed towards the failure of the highway slope.

The failure impact table records information regarding the current and future potential of the slope failure to affect existing roadway and roadway structures. This section requires the engineer to make a subjective evaluation of the failure site and decide on the potential of the slope failure to affect roadway and structures beyond right of way of the Maryland SHA.

The slope materials information table records data pertaining to the origin of soil or rock type on slope, the soil type occurring on the failed slope and the physiographic classification of the failed slope.

The slope characteristics information table records data relating to the slope aspect: convex or concave, slope gradient, vegetation density on slope, surface and sub surface drainage conditions, surface water conditions and groundwater conditions. Vegetation information table stores the percentage distribution of vegetation or land cover type present on the failed slope.

The remediation information table stores data relating to the existing remedial activities present on site, the suggested remediation methodology, the remediation start and end date and the remediation status of the failed slope and the cost of construction of remediation. Vegetation information table stores the percentage distribution of vegetation or land cover type present on the failed slope.

These tables consist of information collected from the field using failure field sheets (Appendix A). The Failure Field Sheet in essence is similar to the survey sheets used by engineers on site. The Field Sheet is a form which records only that information related to slope failure which may be used for further analysis and aid in hazard rating of that particular failure, thereby eliminating the collection of data that may be irrelevant or not directly related to stability analysis and slope hazard rating and is discussed in detail in the following section.

2.3.2 Failure Field Sheet and Remediation Response Categorization

2.3.2.1 Failure Field Sheet

The Failure Field Sheet in essence is similar to the survey sheets used by engineers on site. In a broad sense, it may also be referred to as the input for the SMS. The Field Sheet is a form which records only that information related to slope failure which may be used for further analysis and aid in hazard rating of that particular failure, thereby eliminating the collection of data that may be irrelevant or not directly related to stability analysis and slope hazard rating.

The purpose of the Failure Field Sheet is to standardize the current approach followed by engineers on site with regard to highway slope failures reported to and dealt with by the SHA, Maryland. It also ensures that data is collected in a consistent and uniform manner.

The failure field sheet has provisions to record parameters such as the type of slope (cut, fill, mechanically-stabilized fill etc), types of failures, scale of failures, causes of failures, and mitigation methodologies. Information regarding these parameters is recognized as the most important data to evaluate failure potential as well as performance of slope stability (OHDOT, 2007; AKDOT, 2009; WSDOT, 2002; Lee et al, 2006). These records will be collected to analyze the influence of factors of slope stabilization and evaluate mitigation performance.

This is a vital component of any SMS. The Federal Highway Administration's highway slope maintenance manual has such a form that may be used to survey slope failure sites and is called the slope inspection manual. The slope inspection manual has the provision to record the most basic and rudimentary information regarding slope failures. The failure field sheet derives upon the slope inspection manual provided by the Federal Highway Administration as a base content and adding upon it based on syntheses of expert opinions of Maryland SHA engineers and data collection practices followed by other state agencies.

When a highway slope failure is reported to the Maryland SHA, engineers from the Office of Materials Technology visit the failure site to record initial failure information. Upon arrival at the failure site, the engineers perform a preliminary inspection of the failure site during which they fill in sections 1 and 2 of the failure field sheet. These include establishing general site information such as GPS coordinates- latitude and longitude in decimal degrees with a precision of at least 5 digits, recording Milepoint data, route information, location of failure with respect to roadway, type of failure based on the classification provided in the field sheet. If multiple failures occur along the same highway, a note must be made of the total number of failure sites along the particular highway. Also the weather conditions immediately before failure is retroactively determined and recorded.

The engineers then proceed to measure the various dimensions of failure as illustrated in section 3 of the failure field sheet (Appendix A, page 3). Section 4 requires the engineers to provide a subjective evaluation regarding the potential of the highway slope failure to cause further damage to roadway and structures beyond right of way of the Maryland SHA. In this section, engineers are also required to measure the extent of slope movements by recording the dimensions of dips and cracks visible along the roadway. During the preliminary examination, the structures and utilities in the vicinity of failure are observed and recorded. Also, the type of land usage classification based on section 5 of the failure field sheet is recorded. In section 6, the engineers make note of those structures or utilities that are affected by the highway slope failure.

Once this is complete, the engineers based on in-situ tests and expert opinions establish the slope characteristics information, record vegetation information and soil type data (sections 7 and 8). Also, the cause of failure is determined and recorded using the provisions provided in section 10 of the failure field sheet.

Section 9 is used by engineers to record the existing remediation activities observed on site. Section 10 provides a comprehensive list of slope remediation methodologies. The engineers may provide or suggest ideal remediation methods based on the list provided in this section. Section 11 is used to monitor the remediation phase of a highway slope failure.

All information recorded in the failure field sheet is currently preserved in paper format. The data stored in paper format is transferred to electronic format, by keying in all information into the Oracle database through the eGIS application interface. The eGIS application developed by the Highway Information and Services Division (HISD) of the Maryland SHA is described in detail in the latter part of this chapter.

2.3.2.2 Remediation Response Categorization

The remediation response categorization is included as another component of the SMS to help prioritize the remediation response adopted for the various highway slope failures in the state of Maryland based on an extensive set of categories that are considered to affect the functionality of highways. For example, a particular highway slope failure with high potential to affect the roadway would require immediate attention when compared to another highway slope failure with lower potential to affect the roadway.

As it is impossible to eliminate the subjective bias in determining which of the highway slope failures require immediate attention in relation to the other highway slope failures, a set of parameters that are considered to affect the remediation response for any highway slope failure is introduced to reduce the influence of subjectivity.

The primary purpose of this component is to assign priority for remediation of certain highway slope failures over others based on a range of parameters considered to affect the proper functioning of the highway. Another purpose of this component is to help the Maryland SHA with budget allocation for remediation of highway slope failures. With this component in place, the Maryland SHA would be able to allocate their resources and plan their budgeting appropriately between the various remediation projects effectively; thus saving a significant amount on time and money.

With the SMS being in its nascent stage and its framework being setup recently, the functionality of this component is yet to be formulated in the decision making process of the Maryland SHA. Currently, the remediation response categorization is included as a recommendation sheet along with the final geotechnical report submitted following thorough analysis of the highway slope failure. The sheet provides information on the list of the categories considered while deliberating on the remediation response and will be used as a guide for the engineer to decide on the remediation and maintenance techniques to be implemented. The format of the remediation response categorization sheet is as shown in Figure B.1 in Appendix B.

This section discusses the various categories considered to affect the remediation response towards highways slope failures and how they were shortlisted. The complete list of categories shortlisted and their definitions is provided in Table B.1.

It was decided that a document containing a list of categories that might influence the SHA's remediation response towards highway slope failures would be circulated among engineering staff at the OMT of Maryland SHA. The engineering staff would then provide their recommendations regarding the order or hierarchy of importance of the said categories.

The engineers were asked to assign numbers between 1 and 16 (1 being most important and 16 being the least important) on a survey sheet attached for each of the 16 categories based on their subjective evaluation of the system. These numbers are referred to as hierarchy numbers. This exercise proved to be very productive and brought to light newer categories that might influence the manner in which SHA or a district office may deal with a highway slope failure. The hierarchy numbers provided by the engineers were fed into a MS Excel sheet and the mean hierarchy number for each of the categories was calculated following which the standard deviation for each of the categories were calculated.

Table B.2 provides the hierarchy numbers assigned by the different engineers along with the mean and standard deviation for each category. Categories suggested by engineers during the rating process are shaded in grey (Table B.2). In addition to completing the survey sheet, many engineers provided their recommendations and suggestions to further develop the rating system

Some of the engineers had suggested that newer categories be included. The list of suggested additions to the category sheet is: (i) Distance to closest structure, (ii) Type of structure, (iii) Groundwater conditions, (iv) Vegetation conditions, (v) Utility impact, (vi) Rate of slope movement, (vii) Slope material properties, (viii) Subsurface conditions, (ix) Drainage and seepage conditions, (x) Availability of detour route, and (xi) Numbers of utilities affected.

2.3.3 eGIS Slope Failure Content

The Enterprise GIS (eGIS) Portal web application is an Intranet application utilized by the Maryland State Highway Administration to display, edit, and manage its valuable data. The portal provides broad access to geospatial information to foster collaboration between business units and to support critical business functions. The Office of Materials and Technology (OMT) utilizes eGIS to display, edit, and create slope failures along Maryland roads. Furthermore, users can upload pictures of the slope failure site, hyperlink to as-built plans and geotechnical reports.

2.3.3.1 System architecture

eGIS utilizes a security architecture to facilitate and administrator defined user groups and roles. Figure 2.5 depicts the high-level system architecture for the eGIS application. The eGIS Portal is dependent upon a number of external systems: (i) ArcGIS servers, (ii) eGIS web application and (iii) supplemental services and applications.

The ArcGIS server stores all GIS data in the form of Geometry services or Map services. A map service enables publishing maps, features and data attributes on the web and creating user interfaces. Map services make the data stored in GIS layers available inside various applications accessible via internet or intranet thus catering to a wide range of users. A Geometry service helps web applications to perform geospatial and geometric calculations such as buffering, simplifying, calculating areas and lengths, and projecting.

The ArcGIS server system is setup such that it relies on cached and non-cached map services for most of its map data. Feature services are also usable for editing. A geometry service is used for specific cases throughout the portal.

The configuration and content system works through the eGIS web application. This application enables the users to print maps and also generate MS Excel files from the web portal on to the desktop using tools available in the geometry service. The data is retrieved through the ArcGIS server Map services.

Applications, web sites, and documents can be linked through a variety of means from the eGIS portal; external applications can link to the eGIS system, and if necessary, pass different parameters to focus the user to the necessary data of the application. Widgets, custom result grids, and other functions can rely on other services developed in a variety of ways to provide functionality and data to the specific workflows. The various components of the eGIS application are shown in Figure 2.6.

The eGIS architecture leverages ESRI's "Widget Framework" allowing the application to be easily extended as new features and capabilities are required. The eGIS slope failure content has three widgets to maintain soil slope failures: Details, Edit, Create. The next section will explain the workflow and functionality of the widgets.

2.3.3.2 Workflow and widget functionality

The eGIS slope failure content has three widgets to maintain soil slope failures: Details, Edit, Create. The Details widget displays important and relevant slope failure information based on search parameters. The Edit widget enables engineers to edit slope failure information stored in the database. The Create widget enables users to report a slope failure by creating a new feature on the map content. Figure 2.7 shows the workflow for the slope failure content within the OMT.

The Create widget enables users to create slope failures for OMT approval. The eGIS user determines if the slope failure is emergency or non-emergency, inputs the Failure Date on a preset Calendar and includes their Contact Information of the Create Slope Widget. The Slope Failure location is entered by a Location coordinate or Route information and mile marker. Upon completion of the Create Slope, an email is generated and sent to the OMT Staff which includes the pertinent slope failure information as well as any pictures the eGIS user attaches. The widget uses a security setup where groups and roles are defined for the OMT staff. The email is sent to a pre-defined group using the security parameters. Figure 2.8 shows screenshots of the Create failure widget.

eGIS users utilize the Slope Search Widget to find slope failures based on spatial reference or attribute information. Users can query on slope failures within a SHA District, County, along a route type or a specific route. In addition, users can look for specific attribute information with a spatial reference. Figure 2.9 shows screenshots of the slope search widget

When a slope failure is selected in the eGIS Web Application, the user reviews attribute information for the record in the query results window located at the bottom of the eGIS Window. This panel is configurable by the eGIS Technical Team along with the data owner. Together they determine which fields are presented in the query results grid. By using the "Details" Function, the application invokes the Details Widget which provides further attribute information from the map service. This is configurable in the widget and determined by the data owner which fields are presented. Figure 2.10 shows the list of data currently displayed by in the details tab.

The OMT Slope Editor Group has permissions to edit slope attributes using the "Slope Edit" widget. The Slope Edit Widget updates an Oracle table that replaces the current OMT Access database. The widget uses text fields, pull down menus, multi text boxes and comment fields to maintain the attribution of slope failures. If an eGIS User does not have access to the widget, the widget will be grayed out. Edits made to the slope attribute record are saved in real-time. The Slope Edit is invoked from the Results Grid under the Functions called "Edit." The Slope Edit Widget has 13 tabs. Each updates a separate Oracle table. The following section lists specific information about the Oracle tables mentioned. Figure 2.11 shows the multiple tabs of the editor widget.

2.3.3.3 Oracle SDE database

All these widgets enable SHA users to manipulate the slope failure information stored in an Oracle 11g SDE database. The Oracle SDE database stores all data relevant to the slope failures that have occurred in the State of Maryland. It also consists of data stored in the MS Access database mentioned previously.

The reason for migration from MS Access database file to an Oracle SDE database is that it allows for higher data volume and efficient processing. An Oracle SDE database also provides advanced spatial features and supports high-end GIS solutions.

The MVA Center in Glen Burnie, MD is SHA's central repository of Information Technology servers. The GIS Services Team within the Highway Information Services Division (HISD) maintains the only spatial license/tables for Oracle SDE at the Maryland SHA. The Slope Failure Access tables have been converted to Oracle 11g relational tables stored at the MVA Center. There is one spatial Oracle SDE table and 13 related attribute tables. They are: (i) Project Description, (ii) Site Info, (iii) Failure Type, (iv) Failure Dimensions, (v) Impact Assessment, (vi) Adjacent Structures, (vii) Affected Structures, (viii) Materials, (ix) Characteristics, (x) Observed Remediation, (xi) Cause of Failure, (xii) Suggested Remediation, and (xiii) Remediation Information

The spatial information is stored with PROJECTID as the primary key. Figure 2.12 shows the relationship tree between the multiple Oracle SDE tables stored in the database.

2.4 CONCLUSIONS

A comprehensive management and assessment system has been developed to allow the SHA to better record, evaluate, analyze and review the soil slope failure data and soil slope remediation data, provide recommendations and guidelines for design and maintain embankment and cut soil slopes. The system consists of three components, each aiding in three different phases of highway soil slope management.

The first phase in monitoring and evaluating highway soil slopes is gathering and evaluation of historical data on soil slope failures in the State of Maryland and developing the necessary protocols to incorporate that information into a Geographic Information System (GIS) type database. The component aiding in this phase is the failure field sheet, which facilitates Maryland SHA engineers to collect useful data, by extracting all available soil slope failure and remediation data from the SHA project files and by visiting locations of existing soil slope failures.

The collected data will include the type of slope (cut, fill, mechanically-stabilized, etc), types of failures, scale of failures, causes of failures, and mitigation methodologies. Information regarding these parameters is recognized as the most important data to evaluate failure potential as well as performance of slope stability. These records will be collected to analyze the influence of factors of slope stabilization and evaluate mitigation performance. The failure field sheet has significantly optimized the daunting task of data collection and ensured consistency in collecting high quality information, based on feedback from Maryland SHA engineers.

The second phase is storing and retrieval of the data collected in the field through a web based GIS package. The eGIS slope failure content enables SHA users to view, store, edit and create slope failure records through the SHA intranet. The GIS content developed by the HISD ensures quick and easy access to engineers for data manipulation and analysis. This application also enables data sharing and other cooperative ventures at a wide range.

A database structure containing information relating to soil slope failures or distresses was developed using MS Access. This database structure was then organized into a web-based relational GIS type database with multiple tables for storing site location information, project description, slope characteristics and material information, remediation and maintenance information, type of failure, failure mechanisms and failure dimensions using Oracle SDE tables. All the information stored in the database and analyzed results can now be visualized by using GIS features.

Currently, information relating to 49 highway slope failure sites is stored in the GIS database. Of the 49 highway slope failure cases, information for 18 failure sites were filled in retroactively from site photographs, as built plans, geotechnical reports, boring logs and firsthand accounts of SHA engineers. The information for the other 30 slope failure sites were recorded using failure field sheets on site visits by engineers.

The third and final phase of the slope stability management is system is providing recommendations and guidelines for remediation design and maintenance. Taking into consideration the liability and legal issues that might arise due to the limited number of slope failure datasets and incomplete information regarding remediation information and cost of construction, it was considered premature to perform cost-to-benefit analysis for each type of slope failure and remediation methodology. Since the framework for such a system has just been developed and with further population of the database, coupled with routine inspection and maintenance information, there is definitely a scope for development of a decision based model to ascertain the most cost effective and efficient remediation methodology for a particular type of failure. To respond to this need at present, engineers make use of the remediation response categorization sheet which lists a set of parameters considered to influence Maryland SHA’s response to highway slope failures as discussed in previous sections.

TABLES

Table 2.1: List of landslide causal factors (Source: Popescu, 1994)

1. Ground Conditions
(i) Composition
- Plastic material
- Collapsible material
- Weathered material
- Jointed and fissured material
(ii) Structure
- Mass discontinuities
- Structural discontinuities
(iii) Stratification
- Contrast in permeability and stiffness
2. Geomorphological processes
(i) Erosion - Glacial, fluvial, wave, winds, freezing and thawing
(ii) Transitory - Earthquakes, tectonic uplift, Volcanic uplift
(iii) Deposition loading
(iv) Vegetation removal - erosion, forest fire, drought
3. Physical processes
(i) Intense rainfall
(ii) Rapid melt of deep snow
(iii) prolonged precipitation
(iv) Freezing and thawing cycles
(v) Rapid drawdown - floods, high tides, breaching of dams
4. Man-made processes
(i) Construction - Cuts and excavations, Blasting, Drilling, Heavy machinery
(ii) Removal of retaining walls or sheet piles
(iii) Drawdown (e.g. Lakes, reservoirs, lagoons)
(iv) Deforestation

Table 2.2: List of existing SMS at different DOTs (Source: Lowell et al., 2002)

Organization	Number of sites analyzed
Oregon DOT	3000+
Utah DOT	1099
New York DOT	1700
New Hampshire DOT	85
Missouri DOT	300
Idaho DOT	950
North Carolina DOT	1 (20 mile section of roadway)
Washington State DOT	2500
Kentucky DOT	1800
Tennessee DOT	1943
British Columbia Ministry of Transportation and Highways (MOTH)	N/A
Canadian Pacific Rail	N/A
Ontario MOTH	N/A
Italy	7
Hong Kong Geotechnical Engineering Office	1400
Scottish Office Industry Departmentl Roads Directorate	N/A

Table 2.3: List of Pros and Cons of other unstable slope management programs currently adopted in the USA

SMS Program	Pros	Cons
ODOT	+ Strong rating system + Includes asset management	- Lacks asset management - Does not include soil slopes, fill failures or frozen ground
OHDOT	+ Rates rock slope, soil slopes, and embankments	- Complex and lengthy review procedures
NYSDOT	+ Includes risk assessment	- Does not include soil slopes, fill failures or frozen ground
UDOT	+ Includes risk assessment with adjustments for geology	- Does not include soil slopes, fill failures or frozen ground
WSDOT	+ Good risk and asset manangement program	- Does not include soil slopes, fill failures or frozen ground
TDOT	+ Balanced hazard and risk assessment	- Does not include soil slopes, fill failures or frozen ground - Lacks asset management
AKDOT	+ Rates rock slope, soil slopes, and embankments + Accounts for frozen soils + Strong rating system	- Complex and lengthy data collection procedure

FIGURES

Figure 2.1: A collage of the different types of slope failures that have occurred in the State of Maryland

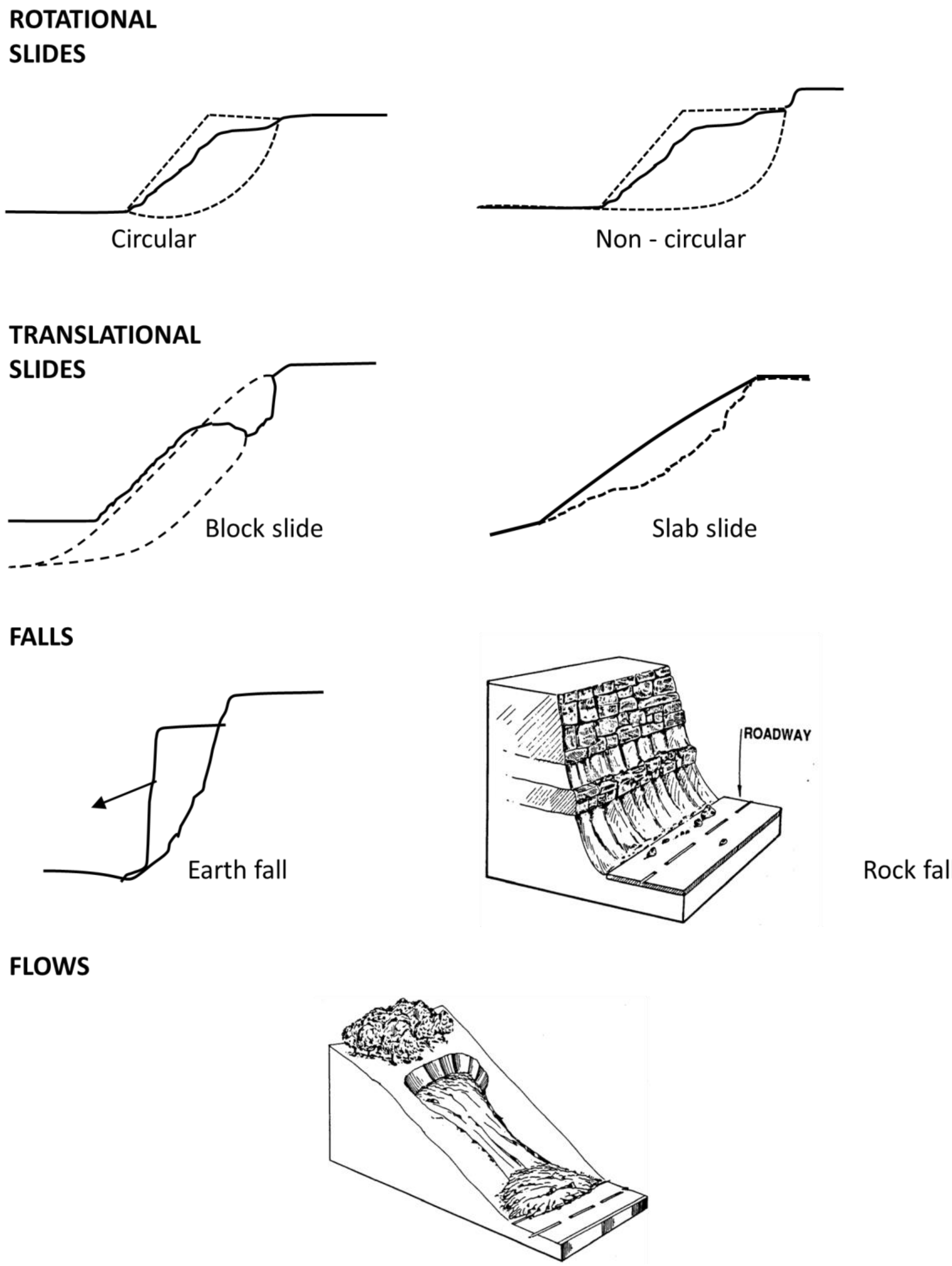


Figure 2.2: Types of landslides (USGS Fact Sheet 2004-3072)

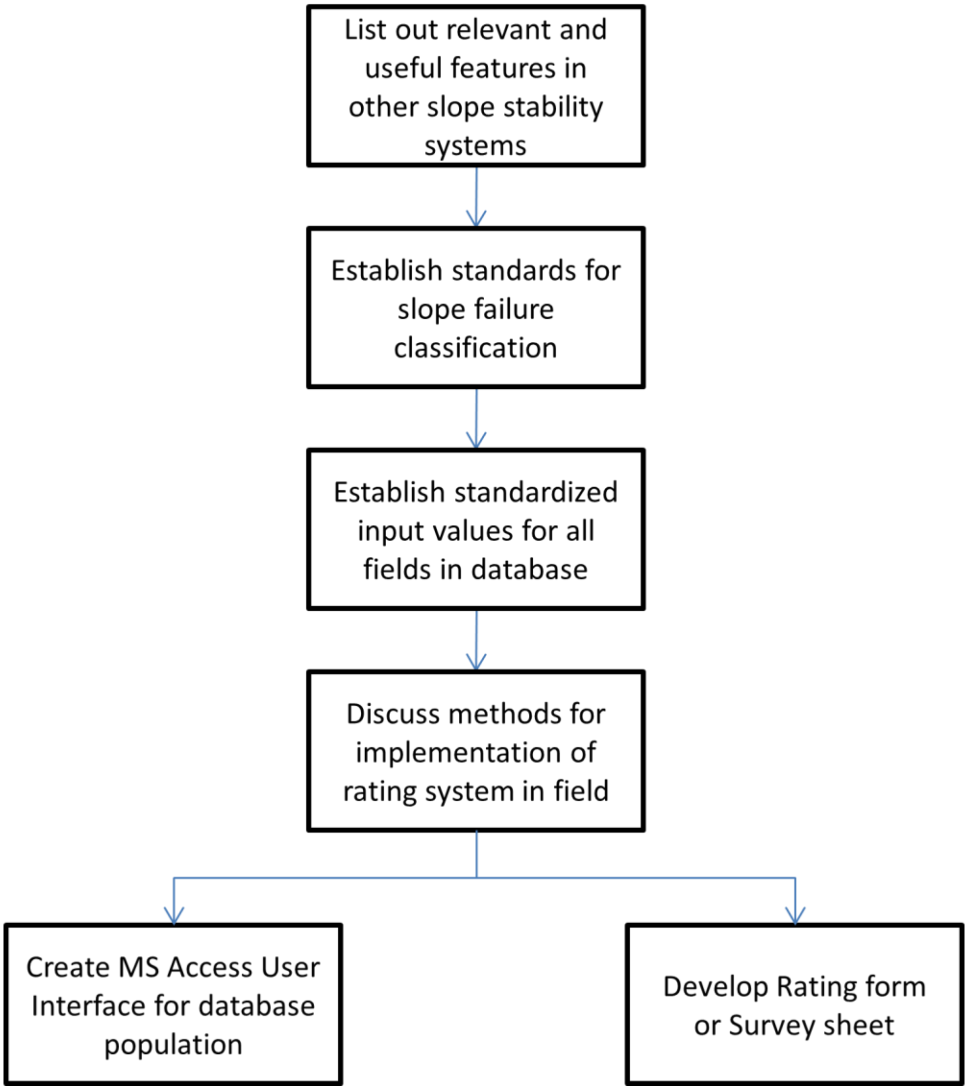


Figure 2.3: Proposed framework for developing a Slope Management System

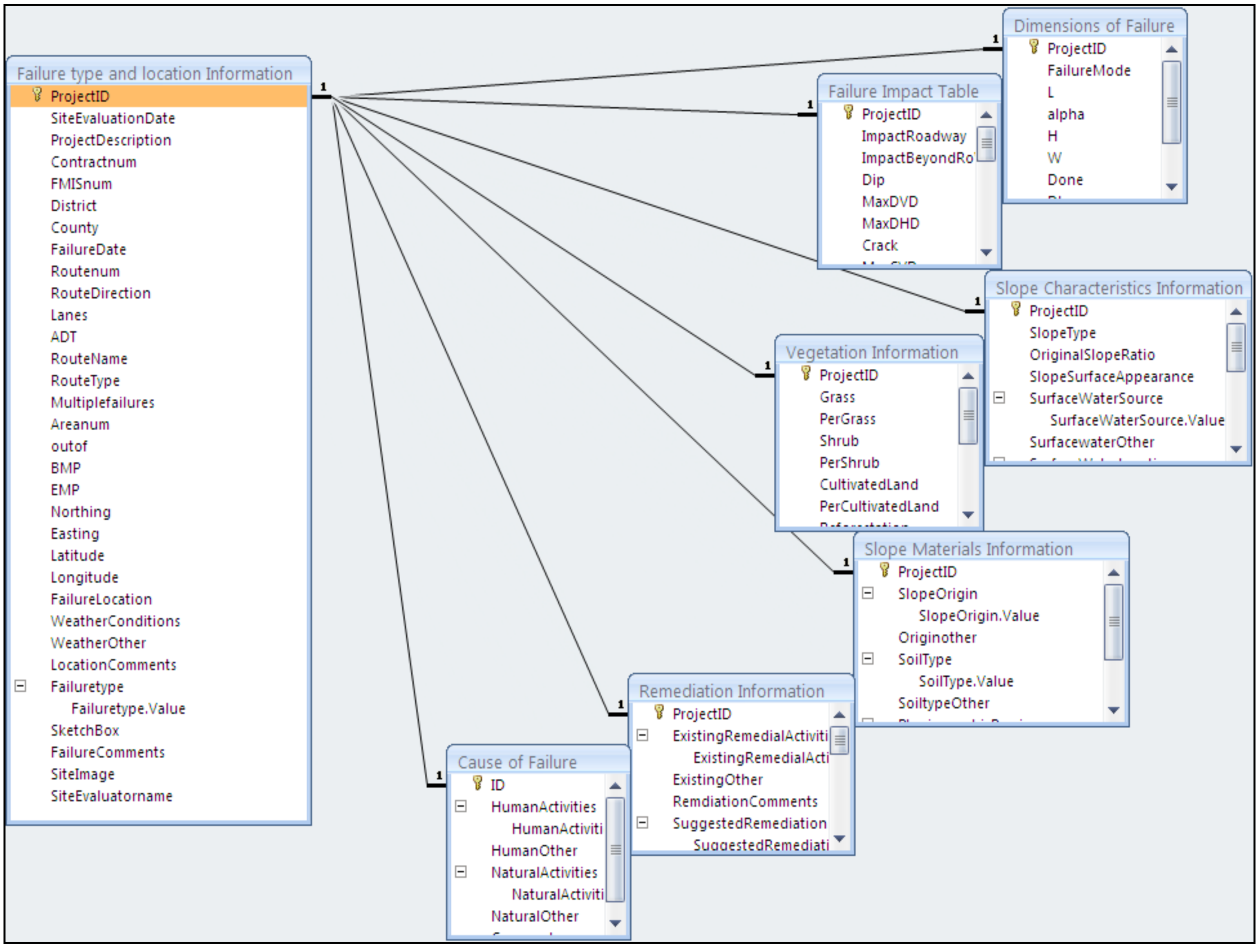


Figure 2.4: The relationship tree for the MS Access database

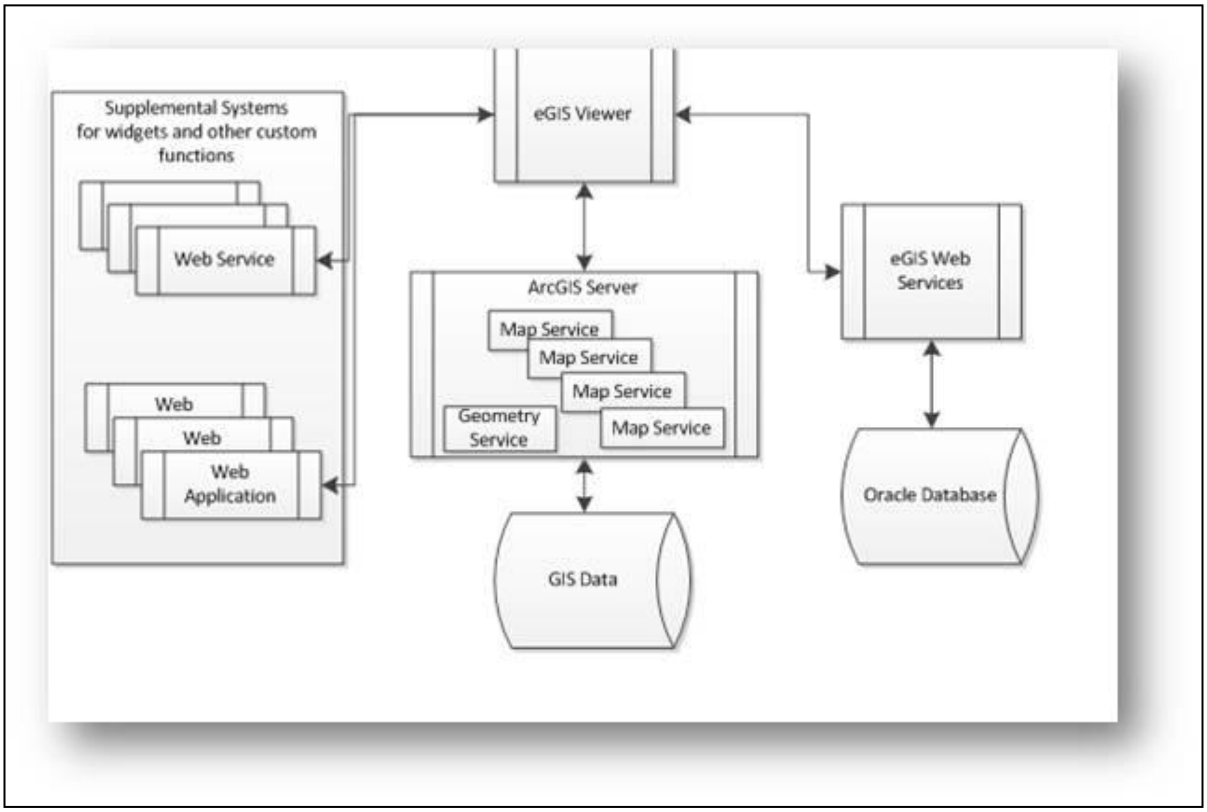


Figure 2.5: eGIS system architecture

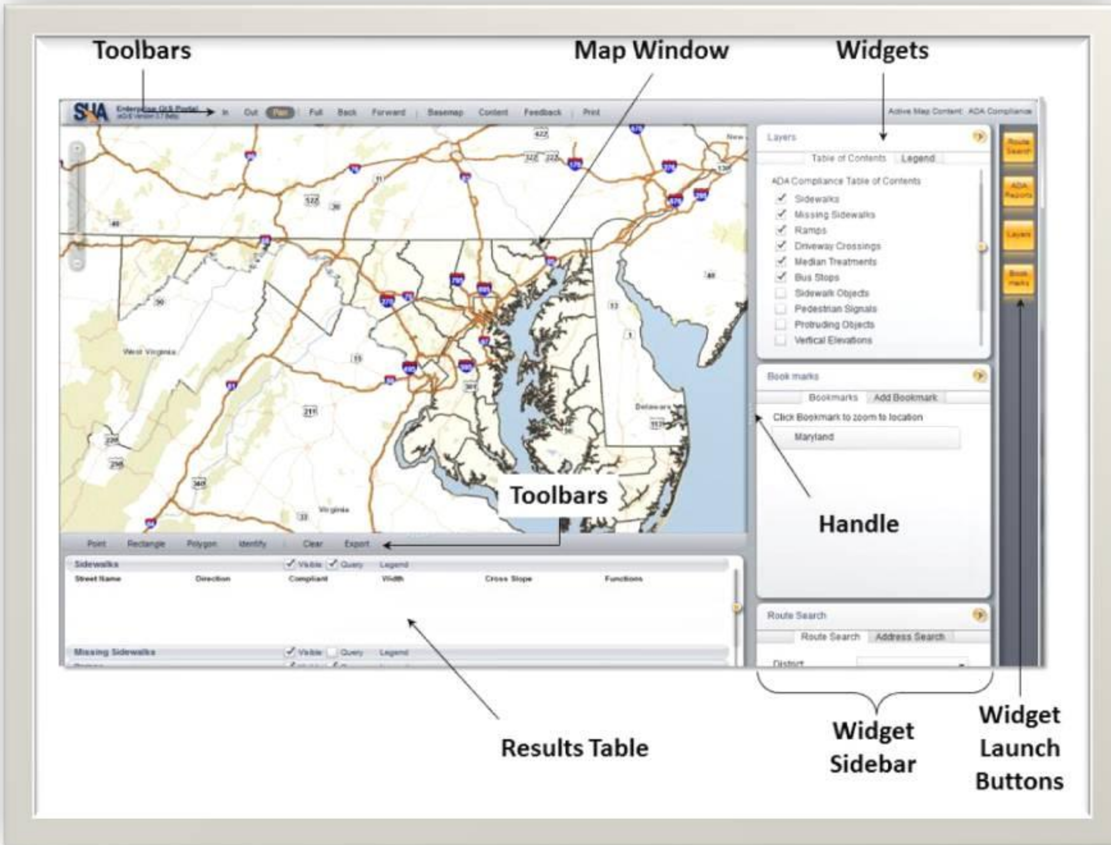


Figure 2.6: Various components of the eGIS content are highlighted

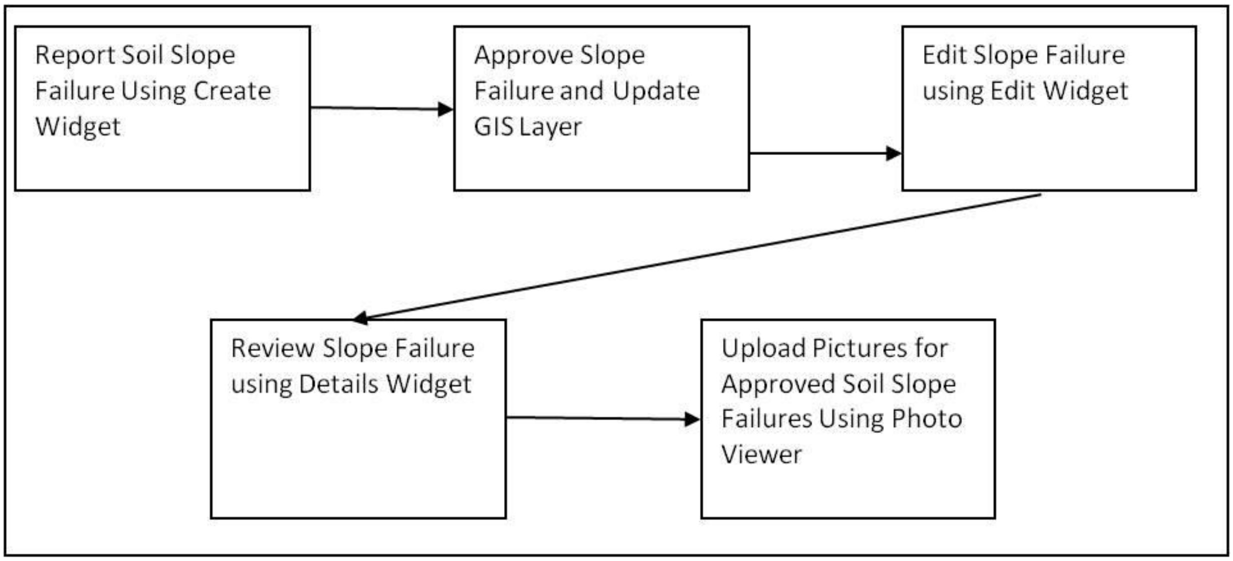


Figure 2.7: Workflow for the slope failure content within the OMT

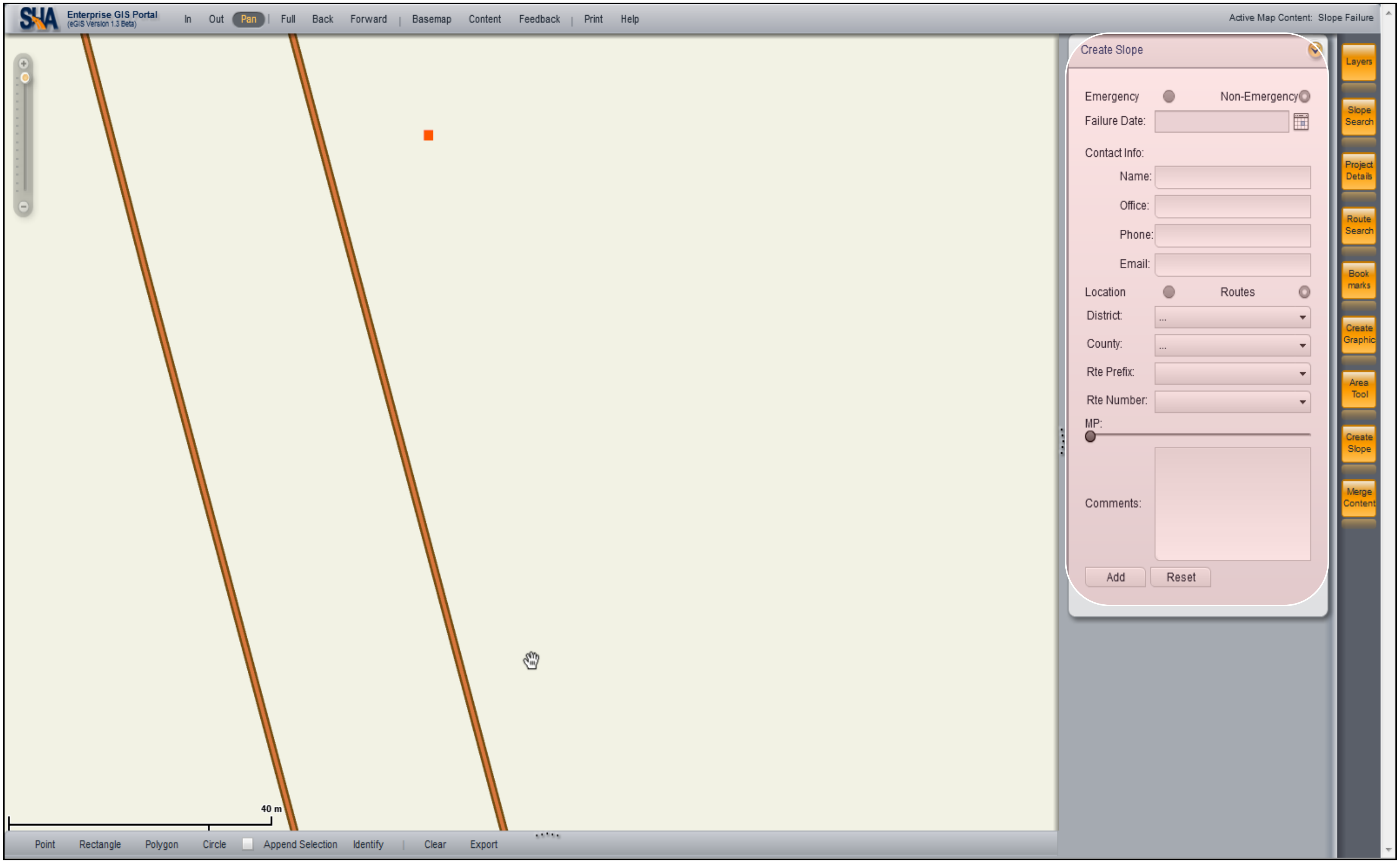


Figure 2.8: A screenshot of the create slope widget. The area highlighted in red indicates the position of the creator widget in the screen.

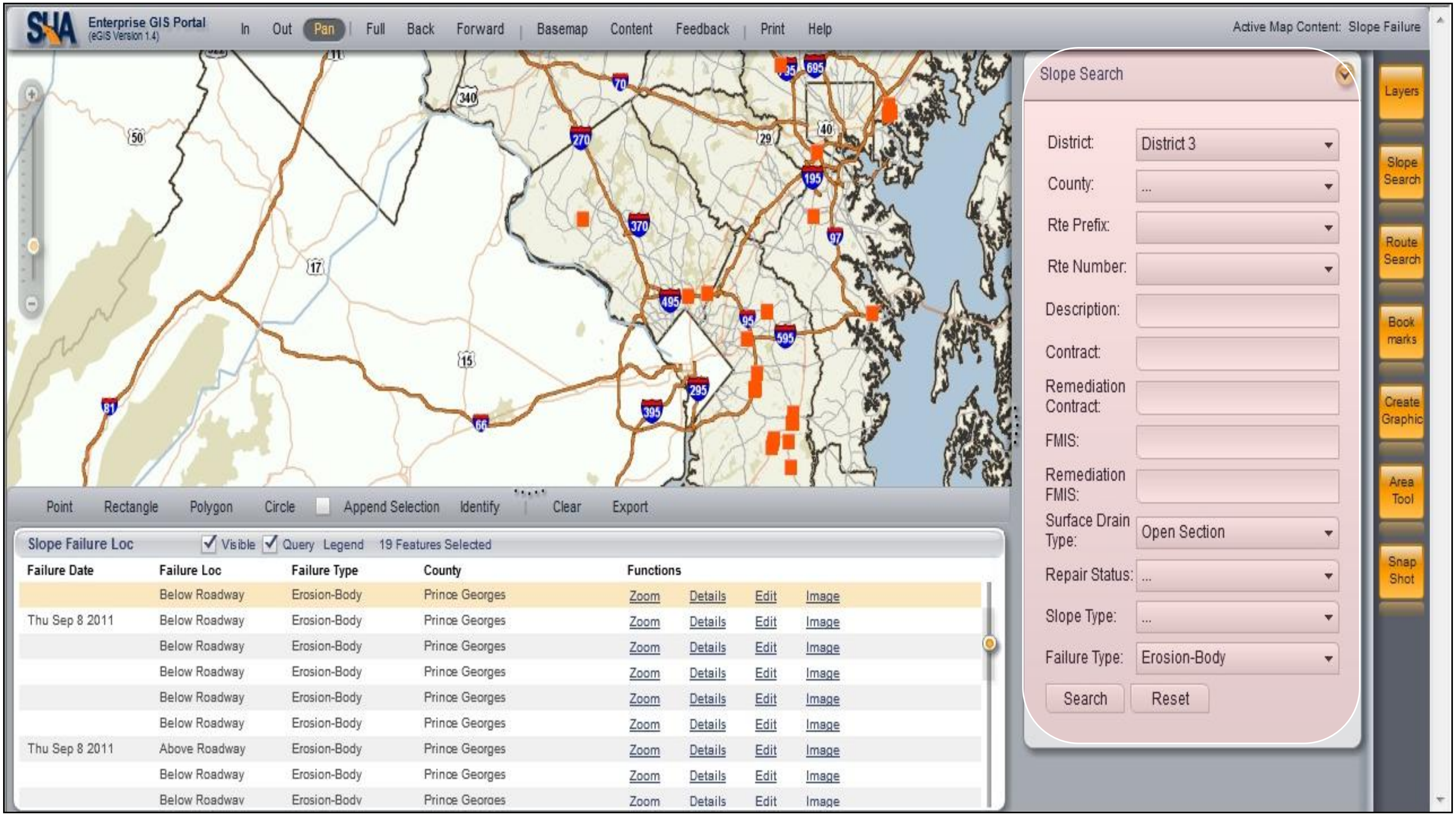


Figure 2.9: A screenshot of the slope search widget. The area highlighted in red indicates the position of the search widget in the screen

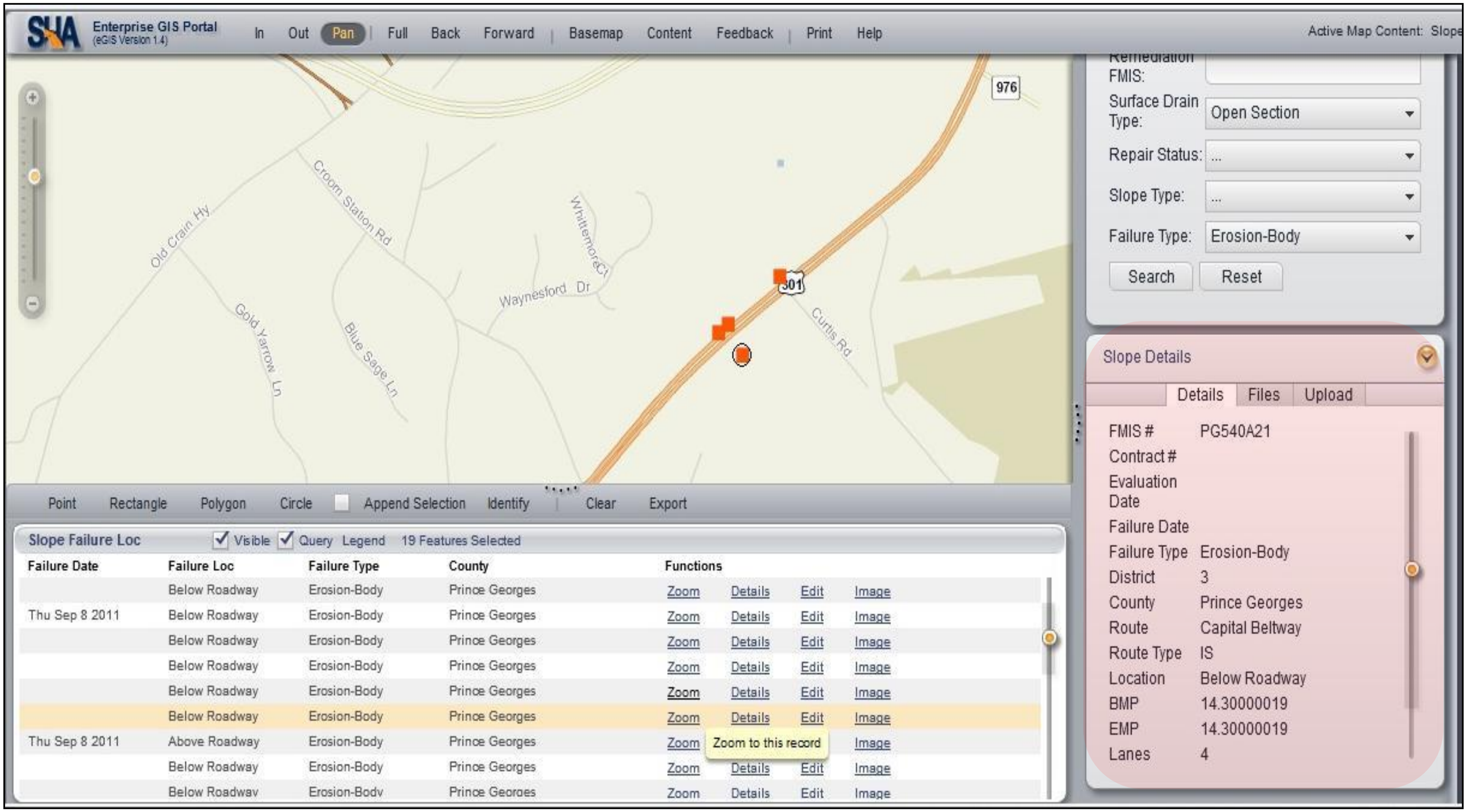


Figure 2.10: A screenshot of the slope details widget. The area highlighted in red indicates the position of the details widget in the screen.

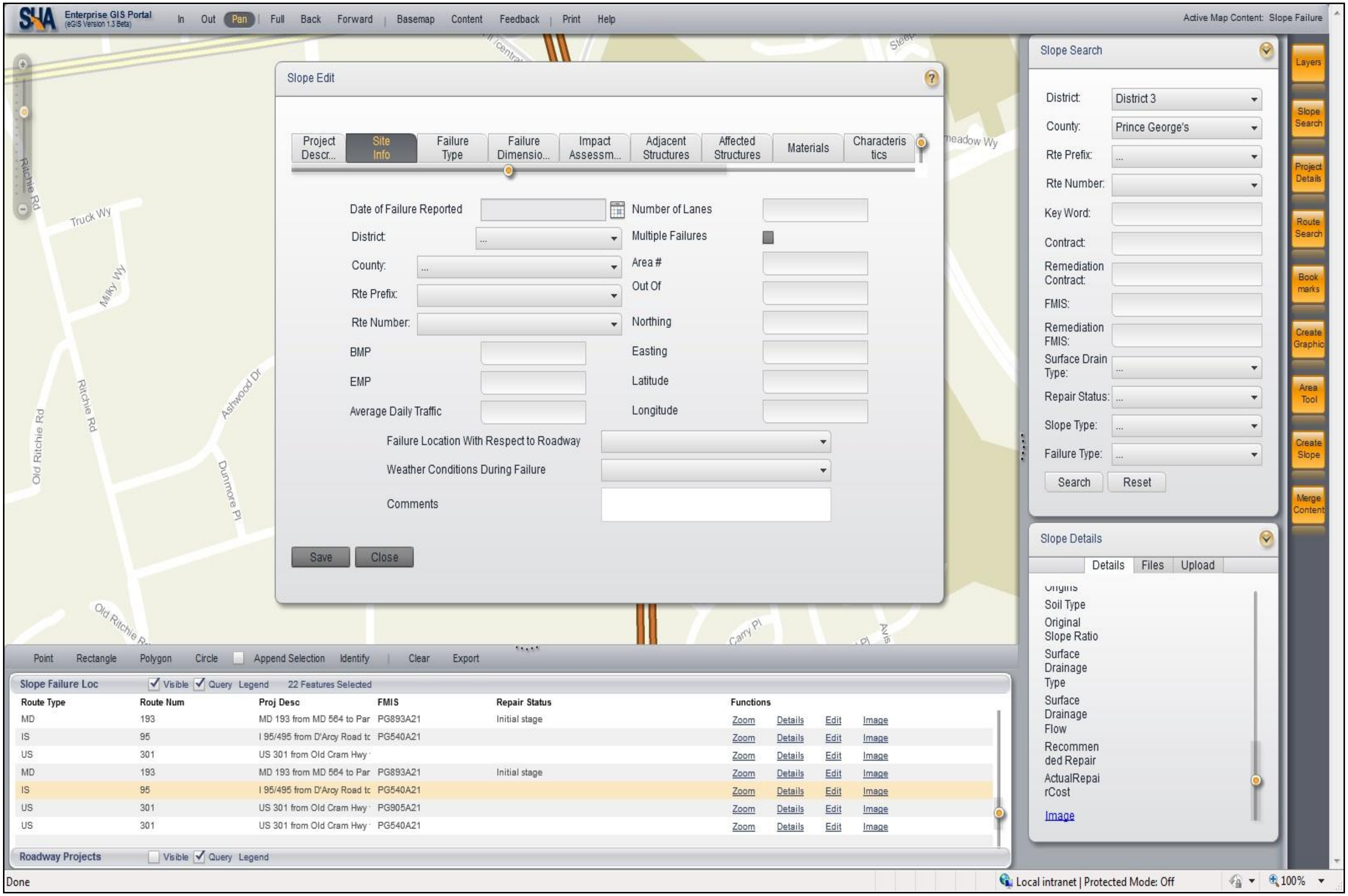


Figure 2.11: A screenshot of the editor widget the multiple tabs for recording information. Each tab represents an Oracle SDE table.

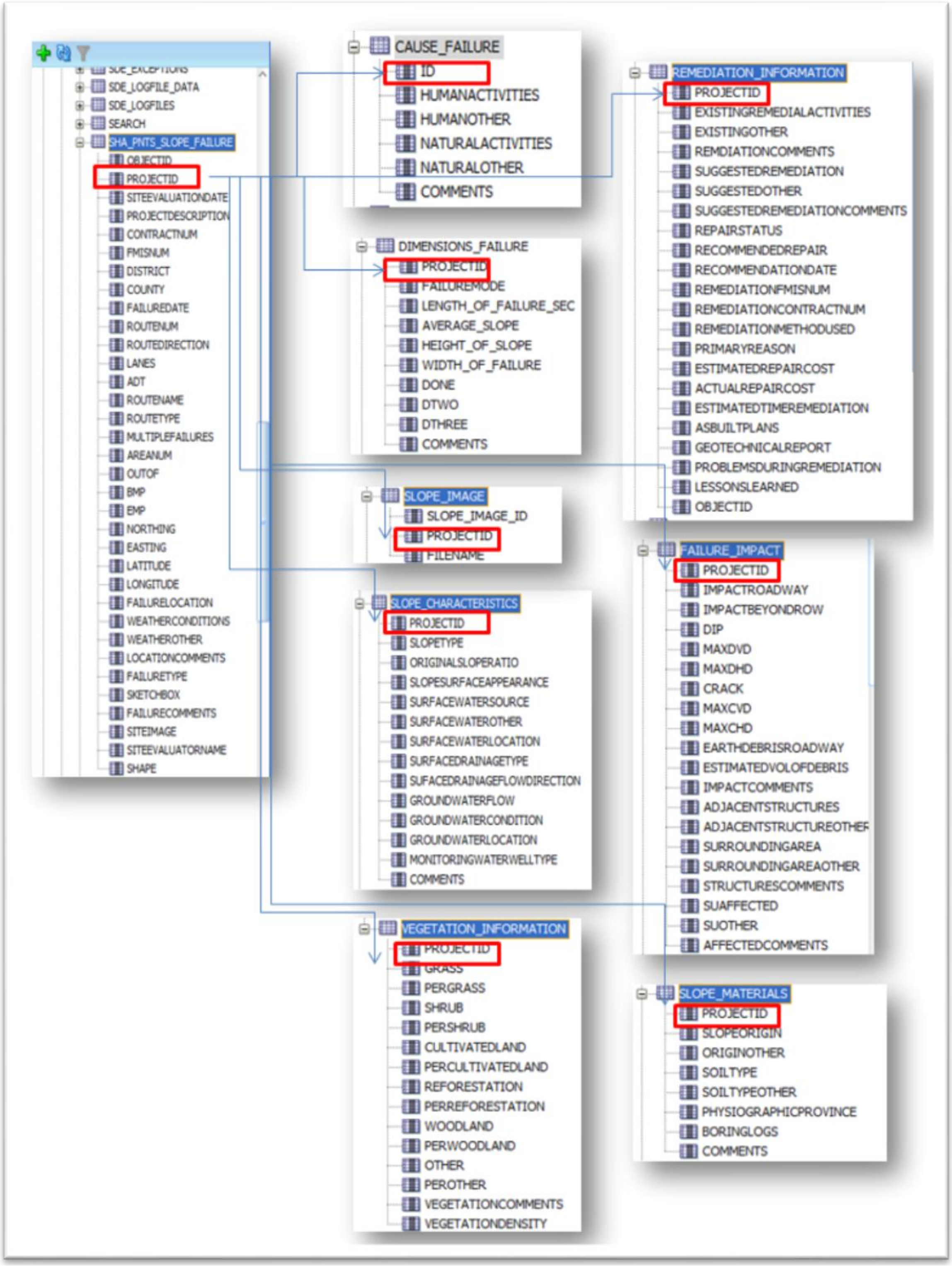


Figure 2.12: The Oracle 11g database's current relationships with PROJECTID as the primary key

CHAPTER 3

3.1 INTRODUCTION

The surface of the earth is a complex and dynamic system constantly subject to modification through physical interactions and processes. Landslides, erosion flows and other soil movements along slopes are some of the processes that modify the landscape (Hansen, 1984). Slope processes such as these are referred to as mass movements. They involve outward or downward movement of soils along slopes under the influence of gravity (Glade et al., 2005).

All slopes on the surface of the earth may be broadly classified into natural slope and engineered slopes (Abramson, et al., 2001) . In every slope, there are stresses that induce outward movement(shear stress) and stresses that resist the induce movement (shear strength). If these stresses are just balanced or when the shear stress exceeds the shear strength, the slope is said to be unstable and prone to failure(Selby, 1993).

All slope movements are a manifestation of slope instability. It is a well documented fact that slope failures can result in extensive property damage and loss of life. In 2004, the National Research Council estimated that landslides in the U. S. cause more than $2 billion in property damange and claim 20-25 deaths annually. Given the increasing economic and societal cost of landslides, there has been an urgent need for improved protection against landslides (He et al., 2007).

Investigation of slope instability and landslide hazard has sparked significant interest internationally and is the primary focus of various research initiatives around the world. Numerous publications have directed efforts towards discussion of the different scales of landlside investigation and slope instability analysis (Brundsen and Prior, 1984; Selby, 1993; Popescu, 1994; Cruden and Varnes, 1996; Dikau et al., 1996; Glade and Crozier, 2005).

The focus of research over the last decade has shifted from site investigations and stability assessments to predictive modelling and consequence analysis (Glade and Crozier, 2005). The main aim is to determine the location of future landslide and slope instability events in time and space based on spatial and temporal information relating to past events.

Considerable amount of publications, reports and books discuss in detail the different aspects involved in developing a predictive model (Leroi, 1996; Aleotti and Chowdhury, 1999; Chung and Fabbri, 1999; Cruden and Fell, 2002; Dai & Lee, 2002; van Westen, 2004). With the current trend being towards developing early-warning systems, Geographic Information Systems (GIS) have become an important and powerful tool in landslide hazard assessment.

GIS is at the forefront of all recent landslide hazard assessment research projects and is the most recommended platform for landslide and slope instability event prediction (Carrara, et al., 1999; Sakellariou et al., 2001; Cavallo, et al., 2001; Bhattarai, et al., 2004; Huabin, et al., 2005). GIS facilitates application of quantitative techniques in mapping and is capable of performing complex statictical and spatial analysis, thus providing a versatile platform for developing powerful probabilistic or predictive models (Carrara et al., 1999; Huabin et al., 2005)

Currently, the Maryland SHA does not have an assessment or predictive model to identify vulnerable highway slopes. Such a model, when used in tandem with the other components of the SMS, would be able to highlight those highway slopes that are more susceptible or vulnerable to movement or failure in comparison to the other slopes along highways. It is the intent of this research project to lay the framework for setting up a robust model to facilitate the Maryland SHA to prioritize and optimize their response to slope failures well in advance.

3.2 BACKGROUND

The application of GIS technology in slope instability mapping has a great potential to reduce the long term impacts of soil movements caused by surface and sub-surface phenomena (Hansen, 1984). This loss-reduction is mainly possible because slope failures such as landslides are considered to be the most potentially predictable type of geological hazards (Alfors, et al., 1973; Leighton, 1976).

To develop a robust predictive model, it is of paramount importance to understand causative parameters triggering slope instability and to establish classifications of failure modes by use of discriminatory factors. Many publications discuss initial and recently modified strategies for classification of slope movements based on a variety of causative factors (Terzaghi, 1950; Varnes, et al., 1978; Popescu, 1994; Dikau et al., 1996)

Skempton (1950) developed one of the first measures to classify slope movements based on geomorphology by portraying correlations between geometrical properties of slopes and their mass movement features (Figure 3.1). Developments in field monitoring and site investigation methods gave rise to a new set of classifiable factors based on the morphology of the slope feature (Brundsen, et al., 1973).

The most commonly adopted classification for slope movements are those of Varnes (1978) and Hutchinson (1988). Later publications produced slightly modified classifications compatible with the former publications (Popescu, 1994; Dikau et al., 1996; Cruden and Varnes, 1996). The International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory reported that the Varnes' (1978) classification is the most widely used system (WP/WLI report, 1990). Table 3.1 shows the abbreviated classification system proposed by Varnes (1978).

The focus of research over the last decade has shifted from site investigations, mechanism classifications and stability assessments to predictive modelling and consequence analysis (Glade and Crozier, 2005). The main aim is to map and locate future landslide and slope instability events in time and space based on spatial and temporal information relating to past events. Varnes (1984) was also one of the early advocates for this integrated approach in landslide research and engineering practice.

Based on the literature reviewed on the principles, concepts, techniques and methodology for slope instability evaluation (Varnes, 1984; van Westen, 1993; Navarro and Garcia., 1996; Chung, et al., 1999; Carrara, et al., 1999; Guzzetti, et al., 1999; Cavallo, et al., 2001; Cruden, et al., 2002; Clerici et al., 2002; Cardinali, et al., 2002; Huabin, et al., 2005; Glade, et al., 2005) all slope instability mapping techniques can be broadly classified into qualitative and quantitative analysis.

Qualitative analysis involve techniques such as geomorphological mapping, Landslide inventory mapping, hueristic analysis and qualitative index overlay. Quantitative analysis can further be classified into statistical techniques and physical or geotechnical models. Figure 3.2 shows the detailed classification tree of the various slope instability mapping techniques.

Geomorphological mapping relies on information about the surface topography and relief features of the site in question. It is the easiest method for mapping instability and was widely used between 1970-80 (Fenti et al., 1979; Kienholz, 1978; Rupke et al., 1988). Landslide inventory mapping systems use information available relating to slope failure events that have occurred on the slope in the past to develop an inventory. However, they only emphasize on slope with failure histories (He and Beighley, 2007). Heuristic or index based analysis makes uses a combination of expert opinion and past experience to analyze slopes (Anbalagan and Singh, 1996; Gupta and Anbalagan, 1997; Wachal and Hudak, 2000; Morton et al., 2003).

Qualitative index overlay or factor mapping is commonly used in the initial stage of regional assesment (Crozier and Glade, 2004). It involves identifying spatial distribution of one or more causative factors or a combination of the causative factors and investigating their influence on slope stability. Weights are assigned to different factors based on the magnitude of influence on slope stability. Crozier (1989), Turner and Schuster (1996) and Guzzetti et al. (1999) studied the effect of a variety of parameters on slope instability. They provide a comprehensive list of causative factors influencing slope stability.

Statistical analysis makes use of regression functions and distribution curves to predict slope failure based on data collected from site or from the lab. Correlation between different physical factors and previous slope failures are mapped using discriminant analysis. Then, quantitative or semi-quantitative estimates are made for those slopes without failure histories (Dai and Lee, 2002). Statistical methods are more appropriate for slope instability mapping as they eliminate the subjective bias present in qualitative analysis (Fall et al., 2006).

Physical or geotechnical models are based on 1D, 2D or 3D factor of safety analysis assuming infinite slopes. These models despite being precise in predicting vulnerable slopes (Wu, et al., 2000; Sakellariou, et al., 2001; Bhattarai, et al., 2004; Singh et al., 2008) require the landforms to have uniform ground conditions. Also due to diversity in distribution of values over a particular region, data collection and sampling may not be logistically feasible for regional scale study.

Limited studies exist (Carrara et al., 1992; 1995; van Westen, 1997; Chung, et al., 2004; Huabin, et al., 2005) that systematically compares these different techniques, in terms of respective strengths and limitations. But it is evident that each technique has limitations with regard to scale of study and data availability (Aleotti and Chowdhury, 1999). It is vital to choose the appropriate scale of study for analysis different work scale affects the selection of the approach. Table 3.2 shows a list of advantages and disadvantages of the various mapping techniques and the recommended scale of study for each technique.

The scale of assesment adopted for this study lies in the regional scale and the method of assessment used is a semi-qualitative index overlay. The primary reason for choosing a semi-qualitative technique for slope instability mapping is due to the insufficient data relating to historic slope failures. With the limited information regarding past events and causative factors, it is not feasible to develop a robust multivariate analysis model at a regional scale. Also, the qualitative index overlay as discussed before can be applied succesfully at all levels of study.

3.3 DESCRIPTION OF STUDY AREA

The State of Maryland is located in the Mid-Atlantic region of the United States. It is the 9th smallest state by area, but the 19th most populous and the 5th most densely populated of the 50 United States (US Census bureau, 2011). The total study region covers an area of 27,076 sq. km. The mean elevation of the State of Maryland is 350 feet above sea level, ranging from 3,360 feet to mean sea level at the Atlantic ocean.

The state is divided into 5 distinct physiographic provinces namely: Appalachian plateaus province, Ridge and valley province, Blue ridge province, Piedmont plateau province and the Atlantic coastal plains province.

The Coastal Plain Province is underlain by a wedge of unconsolidated sediments including gravel, sand, silt, and clay, which overlaps the rocks of the eastern Piedmont along an irregular line of contact known as the Fall Zone. Eastward, this wedge of sediments thickens to more than 8,000 feet at the Atlantic coastline. Beyond this line is the Atlantic Continental Shelf Province, the submerged continuation of the Coastal Plain, which extends eastward for at least another 75 miles where the sediments attain a maximum thickness of about 40,000 feet (Edwards Jr., 1981).

The Piedmont Plateau Province is composed of hard, crystalline igneous and metamorphic rocks and extends from the inner edge of the Coastal Plain westward to Catoctin Mountain, the eastern boundary of the Blue Ridge Province. Bedrock in the eastern part of the Piedmont consists of schist, gneiss, gabbro, and other highly metamorphosed sedimentary and igneous rocks of probable volcanic origin. In several places these rocks have been intruded by granitic plutons and pegmatites. Deep drilling has revealed that similar metamorphic and igneous rocks underlie the sedimentary rocks of the Coastal Plain (Edwards Jr., 1981).

Unlike the Coastal Plain and Piedmont Plateau Provinces, the Blue Ridge, Ridge and Valley, and Appalachian Plateaus Provinces are underlain mainly by folded and faulted sedimentary rocks. The rocks of the Blue Ridge Province in western Frederick County are exposed in a large anticlinal fold whose limbs are represented by Catoctin Mountain and South Mountain. These two ridges are formed by Lower Cambrian quartzite, a rock that is very resistant to the attack of weathering and erosion. A broad valley floored by Precambrian gneiss and volcanic rock lies in the core of the anticline between the two ridges. Figure 3.3 shows the generalized geological map for the state of Maryland (Edwards Jr., 1981).

Despite its small size, Maryland exhibits considerable climatic diversity. Temperatures vary from an annual average of 48°F in the extreme western uplands to 59°F in the southeast, where the climate is moderated by the Chesapeake Bay and the Atlantic Ocean. Monthly average temperatures range from a high of 87.1°F to a low of 24.3°F.

The average annual precipitation values for the eastern half of the State of Maryland ranges from 42 inches to 52 inches per year. Precipitation averages about 49 inches annually in the southeast, but only 36 inches in the west. Higher values of average annual precipitation are observed in the western most tip of the study region.

3.4 DATA SOURCES

The study area was examined in detail using the ArcMap GIS software. The input map layers were imported into ArcMap in their original format for verifying data compatibility and integrity. A major issue with the study was procuring relevant data layers for the various physical parameters at appropriate resolutions. A wide array of physical parameters were considered as causative factors in this study based on literature(Turner and Schuster, 1996; Guzzetti et al., 1999). Due to non-uniformity in the quality of data and the level of resolution only a handful of parameters were shortlisted.

A variety of factors that influence slope stability directly or indirectly were considered, and based on data availability and literature (Turner and Schuster, 1996; Guzzetti et al., 1999; Chau et al., 2004; He and Beighley, 2007; Singh et al., 2008; Bhattarai et al., 2004) the following factors were considered in the study: (i) Elevation, (ii) Slope angle, (iii) Land cover, (iv) Storm event precipitation, (v) Slope history or failure inventory, and (vi) Surface geology. Table 3.3 provides details regarding the source of the data layers used in this study.

The elevation dataset is obtained from the National Elevation Dataset(NED) 1/3 Arc-Second coverage in raster format. The dataset has a resolution of 10 x 10 m and was downloaded from the USGS website. The slope angle dataset was derived from this layer using spatial analysis tools available in the ArcMap software. The derived slope angle data layer was also resampled to a resolution of 10 x 10 m.

The land cover datalayer was obtained from the National Land Cover Database (NLCD) 2006 edition at 30 m resolution. The NLCD dataset was reclassified into six different values: grass, shrubs, woodland, cultivated land, developed land and other. This was performed to make the datalayer compatible with the land cover classification adopted by the GIS database discussed in the previous chapter.

The precipitation data was obtained from the The NOAA Atlas 14, Volume 2 (Ohio River Basin and Surrounding States) dataset. The NOAA Atlas 14 precipitation provides frequency estimates, with upper and lower bounds of the 90% confidence interval, in grid format and are resampled at 30 m resolution at the time of data extent specification. Data are available for the 1, 2, 5, 10, 25, 50, 100, 200, and 500 year storm events and for 6, 12, 24, and 48 hour durations. For this study, the estimates for a 2 year 24 hour duration storm event and a 100 year 24 hour duration storm event were chosen.

The slope history or failure inventory data was derived from the GIS database discussed in the previous chapters. The failure location information table of the GIS database was exported to a .xls file and then imported into the ArcMap software. Since the tables were populated with GPS coordinates of the failure sites, it was easy to project and create the slope failure inventory layer as a shapefile.

The surface geology dataset consists of 2 layers. The first layer depicts the extents of the different physiographic provinces in the State of Maryland. This shapefile was obtained from the Maryland Geological Survey. The second layer is the geological map of the State of Maryland which is obtained from the USGS mineral resources spatial database. This layer provides details regarding the superficial and bedrock geology of the State of Maryland. Both datasets are in vector format in 1 : 250,000 scale. Figures C.1 to C.6 shows all the data layers used in the study.

3.5 PHYSICAL PARAMETERS

Different physical parameters or factors that influence slope stability have been used in different methods of analysis while mapping slope instability (Sakellariou, et al., 2001; Cavallo, et al., 2001; Chau, et al., 2004; Bhattarai, et al., 2004; Saboya Jr., et al., 2006; He, et al., 2007; Singh, et al., 2008).

These factors can be broadly classified into intrinsic factors and extrinsic factors (Huabin et al., 2005). Intrinsic factors include geology, topography, lithology, surface characteristics and slope structure and characteristics (slope angle, soil type, vegetation etc). Extrinsic factors include seismic events, storms and human activities like mining, blasting, drilling and other construction activities.

During the initial stages of this study, the following factors were considered for correlation and feasibility studies: Elevation, slope angle, slope structure: convex or concave, precipitation, storm event, seismic vibrations, human activities, geological formations, fault lines, land cover, land usage, proximity to water bodies/drainage lines, slope history/ landslide history and type of drainage facilities.

Due to issues such as lack of availability of data at required scale, diversity in factor values over large regions, logistical hindrance in data collection through site investigation (regional scale) and quality of data many of these factors had to be disregarded for this study.

After performing feasibility studies based on expert opinions and recommendations from the engineers at the OMT, Maryland SHA, the following physical parameters were shortlisted: (i) Elevation, (ii) Slope angle, (iii) Land cover, (iv) Storm event precipitation, (v) Slope history or failure inventory, and (vi) Physiographic provinces.

The following section will discuss in detail the correlation between each of these factors with slope instability.

3.6 DATA ANALYSIS

Using the SMS tools- the failure field sheet and the GIS database, a total of 48 slope failure cases occurring between 2008 and 2012 were recorded actively and retroactively by engineers at the Maryland SHA. Based on the comprehensive information for the 48 slope failures and using spatial analysis tools available in ArcMap ver. 10 software, certain trends in failure distribution in relation to the selected parameters were established. The trends and data analysis is presented in this section.

3.6.1 Elevation and slope angle

Elevation and slope angle are the two most widely chosen parameters considered to influence slope stability while mapping regions vulnerable to failure (Chau, et al., 2004; He, et al., 2007; Saboya Jr., et al., 2006; Sakellariou, et al., 2001; Singh, et al., 2008). Skempton (1953) and Brundsen (1973) developed and modified, respectively, the relationship between slope angle and slope height in terms of potential failure mechanisms.

In this study, elevation as a separate parameter does not exhibit a strong correlation with slope instability. As shown in Figure 3.4a, 56% of the total number of slope failures has occurred on slopes between 30 m and 90 m in height and nearly a fourth of the total number of failures have occurred on slope with heights between 10m and 30 m. No clear trend or correlation could be observed at present between slope height and soil slope failures in the State of Maryland.

Figure 3.4b shows the failure distribution for the slope angle sub categories. It is clearly evident that a majority (more than 50%) of failures has occurred on slopes with slope angles between 20° and 30° as these failures have occurred along highway slopes. For all engineering and analyses purposes, the Maryland SHA assumes that all or most highway slopes have a 2H: 1V slope unless explicitly mentioned.

The failure distribution pattern for elevation and slope angle correlates with the field conditions observed by engineers, because the Maryland SHA records only those slope failures that are within their right of way. Since a distinct pattern or correlation with slope instability is yet to be drawn with respect to these parameters, it can be concluded that these numbers when combined with failure distribution patterns for other parameters will yield a more conclusive result.

3.6.2 Land cover

Land cover also influences slope behavior (Varnes and IAEG, 1984). A study by Lee and Choi (2004) in southern California found the probability of landslide occurrence to be highest for grass lands and certain forest types. It must be noted that their findings may be a result of co-existing landscape characteristics. For example, they show a high probability of landslide occurrence for vegetation types found in steep, mountainous areas.

In this study, 53% of the total number of failures has occurred on slopes predominantly covered with grass (Figure 3.5). Cross referencing this information with the vegetation density information recorded on site, it is evident that many failures have occurred on slopes with medium to low density of grass vegetation. This trend highlights the importance of type of vegetation cover on highway slopes as an important factor of influence in slope vulnerability studies in the State of Maryland.

52% of the remaining slope failures have occurred on developed land or urbanized regions. This trend presents an interesting insight into the effect of urbanization and land use pattern on slope instability. This relatively large percentage occurrence of failures on developed land can be attributed to the increased amount of human activity such as blasting, drilling, traffic volume and other construction activities.

3.6.3 Storm event precipitation

Precipitation is a fundamental slope instability factor. Hong Kong's densely populated urban areas suffered 185 slips as a result of heavy rains in 1972 (Chau, et al., 2004). Countries like Japan, Malaysia and Nepal are also prone to slope movements triggered by heavy rains or storm events (Schuster, 1995; Singh et al., 2008; Bhattarai, et al., 2004).

In the USA heavy rains during winter have caused significant amounts of social and economic losses (Beighley et al., 2003; NOAA, 2001). Generally, areas receiving higher rainfall relative to the region have a higher probability of landslide occurrence (He and Beighley, 2007).

It is evident from past events across the globe, that failure is more likely to occur in areas with high estimation of precipitation values. In this study, the estimates for a 2 year 24 hour duration storm event and a 100 year 24 hour duration storm event were chosen.

Figure 3.6a shows the failure distribution pattern for the 2 year 24 hour storm event. 87% of the total number of slope failures have occurred in regions estimated to have 50 mm to 60 mm of precipitation. Figure 3.6b shows the failure distribution pattern for the 100 year 24 hour storm event estimates. A similar trend is observed here again, more than 80% of the total slope failures have occurred in regions expected to have heavy amount of rainfall during a storm event.

3.6.4 Slope failure inventory

Slope instability classification systems are usually based on a combination of material and movement mechanism (Dai and Lee, 2002). For this study, the classification system proposed by

Cruden and Varnes (1996) was slightly modified to reflect the failure conditions prevalent locally in the State of Maryland (Figure 3.7).

Figure 3.8 shows the distribution pattern for the different types of failure as per the classification shown in Figure 3.7. 90% of the total numbers of slope failures are surficial erosion failures. Cross referencing with the GIS database, 80% of the total number of slope failures have occurred during or after rainfall. Figure 3.9a shows the distribution pattern for the different types of slopes in the State of Maryland. This trend when compared with the failure distribution pattern for the type of drainage section at failure site (Figure 3.9b) shows the influence of precipitation and drainage conditions on slope instability.

3.6.5 Physiographic provinces and lithology

It may be reasonably expected that the properties of the slope-forming materials, such as strength and permeability that are involved in the failure, are related to the lithology, which therefore should affect the likelihood of failure (Dai and Lee, 2002). The statistic that 87% of the total number of slope failures recorded has occurred in the Atlantic coastal plains province highlights the effect of lithology or soil type of the highway slopes (Figure 3.10a).

The Atlantic coastal plains province predominantly consists of slopes with silty or clayey sand, gravelly sand, coarse sand and gravel type soils. 50% of the total number of slope failures lay on slopes with sand formations and 39% of these slope failures occur on slopes with gravel formations (Figure 3.10b).

3.7 SLOPE INSTABILITY MAPPING

3.7.1 Logistic regression

Logistic multiple regression is a technique that considers several physical parameters that may affect probability. The advantage of logistic multiple regression modeling over other multivariate statistical techniques including multiple regression analysis and discriminant analysis is that the dependent variable can have only two values—an event occurring or not occurring, and that predicted values can be interpreted as probability since they are constrained to fall in the interval between 0 and 1 (Dai and Lee, 2002).

The technique of logistic multiple regression yields coefficients for each variable based on data derived from samples taken across a study area. These coefficients serve as weights in an algorithm which can be used in the GIS database to produce a map depicting the probability of landslide occurrence (Dai and Lee, 2002).

The relationship between the probability of occurrence of an event P, and its dependency on variables influencing the event can be represented by Equation 3.1.

$$P = \frac{1}{(1 + e^{-Z})}$$

(Eq 3.1)

P is the estimated probability of landslide occurrence. As Z varies from -1 to +1, the probability varies from 0 to 1 on an S-shaped curve. Z is the linear regression equation as represented in Equation 3.2.

$$Z = W_0 + W_1 X_1 + \cdots + W_N X_N$$

(Eq 3.2)

where W_i (i = 1,2,…,N) are the coefficients estimated through regression and X_i (i = 1,2,…,N) are the independent variables.

Dai and Lee (2002) used this technique to predict slope instability in the Lantau Island, Hong Kong. They also studied the runoff potential and behavior of landslide masses in this study. Mark and Ellen (1995) described the use of logistic regression on a database of thousands of debris flows and had shortlisted five physical attributes. They used the distribution and frequency of Shallow landslides to model future initiation sites, estimate runoff volumes and run out distances and compared these results with existing landslides. More recently Gorsevski, et al., (2000) applied logistic regression for spatial prediction of landslide hazard in Alberta, Canada.

While this method of analysis is highly recommended for this scale of study and is most compatible with the format in which data is recorded, due to inadequate sample size of slope failures, the application of this method for this study will not be feasible. For this model to be used the sample size of the number of failure cases needs to be exponentially larger. The time required for the GIS database to acquire the appropriate volume of data would render the application of such a statistical model, out of the scope of the present study.

3.7.2 Qualitative index overlay

The qualitative index overlay method may be successfully used at all scales of study. Qualitative index overlay or factor mapping is commonly used in the initial stage of regional assessment (Glade and Crozier, 2005). Since the primary objective of this study is to the lay the framework for developing a robust slope instability model for the State of Maryland, qualitative index overlay would be the most suitable method of analysis for the volume of data collected for this study.

The general concept behind such an analysis is to characterize both spatial and temporal conditions that have determined the occurrence of past instability events and to use these characteristics to highlight those slopes with similar conditions that are vulnerable to failure.

Chau et al. (2004) discuss the principle behind a weighted overlay of index or thematic maps using ArcGIS software: A denotes the whole study area of the instability map and there are m layers of thematic spatial data (elevation, slope angle, lithology, and precipitation etc.) containing causal factors- c_i. A pixel p in A would have m pixel values, $c_1 \ldots c_m$. The model can be programmed to calculate the occurrence of failure in p in terms of conditional probabilities (Clerici et al., 2002) based on pixel values of the causal factors. Figure 3.11 shows schematic of the principle in discussion.

However, in a strict sense, the final pixel value of the instability map produced in this study does not represent probability since the dynamic variables triggering landslides, such as rainfall, are not accounted for. Hence, it may be more appropriate to refer to these values as failure density.

The values of all the physical parameters are classified in to sub classes or categories as shown in Table 3.4. A failure density index is assigned for each sub- class. The purpose of assigning such an index to each sub class is to identify the unstable slopes along regions with no previous slope failure occurrence. The class intervals are decided using statistical tools available in the ArcMap software.

Equation 3.3 outlines the methodology used to calculate the failure density index for each subcategory as shown in Table 3.4. A normalized density index is calculated for a more conservative approach. For a particular factor, the density index for each subcategory is normalized by the maximum density index value for that factor. Figure 3.12 shows the variation of both the failure density index and the normalized failure density index for the different subclasses of parameters. This figure shows how the conservative index provides for more striking variation in failure density values for the same sample set of data when compared to the failure density index.

Figure 2.13 illustrates the variation of failure density indices of parameter subclasses over the area of the study region. The low sample size of slope failures for this study gives rise to insignificant failure density values for some parameter subclasses as shown in Figure 2.13. A conservative index allows for a more well distributed model by rating up slopes that have low failure density values due lack of field data, but might have potential to fail based on spatial and temporal conditions. Table 3.4 shows the density index values and the normalized density index values for each subcategory.

$$Failure\ density\ index\ (v) = \left(\frac{Number\ of\ slope\ failures\ in\ sub\ class}{Total\ number\ of\ slope\ failures}\right)$$

(Eq 3.3)

A weighted mean of the normalized failure density index of the various factors gives the failure density value at any particular pixel (refer Equation 3.4). The weights were assigned based on expert opinion and the trends observed between the failure density index and the causative parameter. A weightage of 3 is applied to parameters exhibiting a clear trend between parameter data and the failure density index, while the weightage of 2 or 1 is provided to other parameters based on expert opinion. 4 trials were conducted and 4 failure density maps were generated. Table 3.5 gives the different weights assigned to the different factors.

$$Failure\ density = \left(\frac{\sum_{i=1}^{m} W_i . v_i}{\sum_{i=1}^{m} W_i}\right)$$

(Eq 3.4)

Figure 3.14 shows the results of the 4 weighted overlay maps using the raster calculator function in ArcMap software.

3.8 CONCLUSIONS

A framework for analyzing slope instability is proposed and developed for the State of Maryland. A total of 48 slope failures recorded by Maryland SHA engineers using the GIS database were analyzed for emerging trends and patterns correlating physical parameters with slope instability.

In this study, six factors were considered to affect highway soil slope stability: event precipitation, geological formation, land cover, slope history, ground slope and elevation. Overlaying statewide GIS data for these factors brings some interesting trends to light: precipitation and poor surface or sub-surface drainage conditions are principal factors causing slope failures. 96% of the failed slopes lie along roads with open drainage section. Majority of the failed slopes lie in regions with relatively high event precipitation values. 90% of the existing failures are surficial erosion type failures, only 4% of the slope failures are deep rotational type failures. Cross referencing this with the GIS database, it is found that 80% of the total number of slope failures has occurred during or after rainfall. 58% of the existing slope failures have occurred in regions having low density land cover. 50% of the failures have occurred in sand and 39% have occurred in gravel formations.

Distinct trends and patterns were recognized for some physical features such as Lithology, Physiographic provinces, precipitation and land cover. These physical parameters presently influence highway slope stability to a greater extent in relation to physical parameters such as elevation and slope angle. The influx of more data relating to failed slopes should give rise to more trends, and thus this system will aid the State Highway Administration (SHA) of Maryland in prudential budget allocation and prioritizing different remediation projects.

It is the intent of this study to lay the groundwork for a robust quantitative mapping system. In the initial stage, the mapping technique used is a weighted overlay of thematic maps. An ideal and suitable multivariate statistical approach was reviewed and presented.

TABLES

Table 3.1: Classification of soil movements by Varnes (1978)

<table>
<tr><th colspan="2" rowspan="3">TYPE OF MOVEMENT</th><th colspan="3">TYPE OF MATERIAL</th></tr>
<tr><th rowspan="2">BEDROCK</th><th colspan="2">ENGINEERING SOILS</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="2">FALLS</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="2">TOPPLES</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="2">SLIDES</td><td>ROTATIONAL</td><td rowspan="2">Rock slide</td><td rowspan="2">Debris slide</td><td rowspan="2">Earth slide</td></tr>
<tr><td>TRANSLATIONAL</td></tr>
<tr><td colspan="2">LATERAL SPREADS</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="2" rowspan="2">FLOWS</td><td rowspan="2">Rock flow
(Deep creep)</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td colspan="2">(Soil creep)</td></tr>
<tr><td colspan="2">COMPLEX</td><td colspan="3">Combination of two or more principal types of movements</td></tr>
</table>

Table 3.2: Various mapping techniques- their scale of use, advantages and disadvantages

Classification of Mapping technique	**Mapping Technique**	**Scale of use recommended**			**Advantages**	**Disadvantages**
		Regional	**Medium**	**Large to small**		
Qualitative- Heuristic analysis	Qualitative map combination	Yes	Yes	No	-Can be used for evaluating large areas of land.	-Subjectivity involved in assigning weights to various layers
Statistical Analysis	Multivariate statistical analysis	Yes	Yes	Restricted use	-Eliminates subjectivity involved in assigning weights to factors. -Correlates influence of parameters with slope instability	-Large efforts to collect and validate data.
	Artificial Neural Netorks	No	Yes	Yes	-Can deal with qualitative and quantitative input. -Adaptive and can deal with incomplete data	-Initial weights are random. -Subjectivity involved in selection of factors
Physical or Mechanistic Analysis	Factor of Safety Analysis	No	No	Yes	-Deals with real time data. -Accounts for intrinsic and extrinsic stresses in a direct manner	-Laborious data collection process. -Impossible to have accurate data due to spatial variablity of parameter values

Table 3.3: List of parameters considered and their data sources

Parameters considered	Data source
Elevation	National Elevation Dataset (NED) 1/3 Arc Second (~10m resolution). Primary elevation data product of the USGS. (*http://seamless.usgs.gov/*)
Slope angle	~10 m resolution. Derived from the NED 1/3 Arc Second datalayer using spatial analyst tools in ArcMap ver. 10
Land cover	National Land Cover Database (NLCD) 2006 edition from the USGS seamless data warehouse. (~30 m resolution)
Storm event precipitation	Data for 2 year and 100 year recurrence intervals for a 24 hour storm duration obtained from the NOAA Atlas 14, Volume 2 (http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html)
Physiographic provinces	Shapefile obtained from the Maryland Geological Survey website (www.mgs.md.gov/coastal/maps/g1.html)
Failure inventory	Based on comprehensive data collected using the failure field sheet and stored in the MS Access database

Table 3.4: Physical parameters classified into sub-categories along with the density and normalized indices for each sub categories

Factor	Class	Area ratio	Failure density index	Normalized index
Slope angle (degrees)	< 10	89.4	0.2083	0.4545
	10 - 20	8.7	0.3125	0.6818
	20 - 30	1.6	0.4583	1.0000
	30 - 40	0.3	0.0208	0.0455
	> 40	0.0	0.0000	0.0000
Land cover (based on NLCD classification)	Grass	13.9	0.5625	1.0000
	Shrubs	1.6	0.0417	0.0741
	Woodland	31.8	0.0625	0.1111
	Developed Land	2.5	0.2292	0.4074
	Cultivated Land	30.4	0.0208	0.0370
	Other: Wetlands, Barren	19.7	0.0833	0.1481
Elevation (meters)	< 10	27.7	0.1250	0.2222
	10 - 30	18.9	0.2292	0.4074
	30 - 90	14.2	0.5625	1.0000
	90 - 270	28.2	0.0833	0.1481
	> 270	9.4	0.0000	0.0000
Physiographic province (Maryland Geological Survey)	Appalachian Plateaus Province	7.4	0.0000	0.0000
	Ridge and Valley Province	6.7	0.0000	0.0000
	Piedmont Plateau Province	26.3	0.1667	0.2000
	Blue Ridge Province	2.9	0.0000	0.0000
	Atlantic Coastal Plain Province	56.6	0.8333	1.0000
Storm event precipitation - 2 year recurrence, 6 hrs. duration (mm)	< 56	26	0.0000	0.0000
	56 - 58	17	0.6250	1.0000
	58 - 60	27	0.2500	0.4000
	60 - 62	17	0.0000	0.0000
	> 62	13	0.1250	0.2000
Storm event precipitation - 100 year recurrence, 6 hrs. duration (mm)	< 135	30	0.0000	0.0000
	135 - 140	34	0.7292	1.0000
	140 - 145	13	0.1458	0.2000
	145 - 150	19	0.1250	0.1714
	> 150	5	0.0000	0.0000

Table 3.5: The weightage scheme assumed for the different test maps

Factor	Map 1	Map 2	Map 3	Map 4
Slope angle	1	3	1	3
Land cover	1	3	1	3
Elevation	1	1	1	1
Physiographic provinces	1	2	1	2
Storm event precipitation - 2yr recurrence 24 hr duration	1	3	0	0
Storm event precipitation - 100yr recurrence 24 hr duration	0	0	1	3
Slope failure history	1	2	1	2

FIGURES

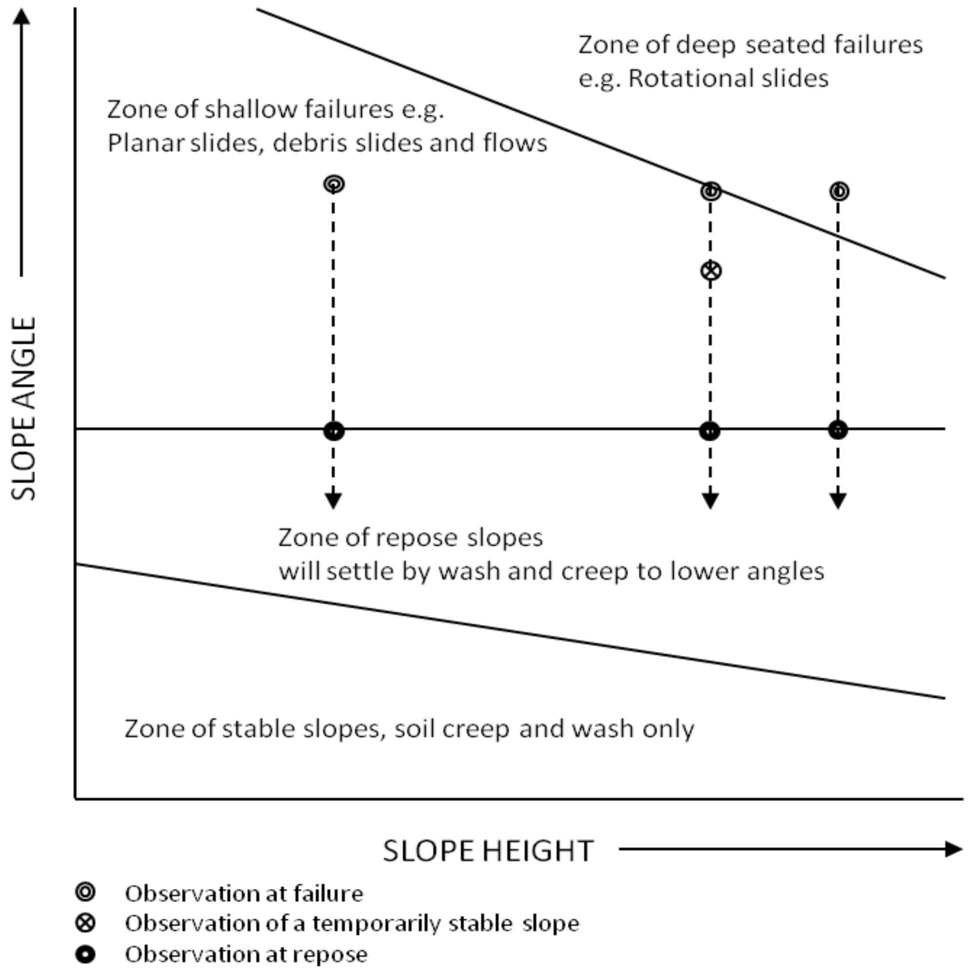


Figure 3.1: Schematic showing the relationship between slope angle and slope height (Skempton, 1953) modified by Brundsen (1973)

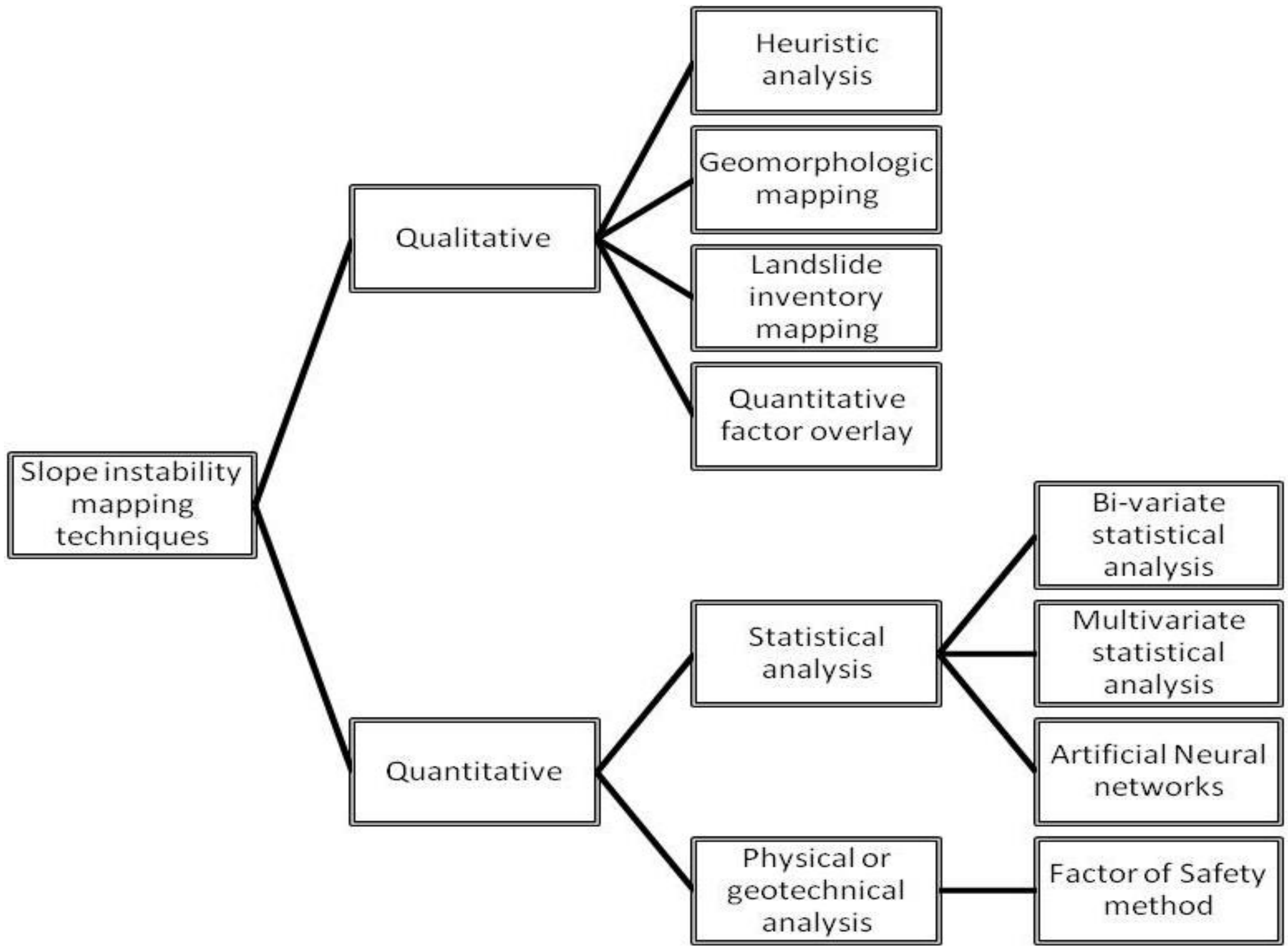


Figure 3.2: A broad classification of all the slope instability mapping techniques developed from Huabin et al., 2005

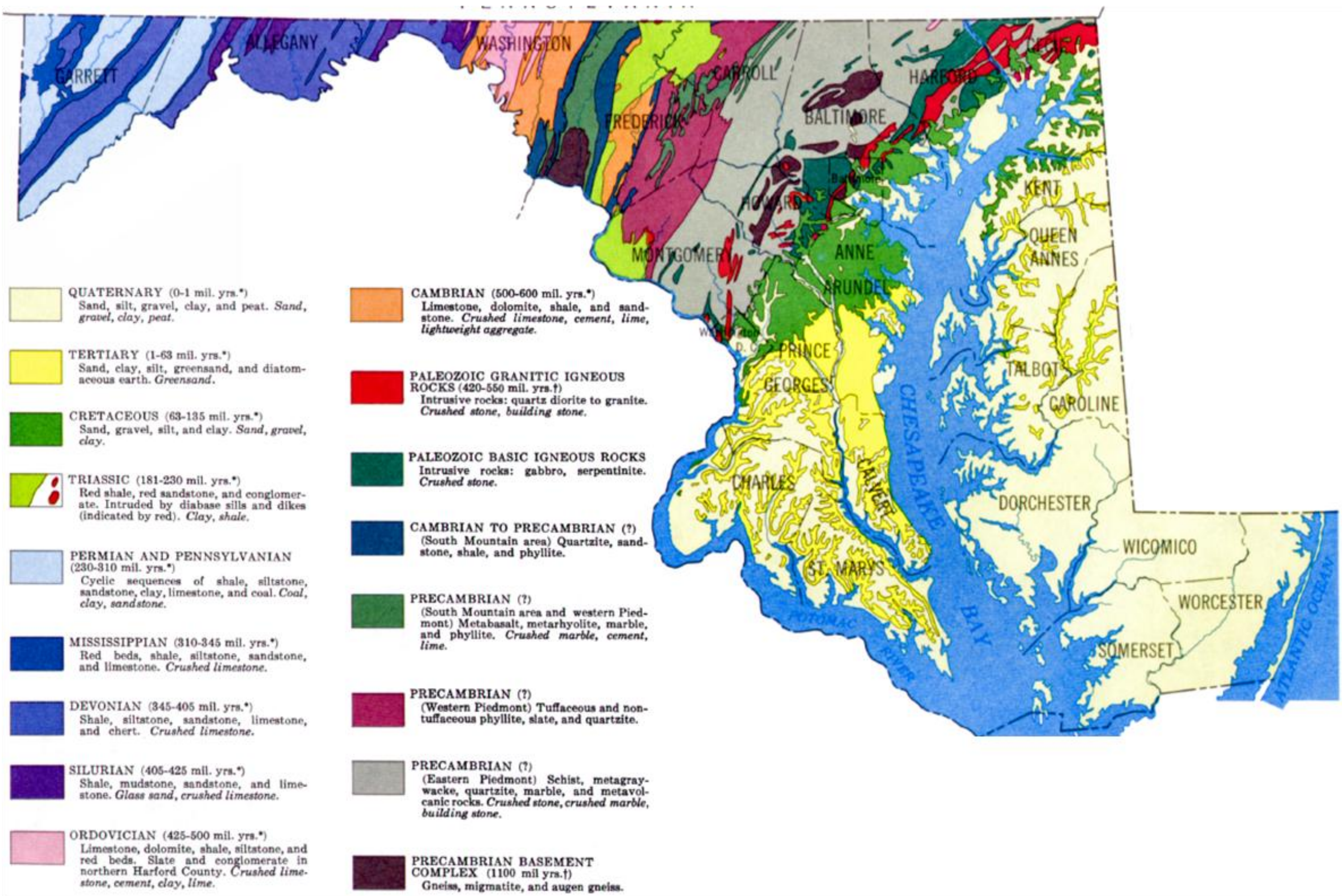
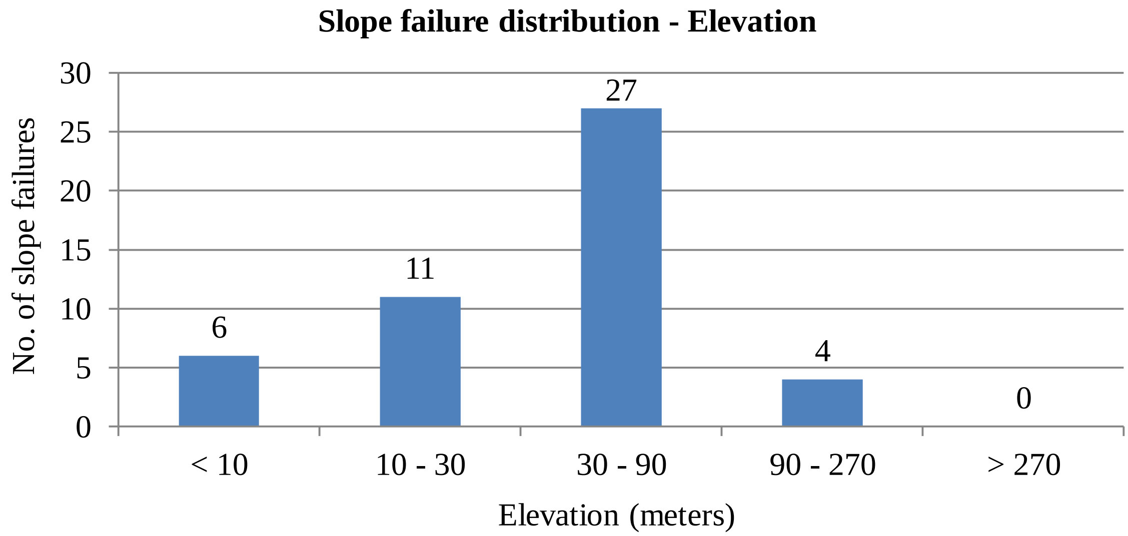


Figure 3.3: A generalized geological map of the State of Maryland (Source: Maryland Geological Survey, www.mgs.md.gov/)

(a)



(b)

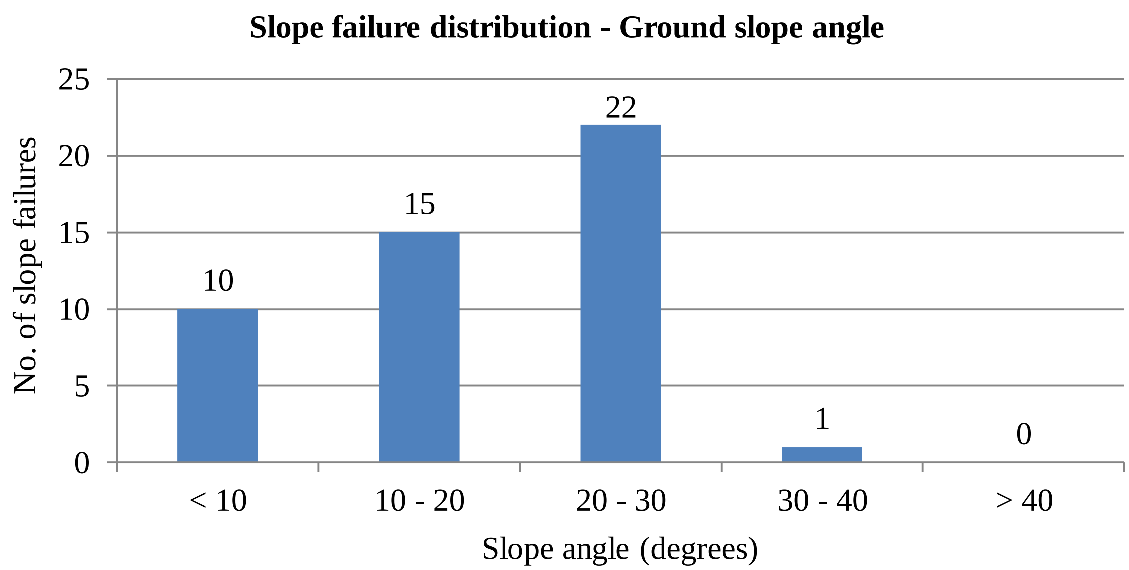


Figure 3.4: Distribution of failures in the different sub categories for (a) Elevation and (b) Slope angle

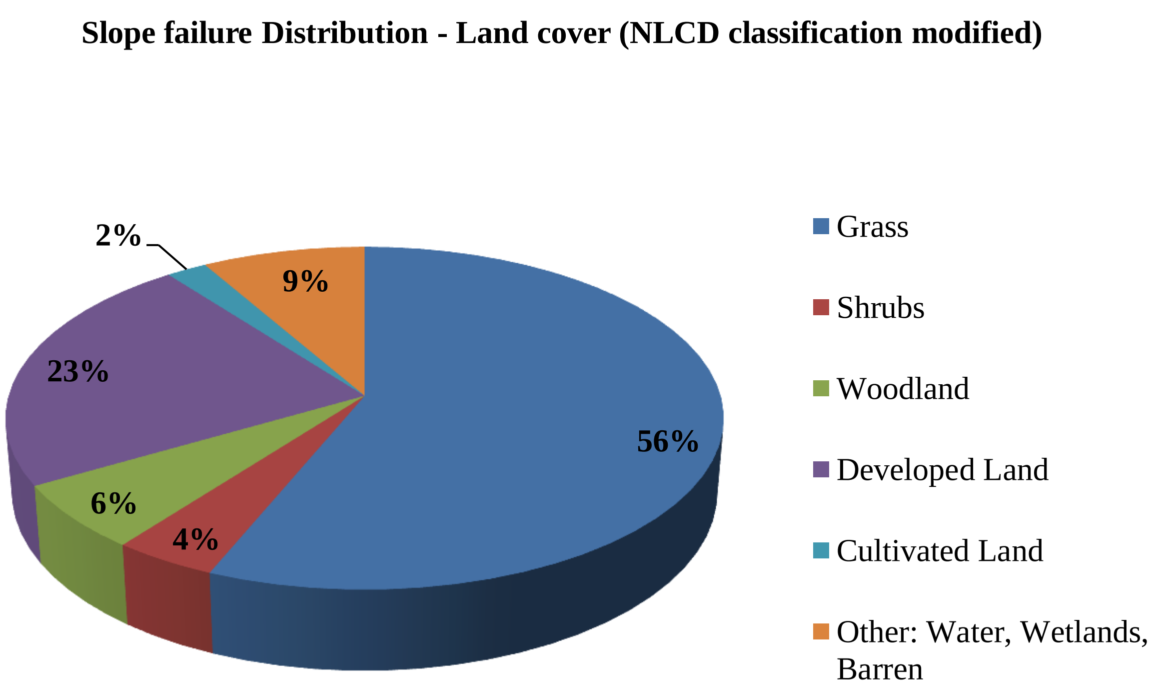
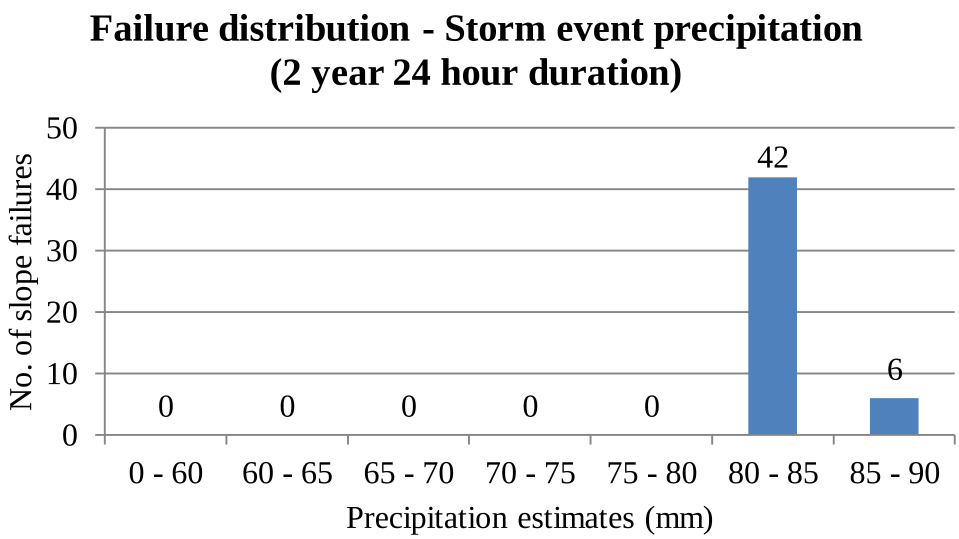


Figure 3.5: The distribution of slope failures for the different classes of land covers in the State of Maryland

(a)



(b)

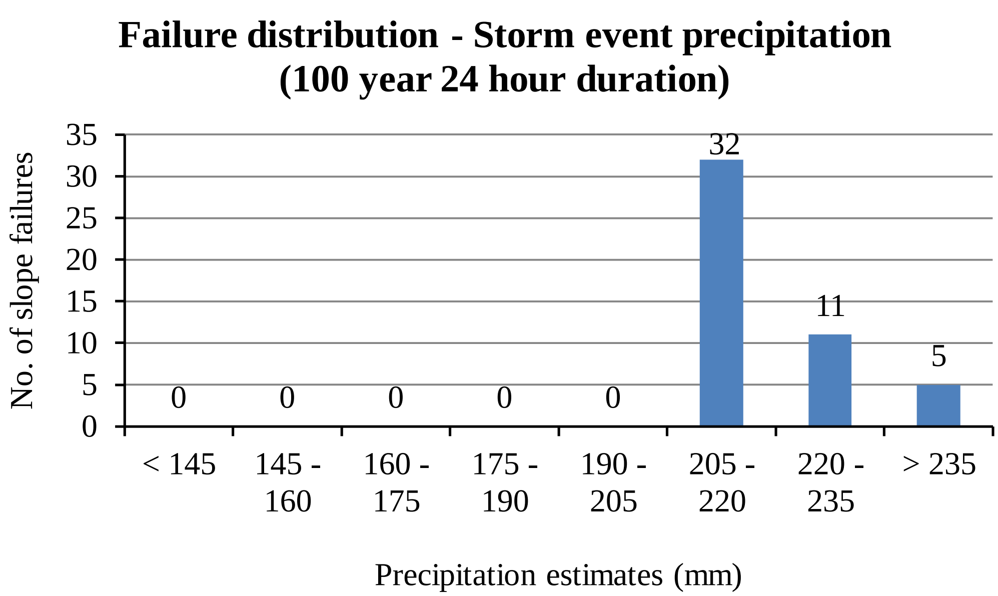


Figure 3.6: The failure distribution pattern for the different sub categories of (a) 2 year 24 hour duration storm event and (b) 100 year 24 hour duration storm event

Failure type		**Failure type sub - classification**			
Erosion	**Erosion Area**	Head	Toe	Flank	Body
Rotational failure		**Circular**	Deep		Shallow
		Non-circular	Deep		Shallow
Translational failure		Block		Slide	
Others		Landslide	Flow		Spread
Compound / Complex (provide sketch below)					

Figure 3.7: Proposed failure type classification used by Maryland SHA based on Cruden and Varnes (1996)

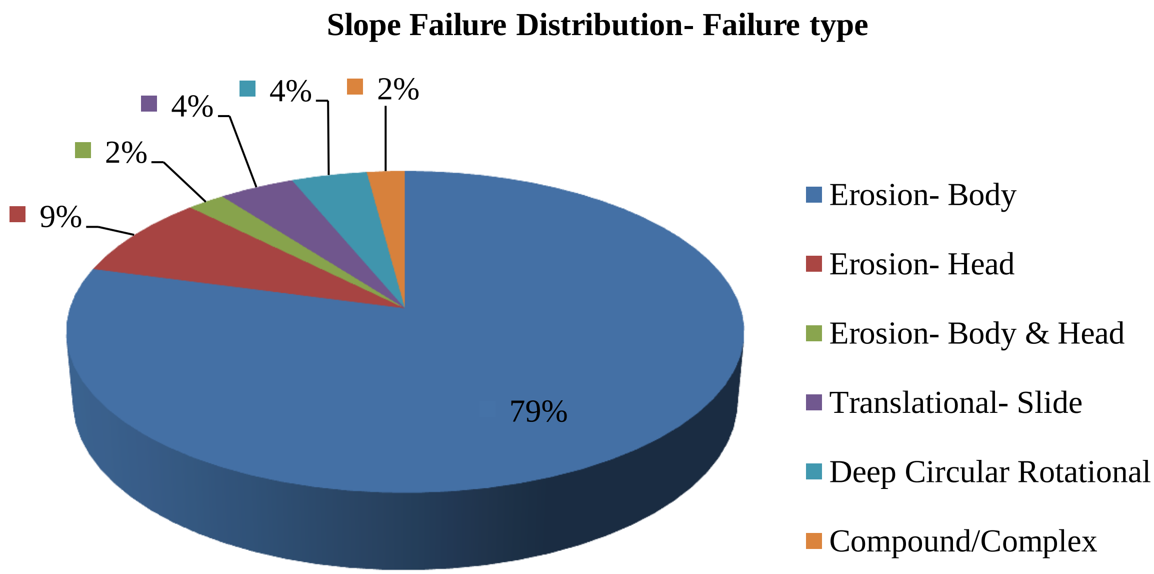
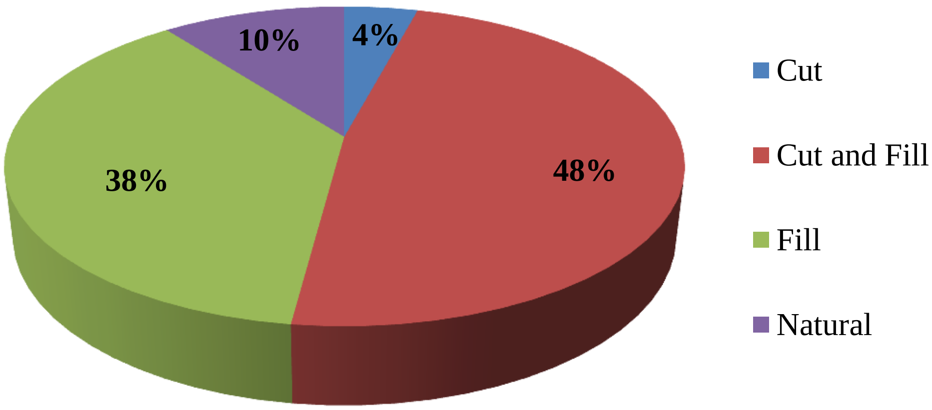


Figure 3.8: Failure distribution pattern for the different types of slope failures as per the modified Cruden and Varnes (1996) classification

Slope Failure Distribution - Slope type

(a)



Slope Failure Distribution- Drainage Section type

(b)

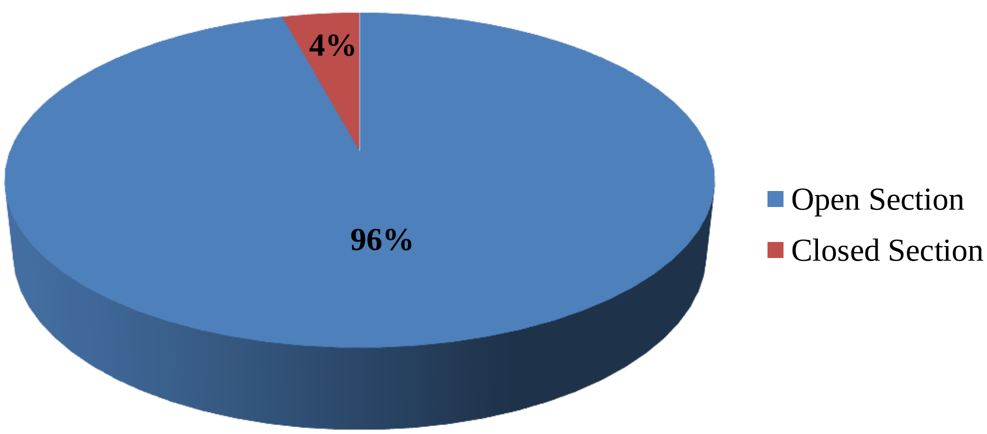


Figure 3.9: Slope failure distribution patterns for different (a) Slope types and (b) Slope drainage section types

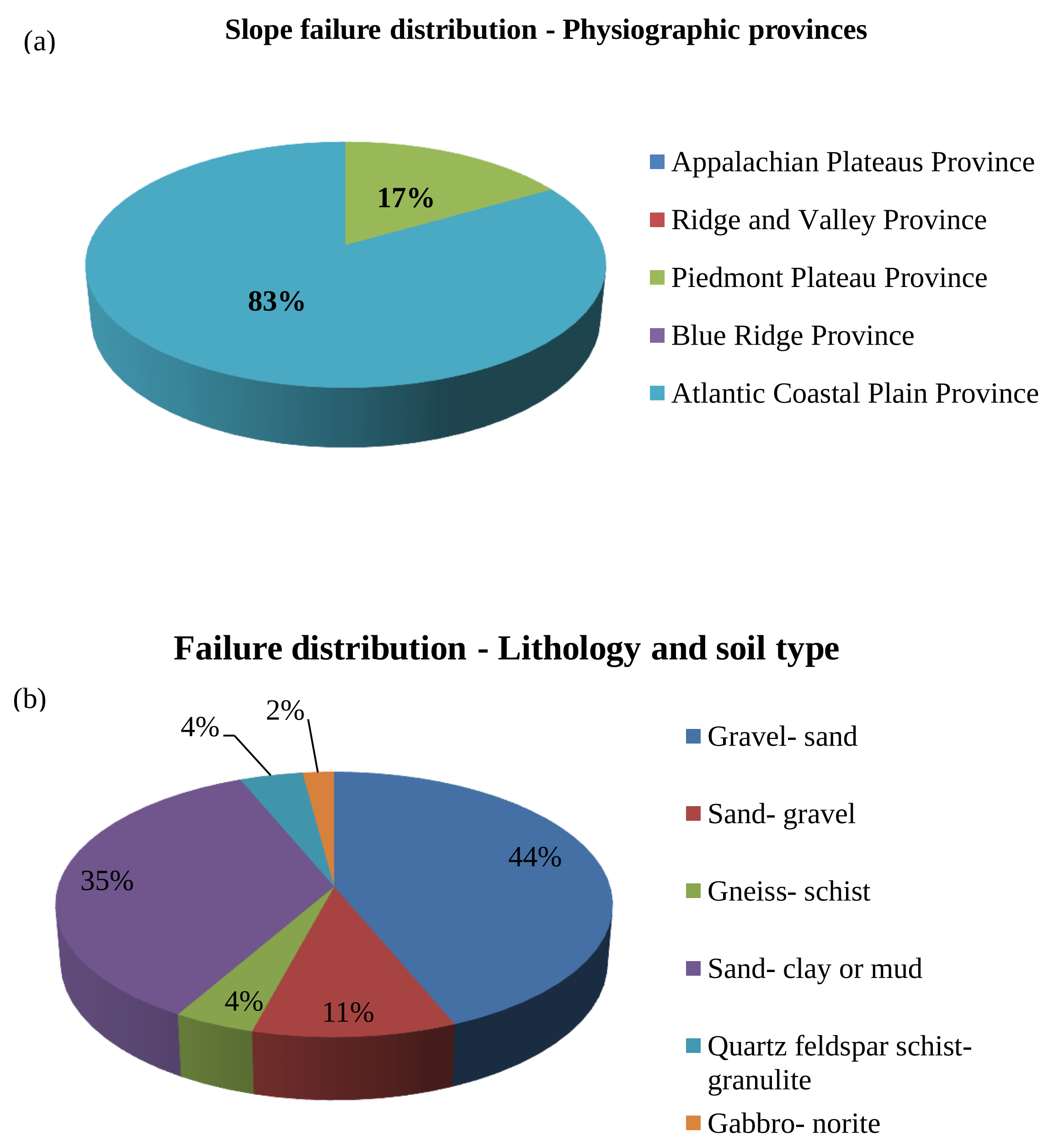


Figure 3.10: The slope failure distribution pattern for (a) the different physiographic provinces and (b) for the different lithology or soil type.

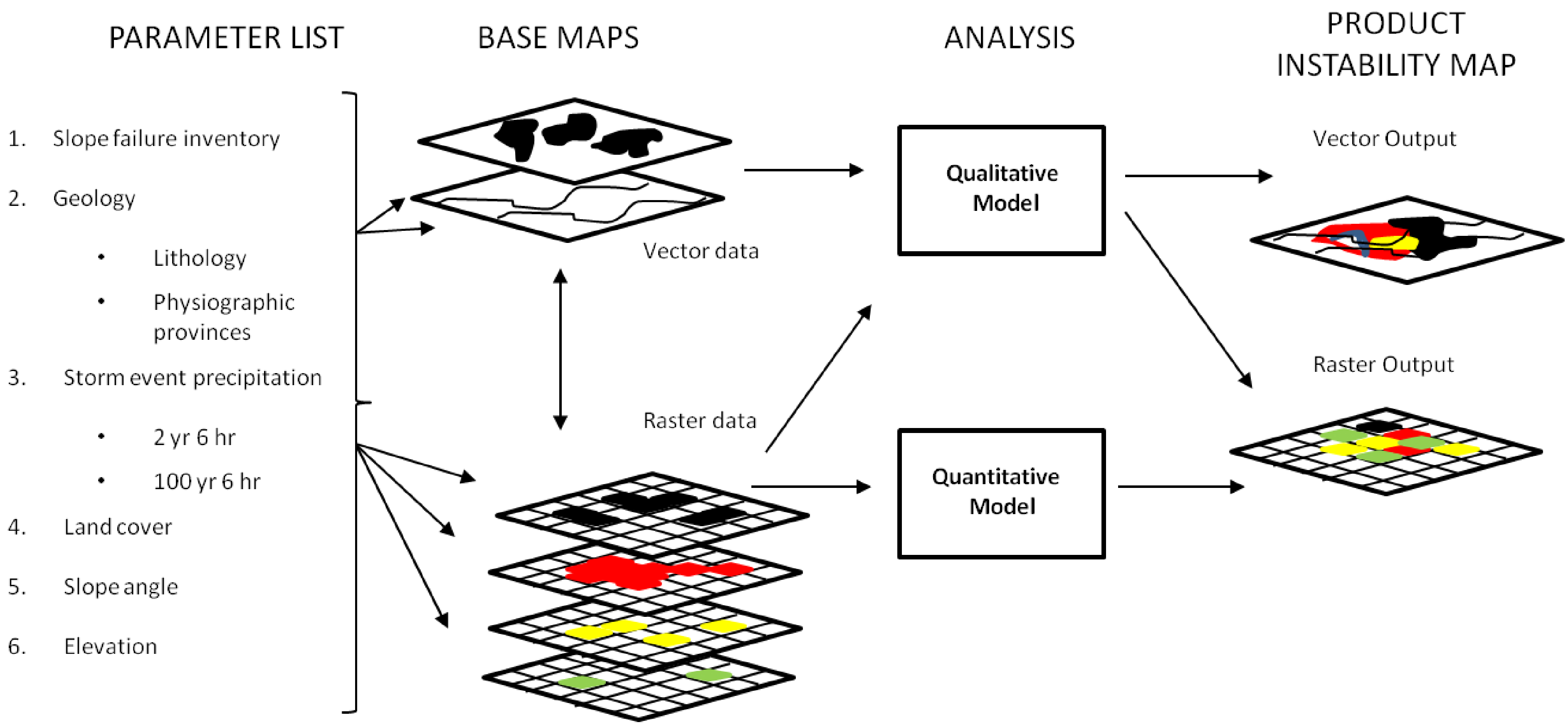


Figure 3.11: Schematic explaining the proposed mapping system. Currently the system uses the qualitative overlay model with a raster output.

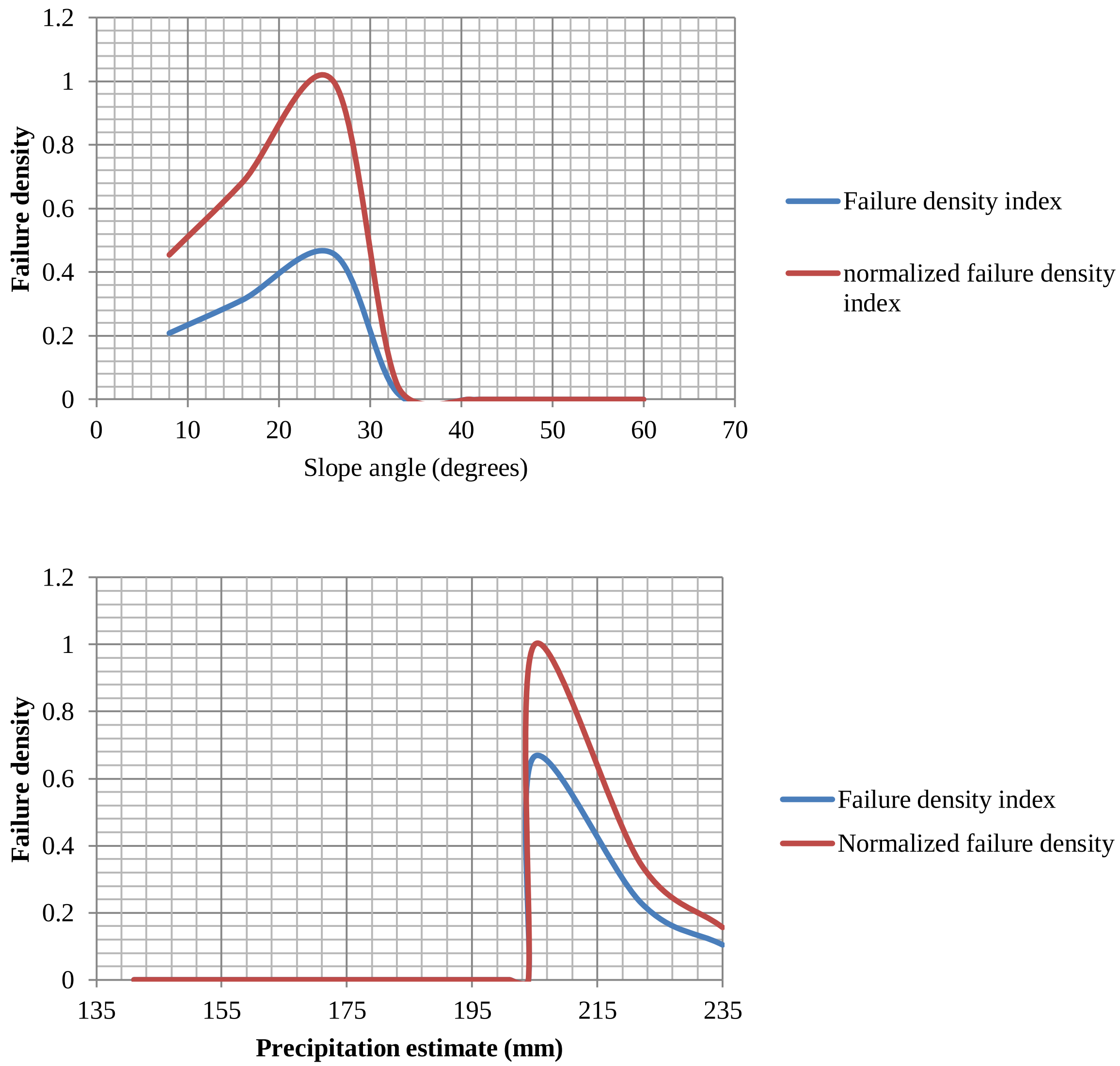


Figure 3.12: Variation of the failure density index and normalized failure density for the subclasses of parameters (a) Slope angle and (b) Storm event precipitation (100 yr, 24 hr)

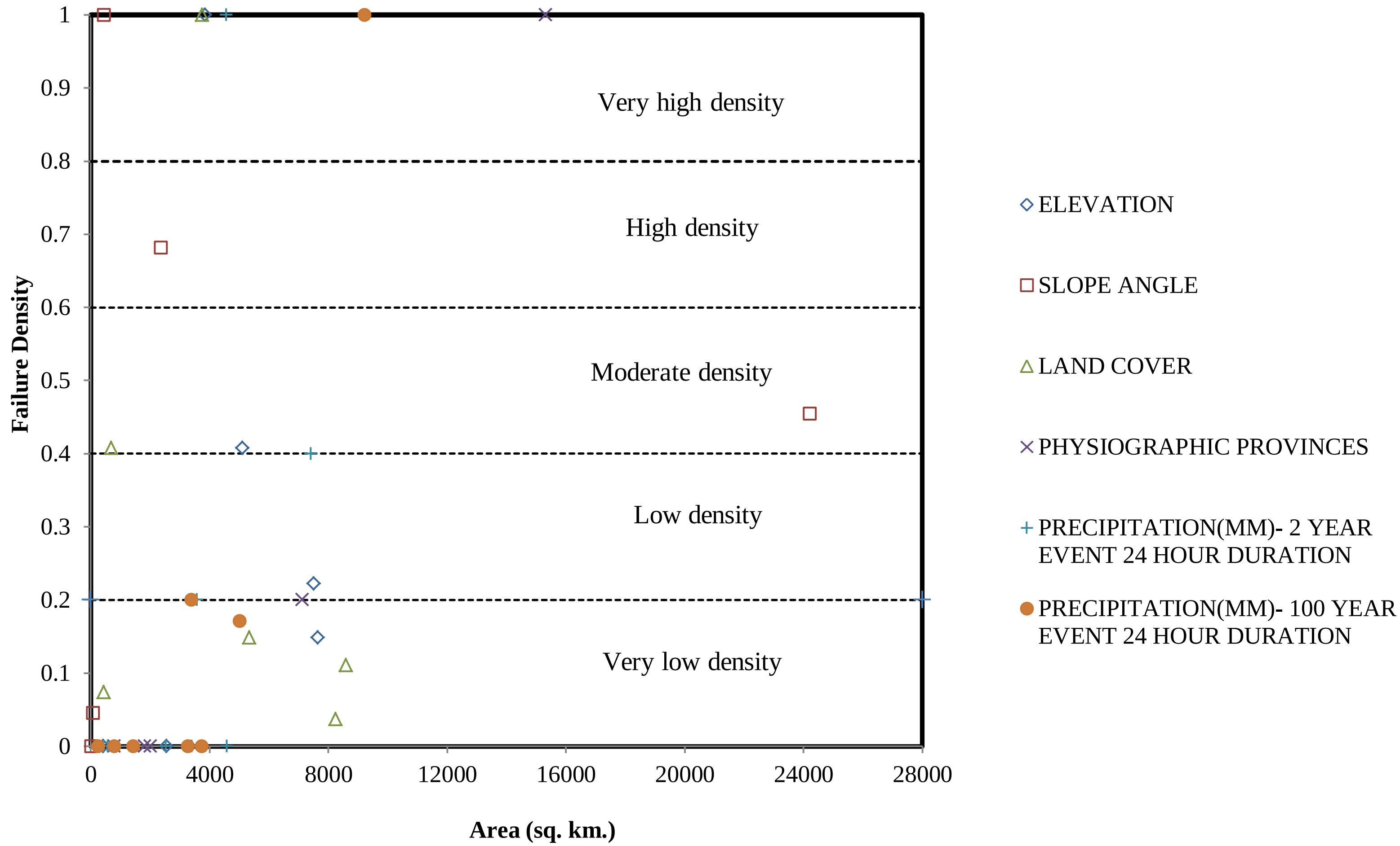


Figure 3.13: Variation of failure density indices for the different parameter subclasses over area of the study region

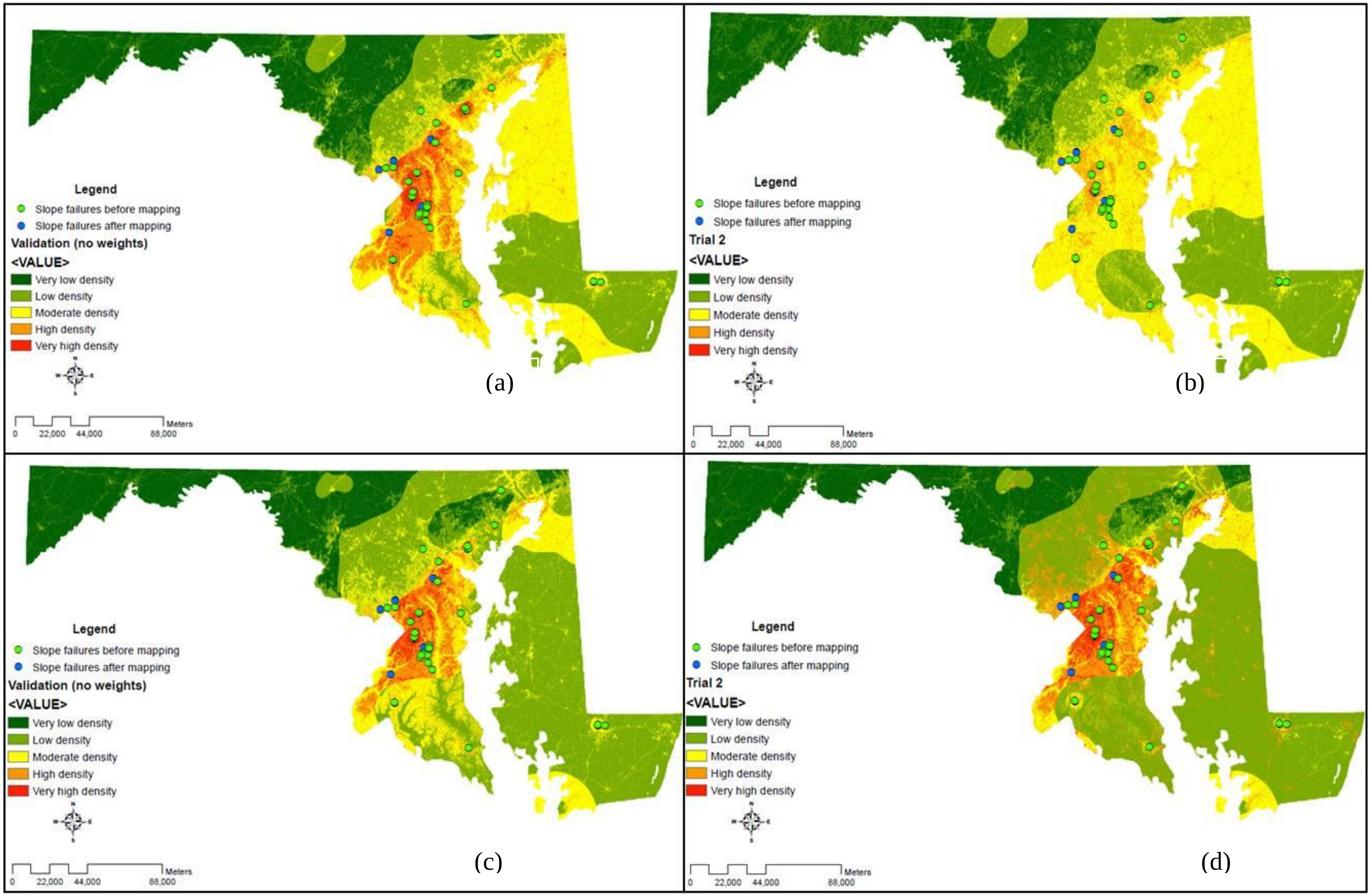


Figure 3.14: Failure density maps generated by layers and weights provided in Table 3.5. (a) Follows weighing scheme – Map 1 (b) follows weighing scheme – Map 2 (c) follows weighing scheme – Map 3 (d) follows weighing scheme – Map 4

CHAPTER 4

4.1 SUMMARY

The purpose of this study were (i) gathering and evaluation of historical data on soil slope failures in the State of Maryland and developing the necessary protocols to incorporate that information into a GIS database, (ii) developing a database structure containing information relating to soil slope failures (iii) laying the framework for the implementation of a quantitative model for predicting the vulnerable highway slopes in the State of Maryland.

A majority of the SMS reviewed in chapter 2 have an inherent factor of subjectivity linked with their study. While the issue of subjectivity while assessing failed slopes wasn't completely eliminated, this study presents and reviews procedures that can quantitatively analyze and rate slopes thus reducing subjective or qualitative analysis to a minimum.

The important conclusions, results and findings are discussed as follows:

a) A comprehensive management and assessment system has been developed to allow the SHA to better record, evaluate, analyze and review the soil slope failure data and soil slope remediation data

b) A database structure containing information relating to soil slope failures or distresses was developed using MS Access. This database structure was then organized into a web-based relational GIS type database with multiple Oracle SDE tables. All the information stored in the database and analyzed results can now be visualized by using GIS features.

c) A comprehensive survey sheet for recording information relevant and specific to highway slope failures in the State of Maryland. This failure field sheet has significantly reduced the time and optimized the data collection process for the engineers in the field. It has also enforced a structured approach towards data collection, entry and storage. The information collected in the field can be keyed in to the GIS database.

d) The Maryland SHA's remediation response towards slope failures was categorized into list of factors based on the consequence of failure. Thus, the initial stage in consequence and risk study is laid out. Taking into consideration the liability and legal issues that might arise due to the limited number of slope failure datasets and incomplete information regarding remediation information and cost of construction, at present engineers simply use this categorization as a guideline for budget allocation and prioritizing remediation projects.

e) A framework for analyzing slope instability is proposed and developed for the State of Maryland. A total of 48 slope failures recorded by Maryland SHA engineers using the GIS database were analyzed for emerging trends and patterns correlating physical parameters with slope instability.

Using the SMS tools- the failure field sheet and the GIS database, a total of 48 slope failure cases occurring between 2008 and 2012 were recorded actively and retroactively by engineers at the Maryland SHA. Based on the comprehensive information for the 48 slope failures and using spatial analysis tools certain trends in failure distribution in relation to the selected parameters were established. The significant and conclusive trends are listed as follows.

a. 56% of the total number of slope failures has occurred on slopes between 30 m and 90 m in height and nearly a fourth of the total number of failures have occurred on slope with heights between 10m and 30 m. No clear trend or correlation could be observed at present between slope height and soil slope failures in the State of Maryland

b. It is clearly evident that a majority (more than 50%) of failures has occurred on slopes with slope angles between 20° and 30° as these failures have occurred along highway slopes. For all engineering and analyses purposes, the Maryland SHA assumes that all or most highway slopes have a 2H: 1V slope unless explicitly mentioned. Thus, the analysis is congruent with field conditions

c. The failure distribution pattern for elevation and slope angle correlates with the field conditions observed by engineers, because the Maryland SHA records only those slope failures that are within their right of way. Since a distinct pattern or correlation with slope instability is yet to be drawn with respect to these parameters, it can be concluded that these numbers when combined with failure distribution patterns for other parameters will yield a more conclusive result.

d. 52% of the remaining slope failures have occurred on developed land or urbanized regions. This trend presents an interesting insight into the effect of urbanization and land use pattern on slope instability.

e. 58% of the existing slope failures have occurred in regions having low density land cover. This relatively large percentage occurrence of failures on developed land can be attributed to the increased amount of human activity such as blasting, drilling, traffic volume and other construction activities.

f. 90% of the total numbers of slope failures are surficial erosion failures. Only 4% of the slope failures are deep rotational type failures. Cross referencing with the GIS database, 80% of the total number of slope failures have occurred during or after rainfall.

g. More than 80% of the total slope failures have occurred in regions expected to have heavy amount of rainfall during a storm event. 96% of the slope failures have occurred along highway slopes with open drainage sections.

h. These trends when correlated with factors such as precipitation, the type of drainage section at failure site shows the influence of precipitation and drainage conditions on slope instability.

i. The statistic that 87% of the total number of slope failures recorded has occurred in the Atlantic coastal plains province highlights the effect of lithology or soil type of the highway slopes. The Atlantic coastal plains province predominantly consists of slopes with silty or clayey sand, gravelly sand, coarse sand and gravel type soils.

j. 50% of the total number of slope failures lay on slopes with sand formations and 39% of these slope failures occur on slopes with gravel formations.

k. The framework and guidelines for developing robust quantitative mapping system have been prepared. An ideal and suitable multivariate statistical approach was reviewed and is presented in this study.

4.2 RECOMMENDATIONS FOR FUTURE WORK

The SMS developed and reviewed in this study is still in a nascent stage. As frequently mentioned in various sections of this document, the full potential of the system will be realized with the inclusion of more slope failure cases.

The SMS developed has recorded only information relating slope failures that have occurred between 2008 and 2012. With the passage of time and continual process of further population of the database, many more improvements can be made to the system to support the influx of new information and analyze and establish more conclusive trends with regard to highway slope failures.

While the skeletal structure or framework of the system has been established, further improvements that were discussed in this study, but are presently out of the scope of this study, can be implemented to realize the full potential of such a tool. This section discusses the recommended improvements to be made to the GIS components in the near future

For the eGIS web map service, there are two important implementations that are required to improve the functionality and are discussed in the following paragraphs:

The first implementation is a photo gallery that can be viewed through the eGIS content. The Photo Viewer Widget allows users to peruse through thumbnail pictures, provide file names and provides save-to-desktop capabilities. This component of the eGIS content allows users to upload and view photographs of the failure site taken after failure, during remediation and after remediation.

Thus, the OMT is able to review and track (i) the performance of the highway slope after remediation projects (ii) the efficiency of a particular type of remediation methodology for a particular type of failure. The eGIS Technical Team recommends an approach similar to that adopted in developing the previous widgets for the same content. One of the many benefits of the eGIS application is the ability to reuse the technology and code for other projects. OMT wants the ability to upload pictures stored on their fileshare with naming conventions and sub-folder structure.

The second implementation is the incorporation of a robust quantitative mapping system based on the mathematical model discussed in the previous chapter. Such a model requires large sample datasets to accurately predict the probability of failure of any given highway slope. While this implementation cannot be adopted immediately, it is definitely imperative, because at the regional scale, only a quantitative mapping system would be ideal and accurate for use.

When sufficient data is available regarding dimensions of initiation sites and volume of debris in the future, it is recommended that the scale of study is leveled down to medium to small scale (analysis is performed at the district level or county level). This increases the accuracy of prediction and presents a multitude of mapping techniques to be chosen from. Also the ratio between the total area of failure sites and the total study area becomes much more significant at this scale of study, thereby presenting conditions for susceptibility analysis or conditional probability analysis.

As and when the GIS database is populated with remediation details and maintenance information, it is recommended that this data is analyzed to ascertain the most cost effective and efficient remediation methodology for a particular type of failure. The results from the data analysis could be used as input for developing an automated remediation response model, which provides the most viable remediation option based on the set of parameters previously discussed. This model may also be able to perform benefit to cost ratio analysis, thereby providing district offices with significant results to allocate budgets and resources accordingly.

APPENDIX A
FAILURE SITE FIELD SHEET

Failure Site Field Sheet

Site Evaluation Date: MM/DD/YYYY

Contract #: FMIS#:

1. Site Location

District:____________________ County: __________________ Date of Failure Reported : ______________

Route #:_____ Route Direction: _____ # of Lanes: ________

Multiple Failures: __ Yes __ No

Location information : Area #___out of ___

Route Name (if any):___________________________________

ADT:______________________ Route Type: ______________

BMP : _____ EMP : _____ Northing (ft) : ______________ Lat. (Deg) : _________________

Easting (ft) : ______________ Long. (Deg): _________________

Failure Location With Respect to Roadway: ☐ Above Roadway ☐ Below Roadway

Weather Conditions during Failure: ☐ Rain ☐ Snow ☐ Flooding ☐ Other: _____________

Comments: ____

2. Slope Failure Type

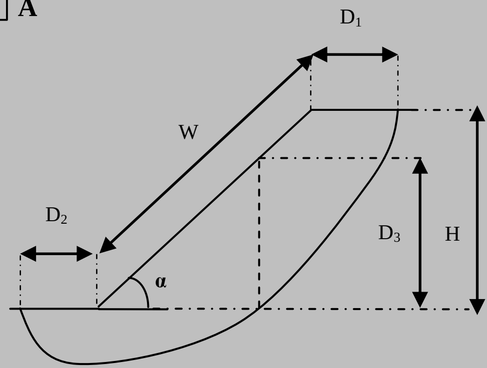
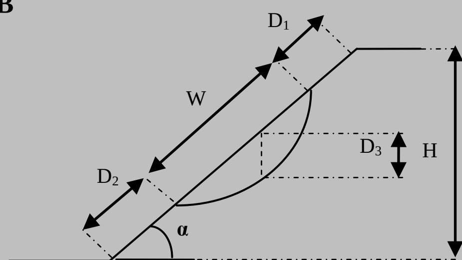
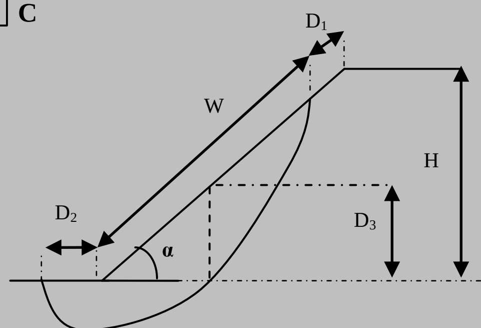
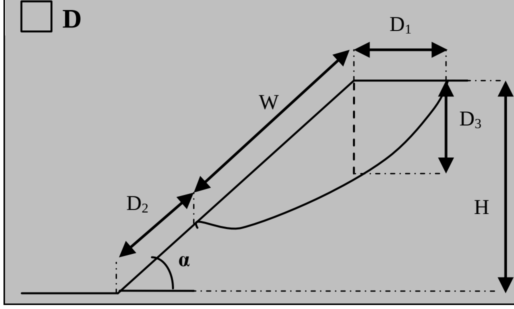
Type of failure:					
☐ Erosion	Erosion Area	☐ Head	☐ Toe	☐ Flank	☐ Body
☐ Rotational (provide sketch below)		Circular	☐ Deep		☐ Shallow
		Non-circular	☐ Deep		☐ Shallow
☐ Translation (provide sketch below)		☐ Block		☐ Slide	
☐ Compound / Complex (provide sketch below)					
☐ Others(provide sketch below)		☐ Landslide	☐ Flow	☐ Spread	

Sketch Box

Comments:

Project Description: ____

3. Detailed Dimensions of Failure

☐ **A** 	1. Length of failure section along roadway, L:_______________Feet 2. Average slope angle, α:_________degrees 3. Height of slope, H:____________Feet 4. Width of failure along slope incline, W:______________ Feet 5. Distance from crest of slope to failure section, D_1: _____________ Feet 6. Distance from toe of slope to failure section, D_2: _____________ Feet 7. Maximum depth of failed section, D_3:______________Feet
☐ **B** 	1. L:_______________Feet 2. α:________________degrees 3. H:________________Feet 4. W:________________Feet 5. D_1: _______________ Feet 6. D_2: _______________ Feet 7. D_3:________________Feet
☐ **C** 	1. L:_______________Feet 2. α:________________degrees 3. H:________________Feet 4. W:________________Feet 5. D_1: _______________ Feet 6. D_2: _______________ Feet 7. D_3:________________Feet
☐ **D** 	1. L:_______________Feet 2. α:________________degrees 3. H:________________Feet 4. W:________________Feet 5. D_1: _______________ Feet 6. D_2: _______________ Feet 7. D_3:________________Feet

Comments:____

____

____

Project Description: ____

4. Impact Assessment on Roadway and Beyond Right of Way

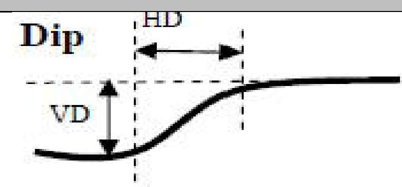
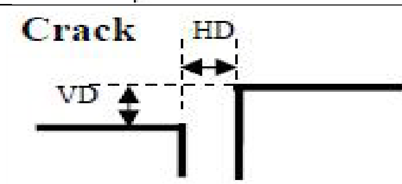
Current and Potential Impact of Slope Failure on Roadway

- ☐ On slope with a low potential to affect shoulder
- ☐ On slope with a low potential to affect roadway
- ☐ On shoulder or on slope with moderate potential to affect roadway
- ☐ On roadway or on slope with high potential to affect roadway or structure

Current and Potential Impact of Slope Failure on Area Beyond Right of Way

- ☐ On slope with a low potential to impact area beyond right of way
- ☐ On slope with a moderate potential to impact area beyond right of way
- ☐ On slope with a high potential to impact area beyond right of way
- ☐ On slope with a high potential to impact building or structure beyond right of way

Natural Activities

Dip	☐ Yes	☐ No	
Maximum displacement of dip			
Vertical displacement (VD) (inch) :______________________			
Horizontal displacement (HD) (inch):______________________			
Crack	☐ Yes	☐ No	
Maximum displacement of crack			
Vertical displacement (VD) (inch) :______________________			
Horizontal displacement (HD) (inch):______________________			
Earth Debris on Roadway	☐ Yes	☐ No	Estimated volume(Yd^3):______________________
Comments			

5. Adjacent Structures and Area

Adjacent Structures

☐ Roads ☐ Railroads ☐ Residential ☐ Buildings ☐ Bridge ☐ Utilities ☐ Culverts ☐ Other(specify):____________

Surrounding Area

☐ Forest ☐ Agriculture ☐ Rural ☐ Urban ☐ Housing development ☐ Others(specify):______________________

Comments	

Failure Site Field Sheet

Site Evaluation Date: MM/DD/YYYY

6. Existing Utilities or Structures Affected

Utilities/ Structures Affected			
☐ Ditch line	☐ Bridge	☐ Sewer line	☐ Electric- overhead
☐ Drainage pipe	☐ Travel lane pavement	☐ Gas line	☐ Electric- underground
☐ Culvert	☐ Shoulder	☐ Water line	☐ Telephone- overhead
☐ Guard rail	☐ Headwall	☐ Cable TV	☐ Telephone- underground
☐ Sign structure	☐ Others(specify):_______________________________		
Comments			

7. Slope Characteristics

Slope Type		☐ Natural ☐ Cut ☐ Fill ☐ Cut and Fill ☐ Reinforced ☐ Rip-rap ☐ Rock	
Original Slope Ratio (H:V)			
Slope Surface Appearance		☐ Straight ☐ Concave ☐ Convex ☐ Hummocky ☐ Terraced ☐ Complex	
Vegetation Cover	☐ Grass	___% Land covered	Comments:
	☐ Shrub	___% Land covered	
	☐ Cultivated land	___% Land covered	
	☐ Reforestation	___% Land covered	
	☐ Woodland	___% Land covered	
	☐ Other	___% Land covered	
Vegetation Density		☐ Sparse ☐ Moderate ☐ Dense	
Hydrogeology	**Surface Water**	**Types of Sources**	
		☐ None ☐ Reservoir ☐ Lake ☐ Pond	☐ Creek ☐ Surface drainage ☐ River ☐ Other : ____________
		Location of Sources with Respect to Highway	
		☐ Above ☐ Below ☐ Both	
		Surface Drainage Type	
		☐ Closed section	☐ Open section
		Surface Drainage Flow Direction	
		☐ Towards slope	☐ Away from slope
	Ground Water	**Groundwater Flow**	
		☐ Into failure area ☐ Off failure area ☐ Both ☐ Unknown ☐ None	
		Groundwater Condition	

Project Description: ____

		☐Spring ☐Seep ☐Both ☐Unknown ☐None
		Location of Groundwater
		☐ Above ☐ Below ☐ Middle ☐ None
		Presence of Monitoring or Water well
		☐ Artesian ☐ Flowing artesian ☐ Pooled ☐ None
Comments		

8. Slope Materials Information

Soil Origin	☐Unweathered rock ☐Weather rock ☐Residual soil ☐Colluvium ☐Alluvium ☐Till ☐ Fill ☐Combination ☐Other(specify):________________________
Soil Type	☐Boulders/cobbles ☐Stone fragments ☐Gravel ☐Sand ☐Fine sand ☐Silty gravel ☐Clayey gravel ☐Silty sand ☐Clayey sand ☐Silty soil ☐Clayey soil ☐Organic ☐Combination ☐Others(specify):________________________
Physiographic Province	☐Appalachian Plateaus ☐Blue Ridge ☐Ridge and Valley ☐Piedmont Plateau – Lowland ☐Coastal Plain - Western Shore Upland ☐Piedmont Plateau – Upland ☐Coastal Plain - Delmarva Peninsula
Comments	

9. Observed Remediation

Existing Remedial Activities	☐Drainage ☐Bio-stabilization ☐Slope Geometry Correction ☐Retaining Structures ☐Internal Slope Reinforcement ☐Erosion Control ☐Chemical Stabilization ☐Rip-rap ☐Other(specify):________________________
Comments	

Project Description: ____

Failure Site Field Sheet

Site Evaluation Date: MM/DD/YYYY

10. Preliminary Determination of Cause of Failure

Human Activities	☐ Excavation/under cutting ☐ Deforestation ☐ Water leakage from pipes ☐ Loose waste dumping	☐ Groundwater pumping ☐ Defective maintenance ☐ Artificial vibrations ☐ Construction related	☐ Loading ☐ Failure of drainage ☐ Poor vegetation ☐ Other(specify):____________
Natural Activities	☐ Rainfall ☐ Ground water ☐ Rapid drawdown/ Surface water level change ☐ Degradation of construction material	☐ Snowmelt ☐ Toe erosion	☐ Earthquake ☐ Inadequate long term strength ☐ Erosion from concentrated surface flow ☐ Other(specify):____________
Comments			

11. Suggested Remediation Measures

☐ Drainage Improvement Remarks: ______________________________

☐ Scour Counter Measures Remarks: ______________________________

☐ Remove & Replace Remarks: ______________________________

☐ Rip-rap Remarks: ______________________________

☐ Light Weight Fills Remarks: ______________________________

☐ Chemical Treatment Remarks: ______________________________

☐ Bio-engineering Remarks: ______________________________

☐ Geosynthetic Reinforcement Remarks: ______________________________

☐ Regrading or Flattening Slope Remarks: ______________________________

☐ Benching and Regrading Remarks: ______________________________

☐ Counter Berm and Regrading Remarks: ______________________________

☐ Shear Key Remarks: ______________________________

☐ Soil Nailing Remarks: ______________________________

☐ Concrete Retaining Wall Remarks: ______________________________

☐ Sheet Pile Remarks: ______________________________

☐ H-Pile Remarks: ______________________________

☐ Drilled Shaft Remarks: ______________________________

☐ Solder Pile Lagging Wall Remarks: ______________________________

☐ Relocation Remarks: ______________________________

☐ Other (specify):

____

____

Project Description: ____

12. Remediation Information

Repair Status :
Recommended Repair :
Recommendation Date : ___/___/______
Remediation FMIS # :
Remediation Contract # :
Remediation Method Used :
Estimated Repair Cost :______________________$
Estimated Time Required for Remediation (days):______________________days
As-built Plans :______________________

Evaluator name :
Evaluator signature :

APPENDIX B
REMEDIATION RESPONSE CATEGORIZATION

Category	Considered	Not Considered	Comments
Accident History/Potential			
Relative Emergency (FHWA rating)			
Impact on Traffic			
Roadway Impedance			
Pavement Damage			
Utility Impact			
Impact of Failure along Length of roadway			
Material Incursion on Roadway			
Maintenance Frequency			
Maintenance Cost			
Annual Average Daily Traffic (AADT)			
Groundwater Conditions			
Vegetation Conditions			

Figure B.1 :The remediation response categorization sheet currently used by OMT engineers while filing geotechnical reports.

Table B.1: The various categories shortlisted and their definitions

Impact on Traffic	Categorizes the impact of failure based on the functioning capability of the highway after failure has occurred. It provides information on whether the traffic flow is normal, or the roadway is partially or completely shut down due to slope failure along the roadway
Annual Average Daily Traffic (AADT)	The total volume of vehicle traffic of a highway or road for a year divided by 365 days.
Maintenance Frequency	Is used to reflect the intensity/frequency of the past maintenance activity of a landslide site.
Maintenance Cost	Is used to reflect the cost involved with remediation of the slope each time it fails
Material Incursion on Roadway: Frequency	Frequency per year at which the slope material falls on the roadway whenever the slope tends to fail
Accident History/Potential	Is used to categorize the accidents/damage caused to the public/property by the failed slope, or the potential of a slope to cause accidents when it fails.
Pavement Damage	Is used to reflect the magnitude of damage inflicted on the pavement as a result of the slope failure along the roadway
Impact of Failure along Length of roadway	Is the length of the failure section in feet measured along the roadway
Roadway Impedance	Is the extent of slope material incursion along the width of the roadway, caused due to slope failure
Relative Emergency (FHWA rating)	Is the failure rating criteria suggested by the FHWA based on the remediation response required for the failed slope. (ref. FHWA Slope stability and maintenance manual)
Utility Impact	Is the category used to reflect the intensity of the failure based on the number of utilities affected at the failure site
Groundwater Conditions	Is used to indicate the nature of groundwater conditions at the failure site
Vegetation Conditions	Is used to indicate the nature of vegetation conditions and the density of vegetation at the failure site.

Table B.2: Hierarchy numbers for categories listed engineer-wise. Cells highlighted in grey are suggested additions for which ratings were provided.

Category	Eng I	Eng II	Eng III	Eng IV	Eng V	Eng VI	Average	Std. Deviation
Impact on Traffic	1	3	13	3	3	5	4.7	4.27
Roadway Impedance	2	2	5	6	13	1	4.8	4.45
Pavement Damage	3	16	3	4	6	1	5.5	5.39
Annual Average Daily Traffic (AADT)	4	15	15	11	4	14	10.5	5.24
Average Vehicle Risk (AVR)	*5*	14	14	2	2	12	8.2	5.81
Failure Depth: Embankment Height	6	9	9	8	14	1	7.8	4.26
Material Incursion on Roadway: Frequency	7	10	10	5	12	1	7.5	4.04
% Decision Sight Distance (DSD)	8	18	8	9	8	15	11.0	4.38
Maintenance Frequency	9	5	11	12	10	5	8.7	3.01
Maintenance Cost	10	7	12	15	11	6	10.2	3.31
Accident History/Potential	11	4	2	1	5	2	4.2	3.66
Relative Emergency (FHWA rating)	12	1	1	10	1	1	4.3	5.20
Impact of Failure along Length of roadway	13	8	4	7	7	1	6.7	4.03
Traffic Speed	14	11	6	13	9	10	10.5	2.88
Highway Classification	15	19	7	14	15	11	13.5	4.09
% of Trucks	16	20	16	16	16	5	14.8	5.08
Utility Impact	N/a	6	N/a	N/a	N/a	N/a	6.0	N/a
Rate of Slope Movement	N/a	12	N/a	N/a	N/a	N/a	12.0	N/a
Groundwater Conditions	N/a	13	N/a	N/a	N/a	N/a	13.0	N/a
Vegetation Conditions	N/a	17	N/a	N/a	N/a	N/a	17.0	N/a

APPENDIX C
BASE MAPS

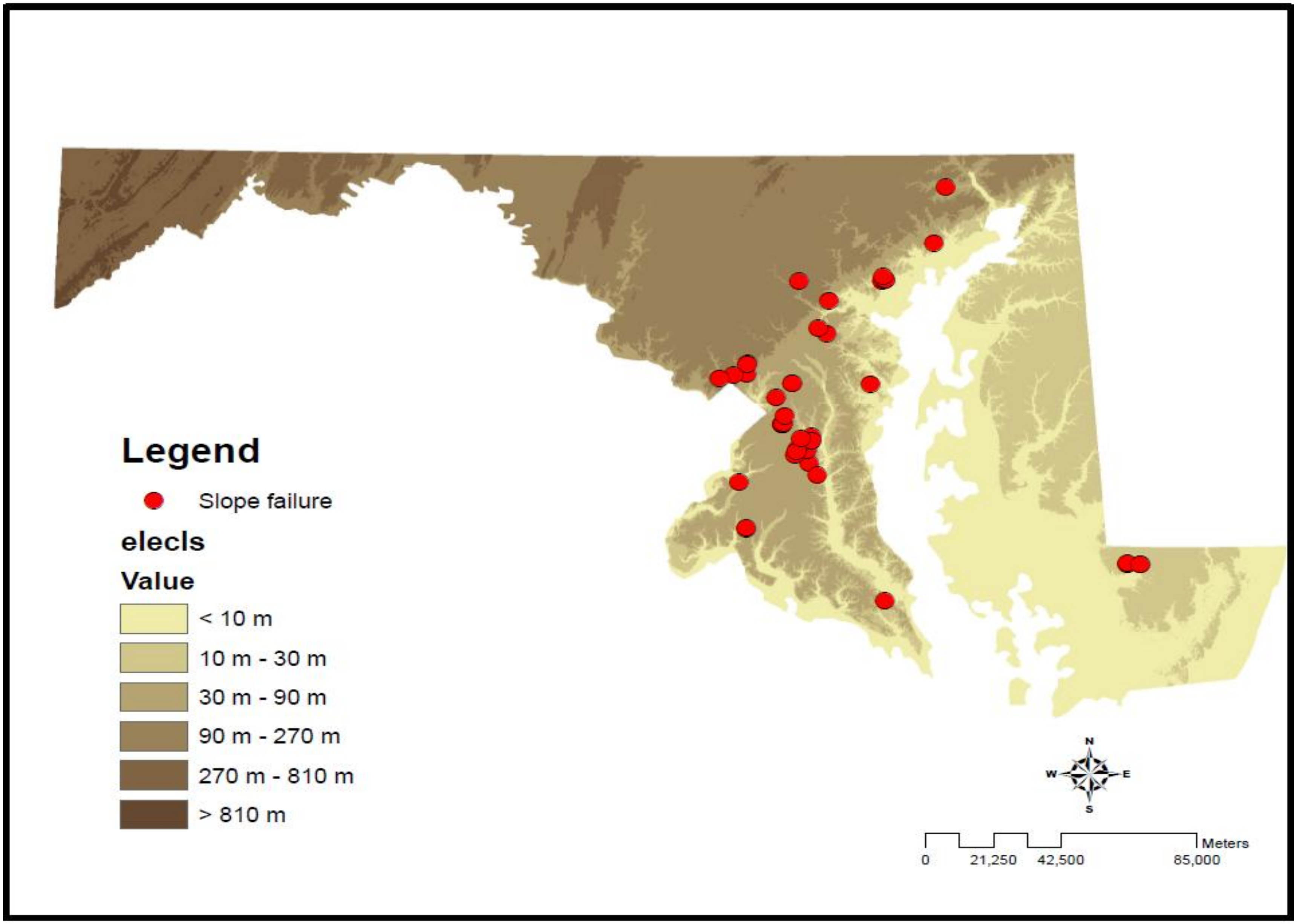


Figure C.1: Elevation data layer in meters along with the spatial distribution of slope failures

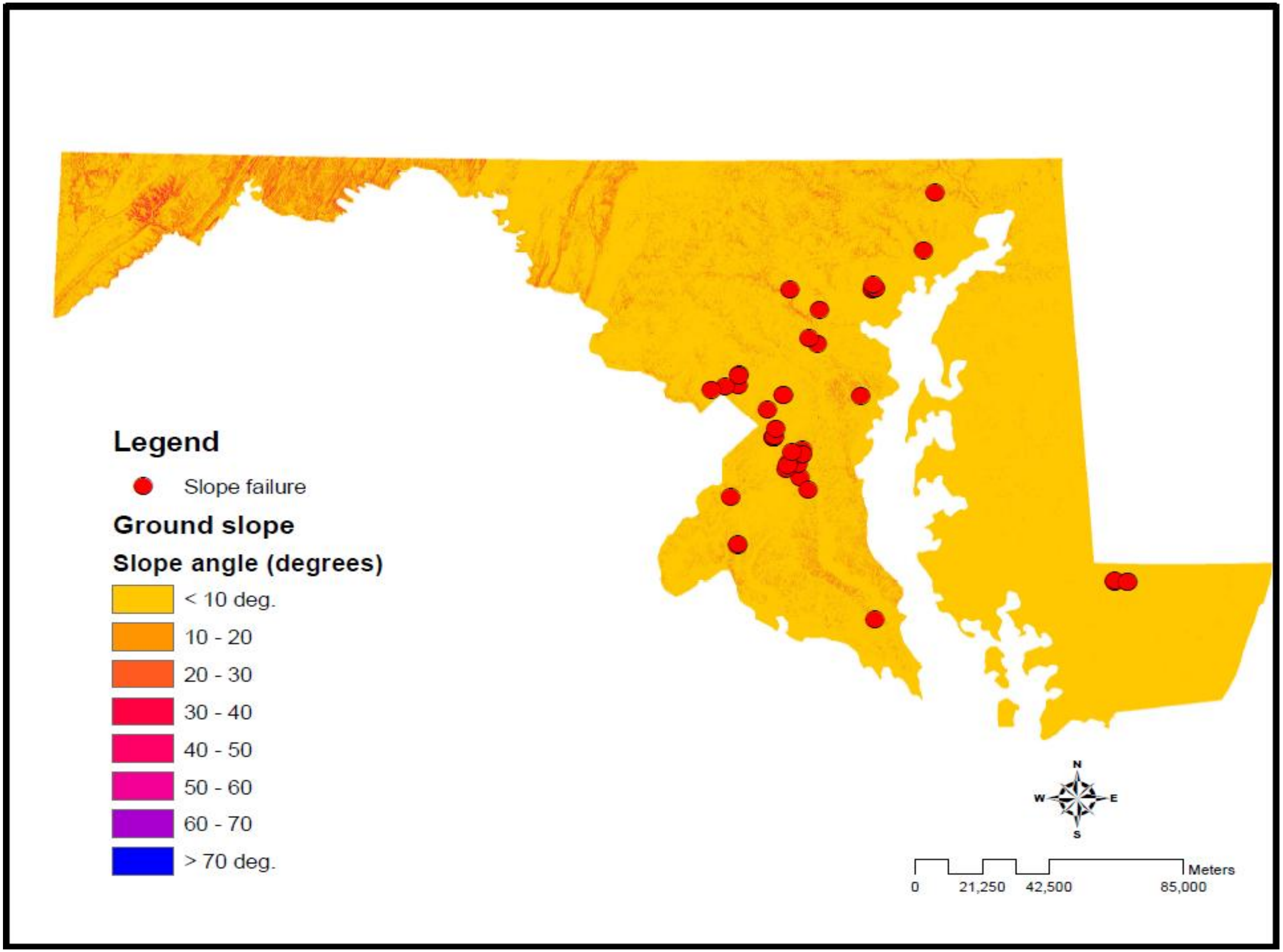


Figure C.2: Slope angle data layer in meters along with the spatial distribution of slope failures

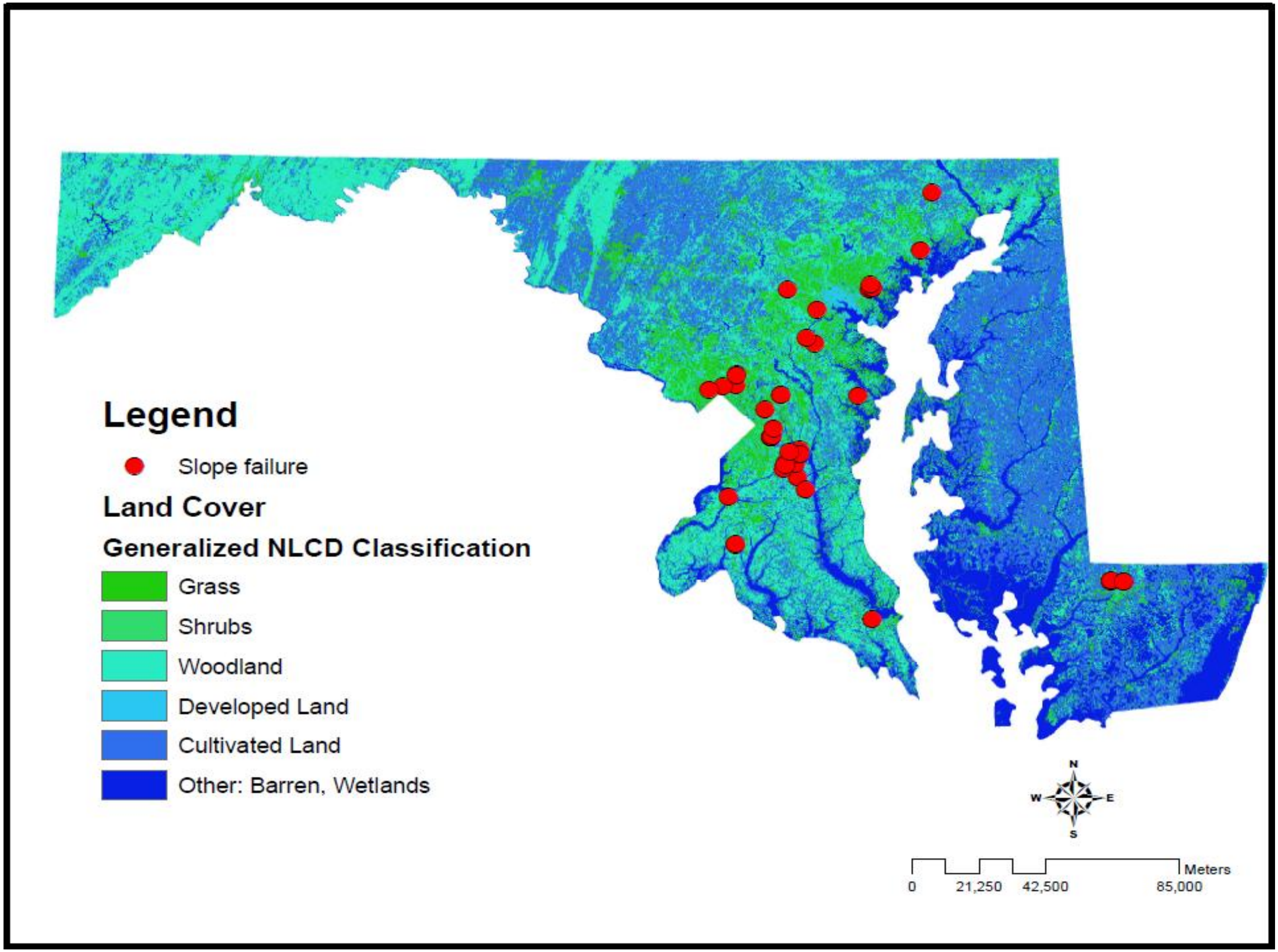


Figure C.3: Land cover data layer in meters along with the spatial distribution of slope failures

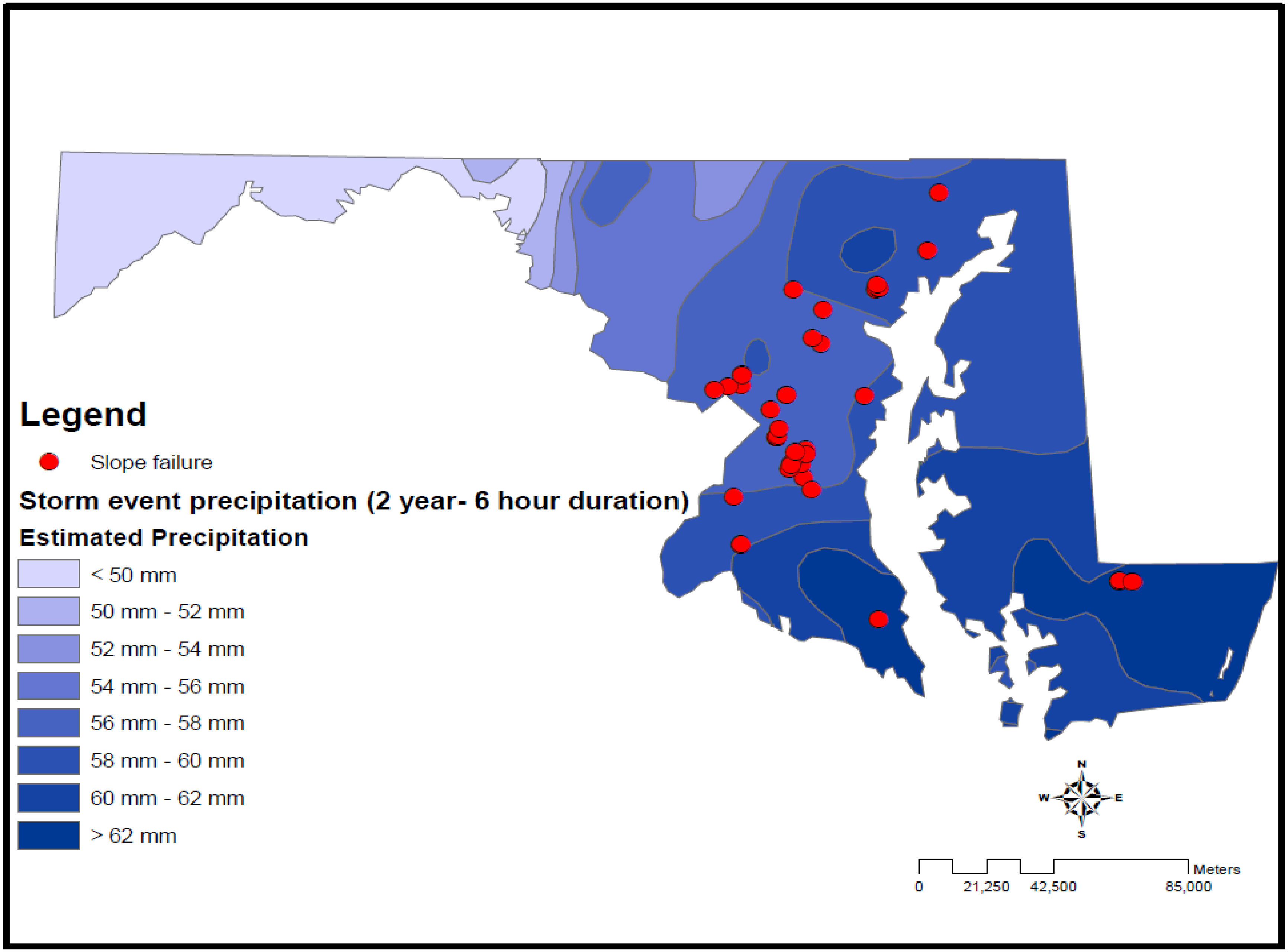


Figure C.4: Storm event precipitation (2 year, 24 hour) data layer in meters along with the spatial distribution of slope failures

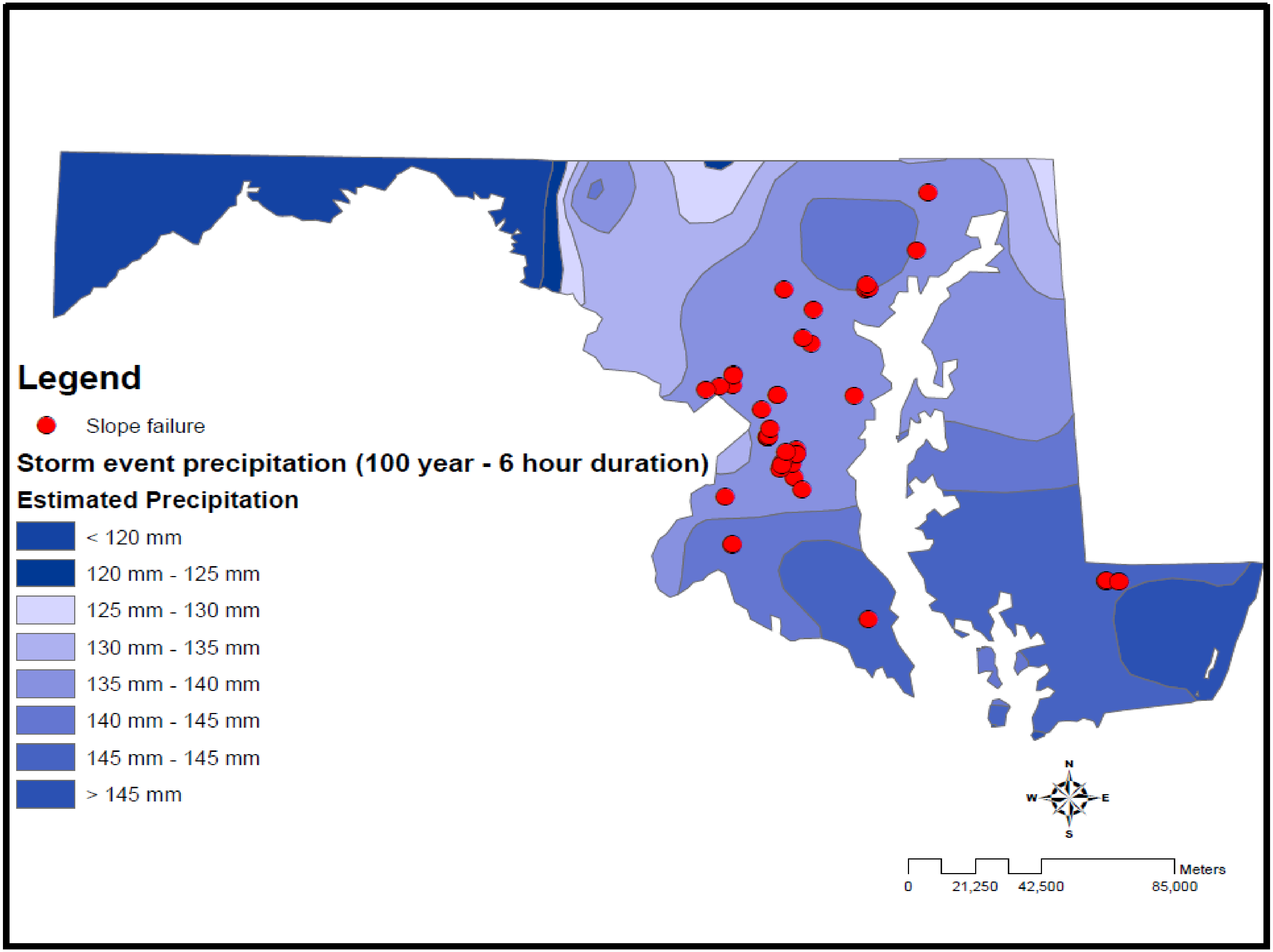


Figure C.5: Storm event precipitation (100 year, 24 hour) data layer in meters along with the spatial distribution of slope failures

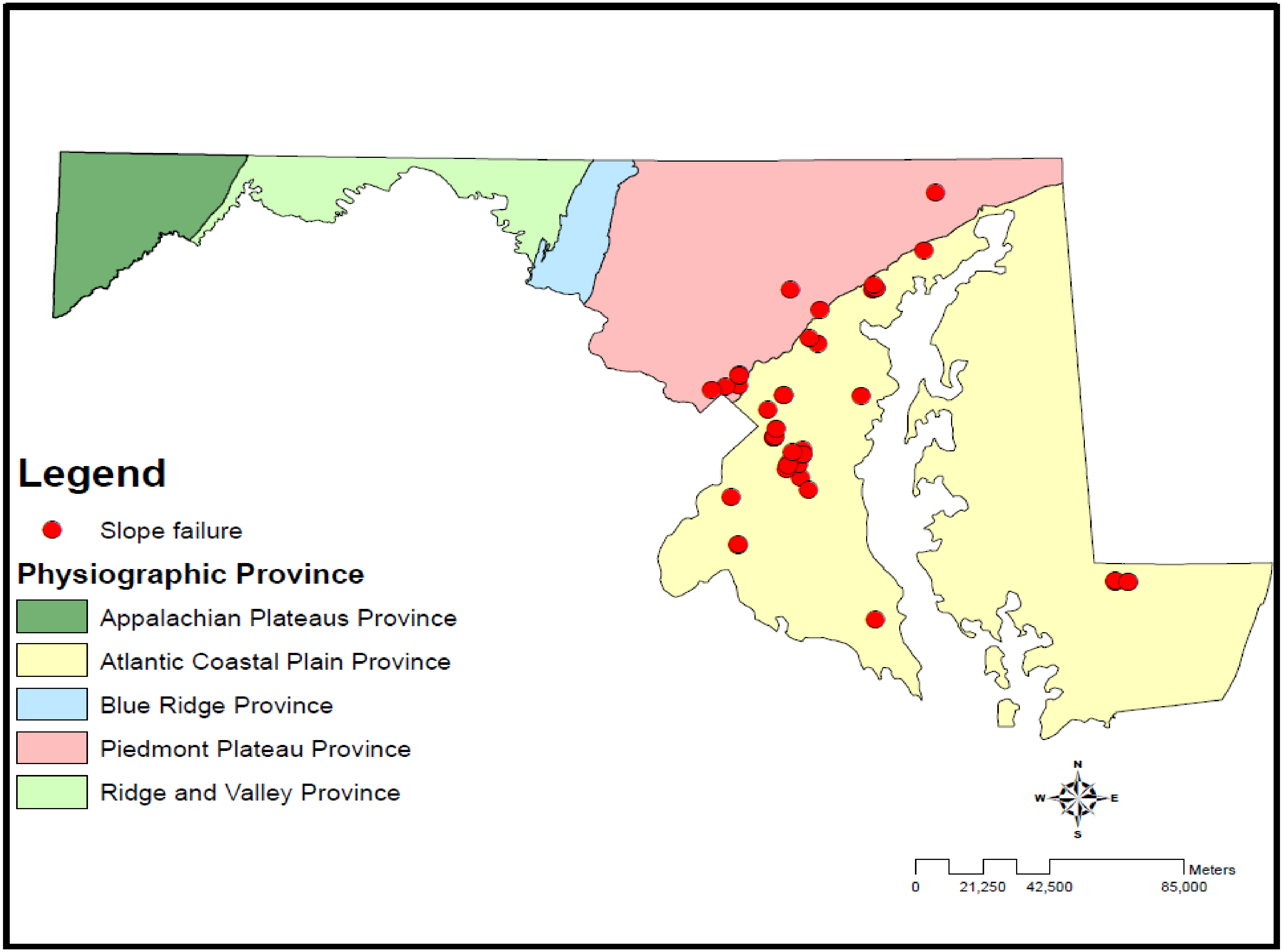


Figure C.6: Physiographic provinces data layer in meters along with the spatial distribution of slope failures

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