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STATE HIGHWAY ADMINISTRATION

RESEARCH REPORT

SLOPE FAILURE INVESTIGATION MANAGEMENT SYSTEM

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Highway slopes are exposed to a variety of environmental and climatic conditions, such as deforestation, cycles of freezing and thawing weather, and heavy storms. Over time, these climatic conditions, in combination with other factors such as geological formations, slope angle and groundwater conditions can influence slope stability. These factors contribute to slope failures that are hazardous to highway structures and to the traveling public. Consequently, it is crucial to have a management system that tracks, records, evaluates, analyzes, and reviews the soil slope failure and remediation data so that cost effective and statistically efficient remedial plans may be developed. The final report 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.</td></tr>
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EXECUTIVE SUMMARY

Highway slopes are exposed to a variety of environmental and climatic conditions, such as deforestation, cycles of freezing and thawing weather, and heavy storms. Over time, these climatic conditions, in combination with other factors such as geological formations, slope angle and groundwater conditions, can influence slope stability. These factors contribute to causing slope failures that are hazardous to highway structures and to the traveling public. Consequently, it is crucial to have a management system for investigating soil slope failure that tracks, records, evaluates, analyzes, and reviews the soil slope failure and remediation data so that cost effective and statistically efficient remedial plans may be developed. This report 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.

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CHAPTER 1

INTRODUCTION

Highway slopes are exposed to environmental and climatic conditions, such as cycles of freezing and thawing weather, and heavy storms. Over time, these climatic conditions, in combination with other factors such as geological formations, slope angle and type of slope vegetation, can influence slope stability. These factors contribute to causing slope failures that are hazardous to highway structures and the traveling public. The Federal Highway Administration (FHWA) has strongly suggested to 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 present focus is on developing an early warning system, using a Geographic Information System (GIS) database and a collective overlay of maps to enable 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: statewide state-of-nature maps that include geological formation maps, land cover data, highway slope failure inventory and elevation data; 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 each factor that reflects their influence on slope stability and slope failure.

Movement of soil mass along slopes can now be assessed by incorporating statistical analysis of data collected on the slopes into the assessment system. A self-sustaining system that analyzes the stability of slopes is called as slope stability management system (SMS) (Lee et al., 2006). Many GIS-based slope instability assessment systems use different methods to analyze the data collected. Each assessment system may have different sets of parameters and weighting scheme because these factors should be defined for different landscapes.

Different soil types and slope characteristics vary in effect 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 (e.g., surficial failure and rotational failures) have also been observed in coarser slope material like gravel or sand. Consequently, it is crucial that a management system for investigating soil slope failure to track, record, evaluate, analyze, and review soil slope failure and remediation data. This system will provide data for evaluating the cause(s) of soil slope failures and will provide design, construction, and maintenance recommendations to minimize the potential of soil slope failures and repair.

There were three primary objectives of this study. The first was to gather and evaluate historical data on soil slope failures in Maryland in order to develop the necessary protocols for incorporating that information into a GIS database. The second was to develop a database structure containing information about soil slope failures. Finally, the third was to create a quantitative model in order to both predict the probability of slope failure for Maryland highways and to translate the model into color-coded vulnerability maps.

The Maryland State Highway Administration (SHA) does not currently have a database or management system to identify and evaluate the details of highway slope failures, or track the remediation methods and costs. Hence, the immediate need to gather relevant information about current and previous highway slope failures is paramount to sustain an efficient slope management system (SMS). Once the relevant information about slope failures is documented on-site using tools such as site survey sheets and handheld Global Positioning System (GPS) devices, the data must be cataloged and stored in a comprehensive yet user-friendly database. These two attributes will enable faster retrieval of required information by future users. With this system of recording and storing information, the process of evaluating and analyzing data stored becomes a less complicated task.

CHAPTER 2

2.1 INTRODUCTION

Soil management systems (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 management system for investigating soil slope failure to better track, record, evaluate, analyze, and review soil slope failure data and soil slope remediation data on SHA roadways. Over the years, many soil slope failures have occurred on or near SHA roadways. Figure 2.1 shows some of the different types of slope failures that occurred in Maryland. These soil slope failures have had negative effects on public and highway safety and have cost SHA millions of dollars. For instance, the repair of the soil slope failure at MD 24 N/B from the CSX Bridge to US 40 Connector caused SHA approximately $1.5 million.

Most of the current research focuses on developing an early warning system, that uses a GIS database and a collection of spatial data. These early warning systems enable prediction of soil slides or failures in advance. Such systems have information from six categories of factors that influence slope stability: slope failure inventory data; geological formations; slope material and characteristics; local topographic (e.g., slope height and angle); remediation and maintenance; and weather condition data.

The SHA does not currently have a database or management system in place to evaluate and identify the details of these failures, or track the remediation methods and costs. Without such a system, SHA is at a disadvantage at preventing slope failures through identification of conditions that precede such slides. Popescu (1994), for example, listed a variety of ground conditions that may be conducive to 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) also listed several natural geomorphologic processes and man-made physical processes that make a direct impact on soil mass movement in slopes (Table 2.1). 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 different types of soil slope instability mechanisms. For these reasons, it is crucial to have a management system for investigating soil slope failure to track, record, evaluate, analyze and review the soil slope failure data and soil slope remediation data. This system will enable evaluation of the causes of soil slope failures and will provide design, construction, and maintenance recommendations to minimize soil slope failures and repair in the future.

Although many reports discuss how to use effects and consequences of failures to categorize slope failures by hazard level (Pierson et. al, 1990; ODOT, 2001; UDOT, 2001; OHDOT, 2007; NYSDOT, 2007), few address issues of how to prioritize remediation responses. This research project lists vital factors that should be considered when choosing remediation techniques for each type of slope failure. This research project also addresses how to prioritize resource and budget allocations to these remediation projects. With this asset-management and decision-support tool, SHA will be able to prioritize and optimize remediation responses to slope failures.

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

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

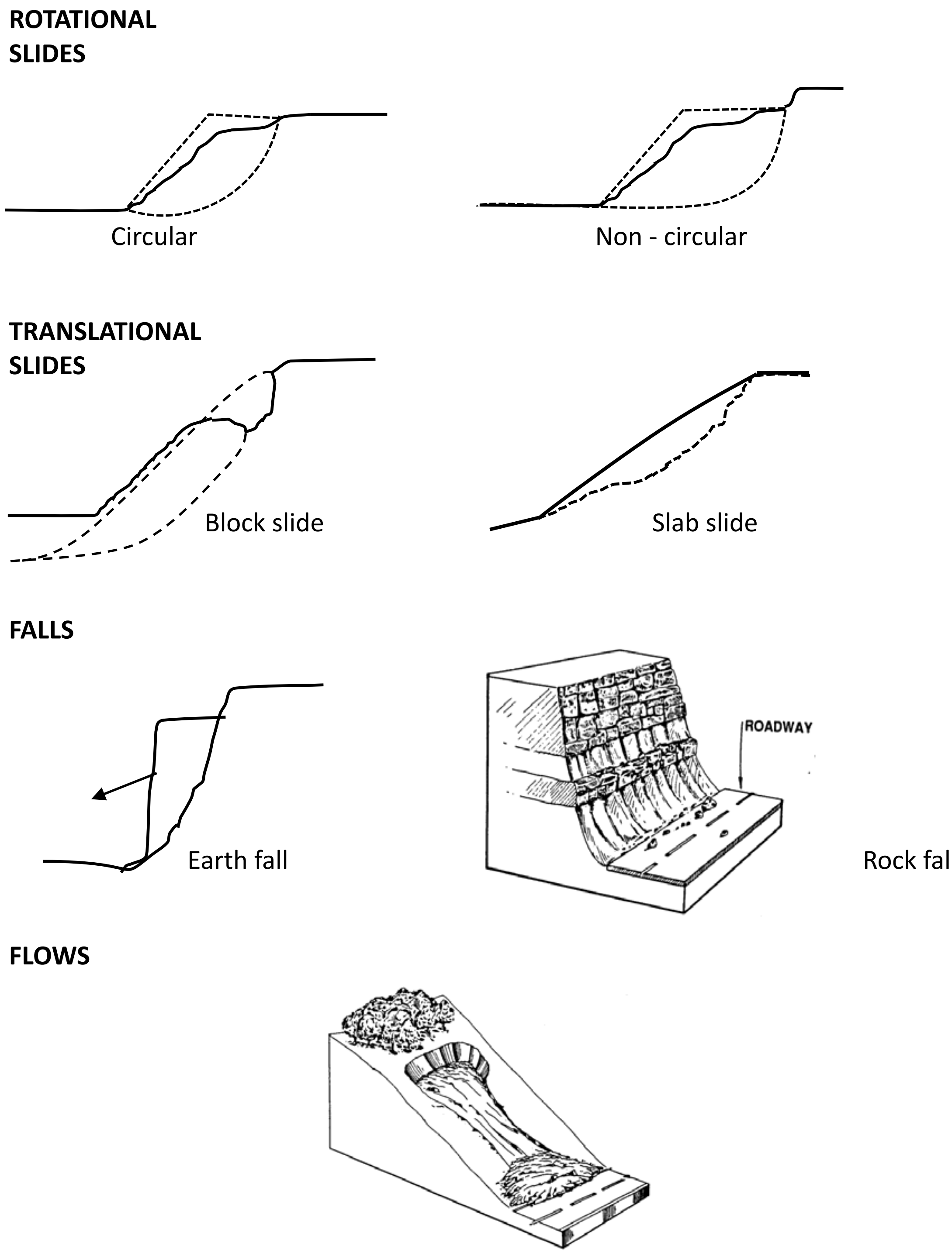


Figure 2.2: Types of landslides (USGS Fact Sheet 2004-3072)

2.2 BACKGROUND

Different soil types and different slope characteristics have various effects on slope stability. Therefore, there are many SMSs used in many parts of the world – each responds to the needs of its immediate geography, climate, and soil structures. Rose (2005) wrote that as of 2005, ten states and four countries adopted SMSs to help identify unstable slopes in need of remediation. The following pages discuss, various slope management programs used to assess slope stability that were developed by different departments of transportation (DOTs).

Different SMSs have different methods of ranking and analysis. These data analysis methods are broadly classified into three types (Glade et al., 2005): Expert or heuristic analysis; statistical analysis of historic events; and mechanical analyses.

Heuristic or expert evaluation analyses rely on experts' experiences to set guideline and analyze slope failures. Experts' experiences are based on evaluation of ground movements and failure modes and mechanisms that control such phenomena. Even though the method is commonly used, it does require a number of subjective judgments (Glade et al., 2005).

Statistical analysis uses regression functions and distribution curves to predict slope failure based on data collected from the site or from a laboratory. It overcomes the insufficiencies inherent in the heuristic or experience based approach. Most statistical models are created using probabilistic analyses in GIS software that linearize variables thought to affect slope stability (Hansen, 1984).

Finally, mechanical analyses involve calculating the Factor of Safety, a stability coefficient, from 1-, 2-. or 3-D slope stability models. Model choice depends on availability of data from the various input parameters (Cruden and Fell, 2001).

Despite small differences that account for local variation in geography, climate, and soil type, all SMSs have the following components, vital for any such model:

a) Data collection and verification system;
b) GIS database management system;
c) Index maps;
d) Statistical or deterministic model; and
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, for easy retrieval, manipulation, and review of data. This integration also creates a data mine compatible with mapping software, enabling researchers to project data onto maps.

Figure 2.3 shows the proposed framework for developing the slope stability management system. The framework is based on the unstable slope management systems adopted by different states, each of which has a similar framework for the rating system. The SMSs currently used by other states served as a benchmark for selecting rating criteria, field classification of failures, etc.

Most of the unstable slope management systems are based on the Rockfall Hazard Rating system (RHRS) developed by the Oregon Deptartment of Transportation (ODOT) and funded by the Federal Highway Administration (FHWA) and ten other states. With this system, Pierson et al., (1990) intended to proactively identify and prioritize rockfall sites.

The FHWA then developed a rockfall database management program (RDMP) specifically for the RHRS. This program has a standalone database that does not require any supporting software. This standalone database offers the advantage of rapid information transfer among users (Pierson et al., 1990). Three thousand slopes were inventoried, and subjectively classified as A, B or C slopes. A and B slopes are rocky and have a higher probability of failure with severe consequences. (Categories A and B are further investigated and rated using field sheets and an exponential scoring system with a base of 3. C slopes are eroded and neglected.

The Tennessee Department of Transportation developed a GIS application to manage landslides along Tennessee highways. This application includes development of a statewide landslide database and production of 31 thematic, Internet-accessible maps. Essential landslide information includes: attribute data (e.g., type of slide, surficial geology, remedial actions taken and associated costs); temporal data (e.g., dates of landslide activity and remedial actions); and spatial data (e.g. geographic location of the landslide, site special geological conditions and nearby, related features). The GIS landslide database links with the above-mentioned attributes and temporal and spatial data in a geodatabase that catalogues, visualizes, and manages landslides along state routes and interstate highways (Rose, 2005).

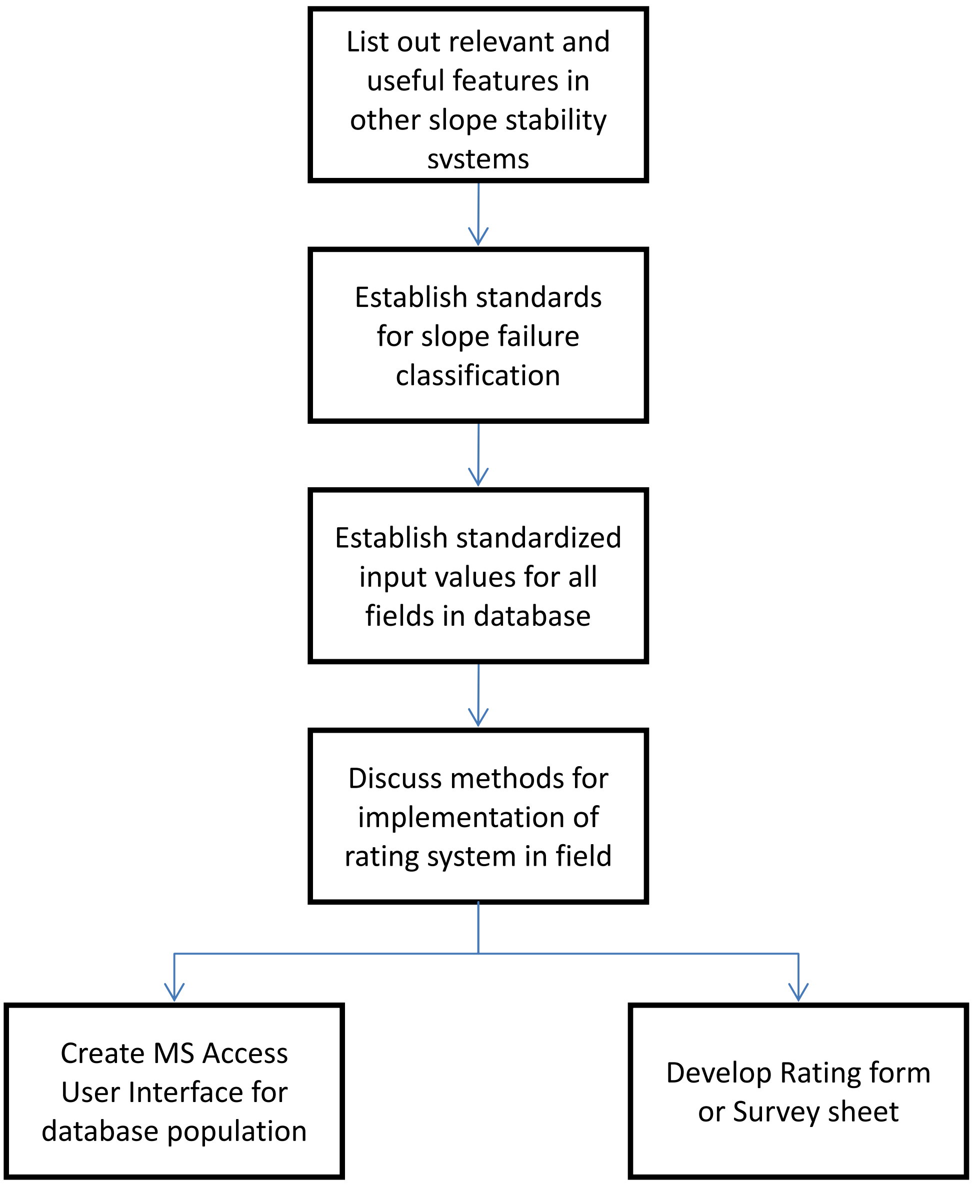


Figure 2.3: Proposed framework for developing a Slope Management System

The Kentucky Transportation Cabinet (KYTC) and the University of Kentucky completed similar work. The KYTC database uses data about rock slope, landslide, and soil and rock engineering data of landslides and rock slopes to manage risk. More than 10,000 rock slopes were examined and were rated using the RHRS. The ratings provided a priority list of sites that required immediate remedial or mitigation measures. An Oracle-based geotechnical database was created that stored rock slope and landslide attributes along with location information and site photographs. The rock slope and landslide segments of the geotechnical database established a program for allocating funding for remediation of slopes that were identified as high risk (Hopkins, et al., 2001).

The Washington State Department of Transportation (WSDOT) developed the Unstable Slope Management System (USMS) and has used the system since 1993. The USMS can be used for both rock-falls and landslides. Slope conditions and economic assessment are incorporated into the slope-maintenance strategy. Information used for assessing slope conditions includes slope location, whether the slope is 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 (ODOT) uses the Geological Hazard Management System (GHMS) to manage geological hazards data and activities related to planning, design, construction, and maintenance of repaired slopes. The ODOT defines geological hazards as including abandoned underground mines, karsts, and shoreline erosion. In 2007, a landslide hazard rating system was developed for ODOT and incorporated into the GHMS (Liang, 2007). This combined system evaluates six landslide risk factors that have the potential to negatively affect the safety and operation of roadways and adjacent highway structures. Each of the risk factors is rated using a scoring system similar to ODOT. Numerical scores of 3, 9, 27 and 81 represent the increasing hazard of each factor.

The Alaska Deptartment of Transportation (AKDOT) uses a three-step procedure to rate slopes. The first step involves preliminarily sorting slopes into three categories: A (high probability of failure), B (moderate probability of failure), and C (low probability of failure). The second step assesses the hazard(s) that a slope poses. In this step, A and B slopes merit a detailed assessment based on their hazard scores, which are calculated from information obtained from a site visit. The final step is completing a slope risk assessment. The assessments are based on the severity of the hazard calculated from the previous step, maintenance frequency, and annual maintenance cost (Huang et al., 2009).

Lee et al. (2006) described an SMS built on a well-designed management information system. The data stored in the system can be displayed using GIS functionalities. The influence of various factors on Taiwanese landslides can then be assessed. The SMS can accept more than one input format. Also, maintaining and monitoring slope information is given priority in the framework. All data collected is meticulously indexed into different databases. Hence, this SMS has four 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, despite using quantitative analysis in calculating hazard indices for rating unstable slopes, the SMSs discussed above 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 United States. Most of the survey forms used to record failure information require on-site engineers to make expert judgments about slope failure characteristics and attributes. These evaluations might lead to an overcompensated hazard rating of relatively less hazardous slopes. In developing an SMS for Maryland, the research team attempted to address this issue.

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

2.3 SMS COMPONENTS

One of the crucial issues in GIS-based hazard assessments is the availability of suitable input data (Huabin et al., 2005). Since the GIS database is a central source for the majority of information about slope failure data, it is vital to review field data collection procedures in order to identify sources of measurement errors and uncertainty of on-site investigation techniques.

Nearly all instability factors collected in the field or derived in laboratory are affected by error. This problem is compounded because the magnitude of such errors cannot readily be estimated and, therefore, controlled for during data analysis or modeling (Carrara et al., 1995). Thus, it is important to minimize measurement error throughout the process of data collection in the field. For this purpose, it is essential to have a systematic method of data collection. This requirement was satisfied by developing the slope failure field sheet that is discussed in detail later in this chapter.

Two fundamental rules must be observed when creating a database (Leroi, 1997): First, the information must be homogeneous, that is, the data must have the same work scale and geographic projection system. Second, 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 are listed as follows:

- *Preliminary data collection*: All slope failures reported to SHA are visited by field engineers who collect necessary data using the slope failure field sheet.
- *Database population*: All data recorded using the failure field sheet are entered 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, maintenance cost-to-repair cost ratio, and frequency of maintenance and related projects.

- *Annual review and update*: An annual report detailing the efficiency of the system is based on feedback from the report and engineers using the system; necessary changes and updates are made to enhance the system's future performance.

There are four primary components of the SMS developed for SHA: a Microsoft Access database; failure field sheet and remediation response categorization; eGIS slope failure content; and failure density mapping. The first three components will be discussed in detail in the following pages of this chapter; the final component will be discussed in Chapter 3.7.

2.3.1 Microsoft Access database

The SMS database is a modified Microsoft Access database that consists of eight tables. The first step was to decide on an efficient data structure. Figure 2.4 shows the database relationship tree. Fields were grouped so that relevant fields remained together in a table; each table represented similar fields that contributed to a particular aspect of slope stability management. Each table has a unique field that is its primary key, the function of which enables the user or the software to uniquely identify a record. Each of the eight primary keys form links among the tables, making it easy to access information from multiple tables.

As shown in Figure 2.4, the primary key for each table is the Project ID, an automatically generated number associated with each record. The data structure is such that there is one primary table to which all other tables are linked (Figure 2.4). This arrangement enhances data management tasks such as creating new records, editing and deleting existing records. The eight tables constituting the database are:

I. Failure type and location information table
II. Dimensions of failure table
III. Cause of failure table
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. Location information includes GPS coordinates, Northing and Easting values, milepost, and route number and name. The failure table includes the mechanism of failure, weather conditions preceding the failure, the project description provided by SHA, and identifying information such as Contract # and FMIS #.

The dimensions of failure table contains information on apparent depth of failure, scarp depth and width, distance of failure surface from original slope crown and toe, slope angle, and slope height.

The cause of failure table records information about cause of failure information consists of information relating to natural or human activities that contributed towards the failure of the highway slope.

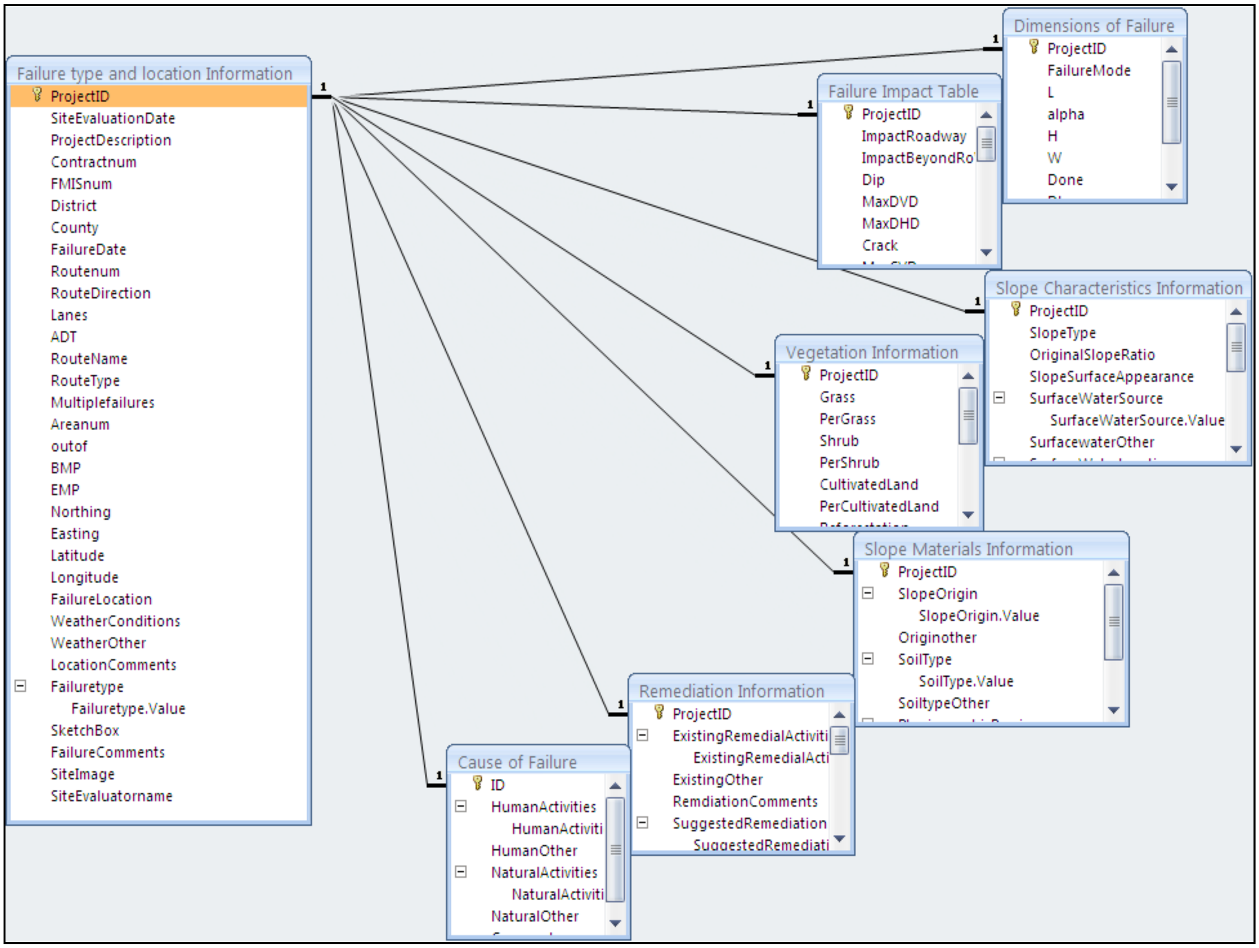


Figure 2.4: The relationship tree for the MS Access database

The failure impact table records information about the current and future potential of the slope failure to affect existing roadways and roadway structures. This section requires engineers to subjectively evaluate the failure site and its impact potential to affect roadway and structures beyond SHA's right-of-way.

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

The slope characteristics information table has data about to the slope aspect (e.g., convex or concave, slope gradient, vegetation density on slope, surface and sub surface drainage conditions, surface water conditions, and groundwater conditions)

The remediation information table stores data about on-site remedial activities, suggested remediation methodology, the suggested beginning and ending dates of remediation, and the remediation status of the failed slope and the cost of remediation construction.

The vegetation information table stores the percentage distribution of vegetation or land cover present on the failed slope.

Again, the data in these tables comes directly from the failure field sheets (Appendix A). The failure field sheet is similar to survey sheets already used by engineers on site. The failure field sheet is a form in which engineers record information only related to the slope failure. This limitation promotes efficiency by eliminating collection of data irrelevant to later stability analyses and slope hazard ratings. These forms are detailed in the following section.

2.3.2 Failure Field Sheet and Remediation Response Categorization

2.3.2.1 Failure Field Sheet

The failure field sheets may also be described as the input for the SMS. Its purpose is to standardize engineers' current slope-failure data collection practices. Additionally, the sheet ensures that data is collected in a uniform manner.

The failure field sheet allows engineers to record parameters such as slope type (cut, fill, mechanically-stabilized fill, etc)., failure type, failure scale, failure cause, and mitigation methods. These parameters are recognized as the most important data for evaluating failure potential and the performance of slope stability (OHDOT, 2007; AKDOT, 2009; WSDOT, 2002; Lee et al, 2006).

The failure field sheets are a vital component of any SMS. The Federal Highway Administration's (FHWA) highway slope maintenance manual has a similar form – the slope inspection manual – that engineers use to survey slope failure sites. The slope inspection manual allows engineers to record only the most basic and failure information. The failure field sheet modifies the FHWA's form a) by adding the expert opinions of SHA engineers and b) by integrating data collection practices followed by other state agencies.

When a highway slope failure is reported to SHA, engineers from the Office of Materials Technology (OMT) visit the failure site to record initial failure information. Upon arrival at the failure site, the engineers fill in sections 1 and 2 of the failure field sheet. These sections require general site information (e.g., GPS coordinates with a precision of at least 5 digits, milepost, route information, location of failure with respect to roadway cross section, type of failure based on the provided failure field sheet classification). Additionally, if multiple failures occur along the same highway, engineers must note the total number of failure sites. Engineers must also record the weather conditions immediately preceding the failure; they may do this off-site.

Engineers then measure the dimensions of the slope failure, guided by the illustrations in section 3 of the failure field sheet (Appendix A, p. 3). Section 4 requires engineers to subjectively evaluate the slope failure's potential to cause further damage to roadway and structures beyond SHA's right-of-way. Engineers are also required to measure the extent of slope movements by recording the dimensions of dips and cracks visible along the roadway in this section. During the preliminary examination, engineers record the structures and utilities in the vicinity of the failure. The land usage classification as described in section 5 of the failure field sheet is also recorded. In section 6, engineers make note of those structures or utilities that are affected by the highway slope failure.

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

Engineers record the observed existing remediation activities in Section 9. Section 10 provides a comprehensive list of slope remediation methods. In this section, engineers may provide or suggest ideal remediation methods based on the list provided in this section. Section 11 monitors 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 converted to a digital format by keying in all information into the Oracle database through the eGIS application interface. The eGIS application was developed by SHA's Highway Information and Services Division (HISD) and is described in detail in the latter part of this chapter.

2.3.2.2 Remediation Response Categorization

The remediation response categorization is another component of the SMS. This categorization is designed to help prioritize the SHA's remediation response. The categories were derived from an extensive set of factors considered to affect the functionality of highways. For example, a highway slope failure with high potential to affect the roadway would require immediate attention.

It is impossible to eliminate bias when prioritizing action for highway slope failures. However, a set of parameters thought to affect the remediation response for any highway slope failure is introduced to reduce the potential for bias.

The primary purpose of this component is to assign priority for remediation of certain highway slope failures based on parameters thought to affect the proper functioning of the highway. An additional purpose is to help SHA with allocating money for the remediation of highway slope failures, thus saving time and money.

Because the SMS and its framework are still in the early stages, the functionality of these prioritization recommendations have yet to be incorporated into SHA's decision making process. Currently, the remediation response categorization is included as a recommendation sheet with the final geotechnical report following the highway slope failure analysis. The current sheet provides information about the categories that should be considered while deliberating about the remediation response. The sheet is used as a guide for engineers to decide on the appropriate remediation and maintenance techniques to implement. The format of the remediation response categorization sheet is as shown in Figure B.1 in Appendix B. The complete list of categories shortlisted and their definitions is provided in Table B.1.

A document that contains a list of categories that might influence SHA's remediation responses for highway slope failures has been circulated among engineering staff at the OMT to make it as complete and valuable as possible. The engineering staff provided their recommendations about the importance the categories. The engineers ranked each of the 16 categories based on their evaluations. (These numbers will be referred to as hierarchy numbers in the rest of this report.) This exercise brought to light new categories that might influence the manner in which SHA or a district office may deal with a highway slope failure. From the engineers' rankings, mean hierarchy numbers and their standard deviations were calculated for each category.

Table B.2 provides information about engineers' rankings, and the means and standard deviations for each category. Categories suggested by engineers during the rating process are shaded in grey (Table B.2). Many engineers also provided suggestions to further refine the rating system.

Some of the engineers suggested that additional categories be included. The list of suggested additions to the category sheet include: distance to closest structure; type of structure; groundwater conditions; vegetation conditions; utility impact; rate of slope movement; slope material properties; subsurface conditions; drainage and seepage conditions; availability of detour route; and number of utilities affected.

2.3.3 eGIS Slope Failure Content

The SHA uses the Enterprise GIS (eGIS) Portal to display, edit, and manage its data. The portal provides broad access to geospatial information in order to foster collaboration between business units and to support critical business functions. The OMT uses eGIS to display and edit slope failures along Maryland roads. Users can upload pictures of the slope failure site, and hyperlink to as-built plans and geotechnical reports.

2.3.3.1 System architecture

eGIS uses a security architecture to facilitate 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 the following external systems: ArcGIS servers, eGIS web application and supplemental services and applications.

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

The ArcGIS server system 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 users to print maps and also Microsoft Excel files from the Web portal 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 via the eGIS portal. External applications can also link to the eGIS system and, if necessary, highlight certain parameters in order to lead a user to the appropriate data. Widgets, custom result grids, and other functions that rely on other services can be developed in a variety of ways in order 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" which allows the application to be easily modified as users request new features and capabilities. 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.

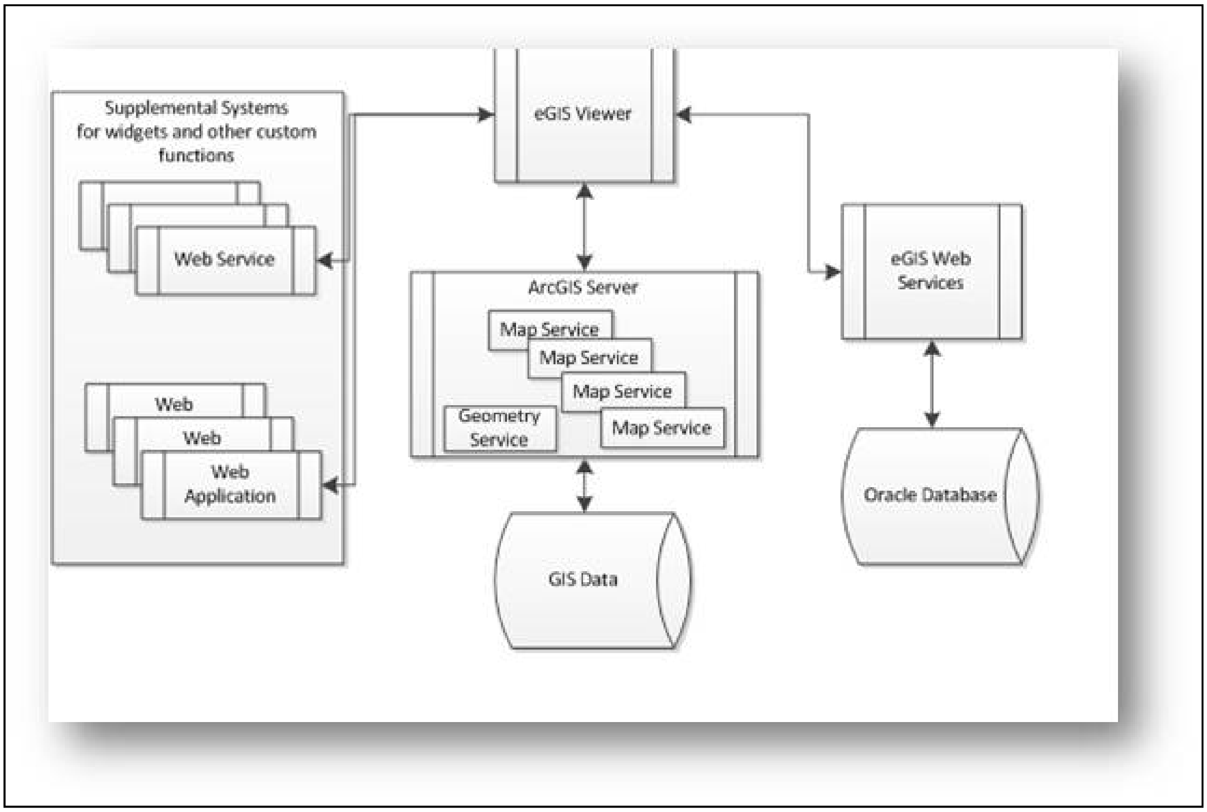


Figure 2.5: eGIS system architecture

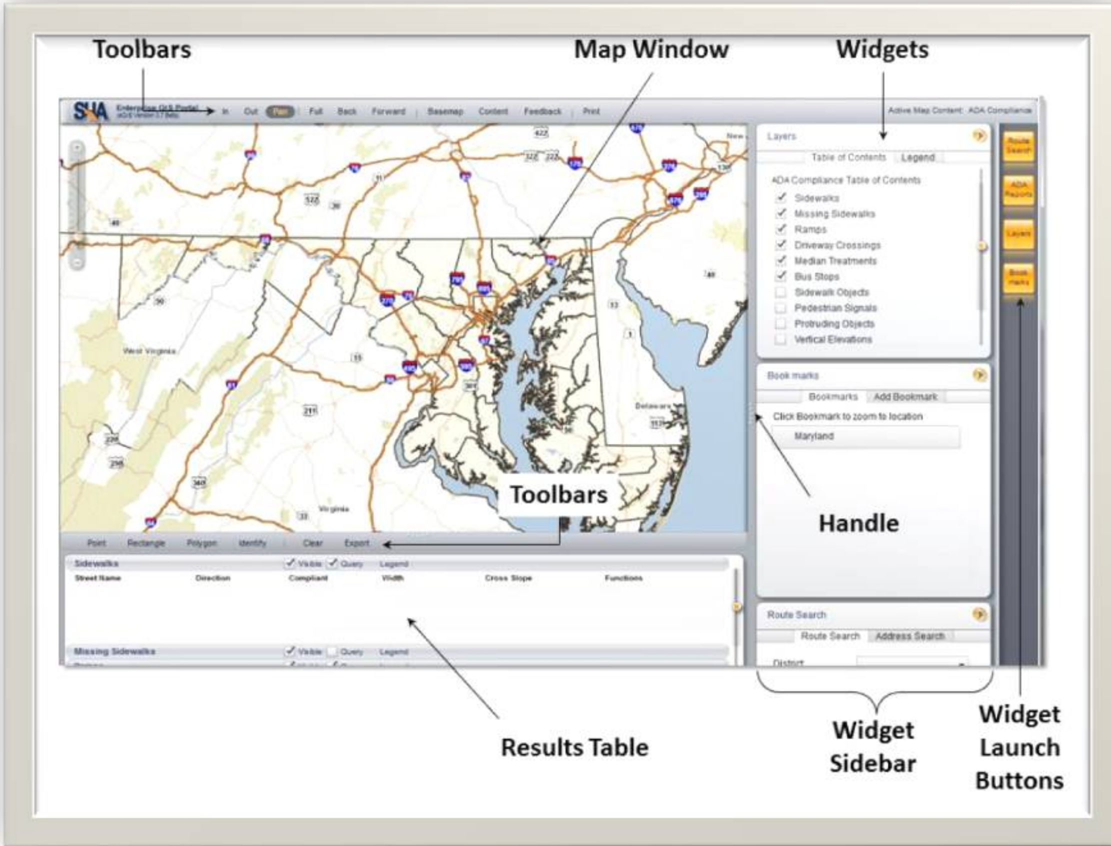


Figure 2.6: Various components of the eGIS content are highlighted

2.3.3.2 Workflow and widget functionality

The Details widget displays important 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 – subject to OMT's approval – on the map content. Figure 2.7 shows the workflow for the slope failure content within OMT. In Create, eGIS users describe slope failures as emergencies or non-emergencies, input the failure date on a preset calendar, and includes their contact information. The location of the slope failure is entered as a GPS coordinate or as route and milepost information. After users create a new entry, the system automatically sends an e-mail detailing pertinent information and any pictures the user includes to OMT staff. The widget allows administrators to define groups and roles for OMT staff. The automatically generated notification e-mail is sent to a pre-defined group using the aforementioned procedure. Figure 2.8 shows a screenshot of the Create failure widget.

The Slope Search Widget allows users to find slope failures based on spatial reference or attribute information. Users can query slope failures within an SHA District, County, route type, or a specific route.

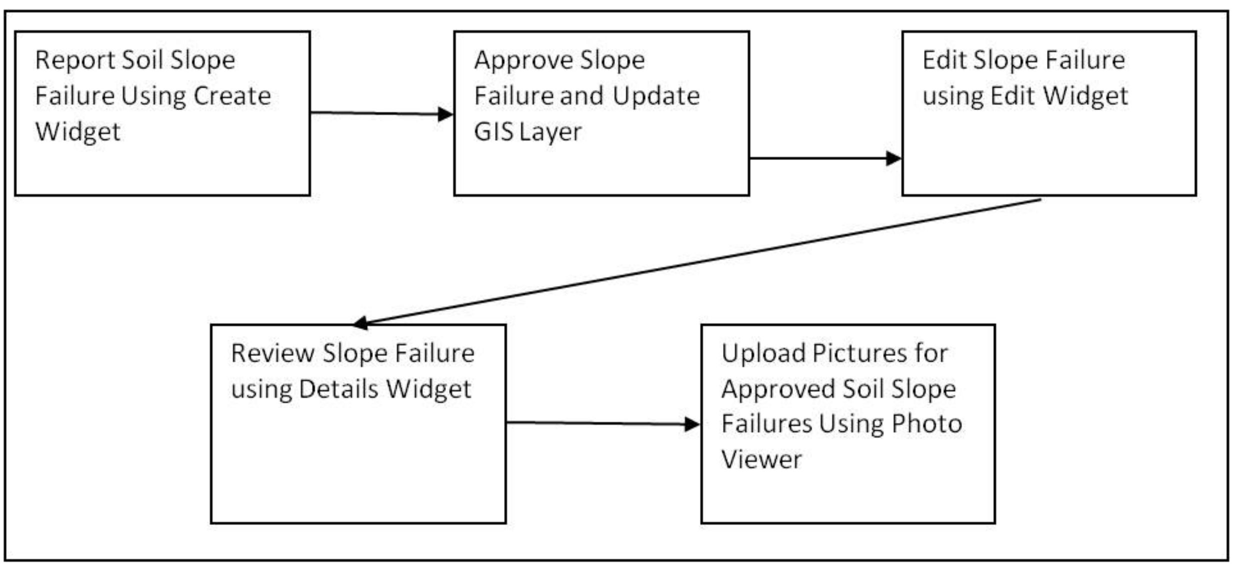


Figure 2.7: Workflow for the slope failure content within OMT

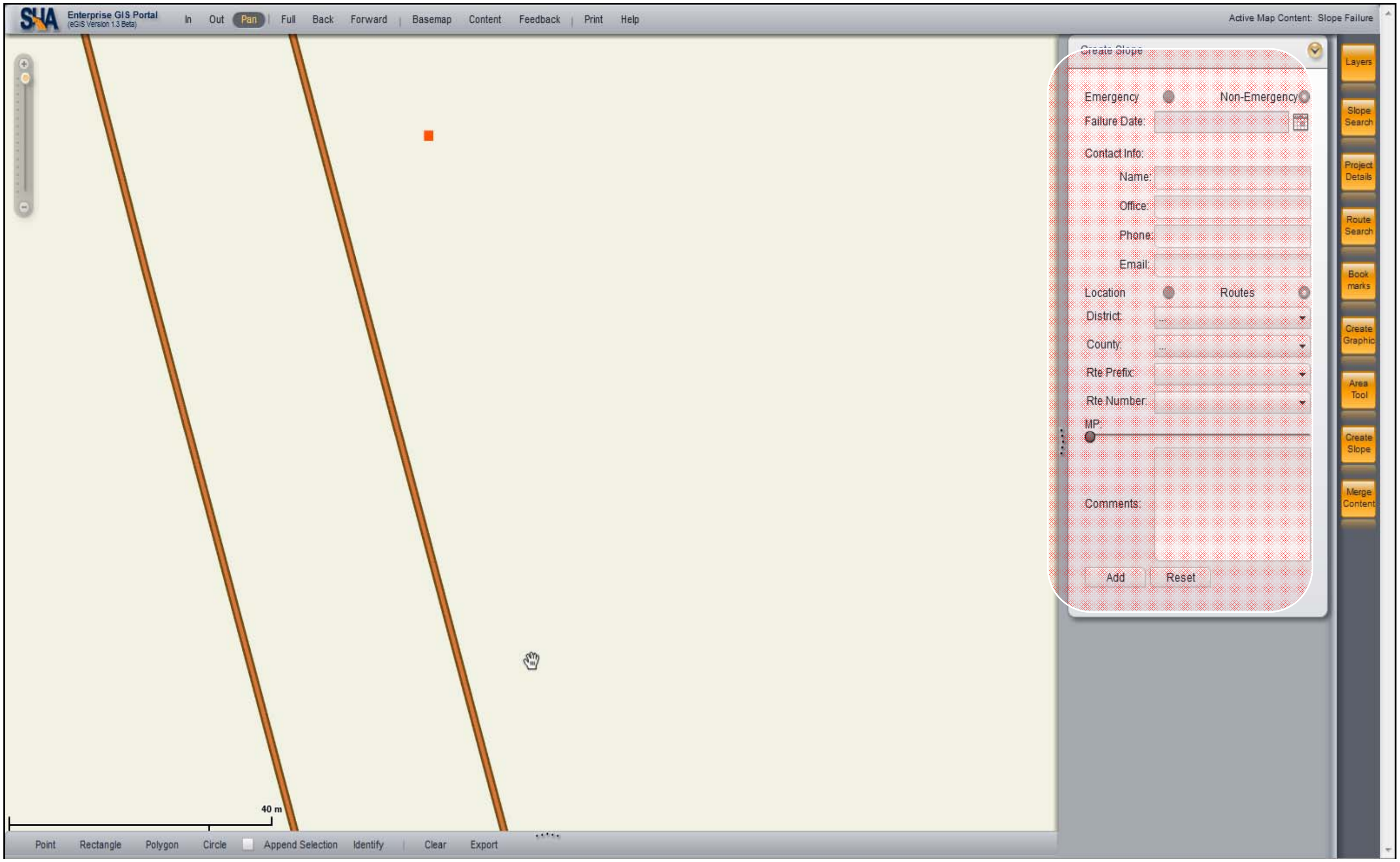


Figure 2.8: A screenshot of the create slope widget. The area highlighted in red indicates the position of the creator widget in the screen

In addition, users can look for specific attribute information with a spatial reference. Figure 2.9 shows a screenshot of the slope search widget

When a slope failure is selected in the eGIS Web Application, users can review records' attribute information in the query results window at the bottom of the eGIS window. (This panel is customizable; the eGIS Technical Team works with the data owners to achieve optimal customization. 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 with default settings.

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, in turn, updates the OMT Access database. The widget uses text fields, drop-down menus, multiple text boxes, and comment fields in order to maintain the details of slope failures. If an eGIS user does not have access to the widget, the widget will be grayed out and unavailable. Changes made to the slope attribute record are saved in real time. The Slope Edit is accessed from the results grid under the functions called Edit. The Slope Edit Widget has 13 tabs (discussed further in next section). Each tab 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

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 Maryland. It also contains data stored in the Access database mentioned previously.

Migrating from an Access database to an Oracle SDE database allows for greater data volume and more efficient processing. An Oracle SDE database also provides advanced spatial features and supports high-end GIS solutions.

The Motor Vehicle Administration (MVA) 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 SHA. The slope failure Access tables have been converted to Oracle 11g relational tables stored at the MVA. There is one spatial Oracle SDE table and 13 related attribute tables: project description, site information, failure type, failure dimensions, impact assessment, adjacent structures, affected structures, materials, characteristics, observed remediation, cause of failure, suggested remediation, and 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.

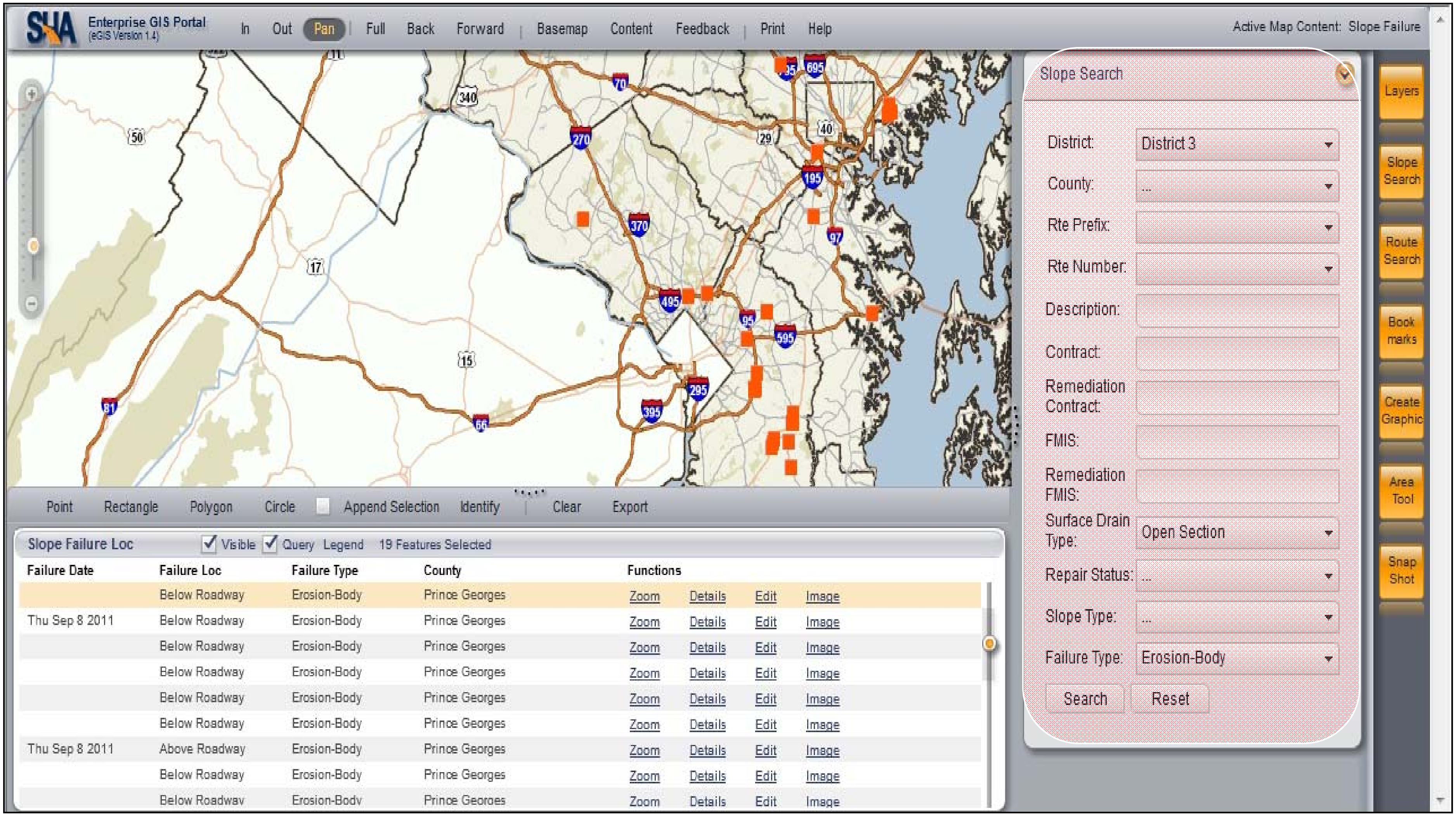


Figure 2.9: A screenshot of the slope search widget. The area highlighted in red indicates the position of the search widget in the screen

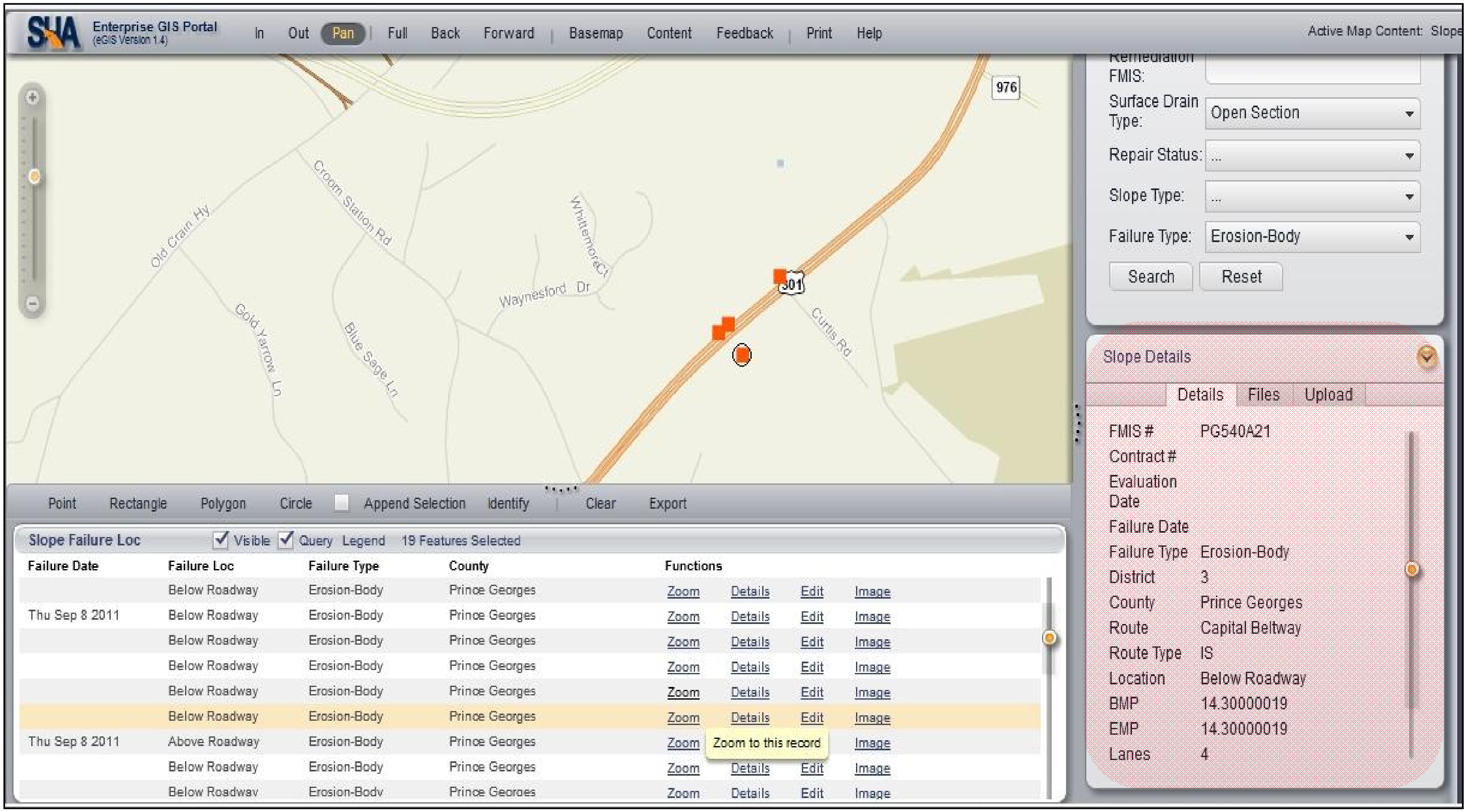


Figure 2.10: A screenshot of the slope details widget. The area highlighted in red indicates the position of the details widget in the screen.

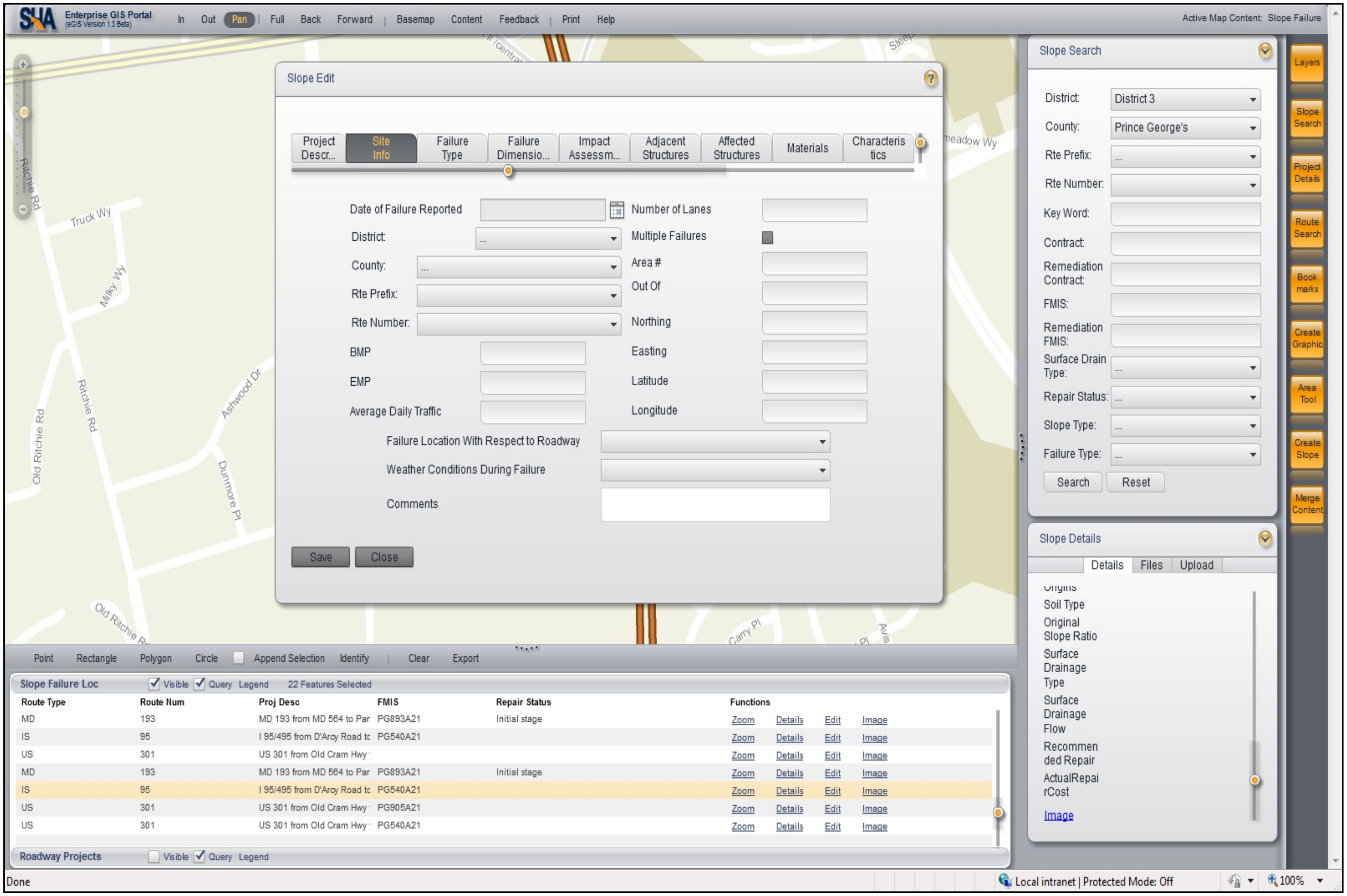


Figure 2.11: A screenshot of the editor widget the multiple tabs for recording information. Each tab represents an Oracle SDE table

2.4 CONCLUSIONS

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

The first phase in monitoring and evaluating highway soil slopes is gathering and evaluating historical data about soil slope failures in Maryland. Additionally protocals need to be developed that incorporate the failure information into a GIS database. The component aiding in this phase is the failure field sheet, which facilitates 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 include the slope type (cut, fill, mechanically-stabilized, etc.), failure types, scale of failures, causes of failures, and remediation methodologies. Information about these parameters and about slope stability performance are recognized as the most important data to evaluate in order to make judgments about future performance of remediation strategies. These records will be collected to analyze the influence of factors of slope stabilization and evaluate remediation performance. The failure field sheet, developed with input from SHA engineers, optimizes data collection and ensures consistency.

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

A database structure containing information on soil slope failures or distresses was developed using Microsoft 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 any associated results can now be visualized using GIS features.

Currently, information about the forty-nine highway slope failure sites is stored in the GIS database. Of the forty-nine highway slope failure cases, information for eighteen failure sites were filled in retroactively based on site photographs, as-built plans, geotechnical reports, boring logs, and the first-hand accounts of SHA engineers. The information for the other thirty-one slope failure sites were recorded using failure field sheets during on-site visits by engineers.

The third and final phase of the slope stability management is a system to provide recommendations and guidelines for remediation designs and maintenance strategies. It was considered premature to perform cost-benefit analyses for each type of slope failure and remediation method because of inherent liability issues that might arise due to the limited number of slope-failure datasets. Because the framework for such a system has just been developed, there is room for further development (based on, for example adding soil-failure cases to the database or including routine inspection and maintenance information). A long-term goal is, of course, to ascertain the most cost effective and efficient remediation methods for particular types of failure. Engineers' current practice is to use the remediation response categorization sheet, which lists a set of parameters considered to influence the SHA's response to highway slope failures.

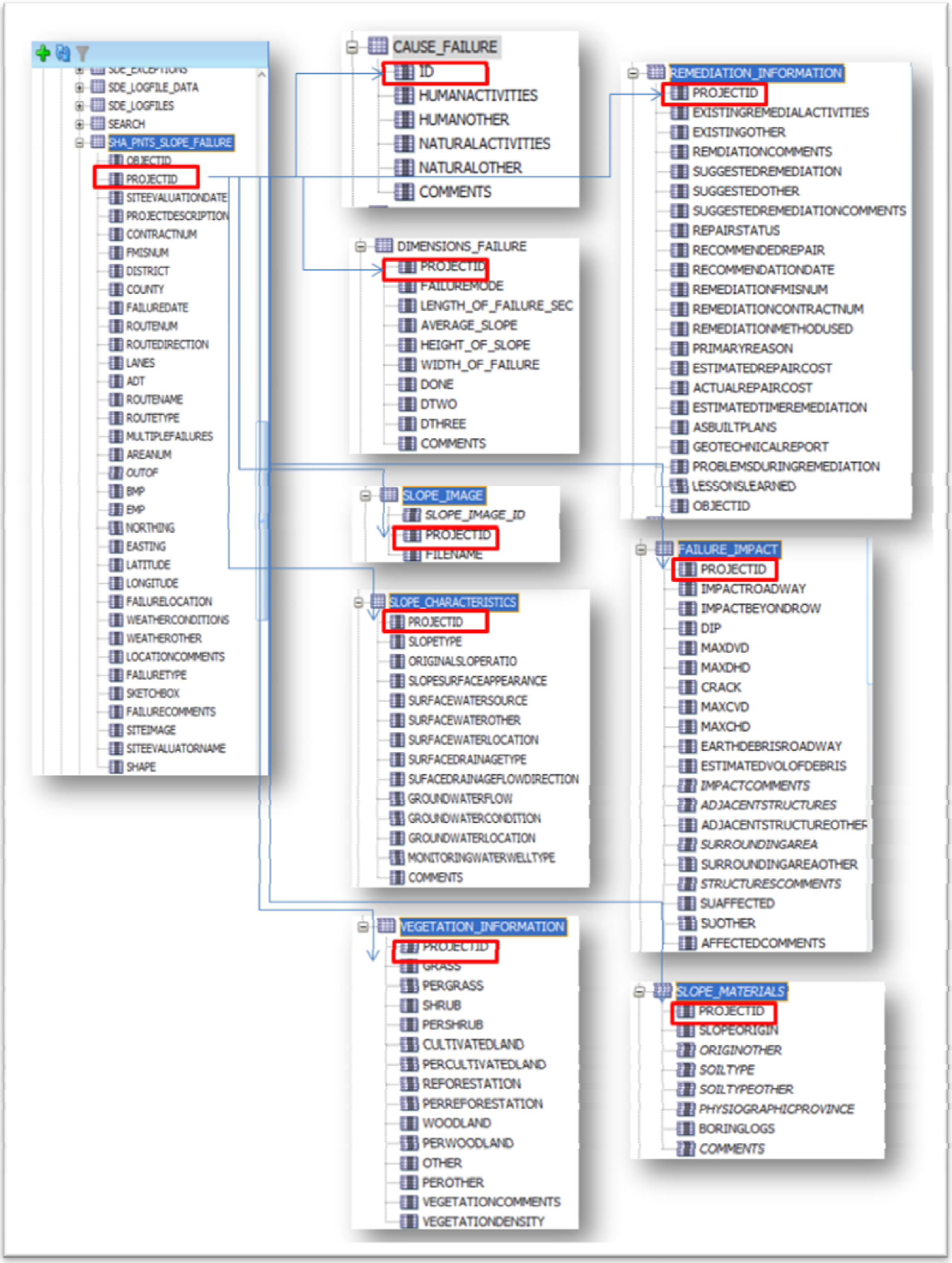


Figure 2.12: The Oracle 11g database's current relationships with PROJECTID as the primary key

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) and 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 slopes and engineered slopes (Abramson, et al., 2001). Every slope has stresses that induce outward movement (shear stress) and stresses that resist the induced movement (shear strength). If these stresses are just balanced or if shear stress exceeds shear strength, the slope is said to be unstable and prone to failure (Selby, 1993).

All slope movements are a manifestation of the slope's instability – when slopes move, they fail. Slope failures can result in extensive property damage and loss of life. In 2004, the National Research Council estimated that each year, landslides in the United States caused more than \$2 billion in property damange and are responsible for 20-25 deaths. Given the increasing economic cost of landslides, there has been an urgent need for improved protection against them (He et al., 2007).

Investigation of slope instability and landslide hazard has sparked significant interest internationally and is the primary focus of research initiatives around the world. Numerous investigations directed efforts towards 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).

During the last decade, the focus of research shifted from site investigations and stability assessments to predictive modelling and consequence analysis (Glade and Crozier, 2005). The main goal is to determine when and where future landslides and slope instability events may occur, 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 toward developing early-warning systems, GIS has become an important and powerful tool in landslide hazard assessment.

GISs are at the forefront of all recent landslide hazard assessment research projects and are the most recommended platform for predicting landslides and slope instability events (Carrara, et al., 1999; Sakellariou et al., 2001; Cavallo, et al., 2001; Bhattarai, et al., 2004; Huabin, et al., 2005). GIS allows engineers to apply quantitative mapping techniques 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)

The SHA does not currently have a model that attempts to identify, assess or predict highway slopes' vulernabilities. 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 enable SHA to prioritize and optimize their response to slope failures in advance of such events.

3.2 BACKGROUND

The application of GIS technology in slope instability mapping has a great potential to reduce the negative long-term effects 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 critical to understand which parameters trigger slope instability and to establish methods for classifying failure modes using discriminatory factors. Many publications discuss initial and recently modified strategies for classifying slope movements based on a variety of causal 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. Skempton's method notes correlations between the geometric properties of slopes and their mass movement features (Figure 3.1). Developments in field monitoring and site investigation methods have given rise to a new set of classification factors based on the morphology of the slope feature (Brundsen, et al., 1973).

The most commonly used slope movement classification method for slope movements were established by 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).

During the last decade, researchers have shifted their focus from site investigations, mechanism classifications, and stability assessments to predictive modeling and consequence analysis (Glade and Crozier, 2005). The main goal is to predict and map future landslides and slope instability events based on spatial and temporal information from 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) slope instability mapping techniques can be broadly classified as either qualitative and quantitative analyses.

Qualitative analyses 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. It is the easiest method for mapping slope instability and was widely used from 1970-80 (Fenti et al., 1979; Kienholz, 1978; Rupke et al., 1988). Landslide inventory mapping systems use available information about past slope failure events; however, they only emphasize on slope with failure histories (He and Beighley, 2007). Heuristic or index based analysis 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).

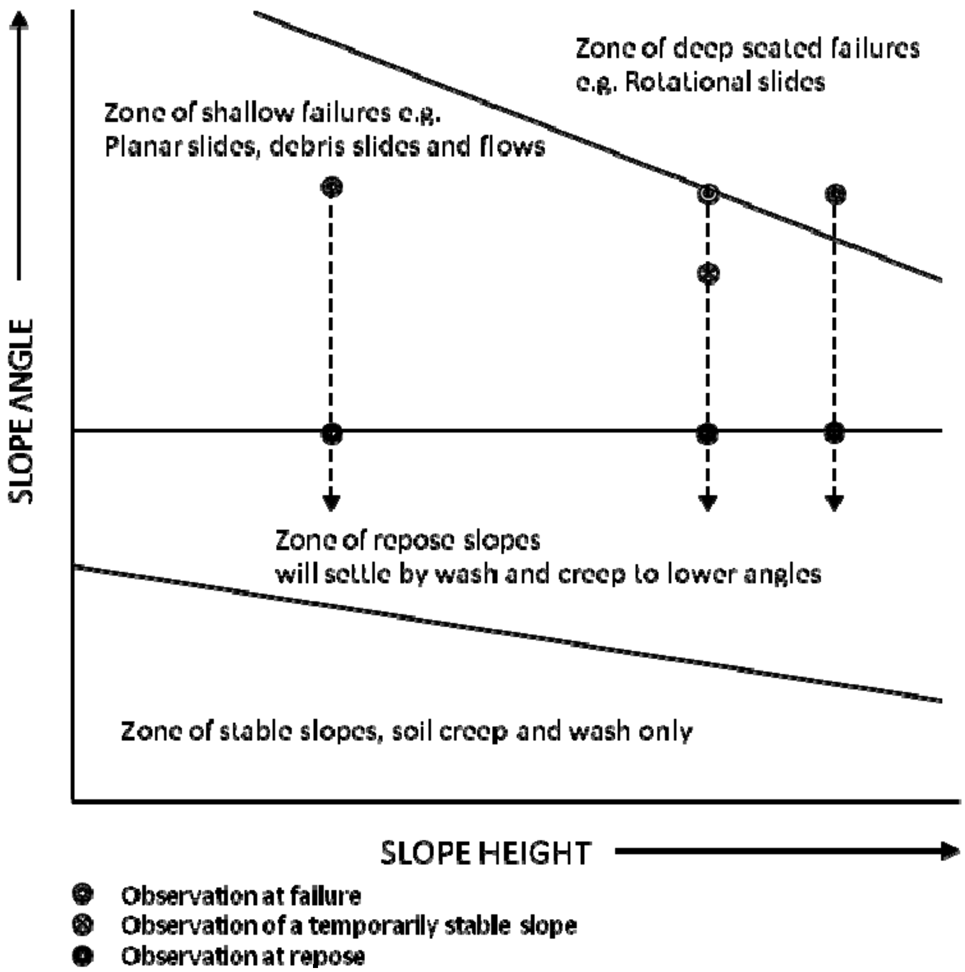


Figure 3.1: Schematic showing the relationship between slope angle and slope height (Skempton, 1953; modified by Brundsen, 1973

Qualitative index overlay (also known as factor mapping) is commonly used in the initial stage of regional assesment (Crozier and Glade, 2004). It involves identifying the spatial distributions of causal factors or a combination of those factors and investigating their influence on slope stability. Weights are assigned to different factors based on their relative 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 input data collected on-site or in a lab into regression functions and distribution curves to predict slope failure. Correlations between physical factors and previous slope failures are mapped using discriminant analysis. Quantitative or semi-quantitative estimates are then made for those slopes without failure histories (Dai and Lee, 2002). Statistical methods are more appropriate for slope instability mapping as they eliminate any subjective bias that may be present in qualitative analysis (Fall et al., 2006).

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

Some studies (Carrara et al., 1992; 1995; van Westen, 1997; Chung, et al., 2004; Huabin, et al., 2005) systematically compare these different techniques and discuss the strengths and limitations of each. A common limitation involves the scale of study and data availability (Aleotti and Chowdhury, 1999). It is vital to choose the appropriate scale of study for analysis and 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.

This study uses a regional scale; the method of assessment used is a semi-qualitative index overlay. The primary reason for choosing a semi-qualitative technique to map slope instability is that there is too little historic data to justify using other methods. With the limited information regarding past events and their causal factors, it is not feasible to develop a robust multivariate analysis model at this regional scale. Also, the qualitative index overlay as discussed before can be applied succesfully at all levels of study.

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>

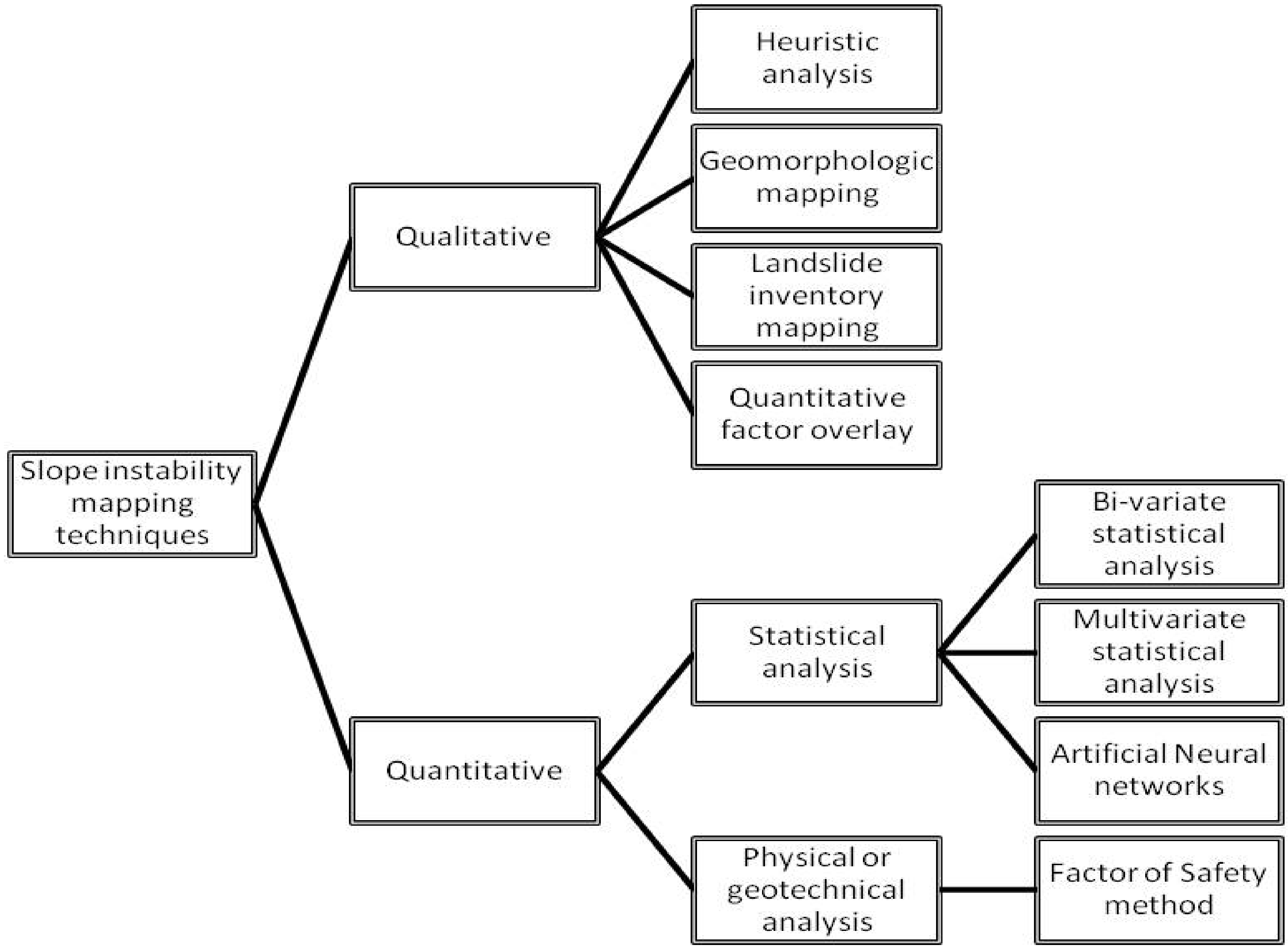


Figure 3.2: A broad classification of all the slope instability mapping techniques developed from Huabin et al., 2005

3.3 DESCRIPTION OF STUDY AREA

Maryland is in the Mid-Atlantic region of the United States. It is the ninth smallest state by area, but the nineteenth most populous and fifth most densely populated of the fifty states (U.S. Census bureau, 2011). The total study region covers 10,454 square miles. The mean elevation of the State of Maryland is 350 feet above sea level, ranging from mean sea level at the at Atlantic Ocean to 3,360 feet above sea level at Backbone Mountain in Western Maryland. The state has five distinct physiographic provinces: the Appalachian plateaus province, the Ridge and Valley province, the Blue Ridge province, the Piedmont plateau province, and the Atlantic Coastal Plains province.

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 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).

The Piedmont Plateau province is composed of hard, crystalline igneous and metamorphic rocks. It 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, granite plutons and pegmatites intruded on these rocks. Deep drilling has revealed that similar metamorphic and igneous rocks underlie the sedimentary rocks of the Coastal Plain (Edwards Jr., 1981).

The Coastal Plain Province sits atop a wedge of unconsolidated sediments including gravel, sand, silt, and clay. This region overlaps the rocks of the eastern Piedmont province along an irregular line of contact known as the Fall Zone. As one moves 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).

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 in July to a low of 24.3° F in January.

Average annual precipitation for the eastern half of Maryland ranges from 42 to 52 inches. Precipitation averages 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.

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

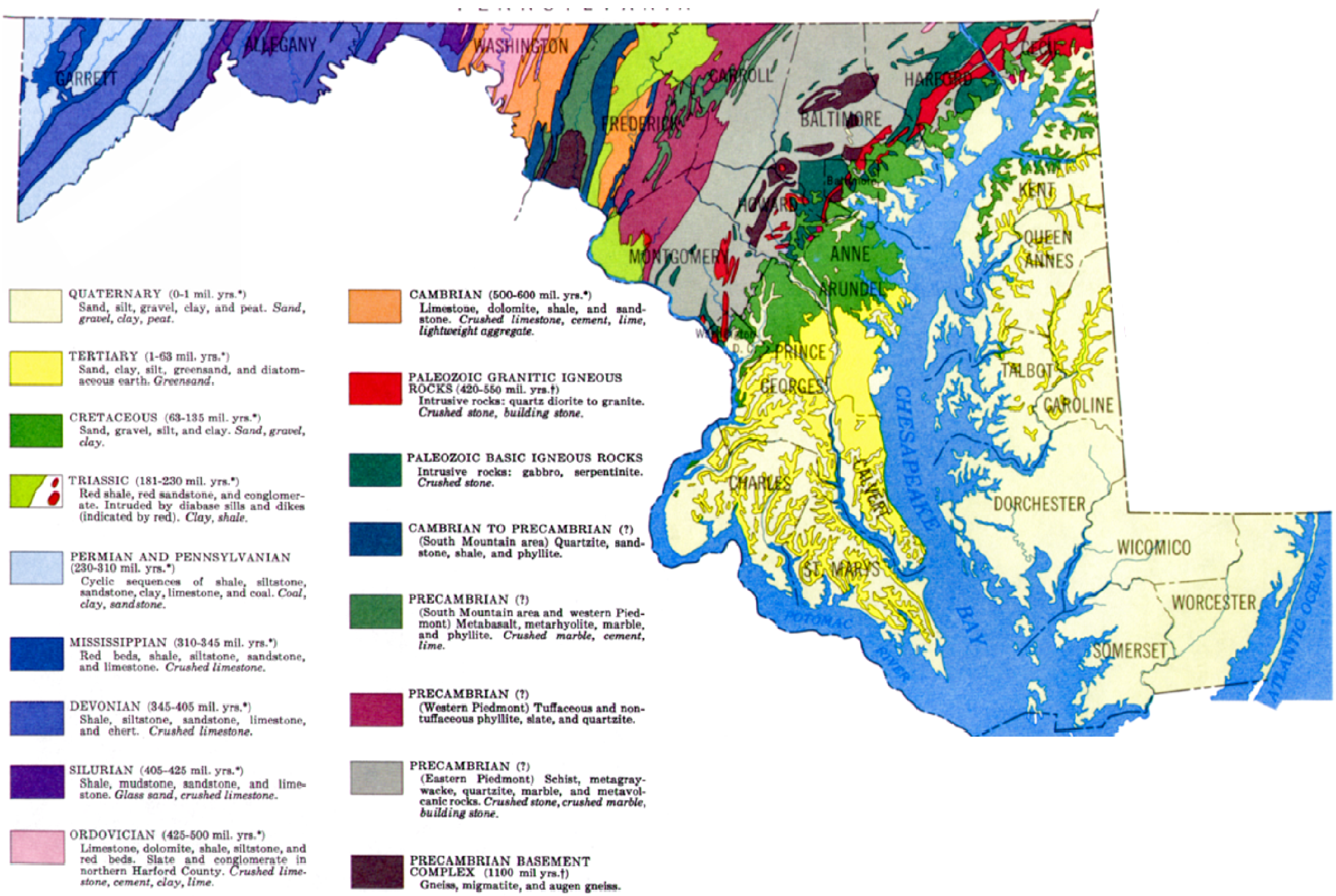


Figure 3.3: A generalized geological map of the State of Maryland (Source: Maryland Geological Survey, www.mgs.md.gov/)

3.4 DATA SOURCES

ArcMap GIS software was used to study this area. The input map layers were imported into ArcMap in their original format in order to verify data compatibility and integrity. A major challenge with this 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). Because data were not uniform in quality or level of resolution, only a handful of parameters were shortlisted.

A variety of factors that influence slope stability were considered, based on data availability and existing 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 this study: elevation, slope angle, land cover, storm event precipitation, slope history/failure inventory, and surface geology. Table 3.3 provides details about the source of the data layers used in this study.

The elevation dataset was obtained from the National Elevation Dataset(NED) 1/3 Arc-Second coverage in raster format. The dataset has a resolution of 10 x 10 meters 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.

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)

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, a common practice in landslide analysis.

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 an Excel format and then imported into the ArcMap software. Because the tables were populated with GPS coordinates of failure sites, projecting and creating the slope failure inventory layer as a shapefile was simple.

The surface geology dataset consists of two layers. The first layer depicts the boundaries of the different physiographic provinces in Maryland. This shapefile was obtained from the Maryland Geological Survey. The second layer is the geological map of Maryland, obtained from the USGS mineral resources spatial database. This layer provides details regarding the superficial and bedrock geology 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

When mapping slope instability, various physical parameters that influence slope stability have been used in different analyses (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 parameters can be broadly classified into intrinsic 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 such as mining, blasting, drilling, and other construction activities.

During the initial stages of this study, the following factors were considered in 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.

Because of such issues as lack of availability of data at the 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 the current research study.

After performing feasibility studies based on expert opinions and recommendations from SHA engineers, the following physical parameters were shortlisted: elevation, slope angle, land cover, storm event precipitation, slope history or failure inventory, and physiographic provinces.

The following section discusses 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), SHA engineers recorded forty-eight slope failure cases occurring between 2008 and 2012. Based on the comprehensive information for the forty-eight slope failures and using spatial analysis tools available in ArcMap (v. 10), 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 parameters most widely thought to influence slope stability (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 did not exhibit a strong correlation with slope instability. As shown in Figure 3.4a, 56% of all slope failures occurred on slopes between 30-90 m in height, and nearly a fourth of the failures occurred on slope with heights 10- 30 m. No clear trend or correlation was observed between slope height and soil slope failures in Maryland.

Figure 3.4b shows the failure distribution for the slope angle subcategories. It is evident that more than half of the failures along highway slopes occurred on slope angles between 20° and 30°. For all engineering and analyses purposes, SHA assumes that all or most highway slopes have a 2H: 1V slope unless explicitly mentioned.

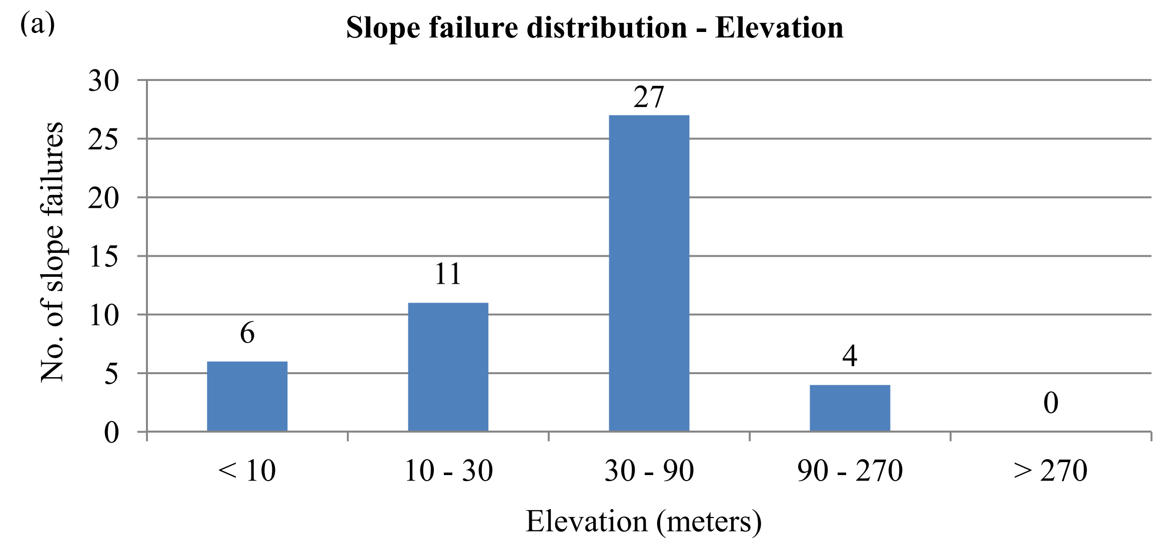
The failure distribution pattern for elevation and slope angle correlates with engineers' observations of field conditions. The SHA records only those slope failures that are within their right of way. Since a distinct pattern or correlation with slope instability is yet to be drawn with respect to these parameters, it can be concluded that these parameters, 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). Lee and Choi (2004) found the probability of landslide occurrences in southern California were highest for grasslands and certain forest types. Their findings, however, 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 slope failures occurred on slopes covered predominantly with grass (Figure 3.5). Cross-referencing this information against vegetation density information shows that many failures occurred on slopes with a low- to medium-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 Maryland.

Fifty-two percent of the remaining slope failures occurred on developed land or in urbanized regions. This trend presents an interesting insight into the effects of urbanization and land-use patterns on slope instability. This relatively large percentage 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.



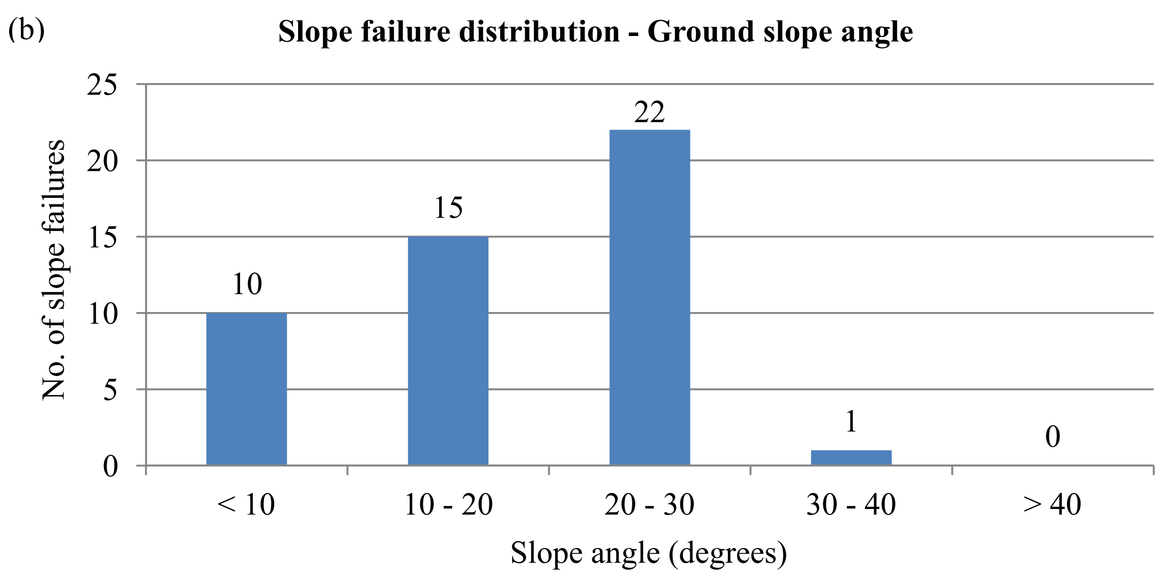


Figure 3.4: Distribution of failures in the different sub categories for (a) Elevation and (b) Slope angle

3.6.3 Storm event precipitation

Precipitation is a fundamental slope instability factor. Hong Kong's densely populated urban areas suffered 185 failures as a result of heavy rains in 1972 (Chau, et al., 2004). Countries such as 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 United States, heavy winter rains caused significant amounts of social and economic losses (Beighley et al., 2003; NOAA, 2001). Generally, areas that receive higher rainfall relative to the rest of a region have a higher probability of landslides occurring (He and Beighley, 2007).

Additionally, 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. Eighty-seven percent of slope failures occurred in regions estimated to have 50 - 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 occurred in regions with heavy rainfall during a storm event.

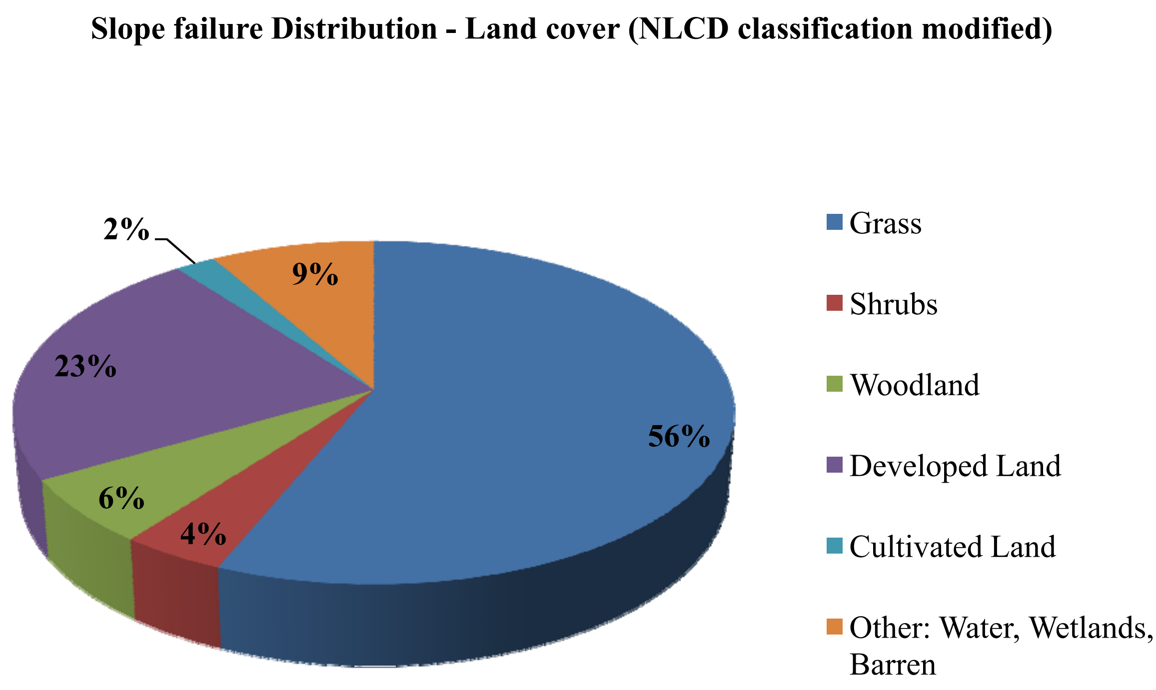
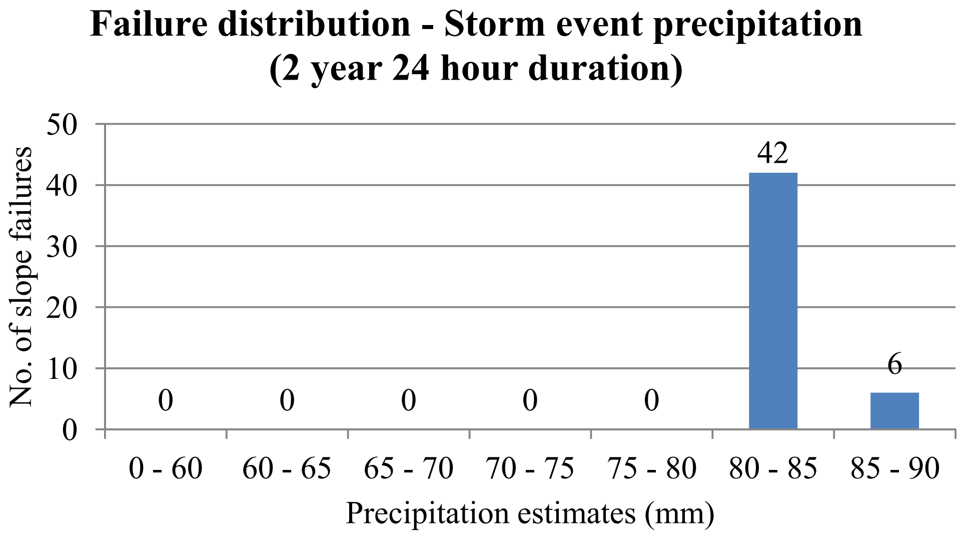


Figure 3.5: The distribution of slope failures for the different classes of land covers in the State of Maryland

(a)



(b)

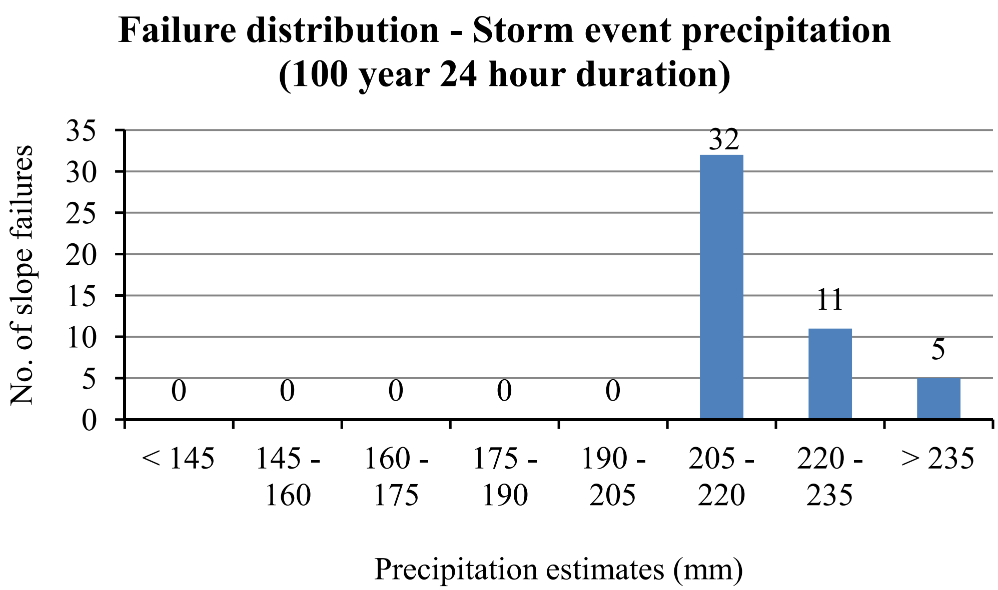


Figure 3.6: The failure distribution pattern for the different sub categories of (a) 2 year 24 hour duration storm event and (b) 100 year 24 hour duration storm event

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 failure conditions in 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. Ninety percent of slope failures were surficial erosion failures. Cross referencing with the GIS database, 80% of slope failures occurred during or after rainfall. Figure 3.9a shows the distribution pattern for the different types of slopes in 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 properties of slope-forming materials (e.g., strength and permeability) involved in a slope failure are related to the lithology (Dai and Lee, 2002). The Atlantic Coastal Plains province consists predominantly of slopes with silty or clayey sand, gravelly sand, coarse sand, and gravel type soils. Eighty-seven percent of slope failures that occurred in the Atlantic Coastal Plains province highlights the effect of lithology of highway slopes (Figure 3.10a). Fifty percent of slope failures were on slopes with sand formations, and 39% of slope failures occured on slopes with gravel formations (Figure 3.10b).

<table>
<tr><th colspan="2">Failure type</th><th colspan="4">Failure type sub - classification</th></tr>
<tr><td>Erosion</td><td>Erosion Area</td><td>Head</td><td>Toe</td><td>Flank</td><td>Body</td></tr>
<tr><td colspan="2" rowspan="2">Rotational failure</td><td>Circular</td><td colspan="2">Deep</td><td>Shallow</td></tr>
<tr><td>Non-circular</td><td colspan="2">Deep</td><td>Shallow</td></tr>
<tr><td colspan="2">Translational failure</td><td colspan="2">Block</td><td colspan="2">Slide</td></tr>
<tr><td colspan="2">Others</td><td>Landslide</td><td colspan="2">Flow</td><td>Spread</td></tr>
<tr><td colspan="6">Compound / Complex (provide sketch below)</td></tr>
</table>

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

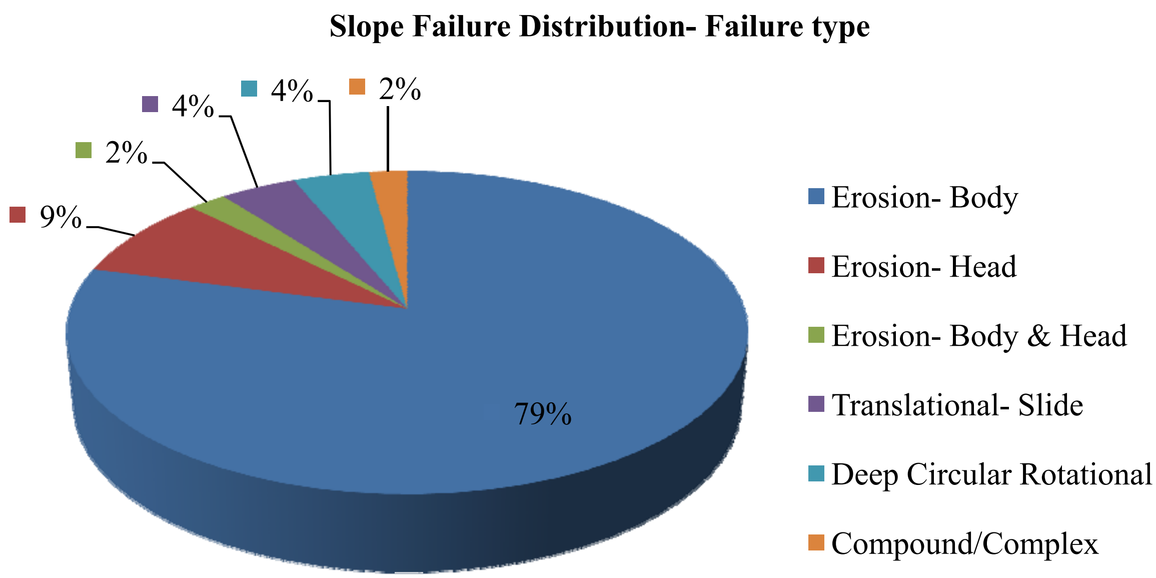
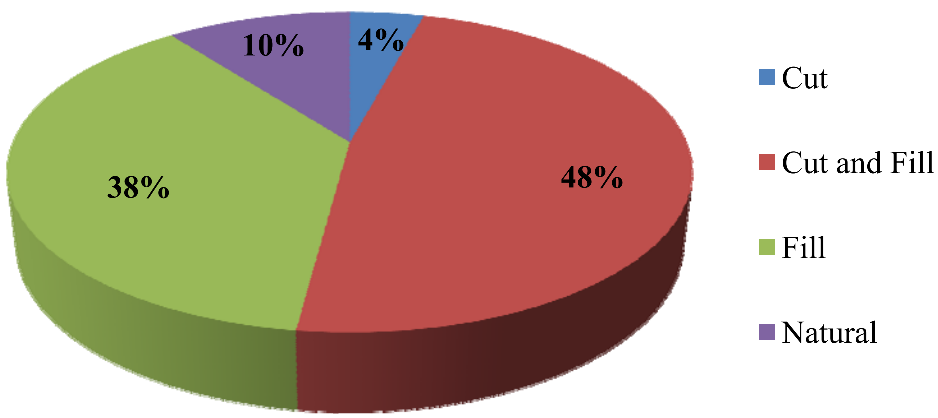


Figure 3.8: Failure distribution pattern for the different types of slope failures as per the modified Cruden and Varnes (1996) classification

Slope Failure Distribution - Slope type

(a)



Slope Failure Distribution- Drainage Section type

(b)

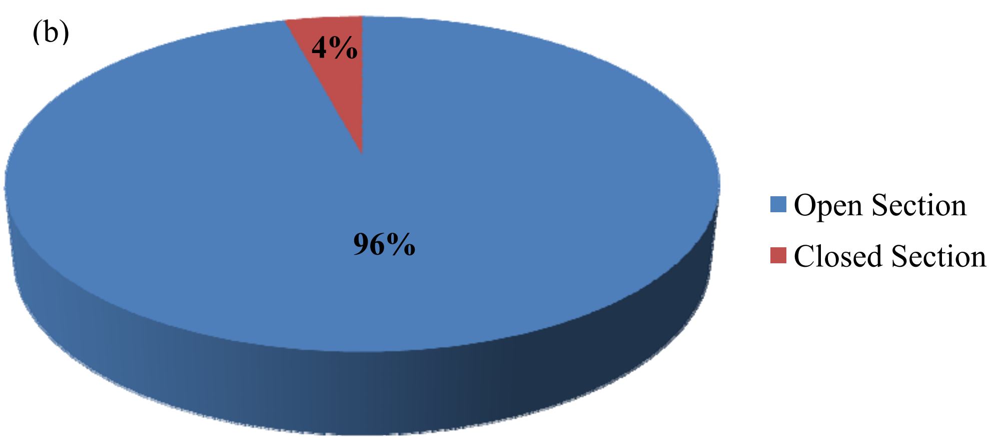
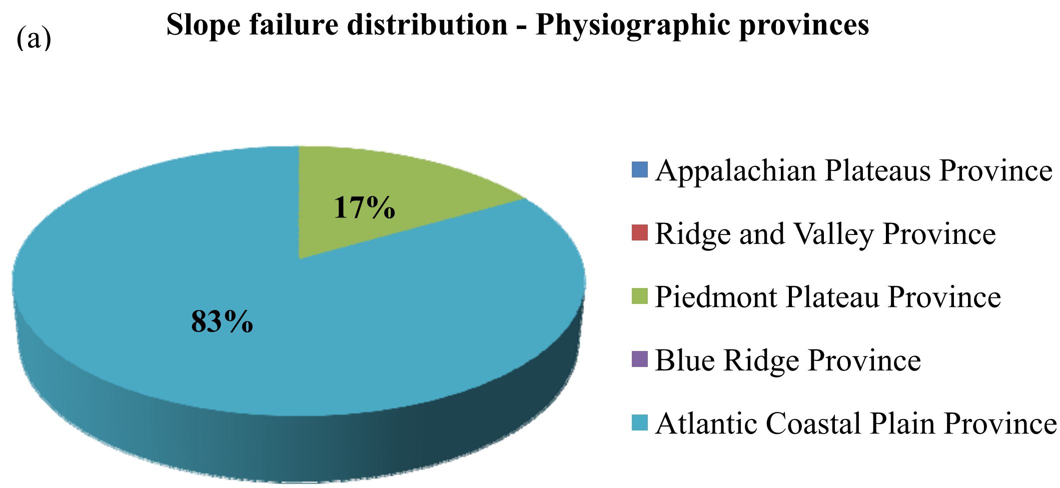


Figure 3.9: Slope failure distribution patterns for different (a) Slope types and (b) Slope drainage section types



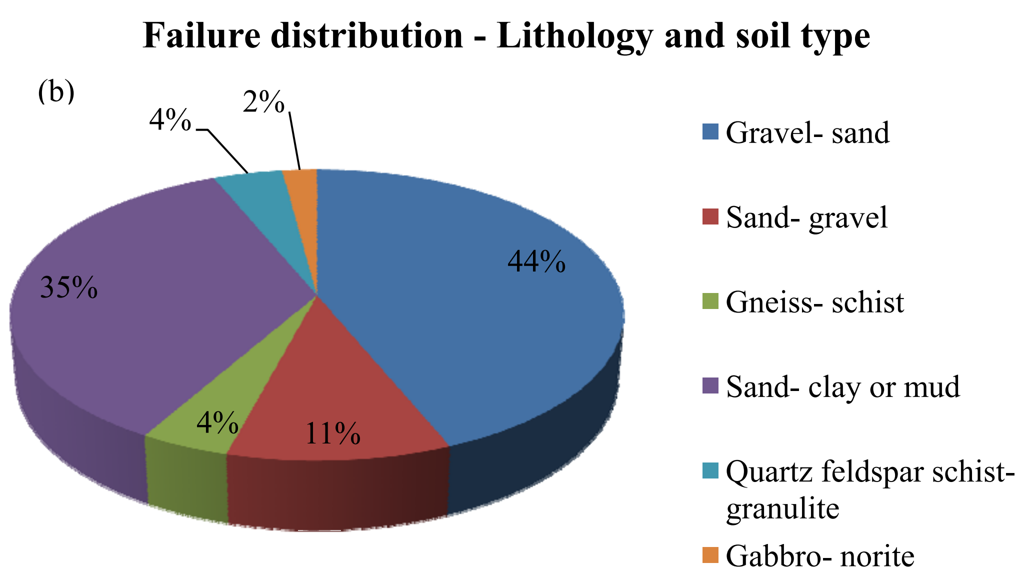


Figure 3.10: The slope failure distribution pattern for (a) the different physiographic provinces and (b) for the different lithology or soil type.

3.7 SLOPE INSTABILITY MAPPING

3.7.1 Logistic regression

Logistic multiple regression is a multivariate technique that models how several physical predictor parameters affect the probability of some event occuring. The advantage of logistic multiple regression modeling over other statistical techniques is that the dependent variable can have only two values—an event either occurs or it does not. As a result, predicted values can be interpreted as probability since they are constrained to fall in the interval between 0 and 1.

Logistic multiple regression yields coefficients for each variable based on data taken from acrossa study area. These coefficients serve as weights in an algorithm and can then used in the GIS database to produce a map depicting the probability of landslide occurrence.

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

$$P = \frac{1}{(1+e^{-Z})} \tag{3.1}$$

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.

$$Z = W_0 + W_1X_1 + \ldots\ldots\ldots\ldots + W_nX_n \tag{3.2}$$

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 Lantau Island, Hong Kong. They also studied runoff potential and behavior of landslide masses. Mark and Ellen (1995) described the use of logistic regression to predict soil failures using a database of thousands of debris flows. Mark and Ellen (1995) used the distribution and frequency of shallow landslides to model future initiation sites, and estimate runoff volumes and runout distances, and compared these results with existing landslides. More recently Gorsevski et al., (2000) used logistic regression to predict landslide hazards in Alberta, Canada.

Although this analysis is recommended for the scale of this study and is compatible with the format in which data is recorded, applying logistic regression is not feasible at this stage because of an inadequately small sample of slope failures. The time required for the GIS database to acquire the appropriate volume of data would render logistic regression outside 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 stages of regional assessment (Glade and Crozier, 2005). Because the primary objective of this study was to lay the ground work for developing a robust slope instability model for Maryland SHA, a qualitative index overlay would be the most suitable method of analysis for the volume of data associated with this study.

The qualitative index overlay characterizes spatial and temporal conditions implicated in past instability events and use these characteristics to identify slopes with similar conditions that are vulnerable to failure.

Chau et al., (2004) discussed the principle behind a weighted overlay of index or thematic maps using ArcGIS software: A denotes the whole study area of the instability map, of which 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, the final pixel value of the instability map produced in this study does not strictly represent probability because 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 were classified into subcategories as shown in Table 3.4. A failure density index was assigned for each subcategory. Assigning an index to each subcategory enables researchers to identify unstable slopes in regions with no previous slope failure occurrence. The class intervals were 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 shown in Table 3.4. A normalized density index was calculated for a more conservative approach. For a particular factor, the density index for each subcategory was normalized by the maximum density index value for that factor. A conservative index allows for a well distributed model by rating slopes that have low failure density values due to lack of field data, but might have potential to fail based on spatial and temporal conditions. Figure 3.12 shows the variation of both the failure density index and the normalized failure density index for the different subclasses of parameters. Figure 3.12 shows how a conservative index provides a more striking variation in failure density values for the same sample.

$$Failure\ density\ index\ (v) = \frac{Number\ of\ slope\ failures\ in\ subclass}{Total\ number\ of\ slope\ failures} \tag{3.3}$$

Figure 3.13 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 3.13. Table 3.4 shows the density index values and the normalized density index values for each subcategory.

A weighted mean of the normalized failure density index of the various factors gives the failure density value at any particular pixel (Equation 3.4). The weights were assigned based on expert opinions and trends observed between the failure density index and the causal parameter. A weight of 3 was applied to parameters exhibiting a clear trend between parameter data and the failure density index, while the weight of 2 or 1 was provided to other parameters based on expert opinion. Four trials were conducted and thus four failure density maps were generated. Table 3.5 gives the different weights assigned, w_i, to the different factors, v_i, used to calculate the failure density as defined in Equation 2.

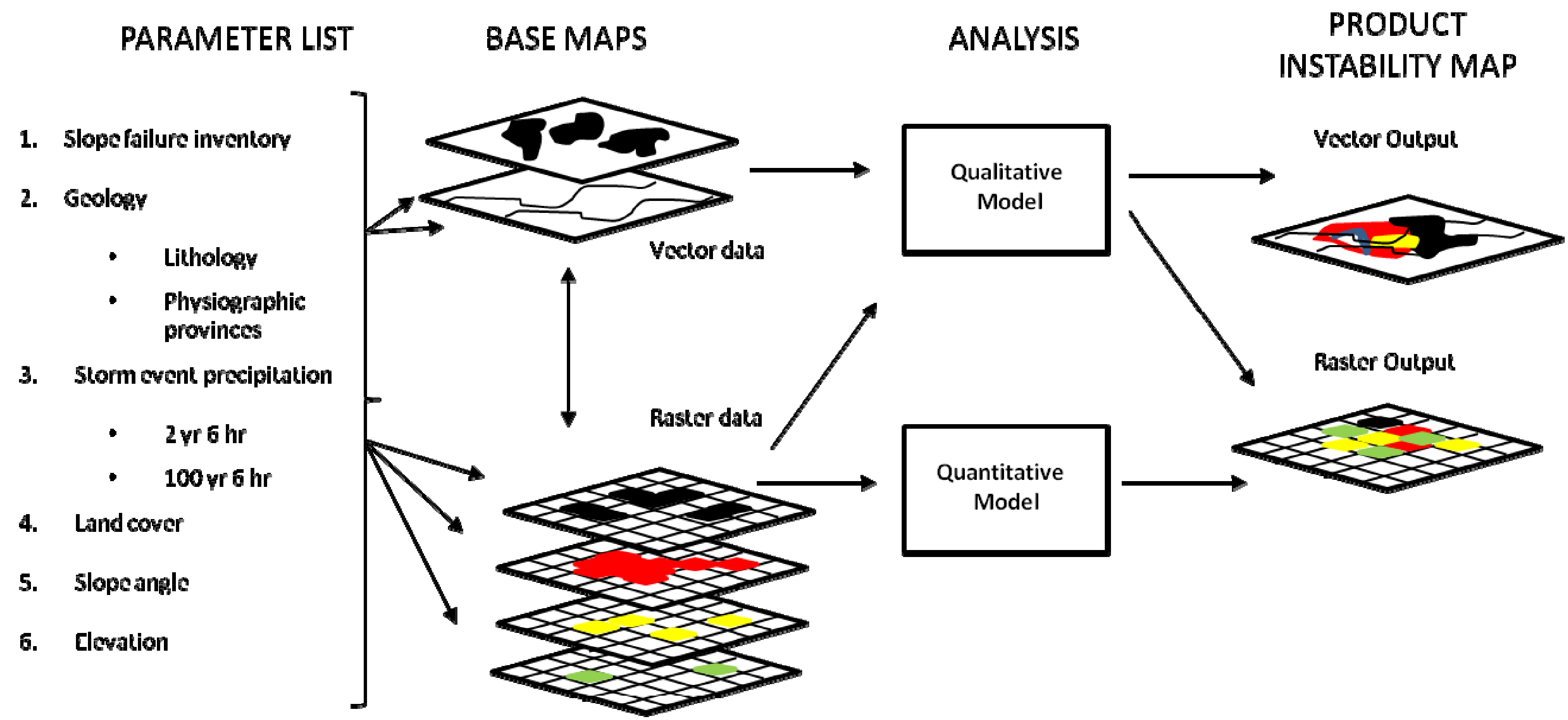


Figure 3.11: Schematic explaining the proposed mapping system. Currently the system uses the qualitative overlay model with a raster

output.

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

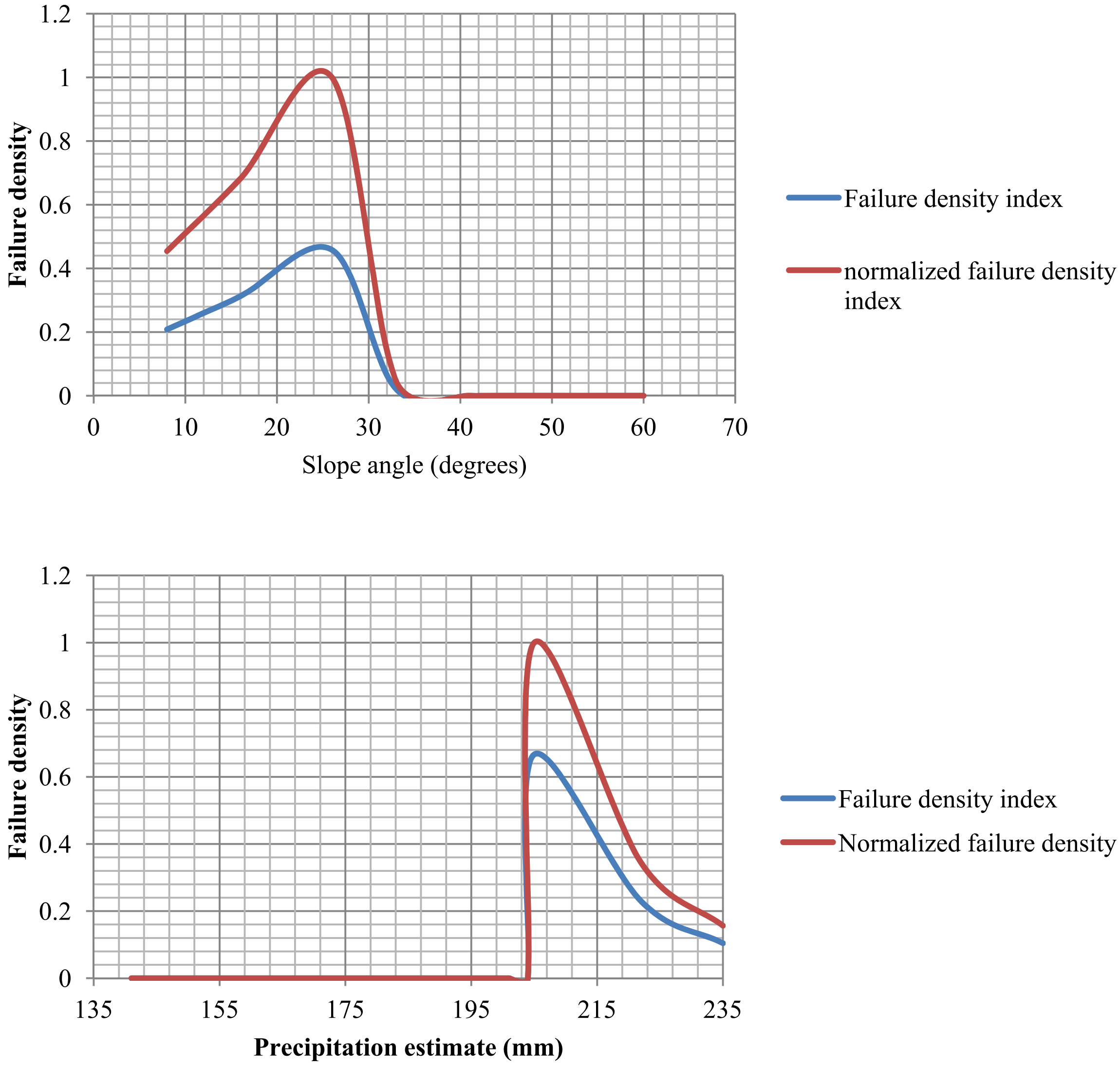


Figure 3.12: Variation of the failure density index and normalized failure density for the subclasses of parameters (a) Slope angle and (b) Storm event precipitation (100 yr, 24 hr

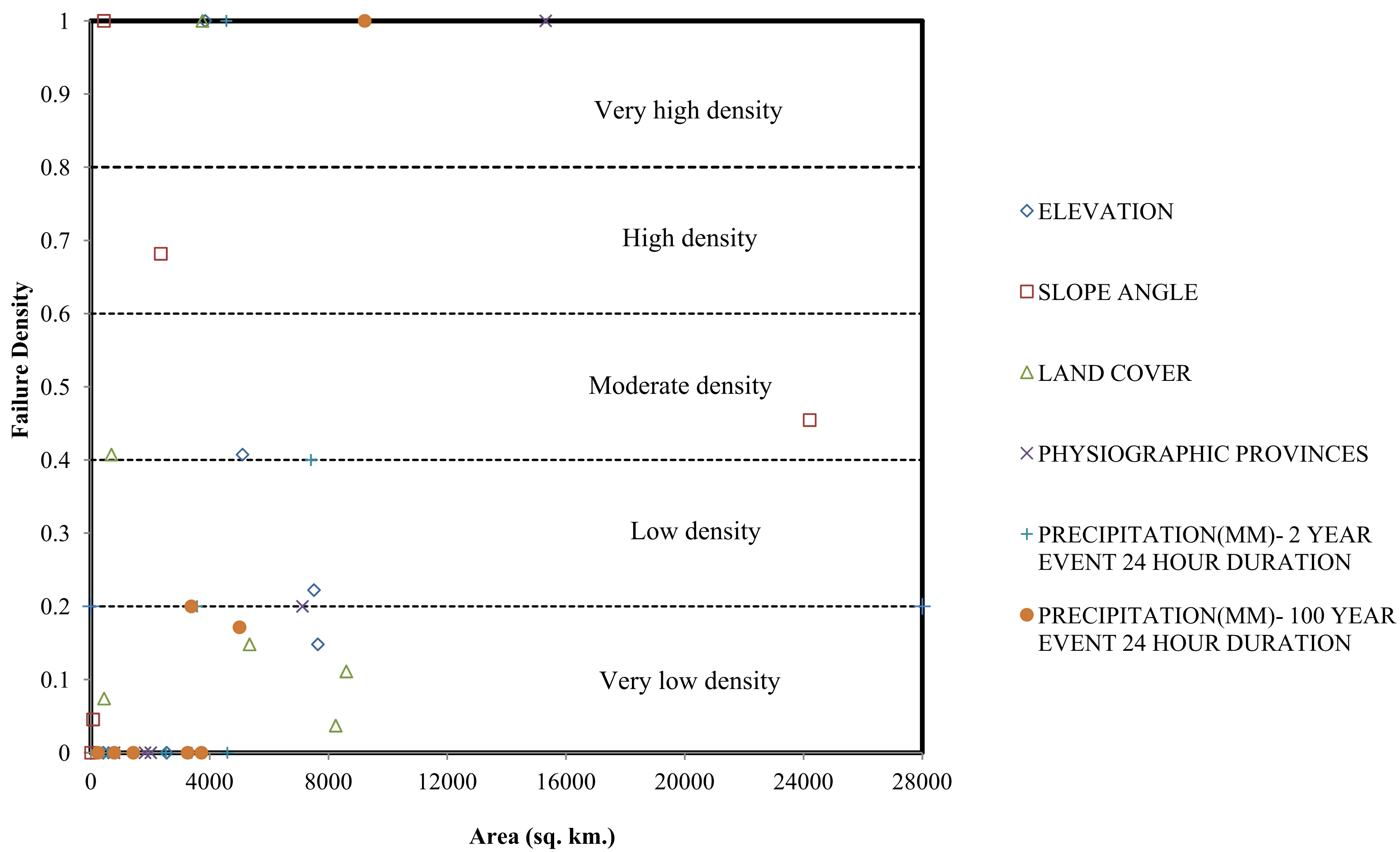


Figure 3.13: Variation of failure density indices for the different parameter subclasses over area of the study region

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

$$Failure\ density = \frac{\sum_{i=1}^{m} w_i v_i}{\sum_{i=1}^{m} w_i} \tag{3.4}$$

Figure 3.14 shows the results of the four weighted overlay maps using the raster calculator function in ArcMap software. The selection of the weights based on expert opinion seems to affect the failure densities; however, in all four cases evaluated in this study, the slope failures were concentrated in greater District of Columbia area. This area is in suburban Washington, DC, and includes a larger number of roads with heavy traffic.

3.8 CONCLUSIONS

A framework for analyzing slope instability was proposed and developed for Maryland SHA. Forty-eight slope failures recorded by SHA engineers using the GIS database were analyzed for trends linking physical parameters to slope instability.

Six factors were considered to affect highway soil slope stability in this study: event precipitation, geological formation, land cover, slope history, ground slope and elevation. Overlaying statewide GIS data for these factors identified some interesting trends. First, precipitation and poor surface and/or sub-surface drainage conditions are principal factors causing slope failures. Ninety-six percent of the failed slopes lie along roads with open drainage. Additionally, a majority of failed slopes lie in regions with relatively high event precipitation values. Ninety percent of the failures are surficial erosion-type failures, but only 4% of slope failures are deep rotational-type failures. Cross-referencing this information with the GIS database, indicates that 80% of slope failures occurred during or after rainfall.

Fifty-eight percent of existing slope failures occurred in regions that have low-density land cover. Half of failures occurred in sand and another 39% occurred in gravel formations.

Distinct trends and patterns were recognized for such physical features as lithology, physiographic provinces, precipitation, and land cover. These physical parameters influence highway slope stability to a greater extent relative to other physical parameters such as elevation and slope angle. Identifying and recording more data relating to failed slopes should uncover more trends and strengthen confidence in the trends reported in this study, and, ultimately, aid SHA in making prudent budget and remediation decisions.

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

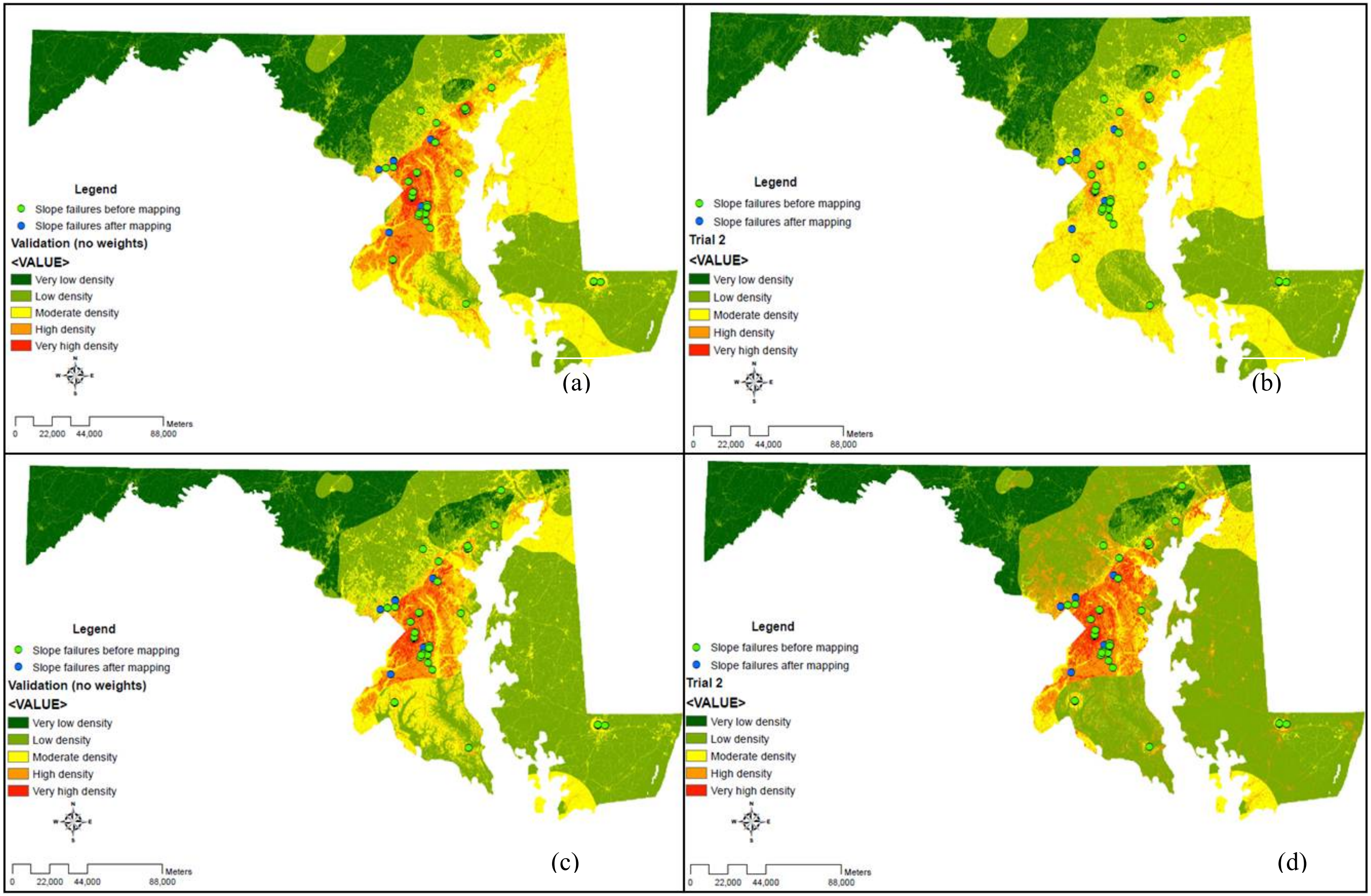


Figure 3.14: Failure density maps generated by layers and weights provided in Table 3.5. (a) Follows weighing scheme – Map 1 (b) follows weighing scheme – Map 2 (c) follows weighing scheme – Map 3 (d) follows weighing scheme – Map 4

CHAPTER 4

4.1 SUMMARY

The purpose of this study was threefold: gathering and evaluating historical data on soil slope failures in Maryland and developing the necessary protocols to incorporate that information into a GIS database; developing a database structure containing information relating to soil slope failures; and laying the framework for the implementation of a quantitative model for predicting the vulnerable highway slopes in Maryland.

A majority of the SMSs reviewed in Chapter 2 are inherently subjective. Although subjectivity in assessing failed slopes was not completely eliminated, this study presented and reviewed procedures that can quantitatively analyze slopes, thus mitigating the effects of subjective evaluations.

The important conclusions, results and findings are below.

a) A comprehensive management and assessment system has been developed to allow SHA to better record, evaluate, analyze, and review the soil slope failure and soil slope remediation data;
b) A database structure containing information relating to soil slope distresses and failures was developed using Microsoft 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 using GIS features;
c) A comprehensive survey sheet was created to record information relevant to highway slope failures in Maryland. This failure field sheet optimized the data collection process for the engineers in the field. It reduced the time necessary for colleting the data and it also enforced uniform data collection, entry, and storage procedures. The information collected in the field can be keyed in to the GIS database;
d) The SHA's slope failure remediation responses were categorized into a list of factors based on the consequences of failures. The initial stage in studying risks and consequence is laid out. Engineers can use this categorization as a guideline for budget allocation and prioritizing remediation projects to avoid liability and legal matters associated with having such a small data set; and
e) A framework for analyzing slope instability was proposed and developed for SHA. A total of forty-eight slope failures recorded by SHA engineers using the GIS database were analyzed for emerging trends and patterns correlating physical parameters with slope instability.

Using the SMS tools, including the failure field sheet and the GIS database, forty-eight slope failure cases occurring between 2008 and 2012 were recorded by SHA engineers. Based on the comprehensive information for the forty-eight slope failures and using spatial analysis tools, certain trends in failure distribution were identified. The significant trends are:

a. Fifty-six percent of slope failures occurred on slopes 30-90 m in height; nearly a quarter of failures occurred on slope with heights 10-30 m. There was no clear trend between slope height and soil slope failures in Maryland;
b. More than 50% of slope failures occurred on highway slopes with angles 20° -30°. For all engineering and analyses purposes, 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. Fifty-two percent of slope failures occurred on developed land or in urbanized regions, which gives insight into the effect of urbanization and land use pattern on slope instability;

d. Fifty-eight percent of slope failures occurred in regions with low-density land cover. These failures can be attributed to an increased amount of such human activity as blasting, drilling, traffic volume, and construction activities;
e. Ninety percent of slope failures are surficial erosion failures. Only 4% of slope failures are deep rotational-type failures. Cross-referencing this information with the GIS database indicates that 80% of slope failures occurred during or after rainfall;
f. More than 80% of slope failures occurred in regions expected to have heavy rainfall during storm events. Ninety-six percent of the slope failures occurred along highway slopes with open drainage sections. When correlated with factors such as precipitation and type of drainage section at failure site, these trends show the influence of precipitation and drainage conditions on slope instability;
g. Eighty-seven percent of slope failures occurred in the Atlantic Coastal Plains province. This finding highlights the effect of lithology, or soil type, of highway slopes. The Atlantic Coastal Plains province consists predominantly of slopes with silty or clayey sand, gravelly sand, coarse sand, and gravel-type soils;
h. Half of slope failures occurred on slopes with sand formations, and 39% of these slope failures occured on slopes with gravel formations; and
i. 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 not fully developed and is a work in progress. 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.

This SMS recorded information form slope failures occurring between 2008 and 2012. With the passage of time and further population of this database, additional improvements can be made to the system to support the influx of new information in order to analyze highway slope failure trends with more conclusive results.

Although the basic framework of the system has been established, further improvements that were discussed in this study should be implemented to enhance its capability. This section discusses the recommended improvements to make to the GIS components.

For the eGIS web map service, two enhancements are required to improve the functionality. OMT wants the ability to upload pictures stored on their fileshare with naming conventions and sub-folder structure. The first enhancement recommendation is a photo gallery that can be viewed through the eGIS. The Photo Viewer Widget allows users to view thumbnail pictures, provide file names, and save photos to their desktops. This component of the eGIS allows users to upload and view photographs of the failure site taken after failure and during and after remediation. OMT could then review and track the performance of the highway slope after remediation projects and the efficiency of remediation methods for particular types of failures. The eGIS Technical Team recommends an approach similar to that adopted in developing the previous widgets. One of the many benefits of the eGIS application is the ability to reuse the technology and code for other projects.

The second enhancement recommendation is to incorporate a robust quantitative mapping system based on the mathematical model discussed in the previous chapter. Such a model requires large samples in order to increase the accuracy of its probabilistic predictions of highway slope failure. Although this enhancement cannot be adopted immediately, it is imperative if SHA wants to sharpen its predictive capabilities – at the scale of this study, only a quantitative mapping system would be accurate.

When sufficient data is available dimensions of initiation sites and volume of debris in the future, it is recommended that analyses be performed at the district level or county level. This smaller scale will increase the model's predictive accuracy and allows use of many mapping techniques. Also, the ratio between the total area of failure sites and the total study area becomes more significant at this scale and thereby presents better conditions for susceptibility analysis or conditional probability analysis.

When the GIS database is populated with remediation details and maintenance information, it is recommended that this data is analyzed in order to ascertain the most cost effective and efficient remediation methods for particular types of failure. The results of the analysis could be used as input for developing an automated remediation response model, which would provide the most viable remediation option based on the set of parameters previously discussed. Such a model may also be able to perform cost-benefit ratio analyses, thereby providing district offices with a more sound foundation when deciding how to allocate budgets and resources.

REFERENCES

Abramson, L. W., Lee, T. S., Sharma, S., & Boyce, G. M. (2001). *Slope Stability and Stabilization Methods.* New York: John Wiley & Sons, Inc.

Aleotti P, Chowdhury R. (1999). *Landslide hazard assessment: summary review and new perspectives.* Bulletin of Engineering Geology and the Environment 58: 21– 44.

Alfors, J. T., Burnett, J. L., & Gay, T. E. (1973). *Urban Geology Masterplan for California- the nature, magnitude and costs of geologic hazards in California and recommendations for their mitigation.* (Vols. 198, 112pp). California Div. of mines and geology.

Anbalagan R, Singh B. (1996). Landslide hazard and risk assessment mapping of mountainous terrains – a case study from Kumaun Hymalaya, India. *Eng Geol 43*: 237–246.

Bhattarai, P., Tiwari, B., Marui, H., & Aoyama, K. (2004). Quantitative Slope Stability Mapping With ArcGIS: Prioritize Highway Maintenance . *Proceedings of ESRI's 24th Annual International User's Conference, San Diego.* ESRI.

Beighley RE, Melack JM, Dunne T. (2003). Impacts of climatic regimes and urbanization on streamflow in California coastal watersheds. *Journal of the American Water Resources Association 29*: 1419–1433.

Brundsen, D. (1973). *Application of systems theory to the study of mass movement.* Geologica e Idrogeologia, Univ. of Baria.

Brundsen, D., & Prior, D. B. (1984). *Slope Instability.* Norwich: John Wiley & sons, Inc.

Cardinali, M., Reichenbach, P., Guzzetti, F., Ardizzone, F., Antonini, G., Galli, M., . . . Salvati, P. (2002). A geomorphological approach to the estimation of landlside hazards and risks in Umbria, Central Italy. (2).

Carrara, A., Cardinali, M., Guzzetti, F. and Reichenbach, P. (1995). GIS technology in mapping landslide hazard. In Carrara, A. and Guzzetti, F., editors, *Geographical Information Systems in assessing natural hazards*, Dordrecht: Kluwer, 135–75.

Carrara, A., Guzzetti, F., & Cardinali, M. a. (1999). Use of GIS technology in the prediction and monitoring of landslide hazard. *Natural Hazards , 20* (2-3). (2002). In D. M. Cruden, *Landlside Risk Assessment.* Rotterdam.

Cavallo, A., & Norese, M. F. (2001). GIS and Multicriteria Analysis to Evaluate and Map Erosion and Landslide Hazards. *INFORMATICA 2001. 12.* Vilinius: Institute of Mathematics and Infomatics.

Chau, K. T., Sze, Y. L., Fung, W. Y., Wong, W. Y., & Fong, E. L. (2004). Landslide hazard analysis for Hong Kong using landslide inventory and GIS. *30*.

Chung, C.-J. F., & Fabbri, A. G. (1999). Probabilistic Prediction Models for Landslide Hazard Mapping. *65*(12).

Chung, C.-J. F., & G., F. A. (2004). Systematic Precedures of Landslide Hazard Mapping for Risk Assessment Using Spatial Models. In T. Glade, M. Anderson, & M. J. Crozier, *LandSlide Hazard and Risk* (Vols. ISBN: 0-471-48663-9). John Wiley & Son, Ltd.

Cruden, D. M., & R, F. (2002). In D. M. Cruden, & F. R, *Landlside Risk Assessment.* Rotterdam.

Cruden, D. M., & Varnes, D. J. (1996). Landslides: Types and Processes. In A. K. Turner, & L. R. Schuster, *Landslides: Investigation and Mitigation, Transportation Research Board Special Report.*

Dai, F. C., & Lee, C. F. (2002). Landslide characterisitcs and slope instability modelling using GIS, Lantau Island, Hong Kong. (42).

Dikau, Brundsen, D., Schrott, L., & Ibsen, M. L. (1996). *Landslide Recognition: Identification, Movement and Causes.* Chichester: John Wiley & Sons Ltd.\

Dikau, R. Cavallin, A., and Jager, S. (1996). "Databases and GIS for landslide research in Europe", Geomorphology, 15, 227-239

Edwards Jr, J (1981). A brief description of the geology of Maryland. *Pamphlet Series.* Maryland Geological Survey, http://www.mgs.md.gov.

Fall M, Azzam R, Noubactep C. (2006). A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping. *Engineering Geology 82*: 241–263.

Fenti V, Silvano S, Spagna V. (1979). Methodological proposal for an engineering geomorphological map, forecasting rockfalls in the Alps.*Bull of the Int Assoc Eng Geol 19:* 134 –138.

Glade, T., Anderson, M., & Crozier, M. J. (2005). *Landslide Hazard and Risk.* West Sussex: John Wiley & Sons. ISBN 10: 0-471-48663-9 (H/B).

Gorsevski, P., Gessler, P., & Foltz, R. (2000). Spatial Prediction of Landslide Hazard Using Logistic Regression and GIS. *4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4):Problems, Prospects and Research Needs.*, Alberta, Canada.

Gupta P, Anbalagan R. (1997). Slope stability of Theri Dam Reservoir Area, India, using landslide hazard zonation (LHZ) mapping. *Quarterly Journal of Eng Geology 30*: 27–36.

Guzzetti, F., Carrara, A., Cardinali, M., & Reichenbach, P. (1999). Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. *31*.

Hansen, A. (1984). Lanslide Hazard Analysis. In D. Brunsden, & D. B. Prior, *Slope Instability* (pp. 523-602). John Wiley & Sons Ltd.

He, Y. P., Xie, H., Cui, P., Wei, F. Q., Zhong, D. L., & Gardner, J. S. (2003). GIS-based hazard mapping and zonation of debris flows in Xiaojiang Basin, southwestern China. *45*(2).

He, Y., & Edward Beighley, R. (2007). GIS-based regional landslide susceptibility mapping: a case study in southern California. *33*(3).

Hopkins, C. T., L, B. T., Sun, C., Ni, B., & Butcher, B. (2001). *Highway Rock Slope Management Program.* Lexington, Kentucky: Kentucky Transportation Cabinet.

Huabin, W., Gangjun, L., & Weiya, X. a. (2005). GIS-based landslide hazard assessment: an overview. *Progress in Physical Geography , 29* (4).

Hutchinson, J. N. (1988). General Report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology.*Proceedings, Fifth International Symposium on* Landslides (Ed: Bonnard, C.), 1, 3-35. Rotterdam: Balkema

Kienholz H. (1978). Maps of geomorphology and natural hazard of Griendelwald, Switzerland, scale 1:10 000. *Artic and Alpine Research 10*:169–184

Lee, W. F., Liao, H. J., Chen, R. H., Wei, C. Y., & Huang, Y. M. (2006). The Development and Application of the Slope Management System. *GeoCongress 2006.* ASCE. ISBN (print): 978-0-7844-0803-2

Leroi, E., (1997). Landslide Risk Mapping: Problems, Limitation and Developments. In: Cruden, Fell, (Eds.), Landslide Risk Assessment. Balkema, Rotterdam, pp. 239–250.

Lee S, Choi J. (2004). Landslide susceptibility mapping using GIS and the weight-of-evidence model. *Int. J. Geographical Information Science 18*: 789–814.

Leighton, F. B. (1976). Urban Landslides: targets for land use planning in California. (174).

Leroi, E. (1996). Landslide hazard-risk maps at different scales: objectives, tools and developements. In K. Senneset, *Landslides.* Rotterdam.

Liang, R. Y. (2007). Landslide Hazard Rating Matrix and Database: Federal Highway Administration, FHWA/OH-2007/18.

Liang, S., & Yang, X. OHDOT. (2008). Landslide Hazard Assessment Based on GIS: A Case Study of a Hydropower Station Area in China. ETTANDGRS '08 Proceedings of the 2008 International Workshop on Education Technology and Training & 2008 International Workshop on Geoscience and Remote Sensing, 1.

Lowell, S. and Morin, P. (2000). “Unstable slope management – Washington state.” *Transportation Research News*, 2

Mark, R., & Ellen,S. D. (1995). Statistical and Simulation Models for Mapping Debris-Flow . In A. Carrara, & F. Guzzetti, *Geographical Information Systems in Assessing Natural Hazards*. Dordrecht: Kluwer Academin Publishers.

Mejia-Navarro, M., & Garcia, L. A. (1996). Natural hazard and risk assessment using decision support systems, application. *II*(3).

Morton D M, Alvares R M, Campbell R H. (2003). Preliminary Soil-Slip Susceptibility Maps, Southwestern California, *US Geological Survey Open-File Report* 03-17.

National Oceanic and Atmospheric Administration (NOAA). (2001). Sulphur Mountain Doppler Radar: a Performance Study, *Technical Memorandum NWS WR-267*. National Weather Service, Los Angeles Weather Service: Oxnard, CA.

NYSDOT. (2007)Rock Slope Rating Procedure – Geotechnical Engineering Manual: New York State Department of Transportation, GEM-15.

ODOT. (2001) Landslide and Rockfall Pilot Study (Final Report): Oregon Department of Transportation Geo-Hydro Section.

Pack, R. T. and Boie, K. (2002) Utah Rockfall Hazard Inventory, Phase I: Utah Department of Transportation, Research Division, UT-03.01.

Pierson, L. A., Davis, S. A., Van Vickle, R. (1990) Rockfall Hazard Rating System Implementation Manual: Oregon Department of Transportation, FHWA-OR-EG-90-01.

Rose, B. T. (2005). Tennessee Rockfall Management System: Ph.D. dissertation, Virginia Polytechnic Institute and State University.

Popescu, M. E. (2002). Landslide Causal Factors and Landslide Remedial Options. *Proceedings 3rd International Conference on Landslides, Slope Stability and Safety of Infra-Structures*, (pp. 61-81). Singapore.

Rupke J, Cammeraat E, Seijmonsbergen AC, van Westen CJ. (1988). Engineering geomorphology of Widentobel Catchment, Appenzell and Sankt Gallen, Switzerland: a geomorphological inventory system applied to geotechnical appraisal of slope stability. *Engineering geology* 26: 33–68.

Saboya Jr., F., Alves, M. d., & Pinto, W. D. (2006). Assessment of failure susceptibility of soil slopes using fuzzy logic. *86*(doi:10.1016/j.enggeo.2006.05.001).

Sakellariou, M. G., & Ferentinou, M. D. (2001). GIS-based estimation of Slope Stability. *Natural*

Hazards Review, 2(1).

Schuster, R. L. (1978). Introduction. In R. L. Schuster, & R. J. Krizek, *Landslide Analysis and Control* (Vol. Transportation Research Board Special Report 176). Washington, DC.

Selby, M. J. (1993). *Hillslope Materials and Processes.* Oxford: Oxford University Press.

Singh, H., & Huat, B. B. (2008). Slope Assessment Systems: A Review and evaluation of current techniques used for cut slopes in mountainous terrain of West Malaysia. *13*(Bund. E).

Skempton, A. W. (1950). *Soil Mechanics in relation to geology.* Proc. Yorkshire Geology Society.

Terzaghi, K. (1950). *Mechanisms of Landslides.* Geol. Soc. Am., Berkey Volume.

"2010 Resident Population Data". U. S. Census Bureau. Retrieved 2010-12-26.

van Westen, C.J. (1993): Application of Geographical Information System to landslide hazard zonation. Enschede: ITC Publication 15, 245 pp.

van Westen, C.J. and Terlien, T.J. (1996): An approach towards deterministic landslide hazard analysis in GIS: a case study from Manizales Colombia. Earth Surface Processes and Landforms 21, 853–68

Van Westen CJ, Rengers N, Terlien MTJ. 1997. Prediction of the occurrence of slope instability phenomena through GIS-based hazard zonation. *Geologische Rundschau 86*: 4004–4414.

Varnes, J. D. (1978). Landslides types and processes. In E. B. Eckel, *Landlsides and Engineering Practice* (Vol. 176). Washington, DC: Transportation Research Board, National Association of Science.

Varnes J. D., IAEG (1984) Commission on Landslides.. Landslide Hazard Zonation, a Review of Principles and Practice. UNESCO: Paris.

Wachal D. J., Hudak P. F. (2000). Mapping landslide susceptibility in Travis County, Texas, USA. *GeoJournal 51*: 245–253.

Wu, T. H., & Abdel-Latif, M. A. (2000). Prediction and mapping of landslide hazard. *37(4): 781-795*(10.1139/t00-006)

APPENDIX A
FAILURE SITE FAILURE 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

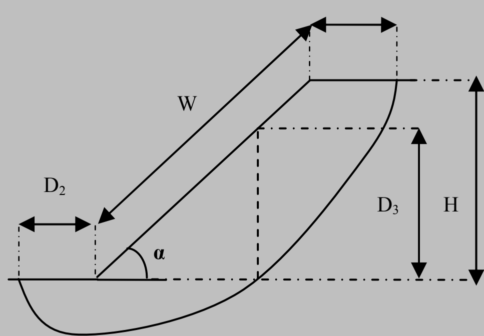
Type of failure:					
☐ Erosion	Erosion Area	☐ Head	☐ Toe	☐ Flank	☐ Body
☐ Rotational (provide sketch below)	Circular	☐ Deep	☐ Shallow		
	Non-circular	☐ Deep	☐ Shallow		
☐ Translation (provide sketch below)	☐ Block	☐ Slide			
☐ Compound / Complex (provide sketch below)					
☐ Others(provide sketch below)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

3. Detailed Dimensions of Failure

Project Description: ____

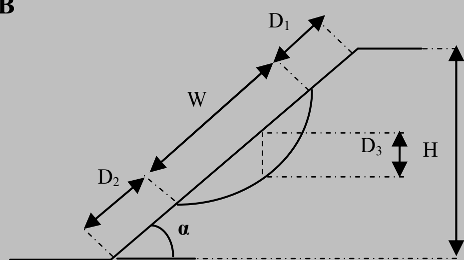
Failure Site Field Sheet Site Evaluation Date: MM/DD/YYYY

☐ **A**



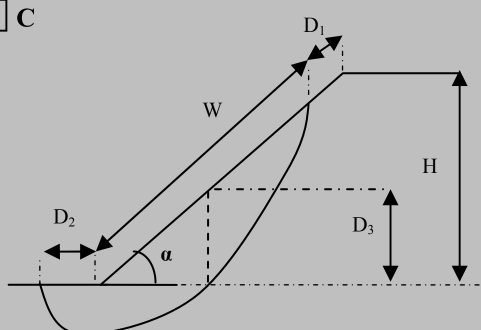
1. Length of failure section along roadway, L:_______________Feet
2. Average slope angle, α:_________degrees
3. Height of slope, H:____________Feet
4. Width of failure along slope incline, W:______________ Feet
5. Distance from crest of slope to failure section, D_1: _____________ Feet
6. Distance from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

☐ **B**



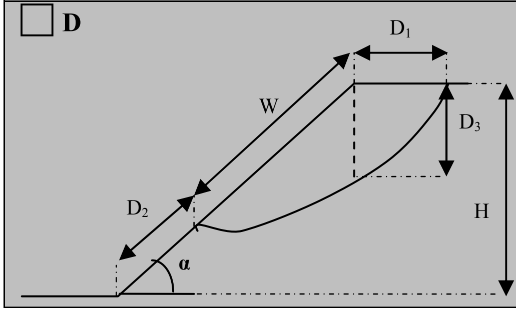
1. L:_______________Feet
2. α:________________degrees
3. H:________________Feet
4. W:________________Feet
5. D_1: _______________ Feet
6. D_2: _______________ Feet
7. D_3:________________Feet

☐ **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

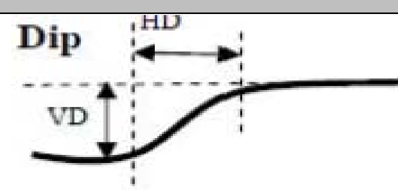
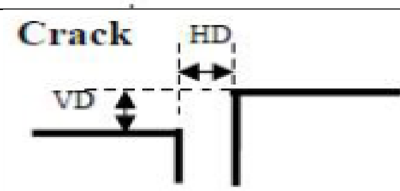
Comments:____
____
____
____

Project Description: ____

Failure Site Field Sheet Site Evaluation Date: MM/DD/YYYY

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	

Project Description: ____

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
	☐ Shrub	___% Land covered
	☐ Cultivated land	___% Land covered
	☐ Reforestation	___% Land covered
	☐ Woodland	___% Land covered
	☐ Other	___% Land covered
	Comments:	
Vegetation Density		☐ Sparse ☐ Moderate ☐ Dense
Hydrogeology	**Surface Water**	**Types of Sources**
		☐ None ☐ Creek
		☐ Reservoir ☐ Surface drainage
		☐ Lake ☐ River
		☐ Pond ☐ 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

Project Description: ____

Failure Site Field Sheet

Site Evaluation Date: MM/DD/YYYY

		Groundwater Condition
		☐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: ______________________________

Failure Site Field Sheet Site Evaluation Date: MM/DD/YYYY

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 :

Project Description: ____

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 because of 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 because of 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

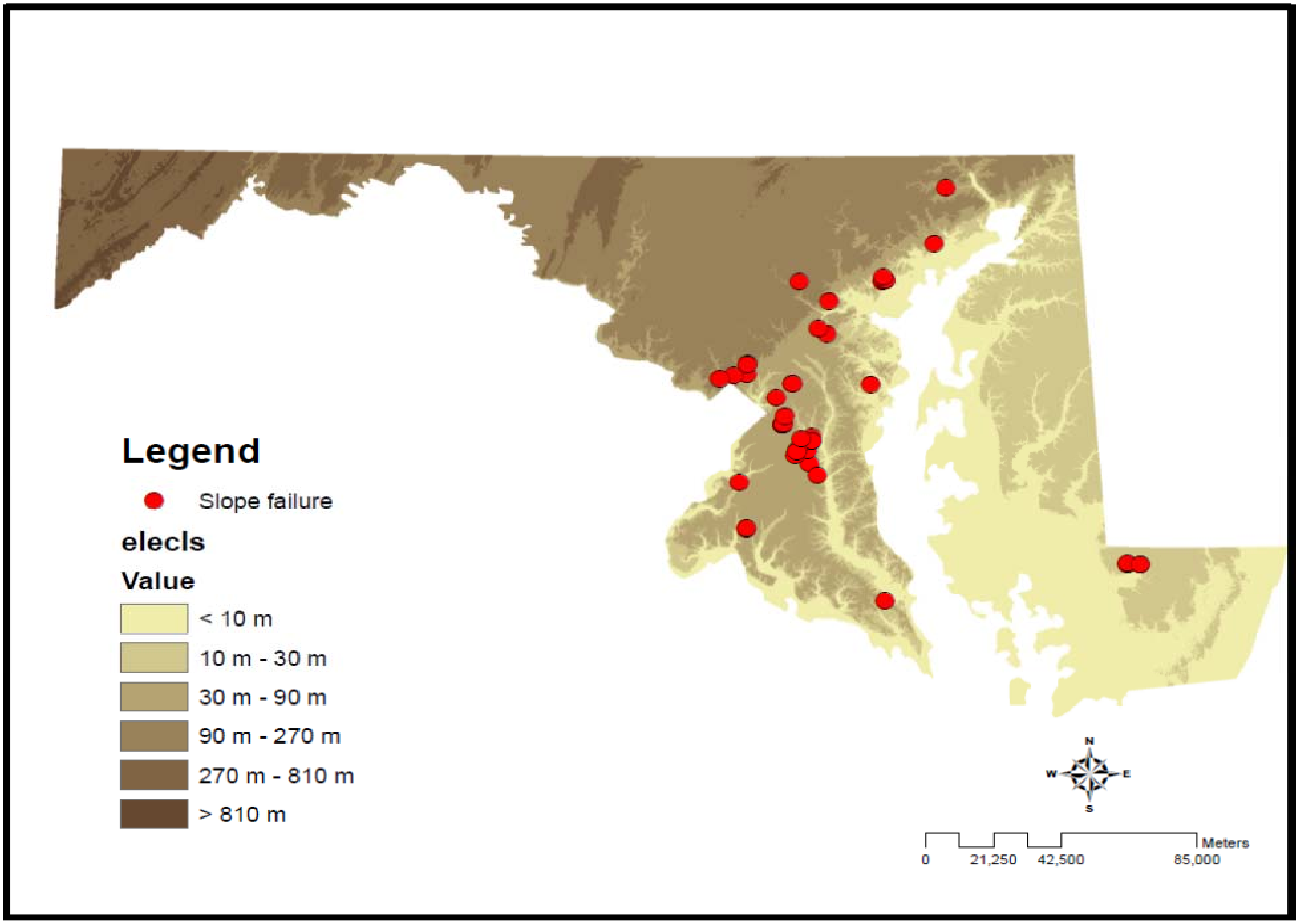


Figure C.1: Elevation data layer in meters along with the spatial distribution of slope failures

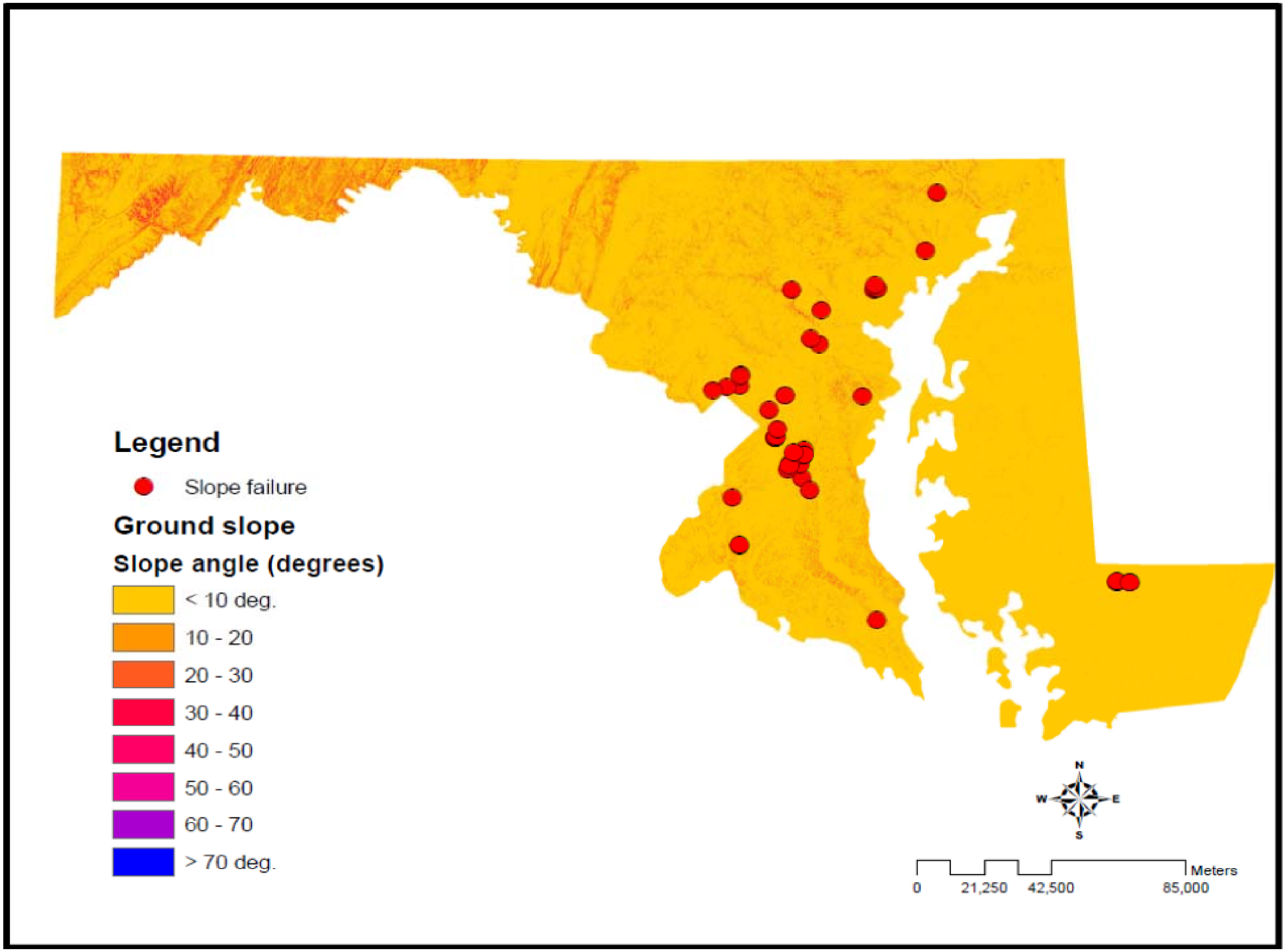


Figure C.2: Slope angle data layer in meters along with the spatial distribution of slope failures

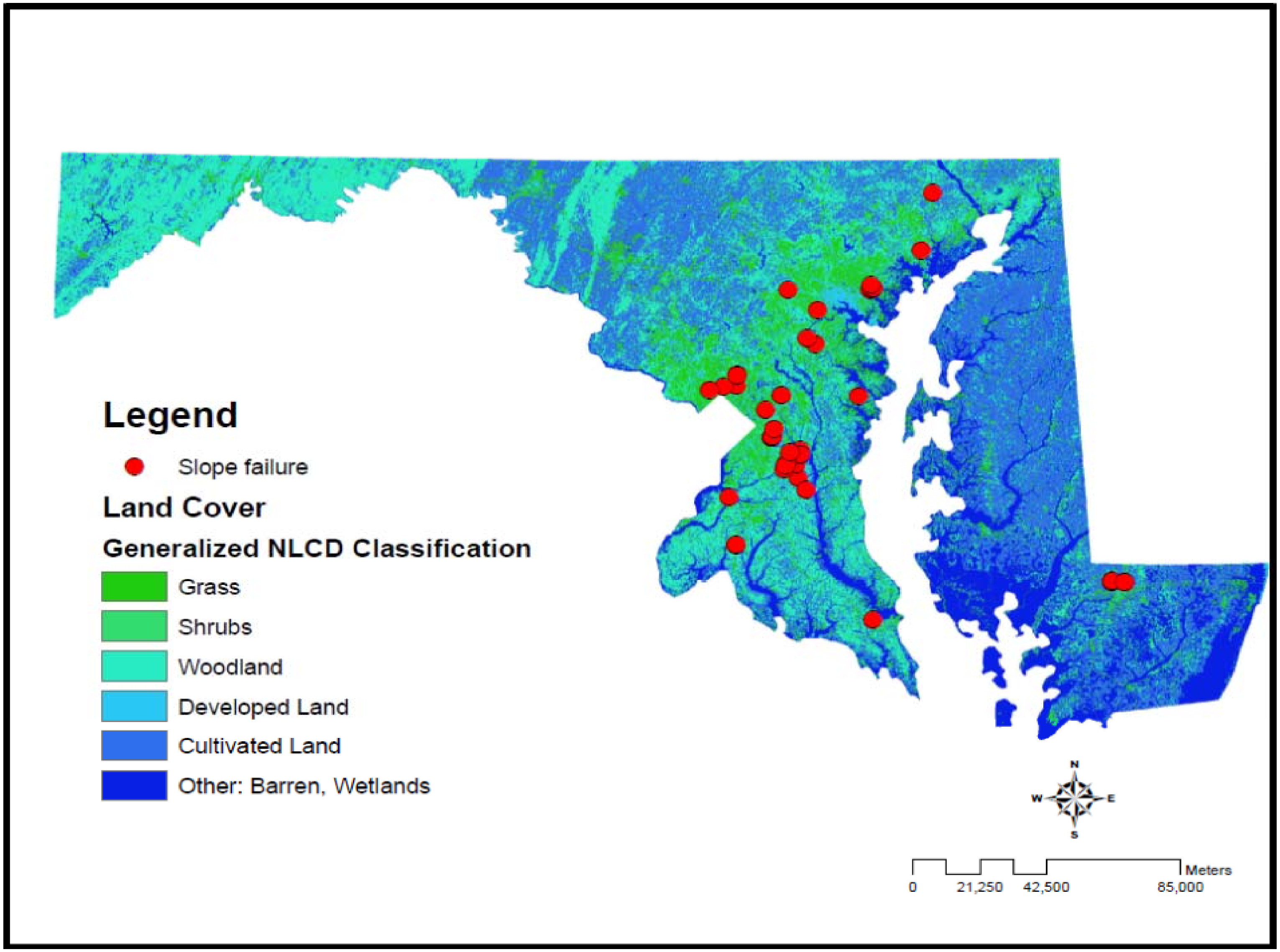


Figure C.3: Land cover data layer in meters along with the spatial distribution of slope failures

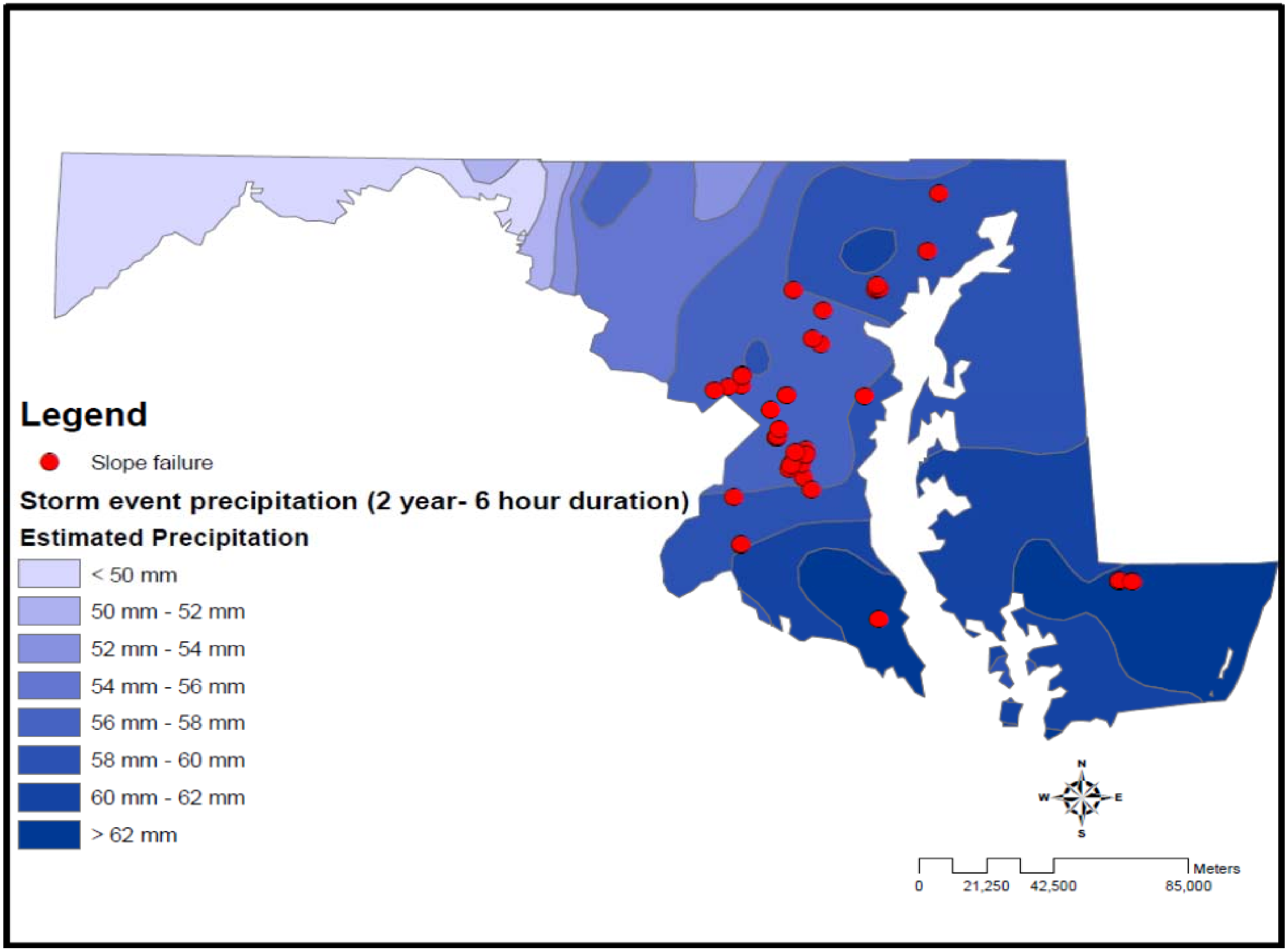


Figure C.4: Storm event precipitation (2 year, 24 hour) data layer in meters along with the spatial distribution of slope failures

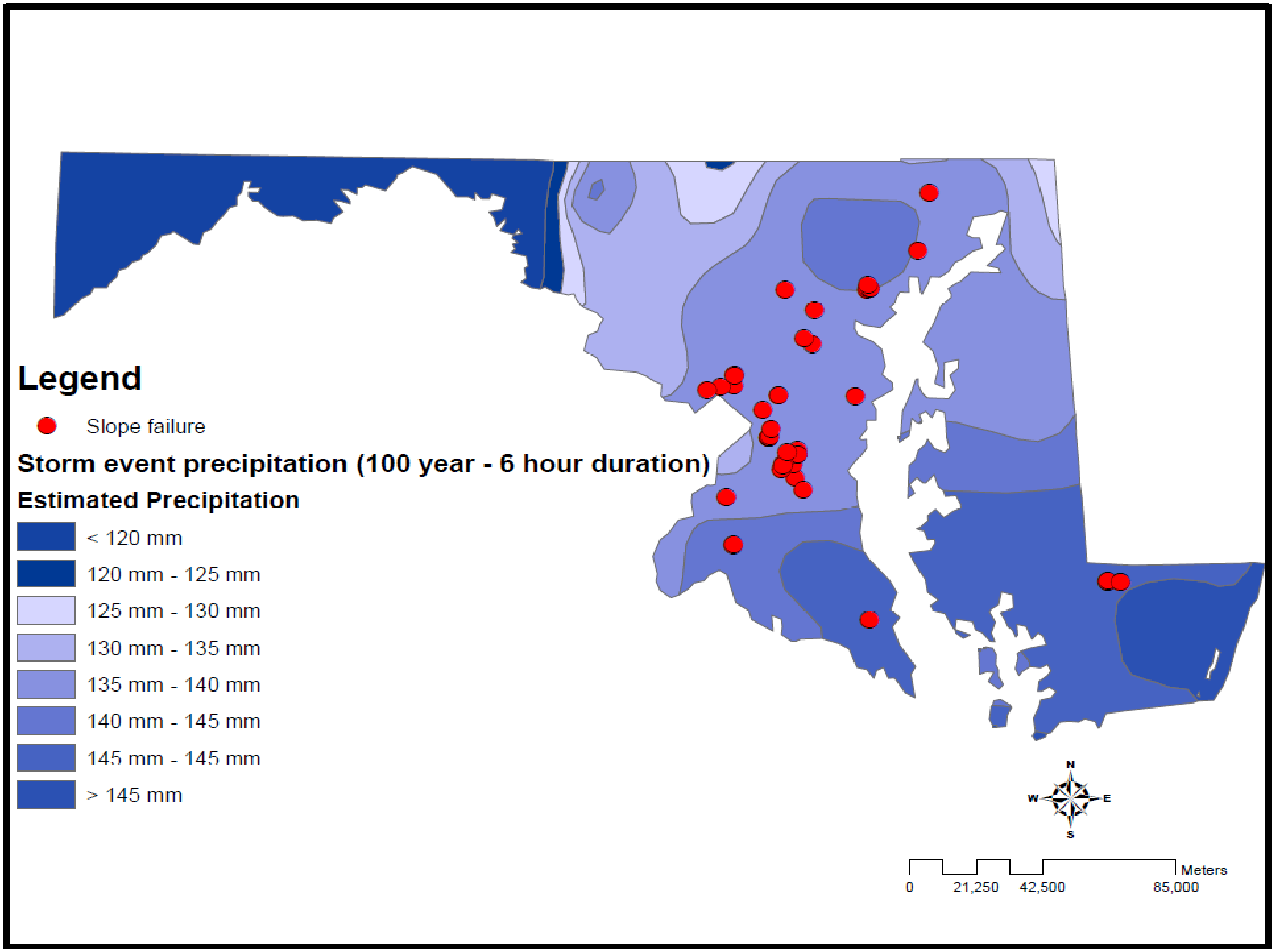


Figure C.5: Storm event precipitation (100 year, 24 hour) data layer in meters along with the spatial distribution of slope failures

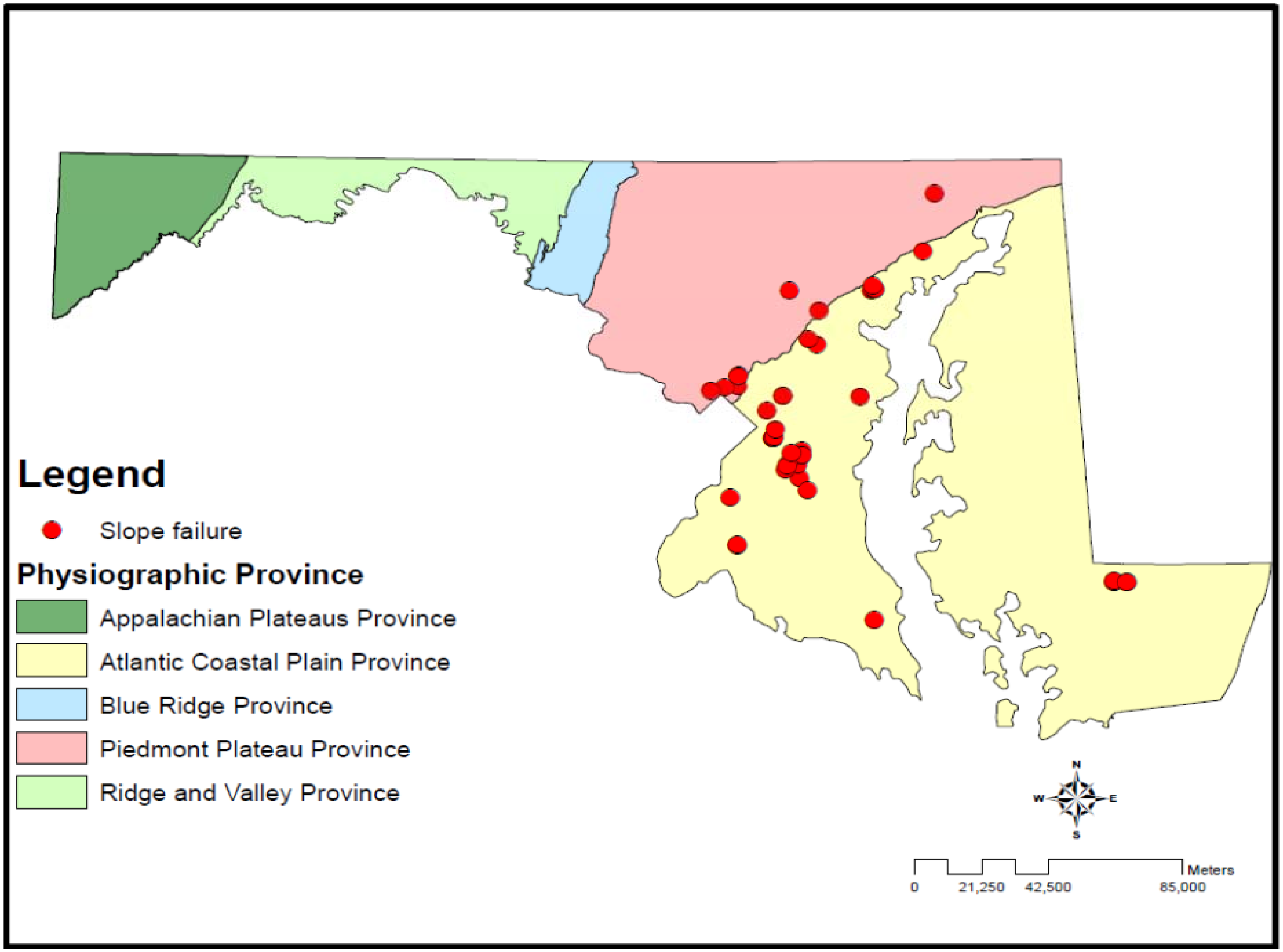


Figure C.6: Physiographic provinces data layer in meters along with the spatial distribution of slope failures

APPENDIX D

GIS TUTORIAL

GIS Tutorial

1. Introduction

Slope vulnerability mapping involves mapping of a set of factors that can be directly or indirectly correlated with slope instability. Based on the detected relationships the scaled land surface on the map is partitioned into area units of different landslide potential. Slope vulnerability or slope failure maps can be broadly classified into three categories based on the information provided by them, namely:

a) Slope failure inventory maps
b) Slope failure density maps
c) Slope failure hazard maps

Inventory maps shows the location of various slope failures that have occurred in the past using the process of direct mapping. These maps are very useful in developing decision systems for slope failure hazard assessment. Density maps provide us with information on the spatial abundance of landslides by indirect mapping. Hazard maps provide us with inferred or derived degree of slope failure hazard based on computer modeling and mapping overlay.

Using the Slope Stability Management System (SMS) tools developed by The University of Maryland- 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 Office of Materials Technology (OMT), of the Maryland State Highway Administration (SHA).

Based on the comprehensive information collected for the various slope failures that have occurred along highways in the State of Maryland, a set of statistical and spatial analysis were performed using the ArcGIS software suite to highlight certain distinct trends between some of the parameters considered to affect highway slope stability.

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 because of the insufficient data relating to historic slope failures. With the limited information regarding past events and causal factors, it is not feasible to develop a robust multivariate analysis model at a regional scale. Also, the qualitative index overlay can be applied succesfully at all levels of study.

The purpose of this section is to elaborate on the data processing techniques used in the study, the procedural detail and software aspects of the study and list the data used along with the data sources.

2. Projections and transformations

When you obtain geographic information system (GIS) data, it often needs to be transformed or projected. Since the data you receive is not always preprocessed, you will often need to place coordinates to your raster image. The transformation tools in the Projections and Transformations toolset can be used to rectify these issues.

All datasets used in this study are projected using the Lamberts conformal conic projection and the projected coordinate system used is NAD 1983 State Plane Maryland FIPS 1900. The geographic coordinate system used is the GCS North American 1983 with datum as D North American 1983. To define a projection for any given dataset in ArcMap simply follow these steps.

I. Figure 1 shows the work area along with the various tools available. Use the add datalayer button to add your datalayer to the Table of contents tab.

II. Once you click on the ’add datalayer’ button the add data layer window pops up (Figure 2). Simply navigate to the dataset you wish to work on.

III. Open the ArcToolbox menu and dock it to the right of the work area as show in Figure 1.

IV. Select Data Management tools from the ArcToolbox window. Select Projections and Transformations tool from the list and double click on the ’define projection’ option. (Figure 3)

V. A new window pops up as shown in Figure 4. Select the data layer for which you wish to define a projection using the dropdown menu for the input dataset field.

VI. Click on the button next to the define projection field. Another pop up window opens as shown in Figure 5. Click the ’Select’ button and choose: ’Geographic Coordinate System’=> ’North America’=> ’NAD 1983.prj’. Finish applying the selection using the ’OK’ in all windows.

VII. After this step, if your dataset happens to be in vector format, choose the ’feature’ option from the Projections and Transformations tool. Repeat step V and VI, but choose ’Projected Coordinate System’ => ’State plane’ => ’NAD 1983 (Meters)’ => ’NAD 1983 StatePlane Maryland FIPS 1900’. Finish applying the selection using the ’OK’ in all windows. Once the processing is complete your datalayer has the same projection as the other datasets used in this study.

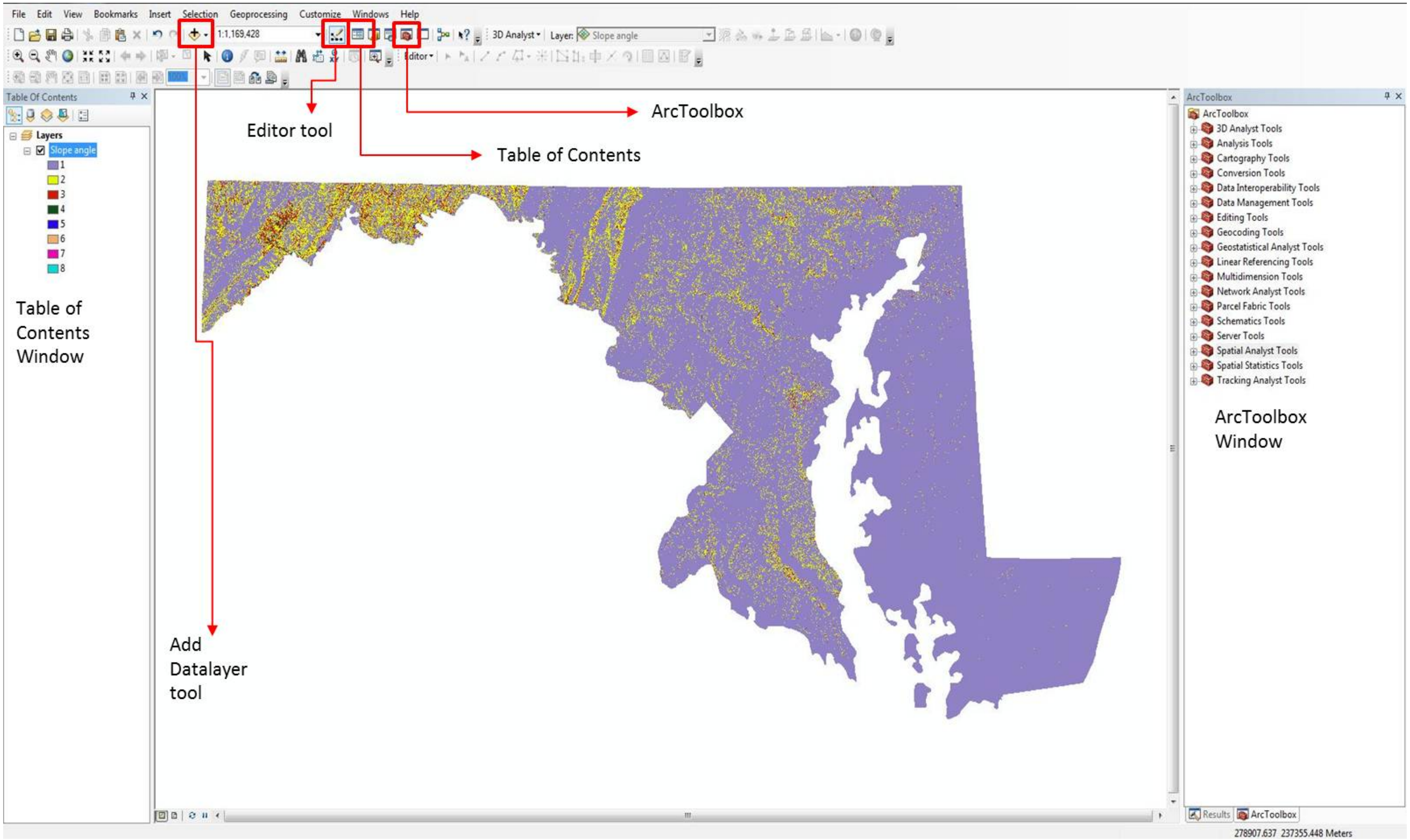


Figure 1: Work area and the various toolboxes

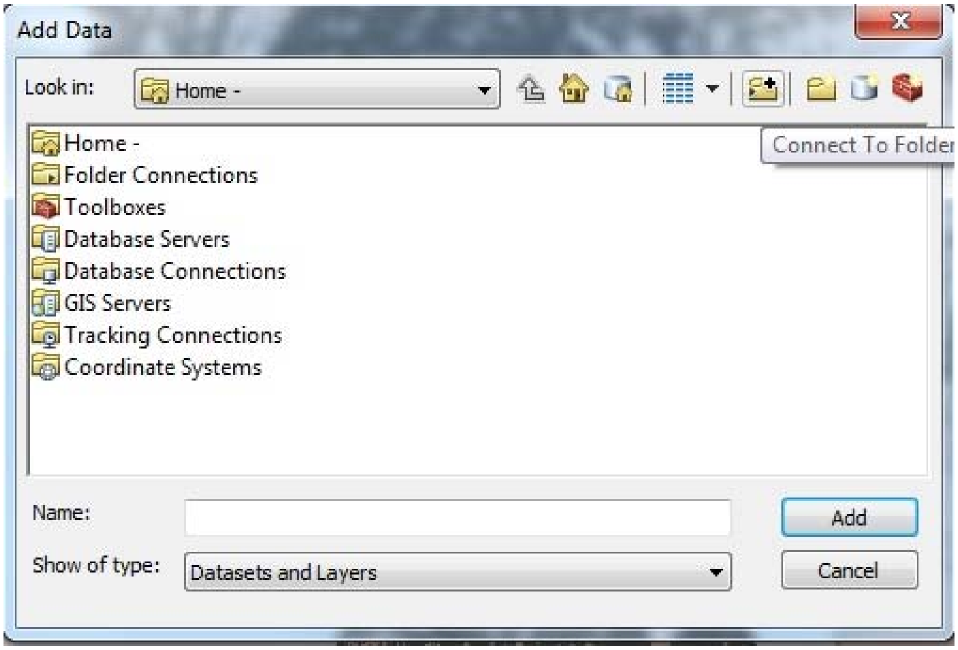


Figure 2: Add data window. You may use the 'connect to folder' option to navigate to the file.

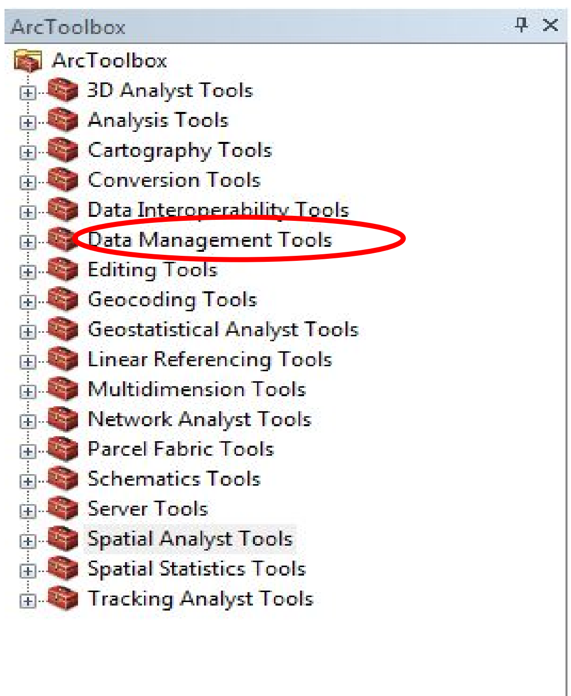


Figure 3: Choose the 'Projections and transformation' tool under 'Data management' tools circled in red

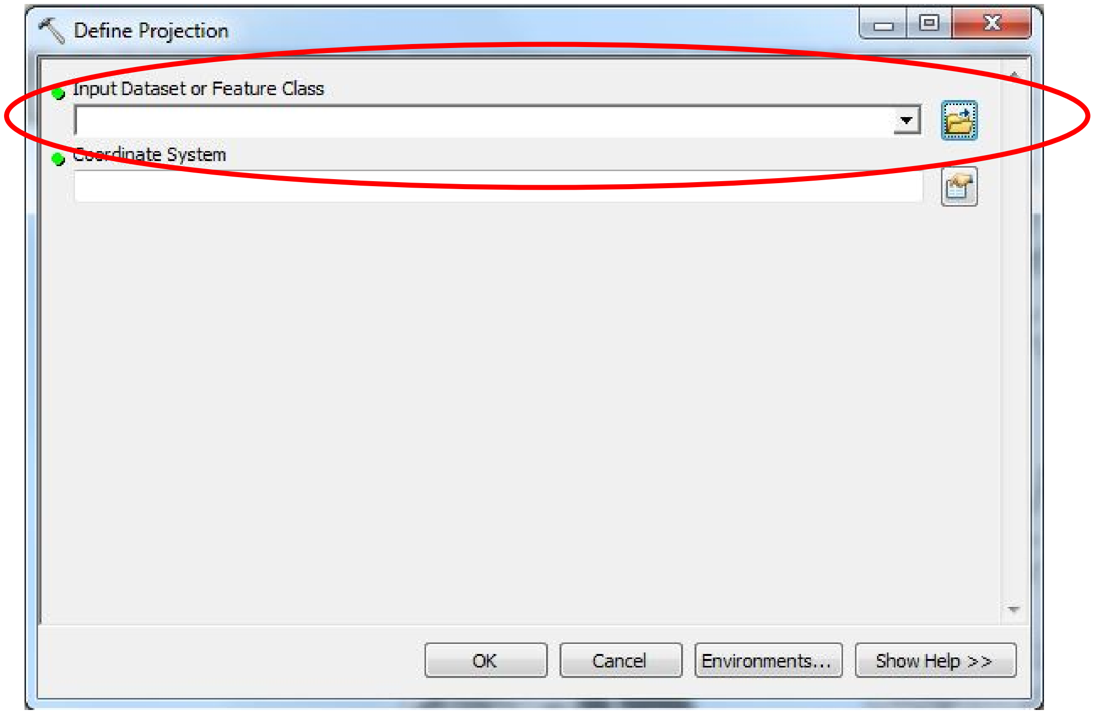


Figure 413: Choose the file using the field circled in red. You may use the drop-down menu or navigate to the file by clicking on the button next to field

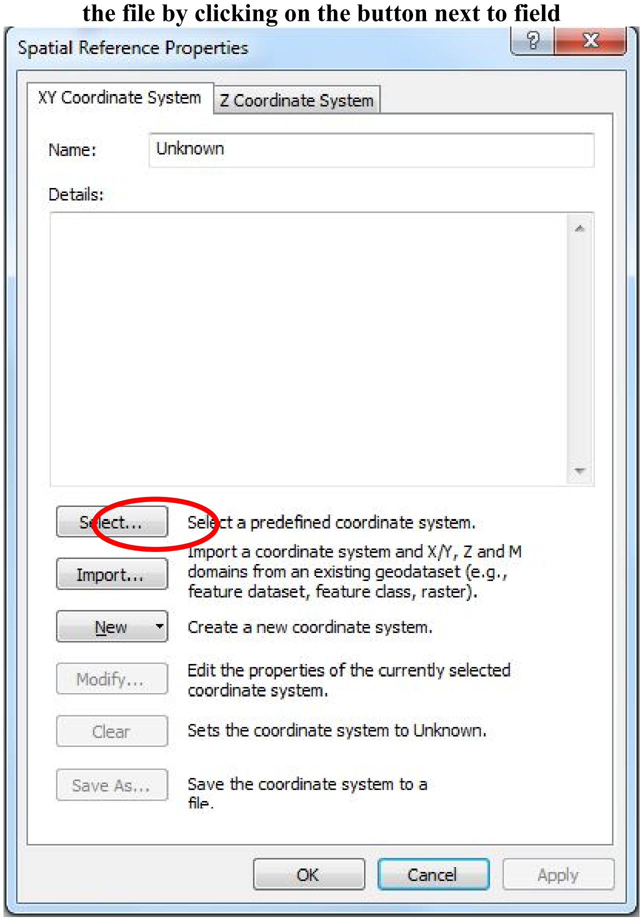


Figure 5: Click the select button to choose the geographic coordinate system

3. Data sources

All data sources (Table 1) used in the study were projected using the steps mentioned in the previous section. The second phase of the study involves identifying distinct trends in the failure distribution pattern for the various parameters. To examine the failure distribution pattern for the various physical parameters chosen, create a correlation must be created between the failure sites and the spatial information of the other parameters.

The various steps involved in establishing a spatial connection between the location of failure sites and the physical parameters are: (i) Reclassification, (ii) conversion to vector, (iii) spatial join, (iv) export table, (v) add fields and field calculation, and (vi) conversion to raster.

The dataset for a parameter may be in a vector or raster format. A vector data is a continuous representation of the real world data and is represented by points, polygons or lines. A raster data consists of real world data stored in a cell, or a grid or a group of cells. Each cell represents a number which in turn represents the real world condition. All data sources used in this study except the physiographic provinces and the failure inventory (both are in vector format) datalayers are in the raster format.

All datalayers representing the physical parameters undergo steps (i) to (vi) except for the datalayers that are already in the vector format. These layers undergo the same steps starting from (iii) to (vi). The slope angle dataset was chosen for demonstrating these steps. Also, slope angle data is the only derived dataset, meaning- it was derived using spatial analysis from the elevation dataset; while other datalayers are available as raw data. This method is also explained in this section.

Table 1: 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

I. Add the elevation data layer to the work area using the ’add data’ tool. Open the ’ArcToolbox’ and navigate to ’Spatial analyst’ tool set => ’Surface’ toolset => ’Slope’ tool (Figure 6).

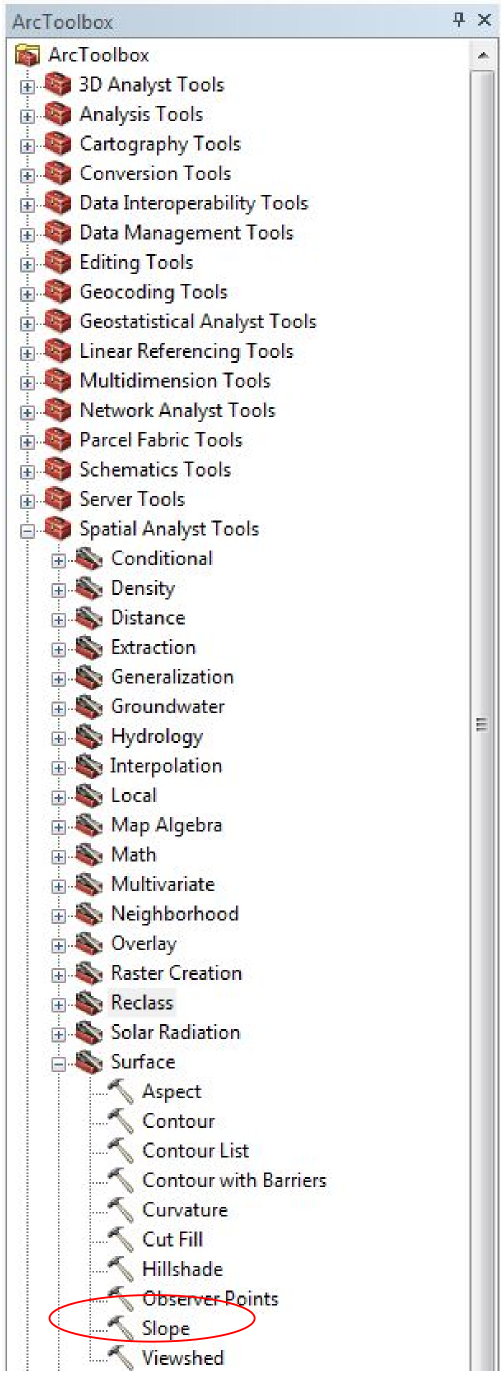


Figure 6: The slope tool is indicated by the red circle, under the surface toolset in the spatial analyst toolbox

II. The ’slope’ tool opens the ’derive slope’ window as shown Figure 7. Choose the elevation datalayer from the ’Input raster’ dropdown menu. Specify the output raster filename and storage path. Here since the elevation data layer store the elevation information in meters and also because the projected coordinates is in meters, the Z factor value is 1. Click okay to perform the spatial analysis and obtain the slope angle datalayer. It is automatically added to the workspace, but maybe accessed using the ’Add data’ tool from the stored path name.

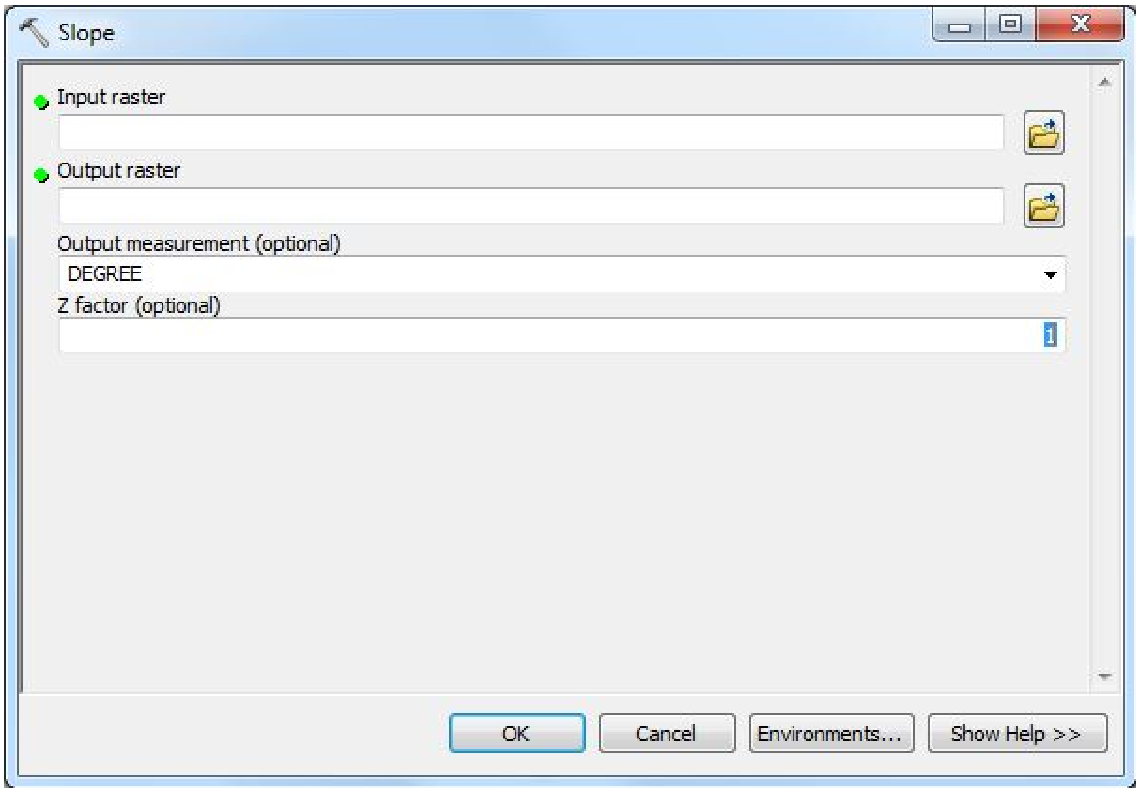


Figure 7: The slope spatial analyst tool window derives the slope angle data for any given set of elevation values.

III. Now the data represented by the slope angle datalayer can be reclassified into subgroups using the Reclassify tool. (Spatial analyst => Reclass => Reclassify). This opens the ’Reclassify’ dialog window as shown in Fig. 8.

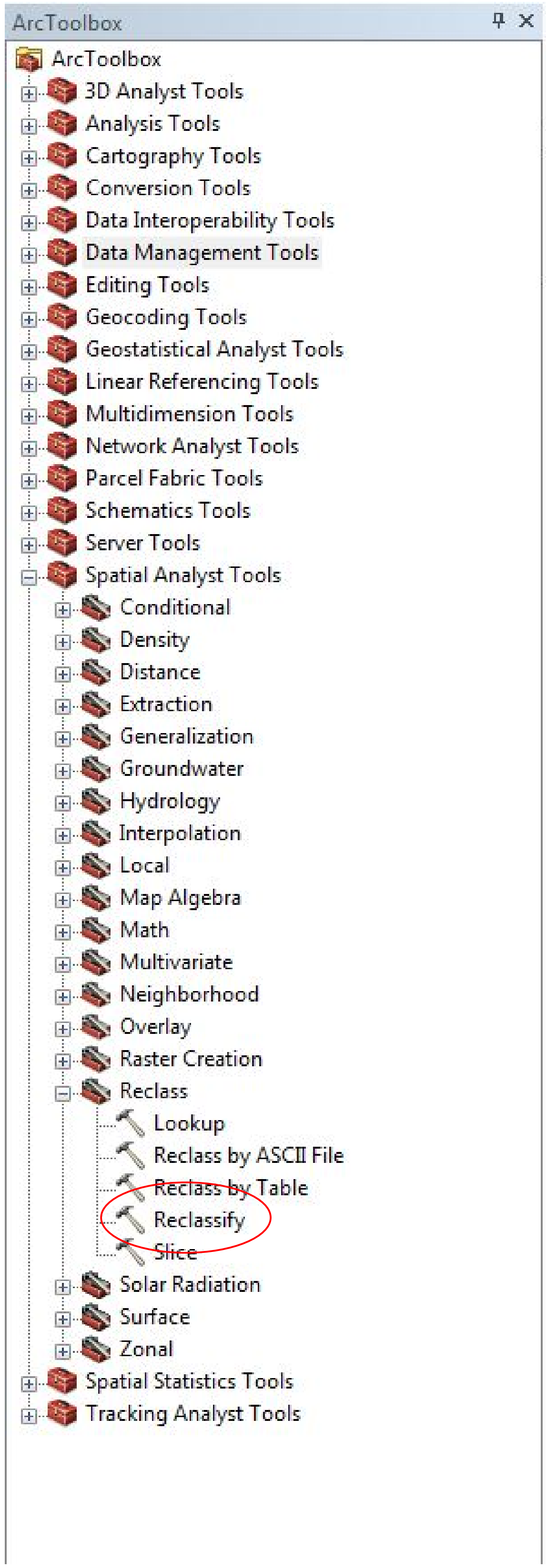


Figure 8: the reclassify spatial analyst tool is indicated by the red circle from the reclass dropdown in the spatial analyst tool list.

IV. In the ’Reclassify’ dialog window shown in Figure 9, choose the slope angle dataset derived from the previous steps, as the input raster. You may use the dropdown menu or the lookup folder button in the right. You may enter the new classification scheme manually under reclassification table or click the classify button on the right to use a pre-defined system of classification and select the total number of classes or division here (Figure 10).

V. To finish the reclassification process, click the OK button after defining the storage path and filename for the reclassified datalayer. This datalayer is automatically added to the workspace, but may also be accessed using the ’Add data’ tool.

VI. Once the ’Reclassify’ tool process the input dataset and provides and output, this output dataset needs to be converted to vector data. For this, open ArcToolbox => select the ’Conversion Tools’=> ’From Raster’ => ’To polygon’ tool as shown in Figure 11.

VII. Choose the reclassified slope angle data in the input raster field from drop down or via the look up folder button on the right. Specify the storage path and filename for the vector data or shapefile. Click OK to begin the conversion process.

VIII. Once the conversion is complete, the datalayer is automatically added to the workspace. It may also be accessed via the ’Add data’ tool. Now using the ’Add data’ tool include the slope failure inventory data shapefile to the work area.

IX. Now to the slope angle vector dataset can be spatially joined with failure data, simply right click the datalayer in the table of contents window (Figure 12).

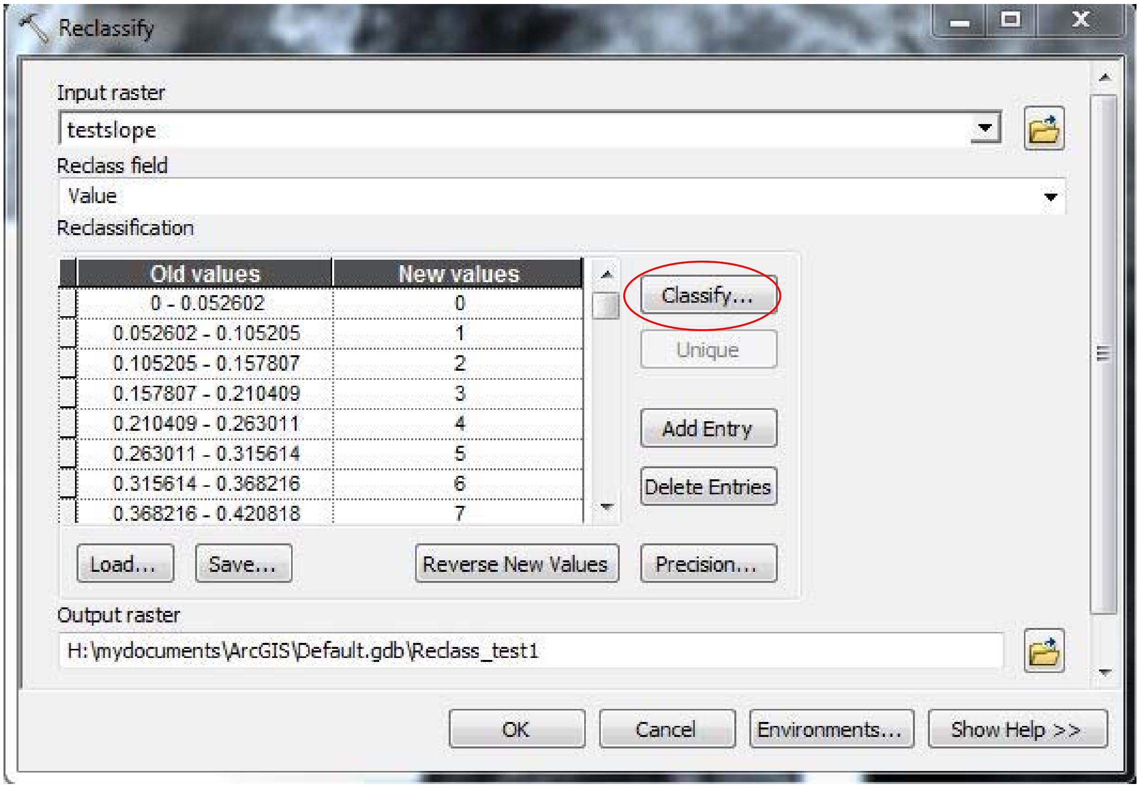


Figure 9: the ne classification scheme can be provided manually or by clicking the classify tool indicated by the red circle

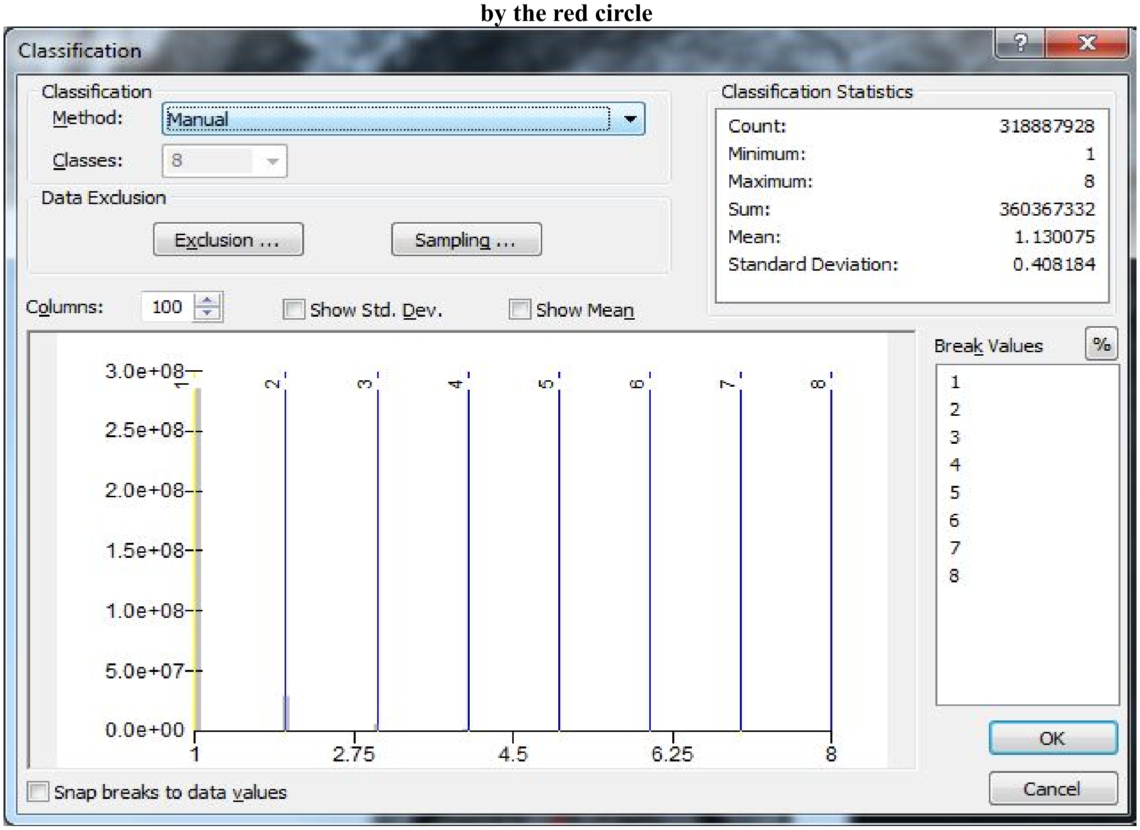


Figure 10: A set of predefined classification systems maybe used and the number of sub classes may also be defined using the classify tool

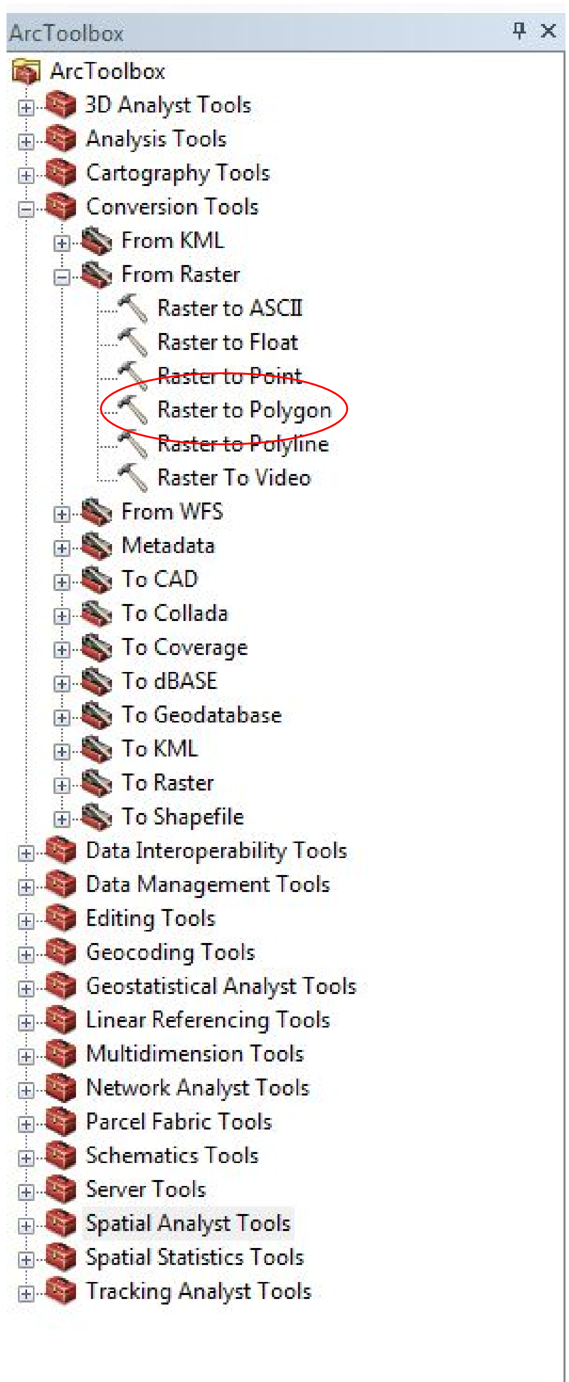


Figure 11: The convert raster to polygon tool is available under 'Conversion' toolset

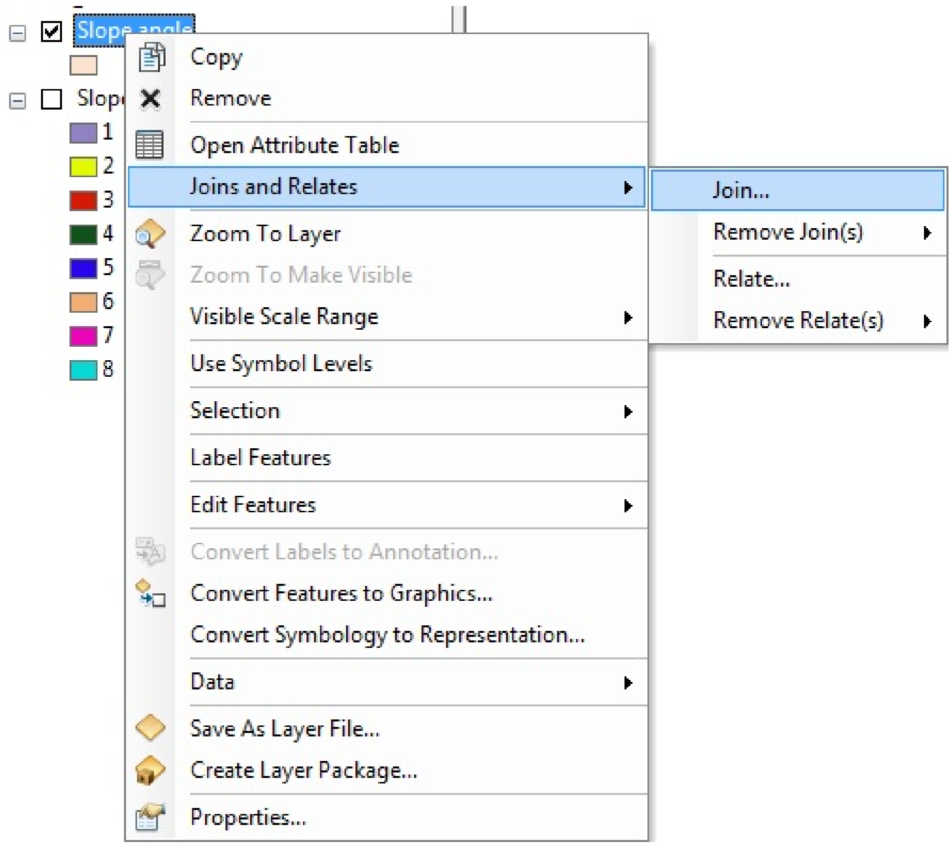


Figure 12: Choose the join tool under joins and relates menu by right clicking the slope angle data in the table of contents window

X. Choose ’Joins and relates’ => ’Join’. A new dialog box opens. Under the ’What do you want to join to this layer’ simply choose ’Join data from another layer based on spatial location’ option from the drop down menu. Select the slope failure inventory layer under 1 and the first option under 2. Specify a storage path and a file name for the output data layer. (Figure 13).

XI. Click OK to join the two data layers. The result is automatically added to the work area. Open the attribute table for the spatial join output by selecting the ‘open attribute table’ from the popup menu after right clicking the data layer in the table of content window. (Figure 14). Export the attribute table by selecting the export option from the drop down menu as shown in Figure 15.

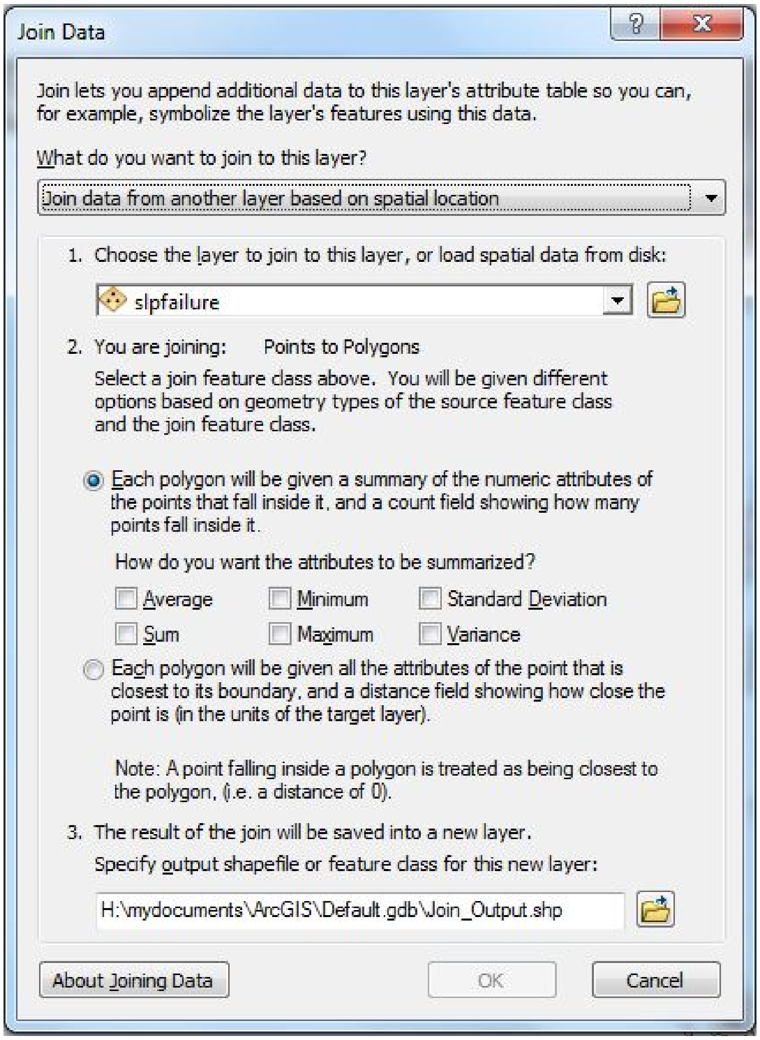


Figure 13: The join data dialog window.

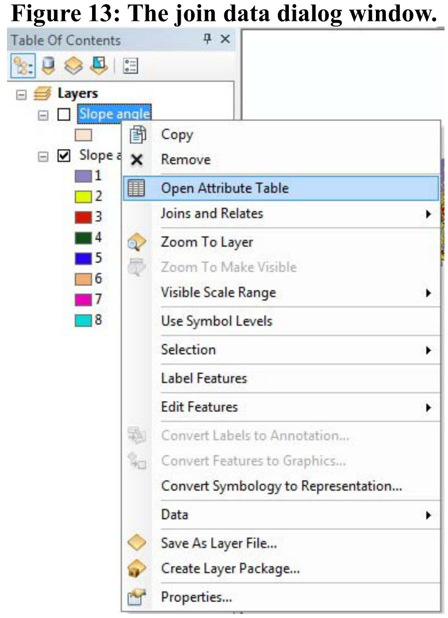
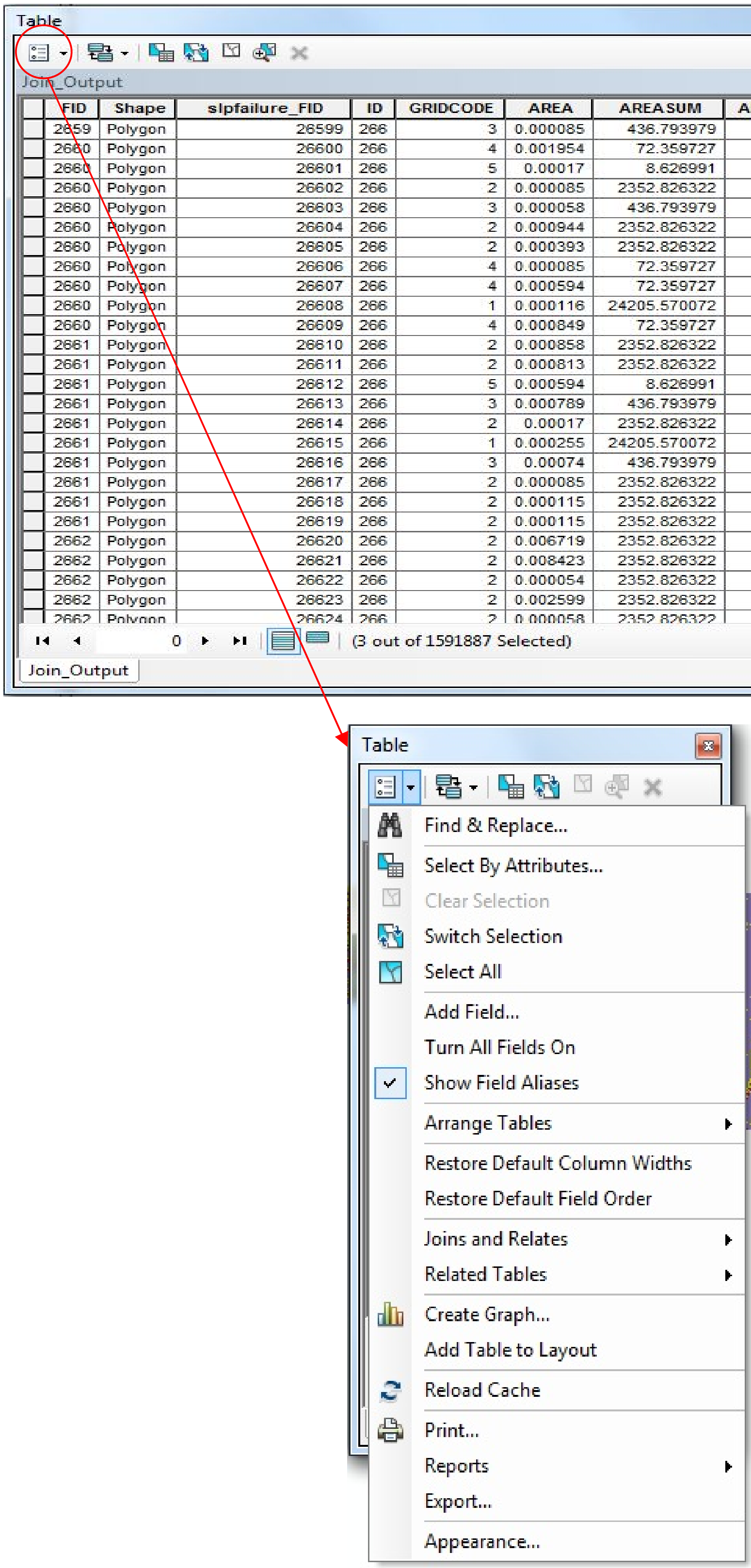


Figure 14: Procedure to open the attribute table for any given vector data. Simply right click and choose open attribute table function from the menu



FID	Shape	slpfailure_FID	ID	GRIDCODE	AREA	AREASUM	AREA_RATIO	VLNRBLTY	Count_
2659	Polygon	26599	266	3	0.000085	436.793979	0	1	0
2660	Polygon	26600	266	4	0.001954	72.359727	0	0	0
2660	Polygon	26601	266	5	0.00017	8.626991	0	0	0
2660	Polygon	26602	266	2	0.000085	2352.826322	0	0.66667	0
2660	Polygon	26603	266	3	0.000058	436.793979	0	1	0
2660	Polygon	26604	266	2	0.000944	2352.826322	0	0.66667	0
2660	Polygon	26605	266	2	0.000393	2352.826322	0	0.66667	0
2660	Polygon	26606	266	4	0.000085	72.359727	0	0	0
2660	Polygon	26607	266	4	0.000594	72.359727	0	0	0
2660	Polygon	26608	266	1	0.000116	24205.570072	0	0.28571	0
2660	Polygon	26609	266	4	0.000849	72.359727	0	0	0
2661	Polygon	26610	266	2	0.000858	2352.826322	0	0.66667	0
2661	Polygon	26611	266	2	0.000813	2352.826322	0	0.66667	0
2661	Polygon	26612	266	5	0.000594	8.626991	0	0	0
2661	Polygon	26613	266	3	0.000789	436.793979	0	1	0
2661	Polygon	26614	266	2	0.00017	2352.826322	0	0.66667	0
2661	Polygon	26615	266	1	0.000255	24205.570072	0	0.28571	0
2661	Polygon	26616	266	3	0.00074	436.793979	0	1	0
2661	Polygon	26617	266	2	0.000085	2352.826322	0	0.66667	0
2661	Polygon	26618	266	2	0.000115	2352.826322	0	0.66667	0
2661	Polygon	26619	266	2	0.000115	2352.826322	0	0.66667	0
2662	Polygon	26620	266	2	0.006719	2352.826322	0	0.66667	0
2662	Polygon	26621	266	2	0.008423	2352.826322	0	0.66667	0
2662	Polygon	26622	266	2	0.000054	2352.826322	0	0.66667	0
2662	Polygon	26623	266	2	0.002599	2352.826322	0	0.66667	0
2662	Polygon	26624	266	2	0.000058	2352.826322	0	0.66667	0

Figure 15: The attribute table for the spatial join output datalayer. Click on the file menu button, highlighted in red, to export data

XII. Export the table in .txt format while saving and specify a storage path and file name for the text file.(Figure 16)

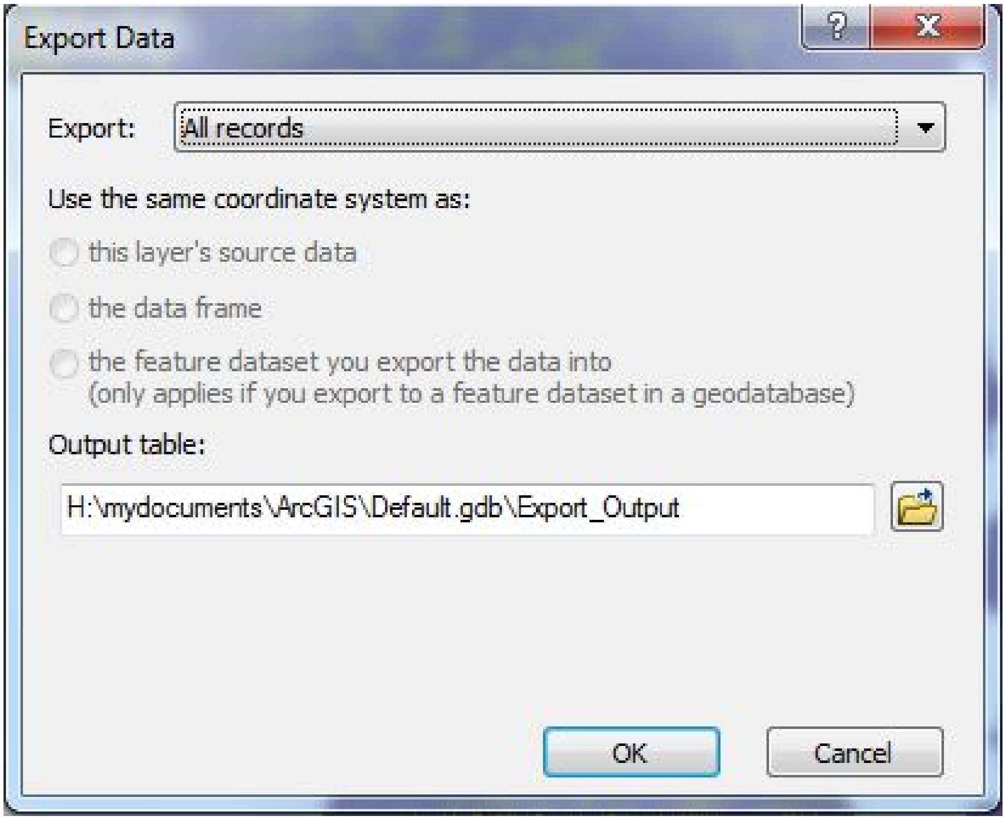


Figure 16: Exporting the attribute table to a text file.

XIII. Open the .txt file via MS Excel. The Count column provides the number slope failures occurring in a particular polygon. Using this, you can sort out the number of failures occurring in each sub class for the slope angle data. Using the methodology mentioned in the failure density mapping report, the failure density index for each sub class is calculated and then fed into the slope angle vector dataset.

XIV. To enter the failure density index values or vulnerability values for each subclass, open ArcMap => add the slope angle vector data using the 'Add data' tool. Open the attribute table, and choose the 'add field' option from the file menu shown in figure 15. Name the table as 'vlnrblty' and specify the precision and scale for this column. For the demonstration and for the study, a precision of 5 and a scale of 4 were used for the field. Also specify the format of the value variable. A floating point variable was used for this study; hence the 'double' field type was chosen from the field dropdown menu.(Figure 17)

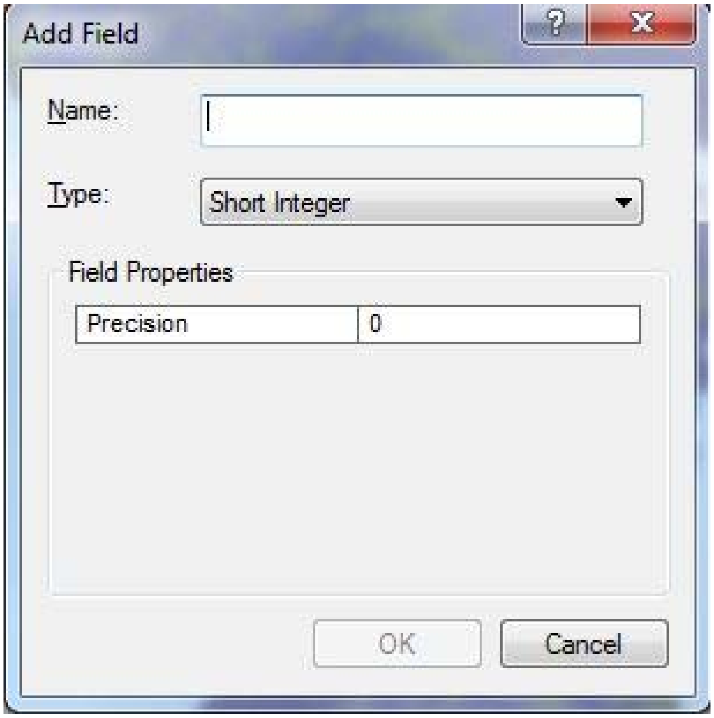


Figure 17: To add a field to an existing attribute table, simply select add field option from the attribute table option menu. Specify a name for the column, variable type and field properties.

XV. Based on the failure density indices calculated in excel, the different subclasses can be assigned these failure density indices by using the select by attributes button as shown in Figure 18.

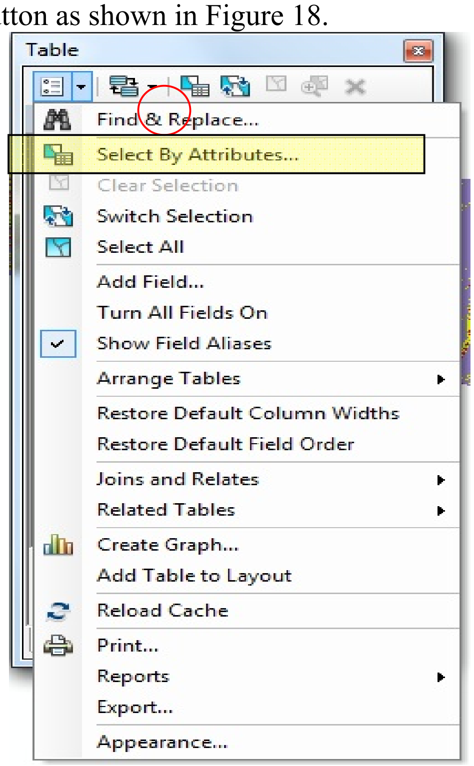


Figure 18: the select by attributes function can be opened either by opening the table's option menu or by directly clicking on the icon highlighted by a red circle.

XVI. Using the select by attributes tool, you can select all slopes within a particular subclass. Simply provide the query “GRIDCODE’ = <CLASS VALUE>. All records having that particular class value are highlighted. You can view only those records that you selected by toggling between the ‘show selected records only’ button shown in Figure 19.

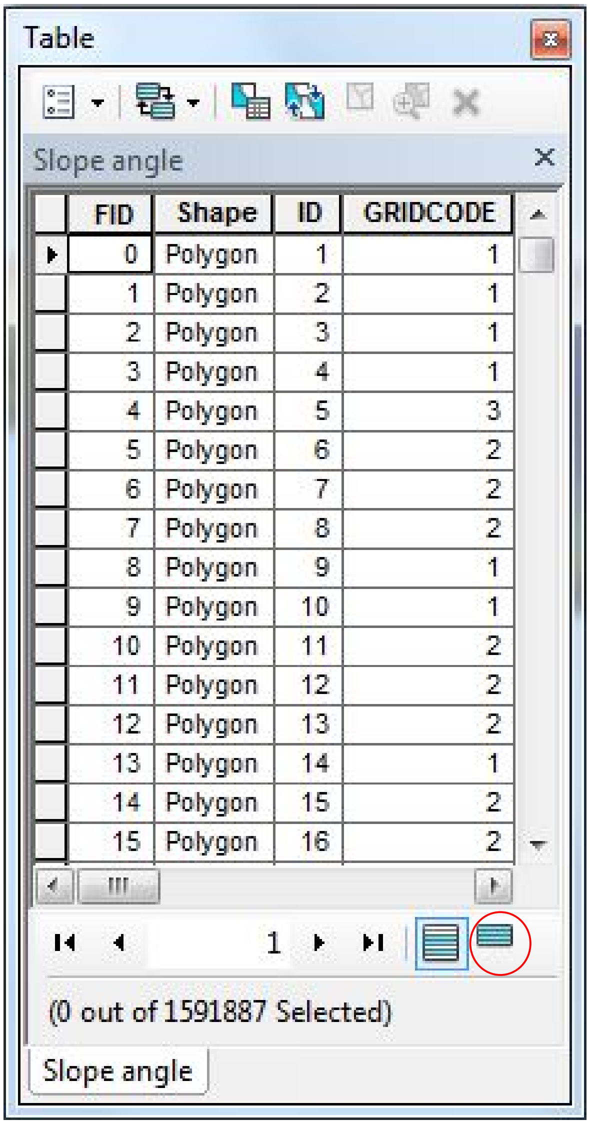


Figure 19: Selected records maybe viewed separately by clicking the show only selected records button highlighted in red.

XVII. Now right click on the 'vlnrblty' field heading and choose the field calculator option from the menu. (Figure 20). This opens the field calculator dialog box as shown in Figure 21. Simply enter the failure density value for that particular subclass (calculated using the MS Excel sheet)

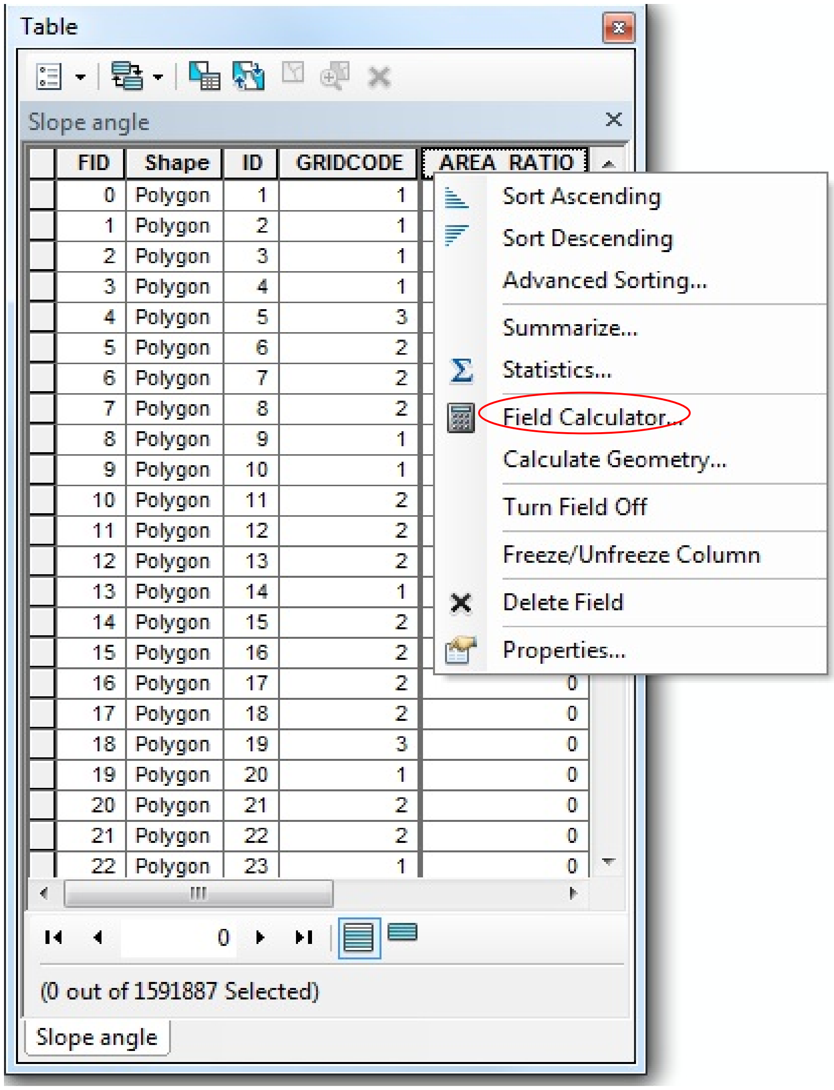


Figure 20: The field calculator tool can be used to assign values to any given field.

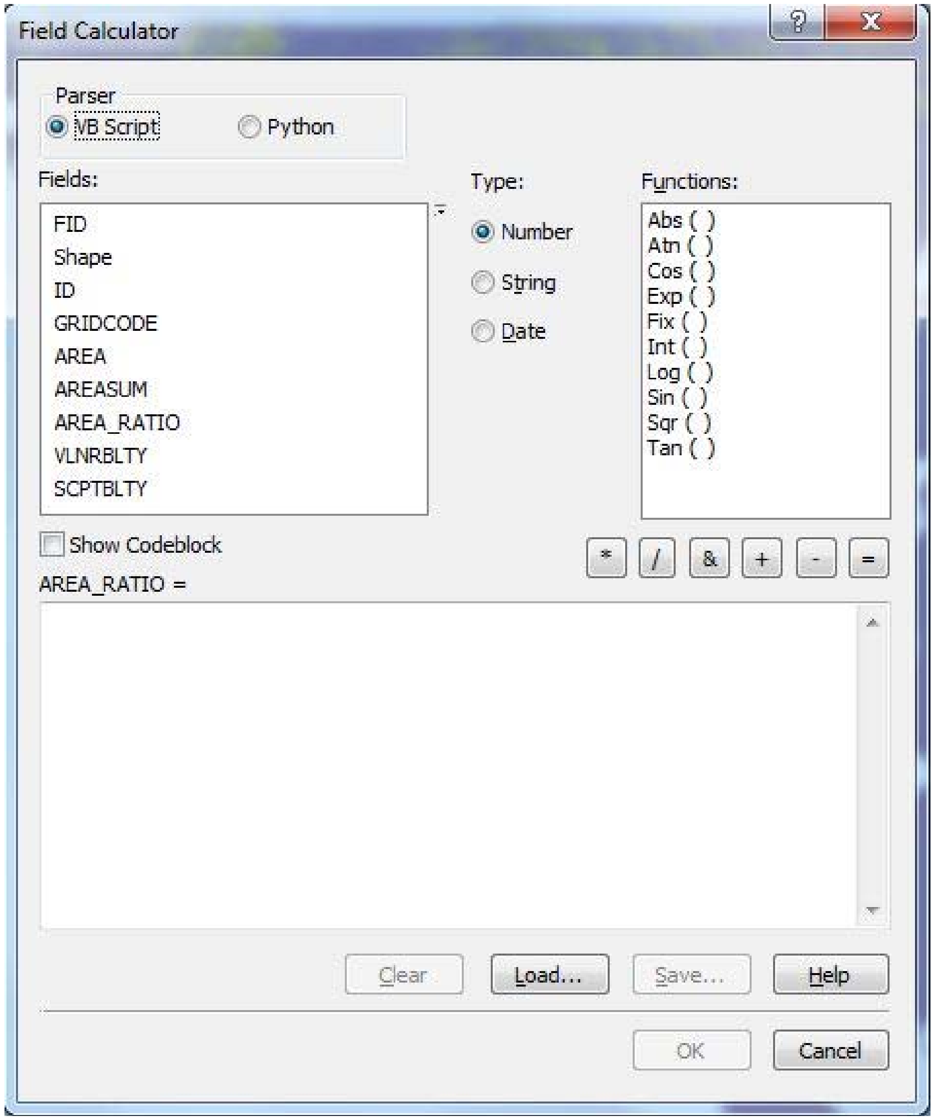


Figure 21: The field calculator tool can be used to assign values to any given field, as a function of other fields or as a constant value.

XVIII. Once all subclasses are assigned the failure density indices following steps XVI and XVII, the vector dataset can now be converted to a raster format using the vlnrblty field as the value field. Choose ArcToolbox => 'Conversion tools' => 'To Raster' tool => 'Polygon to Raster' tool. (Figure 22)

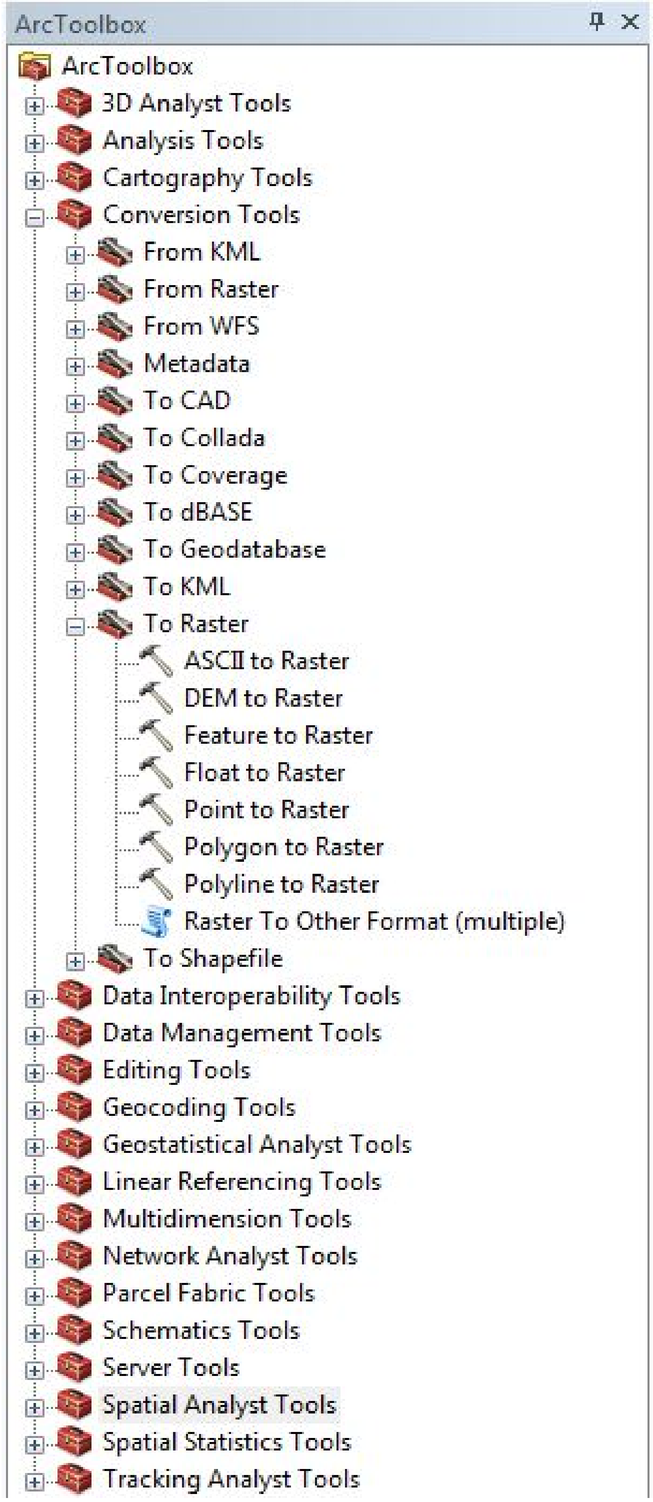


Figure 22: Shapefile (vector) to raster conversion tools

XIX. This opens up the 'convert to raster' dialog box. Simply choose the slope angle vector datalayer from the input featureclass drop down menu. Specify the storage path and the file name for the raster file. Specifying the cell size is optional. But for this study, since many such layers are dealt with, and for the sake of uniformity, a cell size of 30 was specified. Click OK to finish conversion process.

XX. Repeat steps III to XIX for all data sources. Now all data sources with their failure density indices are ready for performing a weighted overlay to generate failure density maps.

4. Failure Density Mapping

I. Add all the final raster files created based on the vlrnrblty / failure density indices to the work area using the 'Add data' tool. Now open the ArcToolbox =>Spatial analyst =>Map algebra => 'Raster Calculator' tool (Figure 23).

II. The raster calculator dialog box opens up. Now you may manipulate the raster data and fit them into any model or equation as you would in a normal calculator. Figure 24 shows the calculation model used for this demonstration. The model follows the general equation given in Figure 24., where W, is the weight assigned for each causal factor and m is the total number of causal factors.

III. Once you specify and fit the raster datasets into an equation, specify the storage path and file name for the resulting raster. Click OK to initiate calculation process. The results are automatically added to the workspace.

IV. The resulting raster dataset is called the failure density map and provides the probability of failure for highway slope in the state of Maryland. The color code for the map maybe adjusted from the symbology tab in the properties dialog box, which can be accessed by right clicking on the raster dataset in the table of contents window and selecting properties. Figure 25 shows such a color-coded map

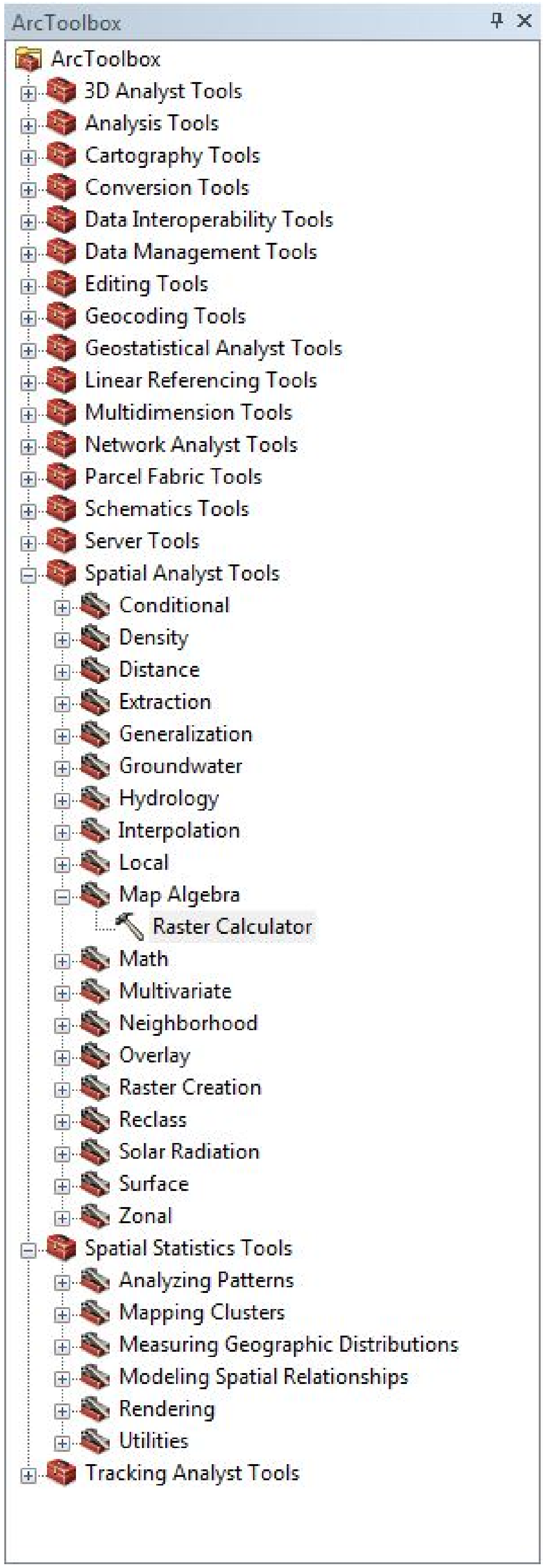


Figure 23: The raster calculator tool can be used to fit different rast datasets into an user defined equation or model.

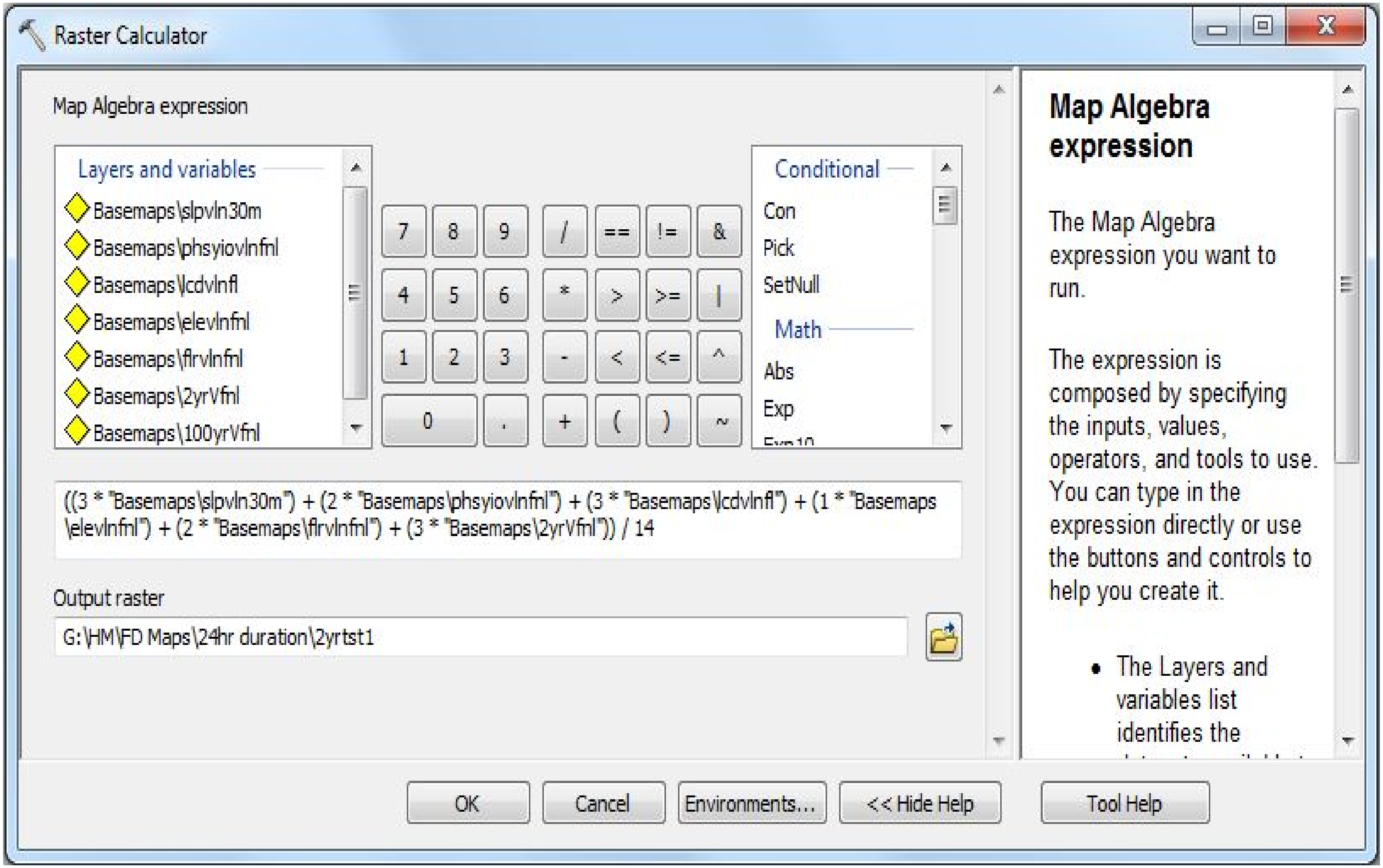


Figure 24: The equation used to calculate the failure probability in this study is show here.

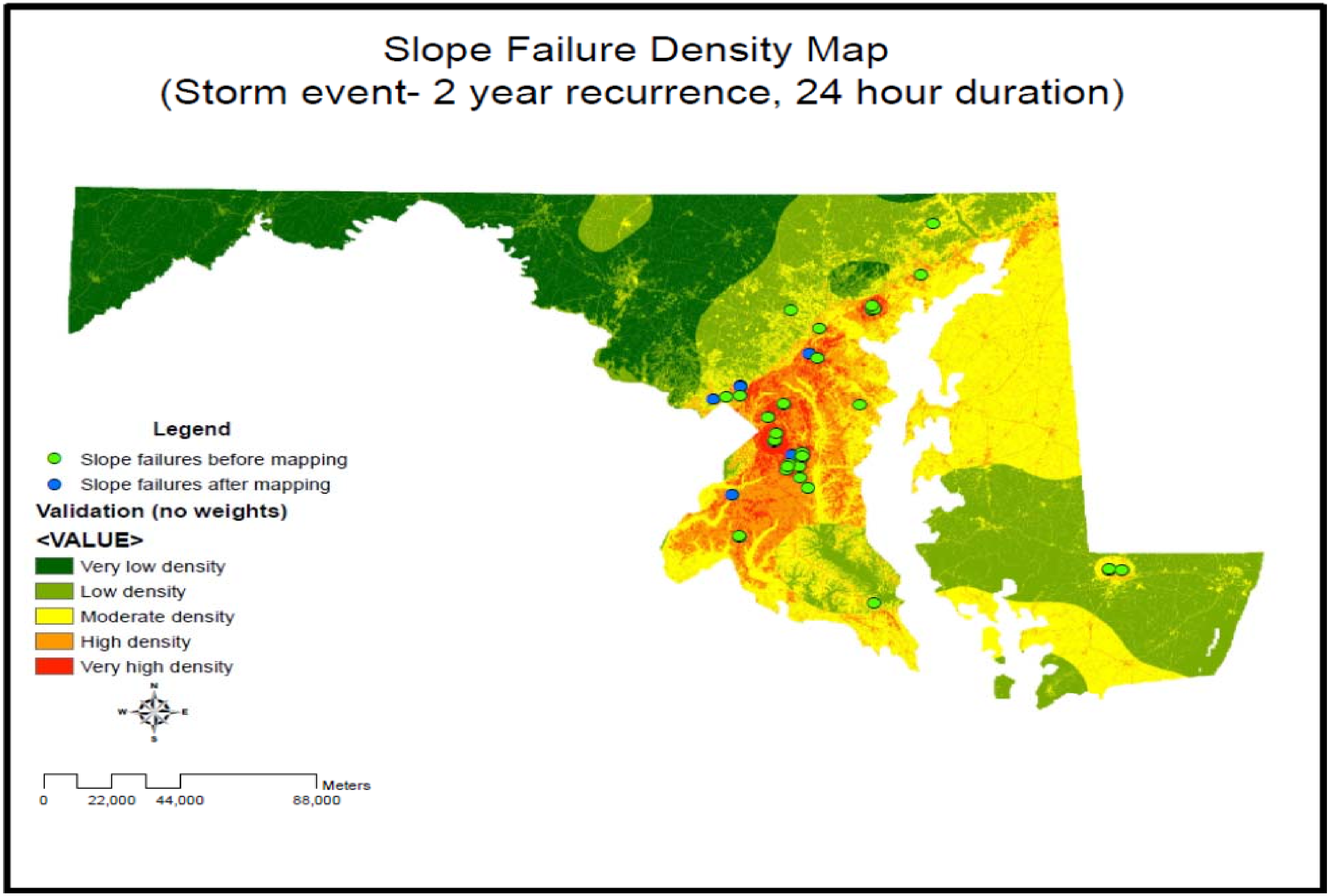


Figure 25: A failure density map developed using the steps mentioned in this document.