DEVELOPMENT OF A ROCKFALL HAZARD RATING MATRIX FOR THE STATE OF OHIO

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fulfillment of the requirements for the
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16. Abstract

Although Ohio is not considered a "mountainous state", it is well documented that rockfalls are prevalent. Rockfalls pose a considerable risk to traffic safety, create maintenance problems, and exert a strain on limited maintenance funds available to the Ohio Department of Transportation (ODOT). In order to assist ODOT in their prioritization for remediation work, a relative rockfall hazard rating matrix has been developed.

108 sites along Ohio roadways were characterized for their geology, geometry and traffic characteristics. As compared to other states (Oregon, New York, and Washington) where rating systems have previously been developed, Ohio geology can be characterized as relatively flat lying alternating sequences of durable and nondurable sedimentary rocks. Because of this, the matrix focuses on differential weathering and undercutting present at road cuts.

Data was collected for all sites and was statistically analyzed, using univariate, bivariate, and cluster analyses, to determine significant variables that characterize slopes. Statistical analyses indicated that slake durability index (SDI), slope angle, and slope height were the most significant variables in differentiating between sites
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A matrix was then developed based on the statistical analysis and information gained from previously developed rating systems. Geologic parameters include geologic conditions (SDI and maximum amount of undercutting; discontinuity extent/orientation and joint roughness coefficient), potential block size, and hydrologic condition. Geometric parameters were evaluated through a comparison of actual field conditions to prescribed Ritchie catchment ditch design. Traffic parameters included average daily traffic, percent decision site distance, and pavement width. Information about rockfall history was unavailable for this research project, but its importance has been well documented (Pierson, 1991). For this reason, a subjective assessment of rockfall history has been included.

The matrix assigns scores on an exponential scale based on relative risk, with higher scores representing more of a hazard. The developed matrix was applied to all sites, and scores ranged from 23 to 157. Based on the final scores, three broad-based categories of hazard were developed to more easily characterize the sites (high>100, moderate 50-100, and low<50). The rating matrix can be used to evaluate other rock slopes in Ohio and neighboring states with similar geology. These relative ratings can aid ODOT in making financial decisions and addressing legal issues of slope safety by examination of slopes using engineering principles.

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TABLE OF CONTENTS

List of Figures……………………………………………………………………….………ix

List of Tables…………………………………………………………………...……… xiv

ACKNOWLEDGEMENTS…………………………………………………….……….xv

ABSTRACT ……………………………………………………………………………..1

CHAPTER

1 INTRODUCTION………………………………………………………..….3

1.1 Background Information on Rockfall Hazards…………………….....3

1.2 Geologic Setting of Ohio………………………..………………...6

1.3 Objectives of Study …………………………...………………10

2 RELATIVE SLOPE RATING SYSTEMS……………..………………..11

2.1 Oregon Rockfall Rating System…..……………………………..…11

2.2 New York Slope Rating System……..……………………………12

2.3 Washington Department of Transportation Hazardous

Slope Rating System……………………………………………14

2.4 Oregon Rockfall Catchment Area Design Guide………………...15

2.5 Colorado Rockfall Simulation Program……………………….....16

3 NATURE OF DISCONTINUITIES AND MODES OF

SLOPE FAILURE IN OHIO……………………………………………17

3.1 Types of Discontinuities in Ohio………………………………...18

3.1.1 Bedding Planes....18

3.1.2 Valley Stress Relief Joints....18

3.1.3 Orthogonal Joint Sets....21

3.2 Modes of Rock Slope Failure....23

3.2.1 Rockfalls....25

3.2.2 Planar Failures....28

3.2.3 Wedge Failures....28

3.2.4 Toppling Failures....33

3.3 Characteristics of Discontinuities....34

3.3.1 Geometry....34

3.3.2 Continuity....36

3.3.3 Joint Spacing....37

3.3.4 Surface Irregularities....37

3.3.5 Physical Properties of Adjacent Rocks....40

3.3.6 Infilling Material....42

3.3.7 Ground Water....42

3.4 Role of Undercutting by Weak Rocks in Promoting Slope Failures....43

4 RESEARCH METHODS....47

4.1 Site Selection....47

4.2 Field Investigations....48

4.2.1 General Slope Information....48

4.2.2 Slope Geometry……………………………………………51
4.2.3 Slope Geology……………………………………………57
4.2.4 Human Interaction………………………………………68
4.3 Use of the Colorado Rockfall Simulation Program……………..71
4.4 Use of Ritchie Ditch Criteria………………………..………..74
4.5 Laboratory Investigations………………………………………76
4.5.1 Slake Durability Testing…………………………………76
5 STATISTICAL ANALYSIS OF VARIABLES
INFLUENCING ROCKFALL HAZARD POTENTIAL…….…………78
5.1 Univariate Statistical Analysis…………………………………..79
5.1.1 Univariate Analysis of Geologic Variables……………...83
5.1.2 Univariate Analysis of Geometric Variables…………….87
5.1.3 Univariate Analysis of Traffic Variables………………...91
5.2 Bivariate Statistical Analysis ……………………………………93
5.2.1 Bivariate Analysis of Geologic Variables………………..94
5.2.2 Bivariate Analysis of Geometric Variables…………….100
5.2.3 Bivariate Analysis of Traffic Variables………………...100
5.3 Cluster Analysis………………………………………………...103
5.3.1 Cluster Analysis of Geological Variables………………105
5.3.2 Cluster Analysis of Geometrical Variables……………..110
5.3.3 Cluster Analysis of Traffic Related Variables…………113

5.3.4 Cluster Analysis of Geological and Geometric Variables Combined.............................113
5.4 Summary of Statistical Analysis..................................116
6 DEVELOPMENT OF THE RATING MATRIX...........................119
6.1 Evaluation Parameters..119
6.1.1 Parameters Required for Evaluation of Rockfall Potential..119
6.1.2 Parameters Required for Evaluation of Catchment Areas..121
6.1.3 Parameters Required for Evaluation of Traffic Hazard Potential...................................122
6.1.4 Evaluation of Rating Scales.................................123
6.2 The Rockfall Rating Matrix....................................123
6.2.1 Geologic Parameters..126
6.2.2 Geometric Parameters.......................................128
6.2.3 Traffic Parameters...130
6.2.4 Rockfall History...130
6.2.5 Overall Score..131
6.2.6 Application of the Matrix to an Individual Site............131
6.3 Hazard Potential Evaluation of Individual Sites...................136
6.4 Hazard Potential Characterization of Sites.........................144
6.5 Preliminary Ratings..146

6.5.1 Rockfall History……………………………………………..…...146

6.5.2 Rockfall Potential……………………………………………..…154

6.5.3 Preliminary Rating………………………………………………...155

6.6 Limitations and discussion of the Rockfall Hazard

Rating Matrix……………………………………………………….157

6.6.1 Geologic Parameters (Differential Weathering)………..157

6.6.2 Geologic Parameters (Role of Discontinuities)………...158

6.6.3 Geometric Parameters …………………………………159

6.6.4 Rockfall History…………………………….………….160

7 ROCKFALL MITIGATION AND COST ANALYSIS………….……….161

7.1 Rockfall Protection Measures…………………………..……...161

7.1.1 Catchment Ditches……………………………….…………163

7.1.2 Barriers……………………………..………………..….163

7.1.3 Rockfall Protection Measures on the Slope……..……...167

7.2 Slope Stabilization…………………………………………...172

7.2.1 Rock Bolts……………………………………….…..…..172

7.2.2 Dowels………………………………………………….173

7.2.3 Shotcrete…………………………...…………….173

7.3 Slope Modification……………………………………….……..174

7.3.1 Scaling and Trimming………………………….………..174

7.3.2 Slope Re-design……………………………..……..175

7.4 Cost Analysis…………………………………..…………….178

7.4.1 Cost Estimates......181

7.4.2 Placement of Barriers......181

7.4.3 Slope Re-design......184

8 CONCLUSIONS AND RECOMMENDATIONS......189

8.1 Conclusions......189

8.2 Recommendations for Future Research......191

8.3 Recommendations for Implementation......192

REFERENCES......195

APPENDICES......201

A: Field Collection Sheets and Reference Guides......202

B: Stratigraphic Sections and Weathered Profiles......211

C: Raw Data Collected from all Sites......260

D: Frequency-Distribution Histograms and QQ-Plots......264

E: X-Y Scatter Plots......287

F: Photographs of Sites with Assigned Hazard Potentials and Scores......313

G: Rockfall Event Collection Sheet......368

LIST OF FIGURES

Figure		Page
1.1:	A large rockfall causing damage to the roadway and storm culvert 6 feet (1.8 m) below the road level along S.R. 7, Jefferson County	4
1.2:	A large slope failure responsible for closing the south bound lanes on S.R. 7 just south of Steubenville, Jefferson County	5
1.3:	Five subdivisions of Ohio with respect to regional geology (taken from Feldman, 1996)	7
1.4:	Differential weathering creating overhangs of the more durable units in a road cut along S.R. 7 in Washington County.	9
3.1:	Types of discontinuities commonly encountered along Ohio roadways: (a) bedding planes and orthogonal joint set, (b) a valley stress relief joint	19
3.2:	An example of horizontal bedding planes. Notice the undercutting of the stronger layers by the weaker layers	20
3.3:	Example of sub-vertical valley stress relief joints that parallels the slope face	22
3.4:	Generation of rockfalls by the intersection of different types of discontinuities and by the process of undercutting (taken from Geiger, 1992)	24
3.5:	Ritchie's ditch criterion using the relationships between slope height and slope angle to obtain effective ditch widths and depths (taken from NYDOT, 1996)	27
3.6:	Types of slope failures with associated dip vector stereoplots illustrating the identification of each failure type: (A) circular failure, (B) plane failure, (C) wedge failure, and (D) toppling failure (taken from Watts et al., 2000)	29

3.7: Example of a plane failure found in Ohio along State Route 7 at a site designated as JEF-7-14.4b. The large block first failed along the valley stress relief joint as a planar failure before tilting........30

3.8: Example of a potential wedge failure caused by undercutting at site designated WAS-7-19........32

3.9: Example of a typical road cut, from site designated as WAS-7-39.5, with its associated dip vector stereoplot. Notice that neither plane failures nor wedge failures can be identified through the conventional use of Markland failure criterion as almost all of the dip vectors fall outside the critical zone........35

3.10: Effect of joint spacing on size of failure (a) large joint spacing promoting large block failures and (b) small joint spacing promoting development of small failures........38

3.11: Barton's definition of Joint Roughness Coefficient JRC (taken from Hoek and Bray, 1981)........41

3.12: Correlation between maximum rate of undercutting and slake durability index values from Shakoor and Rodgers, 1992........46

4.1: Map of Ohio showing the locations of the study sites. Lighter lines delineate county boarders, whereas darker lines define Ohio Department of Transportation districts........49

4.2: Slope classification: (a) single-angle slope with back slope, (b) multiple-angle slope, and (c) benched slope........50

4.3: Example of a natural back slope above an engineered rock cut where rockfalls can generate from the material accumulating on the back slope........52

4.4: Relationship between slope height and geometrical parameters (HI=height of instrument, x= distance between the two points used for measurement of angles (θ and β= angles measured from horizontal, EP= edge of pavement)(adapted from Pierson et al., 1991)...54

4.5: Measurement of ditch width, depth, and angle........56

4.6: Measurement of discontinuities in accordance with the detailed line survey method....60

4.7: Example of a delineated watershed that most likely contributes groundwater to road cut....62

4.8: Average annual precipitation in Ohio (Ohio Department of Natural Resources, Division of Water; Harstine, 1991)....64

4.9: Average annual water loss in Ohio (Ohio Department of Natural Resources, Division of Water; Harstine, 1991)....65

4.10: Example of a stratigraphic section for the site located at ADA-41-16.1....67

4.11: Example of a CRSP output profile....72

5.1: Example of outliers found in frequency distribution histograms: (a) initial roadway width data with data indicating widths beyond 50 feet (15 m), and (b) corrected roadway width data. 81

5.2: Frequency histogram of maximum amount of undercutting data; (top) raw data, (bottom) transformed data....86

5.3: Frequency distribution histogram of ditch depth data. Note the possible outliers to the far right of the graph....90

5.4: An x-y scatter plot of slope angle versus ditch depth. 95

5.5: Relationship of slake durability index with: (top) maximum amount of undercutting and (bottom) log of hydrologic value. Note the truncation or stopping of continual reporting of the slake durability index values beyond 100%....97

5.6: Relationship between maximum amount of undercutting and average amount of undercutting. Note the strong relationship (r=0.82) between the two variables....99

5.7: Cluster groupings for the geologic variables of slake durability index and maximum amount of undercutting. Note the group assignments are visually based on the slake durability index and not on the maximum amount of undercutting....109

5.8: Cluster groupings for the geometric variables of slope angle and log of slope height. Group assignments listed above show the differences in the groups dominated by the slope angle………………. 112

5.9: Illustration of the Differentiation of all 108 sites in three dimensions as a result of cluster analysis. ……………………………………….…118

6.1: Relationship between the Ritchie score and point score for the rating matrix………………………………………………………….……129

6.2: Rock slope located at MUS-60-5.3 and used in the rating matrix example……………………………………………………….……133

6.3: Relationship between the average vehicle risk and point score for rating matrix…………………………………………………………………...137

6.4: Distribution of study sites rated as high, moderate, and low hazard potential…………………………………………………….……147

6.5: Distribution of study sites rated as having a high hazard potential…….148

6.6: Distribution of study sites rated as having a moderate hazard potential.149

6.7: Distribution of study sites rated as having a low hazard potential….….150

6.8: Example of a high hazard potential site located at JEF-7-5A, (top) entire slope (bottom) narrow catchment ditch for large rockfalls...151

6.9: Example of a moderate hazard potential site located at JEF-7-22.1…....152

6.10: Example of a low hazard potential site located at MOE-7-27………….153

6.11: Example of the preliminary rating applied to a site located at LAW-52-12.5……………………………………………….…………..156

6.12: Sample Organizational Chart…………………………………...….….158

7.1: Example of a modified D-50 barrier…………………………...….….166

7.2: Example of a rockfall catchment fence with breaking system (photograph from www.geobrugg.com)……………………………….168

7.3: Simple rockfall fence employed by Ohio DOT shown parallel to roadway.........169

7.4: Mid-slope bench found at COS-715-6.........170

7.5a: Global failure of road cut located at JEF-7-14.6.........176

7.5b: Re-designed slope at JEF-7-14.6 with a geologically placed mid-slope bench.........177

7.6: Slope re-design for JEF-7-10.6.........186

7.7: Slope re-design for MOE-78-24.5.........187

7.8: Slope re-design for JEF-7-24.5.........188

LIST OF TABLES

Table Page

3.1: Causes of rockfall occurrence in California and their relative Significance (taken from McCauley et al., 1985)..............................26

3.2: Classification of discontinuity spacing according to Deere (1964).........39

4.1: CRSP coefficient guide for normal and tangential coefficient. Note the wide range of values for each description (Jones, 2000).........73

4.2: Chart showing the relationships between the hardness guide (Piteau, 1971) and the coefficients used in the CRSP computer program.75

5.1: Summary of statistical analyses performed and conclusions drawn........80

5.2: Summary statistics of the geological variables. The highlighted values indicate departure from normalcy...85

5.3: Summary statistics of the geometric variable. The highlighted values indicate departures from normalcy..89

5.4: Summary statistics for the traffic variables. The highlighted values indicate issues with normalcy...92

5.5: Correlation coefficient (r) values for geologic variables...................96

5.6: Correlation coefficient (r) values for geometric variables..................101

5.7: Correlation statistics (r) values for traffic variables........................102

5.8: Initial ANOVA table for the cluster analysis of the geologic variables. Highlighted values indicate F-test and significance values at a range that those variables are not aiding in differentiation of slopes............106

5.9: ANOVA table for the cluster analysis of slake durability index and maximum amount of undercutting......................................108

5.10: Initial ANOVA table for the cluster analysis of the geometric variables. Highlighted values indicate F-test and significance values at a range suggesting that those variables are not aiding in differentiation of slopes…………………………………………………..111

5.11: ANOVA table for the cluster analysis of slope height and slope angle…………………………………………………………...111

5.12: ANOVA table for cluster analysis grouping of traffic related variables. Note all the F-test and significance values indicate the ability to differentiate each of the three groups determined by the cluster analysis……………………………………………………...114

5.13: ANOVA table for cluster analysis grouping of geologic and geometric variables. Highlighted values indicate F-test and significance values at a range suggesting that those variables are not aiding in differentiation of slopes…………………………………………………..115

5.14: ANOVA table for cluster analysis grouping log slope height, slope angle and slake durability index……………………………………115

6.1: The rockfall hazard rating matrix for Ohio……………………………..124

6.2: Scoring sheet for the rockfall rating matrix……………………………125

6.3: Scoring sheet for the rockfall rating matrix applied to MUS-60-6.9…...135

6.4.a: Geologic scores for all 108 study sites………………………………...138

6.4.b: Geometric and traffic scores for all 108 study areas……………………141

6.5: Hazard Potentail for individual sites…………………………………..…145

6.6: Preliminary slope rating matrix…………………………………..……146

7.1: Examples of rockfall mitigation measures (from McCauley et al., 1985)…………………………………………...162

7.2: Rockfall hazard potential and ditch evaluation………………………...179

7.3: Unit costs for different remediation types provided by ODOT………...182

7.4(a): Rockfall barrier recommendations and cost analysis based on CRSP bounce heights for slopes rated high with inadequate catchment ditches……183

7.4(b): Recommendation of slope re-design and associated costs for selected high hazard potential sites……183

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DEVELOPMENT OF A ROCKFALL HAZARD RATING MATRIX FOR THE STATE OF OHIO (363 pp.)

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Although Ohio is not considered a “mountainous state”, it is well documented that rockfalls are prevalent. Rockfalls pose a considerable risk to traffic safety, create maintenance problems, and exert a strain on limited maintenance funds available to the Ohio Department of Transportation (ODOT). In order to assist ODOT in their prioritization for remediation work, a relative rockfall hazard rating matrix has been developed.

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The matrix assigns scores on an exponential scale based on relative risk, with higher scores representing more of a hazard. The developed matrix was applied to all sites, and scores ranged from 23 to 157. Based on the final scores, three broad-based categories of hazard were developed to more easily characterize the sites (high>100, moderate 50-100, and low<50). The rating matrix can be used to evaluate other rock slopes in Ohio and neighboring states with similar geology. These relative ratings can aid ODOT in making financial decisions and addressing legal issues of slope safety by examination of slopes using engineering principles.

CHAPTER 1

INTRODUCTION

1.1 Background Information on Rockfall Hazards

A rockfall is a catastrophic process of slope movement that occurs as a direct result of the influence of gravity on a rock mass. As with any type of mass movement, rockfalls are very dangerous (Morgan, 1997). Hoek (1996) states that the number of people killed by rockfalls tends to be of the same order as the people killed by all other forms of slope instability combined. Landslide-related deaths in the United States have been estimated at 25-50 per year (Committee on Ground Failure Hazards, 1985). According to Badger and Lowell (1992), 45 percent of unstable slope problems are rockfall related. With the United States population expanding and moving into mountainous terrain, the potential for a rock-vehicle accident occurring is increasing. In many states, a rockfall is no longer legally considered an "act of God", but in most cases a preventable accident (Pierson, 1991). Even though the state of Ohio is not considered a "mountainous state", it has been well documented that the problem of landslides and rockfalls are prevalent (Gray et al., 1979; Young and Shakoor, 1987; Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Geiger et al., 1992; Shakoor, 1995).

Figures 1.1 and 1.2 show examples of slope instability problems along Ohio's roadways. Rockfalls constitute a major hazard along these highways. They pose a

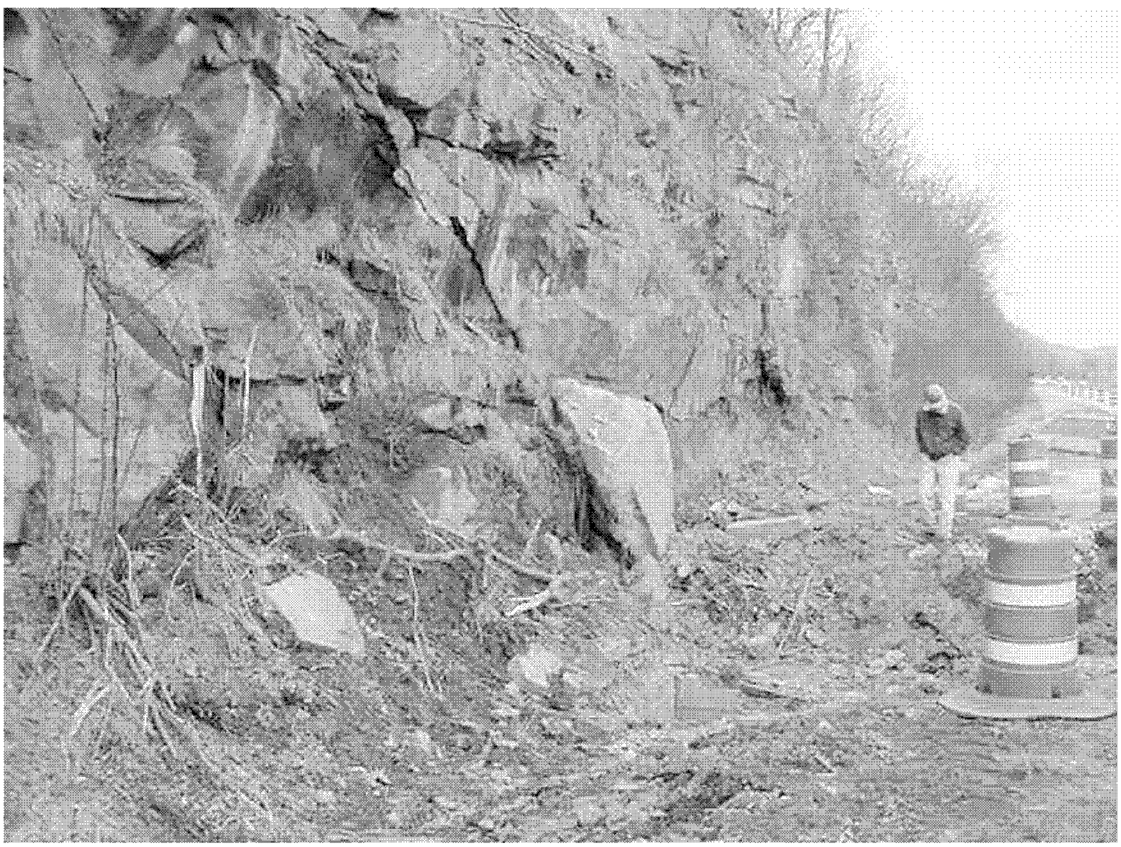


Figure 1.1: A large rock fall causing damage to the roadway and a storm culvert 6 feet (1.8 m) below the road level along S.R. 7, Jefferson County.

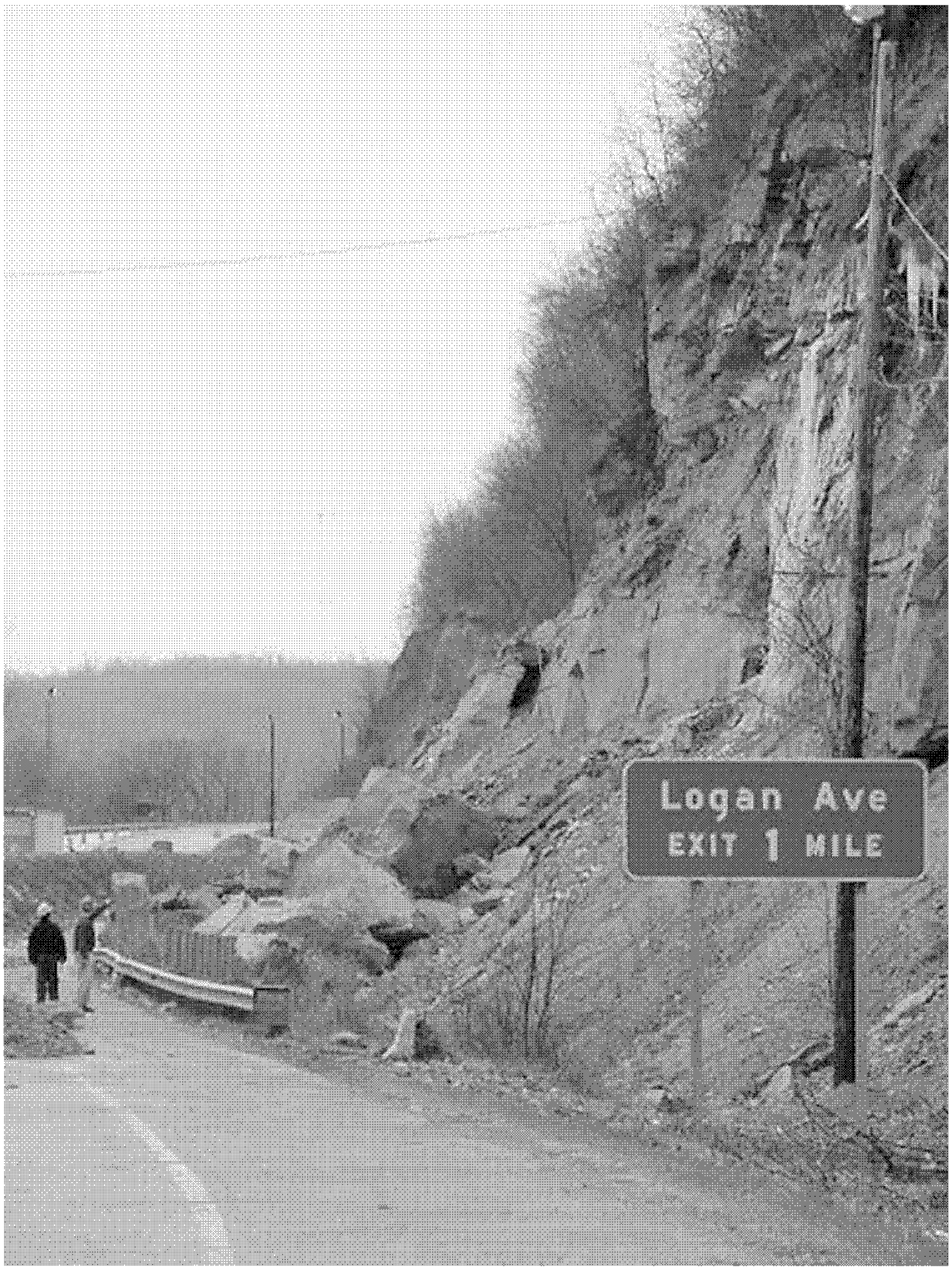


Figure 1.2: A large slope failure responsible for closing of the south bound lanes on S.R. 7 just south of Steubenville, Jefferson County.

considerable risk to traffic safety, create maintenance problems, and exert a constant strain on the limited amount of maintenance funds available to Ohio Department of Transportation (ODOT). State and Federal Departments of Transportation (DOT's) are becoming all too conscious of the task concerning roadway safety (Morgan, 1997), and drivers are increasingly expecting safer roadways. With the thousands of miles of potentially problematic roadways in the United States, it is an overwhelming task to properly design all rock slopes to ensure 100% safety for travelers. A 100% safe road cut indicates that there is no possibility of a rockfall entering a roadway. However, it is generally not feasible to have all slopes designed to obtain 100% safety due to problems such as the lack of adequate funding or a limited right of way. Therefore, the DOT's must prioritize the slopes with respect to the need for preventative measures.

In order to assist the DOT's in better identification of potentially hazardous rock slopes, a relative rating procedure is used. In this procedure, the individual slopes are rated according to a set of simple criteria. The individual slope ratings are then compared with each other to determine areas exhibiting a potentially higher risk of a consequential rockfall. A consequential rockfall is a rockfall that enters the roadway and poses a hazard to the public. These relative ratings aid DOT's in prioritizing slopes for remediation work, making financial decisions, and addressing legal issues of slope safety.

1.2 Geologic Setting of Ohio

Ohio can be divided into five geological regions as shown in Figure 1.3. The southwestern (SW) portion of Ohio is characterized by abundant outcrops of Upper-Ordovician shales and limestones in the hills of Cincinnati and surrounding areas. The

Figure 1.3: Five subdivisions of Ohio with respect to regional geology (taken from Feldman, 1996).

central (C) area contains relatively fossiliferous carbonates interbedded with shales of Silurian-age rocks. The northeastern area (NE) of Ohio is comprised of siliciclastic rocks of the Late Devonian through Early Pennsylvanian age, which crop out in the deeper valleys and road cuts to the north. Southward in the central area, other Mississippian formations and Lower Pennsylvanian rocks are exposed. In eastern Ohio (E), the surface rocks are primarily of the Pennsylvanian and Permian age; Mississippian rocks are present in the western part of this area. Stream and road cuts expose Pennsylvanian-age interbedded sandstones, shales, coals, and thin limestones. Permian rocks are limited to southeastern (SE) part of Ohio (Feldman et al., 1996). The northwest (NW) region of Ohio is relatively flat, and ODOT personnel reported no occurrences of rock slopes.

The geology in Ohio is characterized by the presence of gently dipping, harder, more competent strata (siltstones, sandstones, limestones) alternating with softer, less competent strata (claystones, mudstones, shales). This type of stratigraphy is highly susceptible to differential weathering that results in undercutting of the competent layers by erosion of the incompetent layers (Figure 1.4). Undercutting promotes a variety of slope movements such as rockfalls, plane failures, and wedge failures that may not occur otherwise (Shakoor and Weber, 1988; Shakoor, 1995). Many of the slope failures in Ohio initiate as plane failures and wedge failures in competent strata at higher elevations and descend as rockfalls. The frequency and size of these falls depend upon joint spacing within the competent unit and the extent by which it has been undercut. The undercutting-induced failures can be quite hazardous because of their instantaneous occurrence, high speed, and occasionally large volume of rock involved. There are many

Figure 1.4: Differential weathering creating overhangs of the more durable units in a road cut along S.R. 7 in Washington County.

road cuts in Ohio, however, where closely jointed rock units lead to rockfalls without the presence of undercutting (Shakoor, 1995).

1.3 Objectives of Study

In order to develop a rockfall hazard-rating matrix for the State of Ohio, research was undertaken to identify the significant variables that can be used to distinguish between sites of varying degrees of hazard. After identification of the significant variables, a matrix was developed that can be used to identify future sites in terms of hazard potential. The specific objectives of the research were to:

1. Identify statistically significant variables that can be used to categorize sites with respect to rockfall hazard.
2. Develop a rockfall hazard-rating matrix for Ohio that takes into account the topographical, geological, and climatological conditions.
3. Establish procedures for collecting field, laboratory, and other data required for rank- ordering the sites according to the matrix developed.
4. Develop tentative remediation plans for slopes rated as having a high hazard potential.

CHAPTER 2

RELATIVE SLOPE RATING SYSTEMS

Relative slope rating systems are used to cost-effectively evaluate large areas for identification of the most problematic slopes. Based on the early work on relative slope rating by Brawner and Wyllie (1975) and Wyllie (1987), Pierson (1991) developed the Oregon Rockfall Hazard Rating System. Similar systems have been developed by New York State DOT (NYDOT, 1996) and Washington State DOT (Lowell and Morin, 2000). Furthermore, the Colorado Department of Transportation (CDOT) has developed several innovative techniques for predicting and controlling rockfalls. The most significant development to-date is the Colorado Rockfall Simulation Program (CRSP), which models the behavior of rocks in motion. The engineering geologists of CDOT, in conjunction with the Colorado School of Mines, developed CRSP during the construction of I-70 through Glenwood Canyon (Barrett and White, 1991).

2.1 Oregon Rockfall Rating System

The Oregon Department of Transportation has developed a Rockfall Hazard Rating System (RHRS) based on an evaluation of 12 different factors (slope height, ditch effectiveness, average vehicle risk, percent decision sight distance, roadway width, geologic characteristics, block size or quantity of rockfall per event, climate and presence of water in slope, rockfall history) that are considered to contribute toward the overall hazard (Pierson, 1991). The RHRS uses two phases of inspection: the preliminary rating phase and the detailed rating phase. During the preliminary phase, the sites are classified into three groups, A, B, and C, based on the high, moderate, and low potential, respectively, for the rockfall to approach the highway and the historic rockfall activity. The detailed rating system involves assignment of scores that increase exponentially from 3 to 81 points, and represent a continuum of points from 1 to 100 (e.g., 3 points for few falls, 9 points for occasional falls, 27 points for many falls, and 81 points for constant falls). The final score for a given site is the sum of scores assigned to the 12 factors. Pierson (1991) and his colleagues believe that an exponential scale quickly distinguishes the more hazardous sites and that a continuum of points allows the rater greater flexibility in evaluating the relative impact of conditions that are highly variable. The RHRS has been successfully tested at nearly 3000 sites in Oregon.

2.2 New York Slope Rating System

The New York Slope Rating System is a revised version of an older system. It is based on a study of 1741 sites, uses geological, cross-sectional, and traffic related factors to create a number representing the total relative risk of a rockfall causing a vehicular accident at each rock slope on the statewide inventory. The three categories of factors considered in this procedure are designated as the geologic factor (GF), section factor (SF), and human exposure factor (HEF)(NYDOT, 1996). The numerical value of the geologic factor (GF) is obtained by summing the points assigned to a series of geologic parameters (fractures, bedding planes, block size, rock friction, water and ice conditions, rockfall history, and condition of back slope above the cut) and dividing that sum by 10.

Like the Oregon system, the New York system also uses an exponential scale to determine the GF value. The section factor (SF) represents the risk that the fallen rocks would actually reach the pavement by comparing actual ditch geometry and rock slope offset with the widely accepted "Ritchie Ditch Criteria" (Ritchie, 1963). The section factor is computed as the ratio of the required Ritchie criteria to the actual ditch dimensions, yielding a number ranging from 1 or less (best situation) to 11 (worst situation). The human exposure factor (HEF) represents the risk to the vehicle if a rock does fall and reach the roadway. The fallen rock can threaten the safety of the vehicle in two different ways: i) the rock actually hits a vehicle or lands so close to an approaching vehicle that it runs into the rock (active condition), or ii) the vehicle hits a previously fallen rock that has come to rest on the roadway (passive condition). The HEF number is defined as the sum of active and passive risk values divided by 3. The information needed to compute active and passive values includes average travel speed, average annual daily traffic (AADT), stopping sight distance (SSD), and decision sight distance (DST). The total relative risk value is obtained as GF*SF*HEF.

The NYSDOT ranking procedure claims to have the following three advantages: a) it isolates three components of a possible rock-vehicle accident as independent factors; b) it more objectively addresses the question of how much risk is associated with a falling rock hitting a vehicle, as well as a vehicle hitting a fallen rock; and c) it considers not only the risk proposed by an existing rock slope but also the level of risk remaining after remediation.

The rockfall hazard rating systems summarized above are currently being used, with necessary modifications, by some other states such as Kentucky, Pennsylvania, Colorado, Hawaii, and Virginia to prepare inventories of rock cuts along their highways.

2.3 Washington Department of Transportation Hazardous Slope Rating System

In 1993, the Washington State Department of Transportation (WASHDOT) developed an Unstable Slope Management System (USMS) as part of a proactive approach to address unstable slopes. The system was designed to evaluate all unstable slopes, conduct cost-benefit analysis of unstable slopes, and prioritize the mitigation of known unstable slopes according to the expected benefits. The selection of unstable slopes for the development of this system was based on the types of slope instability, frequency of failure, and estimated maintenance costs. District managers, on the basis of their knowledge of the area, did the actual site selection. The USMS is based on 11 contributing factors including the soil/rock type, average daily traffic, decision sight distance, impact of failure on roadway, roadway impedance, average vehicle risk, pavement damage, failure frequency, annual maintenance costs, economic factor (dealing with detours), and number of accidents in the last 10 years (Lowell and Morin, 2000). Like the Oregon RHRS, the USMS assigns exponentially increasing scores of 3, 9, 27, and 81 for the 11 risk factors. In this case the total points range from a low of 33 to a high of 891. The developers of the USMS consider their system to be distinctive in that it addresses both soil and rock slope instabilities (rockfalls, landslides, slope erosion), with a greater focus on risk assessment than failure mode (Lowell and Morin, 2000). During the preliminary evaluation stage, the system divides the selected unstable slopes into three categories: category A (high risk potential), category B (medium risk potential), and category C (low risk potential).

The WASHDOT has applied the USMS to inventory 2,500 slopes statewide. To ensure the maximum return on the dollars spent, the USMS grouped unstable slopes in the inventory on the basis of highway functional class (Interstate, State Route, low volume facilities, etc.). Within each highway functional class, the slopes are ranked in descending numerical order so that the highest risk slopes in that class are considered first for mitigation. This seems to be a repetitive step since earlier in the assessment both the average daily traffic and average vehicle risk have already been factored.

2.4 Oregon Rockfall Catchment Area Design Guide

In 2001, the Oregon Department of Transportation developed a Rockfall Catchment Area Design Guide (Pierson et al., 2001) that was intended to build and improve upon the work by Ritchie in 1963. The design guide contains a series of charts that compare the slope height, slope angle, catchment angle, catchment width, and rollout distance of the rocks with the percentage of rocks retained in the catchment area. The charts can be used for either design of a new catchment area or in the evaluation of existing catchment areas. The design requirements for most instances are based on the percentage of rocks the catchment is designed to retain. The charts are based on more than 11,250 rocks rolled down cut slopes of varying heights (40, 60, and 80 feet or 12, 18, and 24 m) and angles {vertical (90°), 0.25H: 1V (76°), 0.5H: 1V (63°), 0.75H: 1V (53°), and 1H: 1V (45°)}, as well as catchment area angles {flat (0°), 6H: 1V (9.5°), and 4H: 1V (14°)}. For each rock rolled in the study, its impact distance, energy, and total rollout distance were determined. The results of these tests were compared to Ritchie criteria (FHWA criteria) and Colorado Rockfall Simulation Program expected results. Based on these comparisons, the research concludes that ditches designed in accordance with the Ritchie criteria can retain 85% of rocks and that the CRSP models predict fairly well the empirical results of the study.

2.5 Colorado Rockfall Simulation Program

The Colorado Rockfall Simulation Program (Colorado Department of Transportation) uses slope geometry, slope height, slope surface roughness, a normal coefficient of restitution (a measure of the degree of elasticity of a rock colliding normal to the slope), a tangential coefficient of frictional resistance (a measure of frictional resistance parallel to the slope), and rock physical characteristics (size, shape, and unit weight) as the controlling variables to limit rock behavior (Barrett and White, 1991; Jones et al., 2000). CRSP's output provides rockfall trajectories bounce heights, and velocities over the entire slope. The Colorado Department of Transportation and the Colorado Geological Survey together have also created a rockfall hazard rating system that is a modification of the rockfall hazard rating system developed by the Oregon Department of Transportation. The modification places a higher emphasis on accident histories and slope characteristics (height, inclination, irregularity, etc.) and de-emphasizes highway geometry.

CHAPTER 3

NATURE OF DISCONTINUITIES AND MODES OF SLOPE FAILURE IN OHIO

The Appalachian Plateau area, commonly associated with western Pennsylvania and West Virginia, extends into Ohio along the Ohio River Valley in eastern and southern Ohio. This is the region where most rockfalls occur within the state. The Appalachian Plateau is a maturely dissected plateau with deep valleys, moderate to steep slopes, and local relief on the order of 200 to 350 feet (60 to 100 m) (Gray et al., 1979). As previously stated, the geology of this region, along with the entire state, is comprised of Paleozoic, nearly flat-lying, interbedded strata such as shales, claystones, mudstones, siltstones, sandstones, carbonates, and some coal seams. Throughout Ohio, tectonically derived sub-vertical orthogonal joint sets and sub-vertical to vertical valley stress relief joints, associated with the river valleys, are present.

Differential weathering of interbedded layers of varying durability within the road cuts promotes undercutting of the more durable layers by the less durable layers. The removal of the weaker material leaves unsupported blocks of the stronger material, which ultimately fall. Rockfalls generally occur when undercutting proceeds to a point where near vertical joints daylight on the slope and the rock blocks bounded by the joints fall (Gray et al., 1979; Young and Shakoor, 1987; Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Geiger et al., 1992; Shakoor, 1995).

3.1 Types of Discontinuities in Ohio

Three types of discontinuities are commonly encountered along Ohio roadways. These are nearly horizontal bedding planes, valley stress relief joints, and tectonically derived orthogonal joints (Figure 3.1). Each contributes to rockfall generation by acting as a release surface or sliding surface for plane, wedge or toppling failures after undercutting helps daylight the discontinuities on the slope face (Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Shakoor, 1995).

3.1.1 Bedding Planes

The major discontinuity associated with sedimentary rocks is the bedding planes (Figure 3.2). Bedding planes throughout Ohio generally dip to the southeast at angles ranging from horizontal to 10 degrees. In some rare cases bedding plane inclinations can be found nearing 30 degrees (e.g. stratigraphic pinchouts). However, this is not common and is generally only associated with stratigraphic pinch-outs. For stereonet analysis all bedding planes were assumed to be generally horizontal. Due to their low dip angle, kinematically, the bedding planes do not meet the Markland's failure criterion for plane failures Markland, 1972).

3.1.2 Valley Stress Relief Joints

Ferguson (1967, 1974), Hamel (1971, 1980), Ferguson and Hamel (1981), Young and Shakoor (1987), and Geiger et al. (1992) all discussed the relationship between valley stress relief jointing and slope stability in the Appalachian Plateau. According to these authors, valley stress relief joints are steeply dipping to vertical fractures that

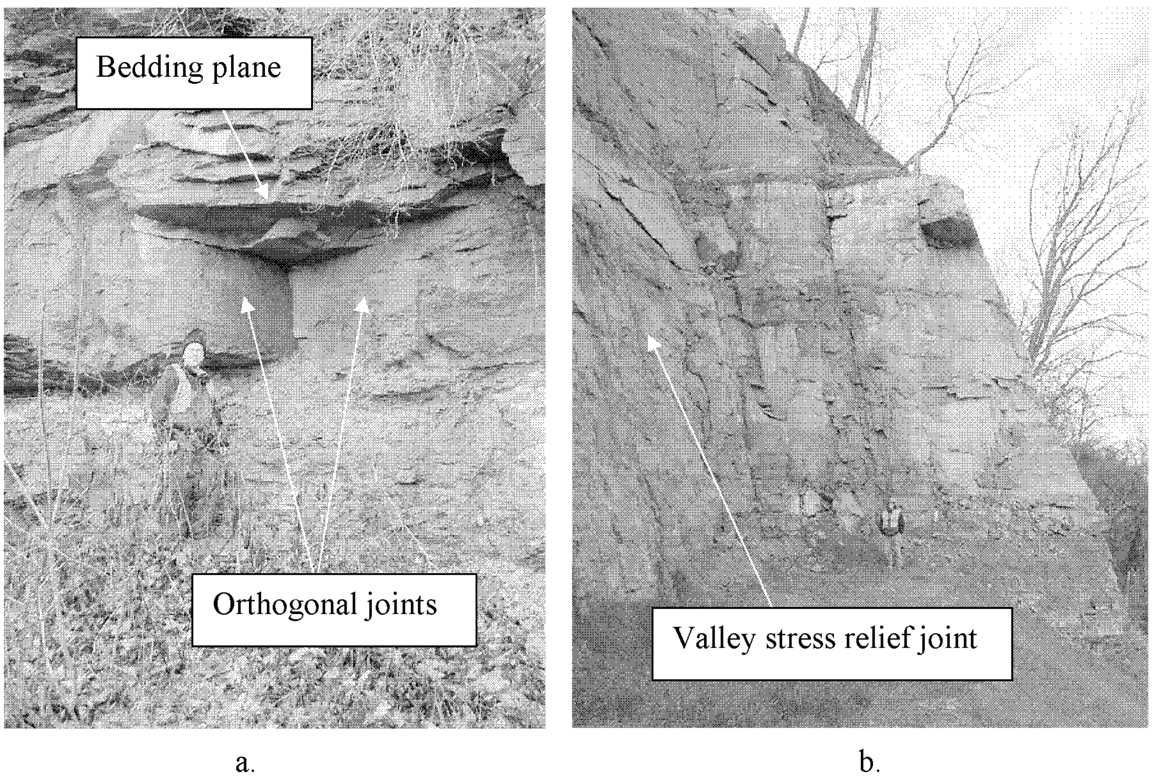


Figure 3.1: Types of discontinuities commonly encountered along Ohio roadways: (a) bedding planes and orthogonal joint set, (b) a valley stress relief joint.

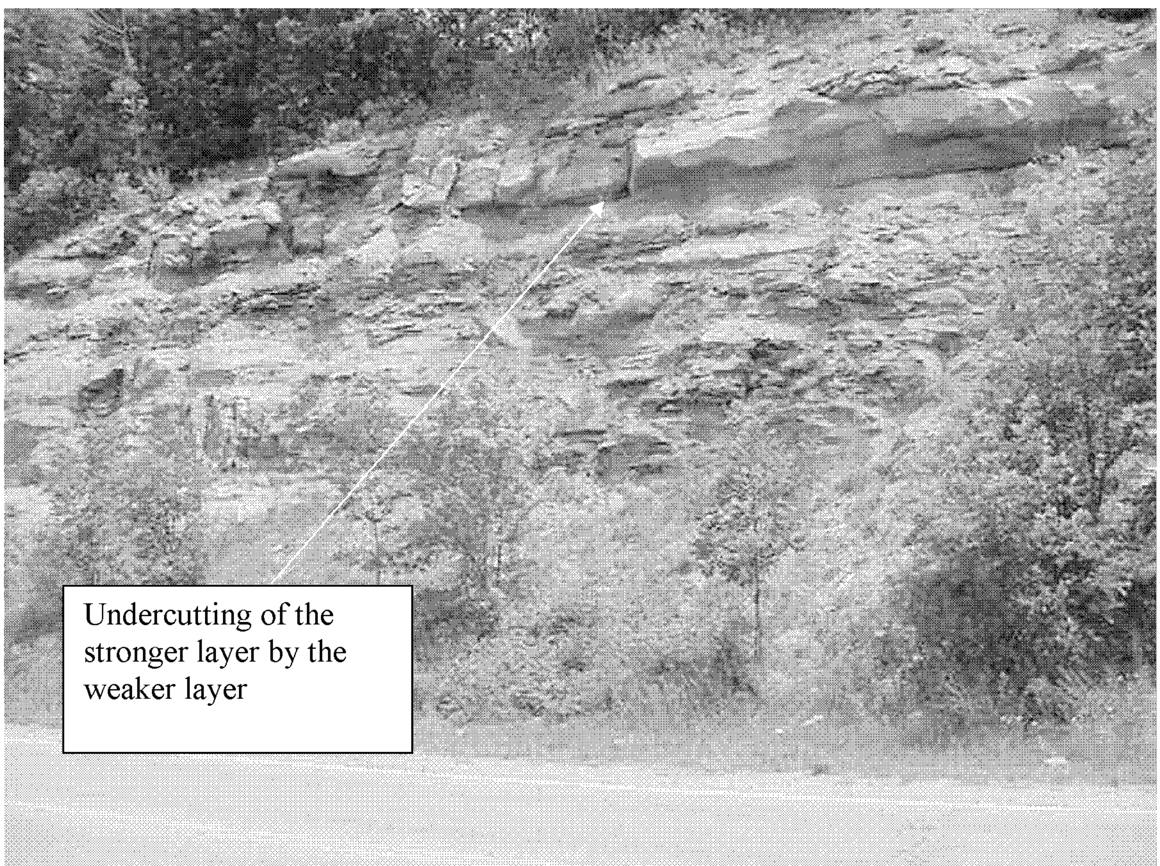


Figure 3.2: An example of horizontal bedding planes. Notice the undercutting of the stronger layers by the weaker layers.

resulted from stress relief accompanying valley formation. Unlike deep-seated regional joints created by tectonic stresses (orthogonal joint sets), valley stress relief joints exist near the valley, attenuate across beds of differing strength, and become less frequent with depth below the valley floor and distance away from the valley wall. The pattern of these joints depends on the thickness and competency of the strata in which they form, competency of adjacent strata, and their position in the valley wall. Generally, valley stress relief joints are smaller and more closely spaced in the less competent rocks, such as clayey shales, claystones, and coal seams than in the more competent units such as sandstones and limestones. The following process can explain the formation of valley stress relief joints. During downcutting, the residual stresses are released normal to the orientation of the river valley. Within valley walls, weak beds are destressed by release of confining pressures. More competent layers are dragged along and fractured, creating joints paralleling the river valley (Gray et al., 1979). The orientation of the valley stress relief joints is parallel to sub-parallel to the valley walls. Since most of the road cuts in Ohio are created near parallel to the valleys, the valley stress relief joints are most commonly found parallel or sub-parallel to the road cuts (Figure 3.3).

3.1.3 Orthogonal Joint Sets

The orthogonal joint sets found in rock slopes in Ohio are deep-seated regional joints created by tectonic stresses (Gray et al., 1979; Young and Shakoor, 1987; Geiger et al., 1992). Orthogonal joints are more pervasive than the valley stress relief joints. There is a relationship between joint spacing and the strength of a rock layer; in general, the

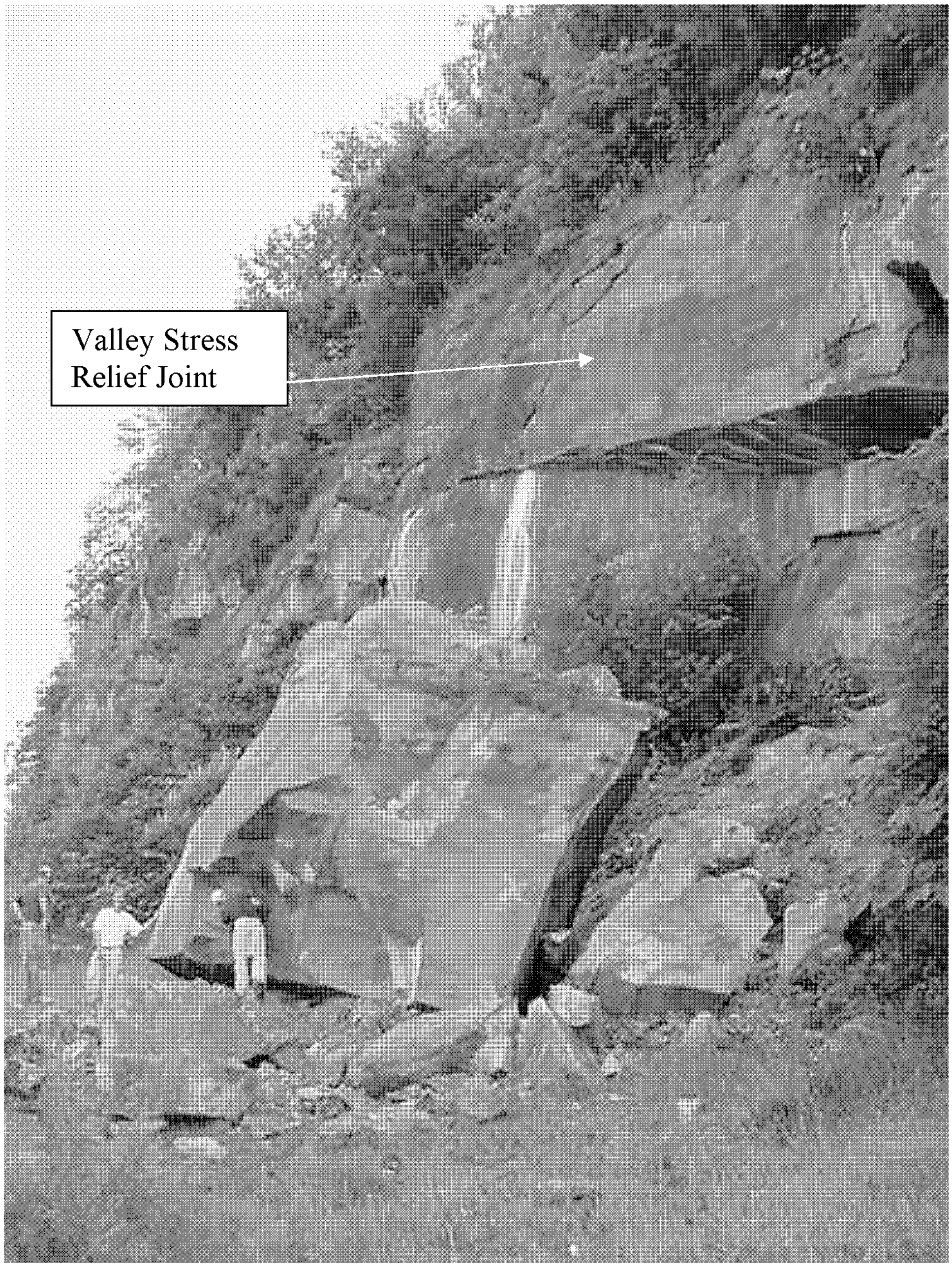


Figure 3.3: Example of a sub-vertical valley stress relief joint that parallels the slope face.

stronger the rock the greater the joint spacing. Also, orthogonal joints have a regional occurrence compared to valley stress relief joints that disappear away from the valley walls. Figure 3.4 illustrates the relationships between the three types of discontinuities and their role in generation of rockfalls.

3.2 Modes of Rock Slope Failure

The common forms of slope failure in rock include rockfalls, plane failures, wedge failures, and toppling failures as defined by Varnes (1978). A rockfall is defined as a rock mass that has detached from a steep slope or cliff, along a surface on which little or no shear displacement occurs, and descends most of its distance through air (Hoek and Bray, 1981). A planar or translational slide involves a downward and outward movement along a more or less planar or gently undulating surface of failure whose strike is within 20° of the strike direction of the slope face. Also, for a plane failure to occur, the dip of the discontinuity must be less than that of the slope face but more than the angle of friction along the discontinuity (Hoek and Bray, 1981). A wedge failure is a rapid, downward and outward movement of a wedge-shaped block of rock along the line of intersection of the two discontinuities forming the block, or along the steeper of the two discontinuity surfaces. A wedge failure occurs when the inclination of the line of intersection (plunge) is less than that of the slope face, but greater than the friction angle (Hoek and Bray, 1981). Toppling involves forward rotation about a pivotal point below the base of the block and occurs under the influence of gravity as well as the forces exerted by the adjacent blocks (Hoek and Bray, 1981). In Ohio most rockfalls initiate as

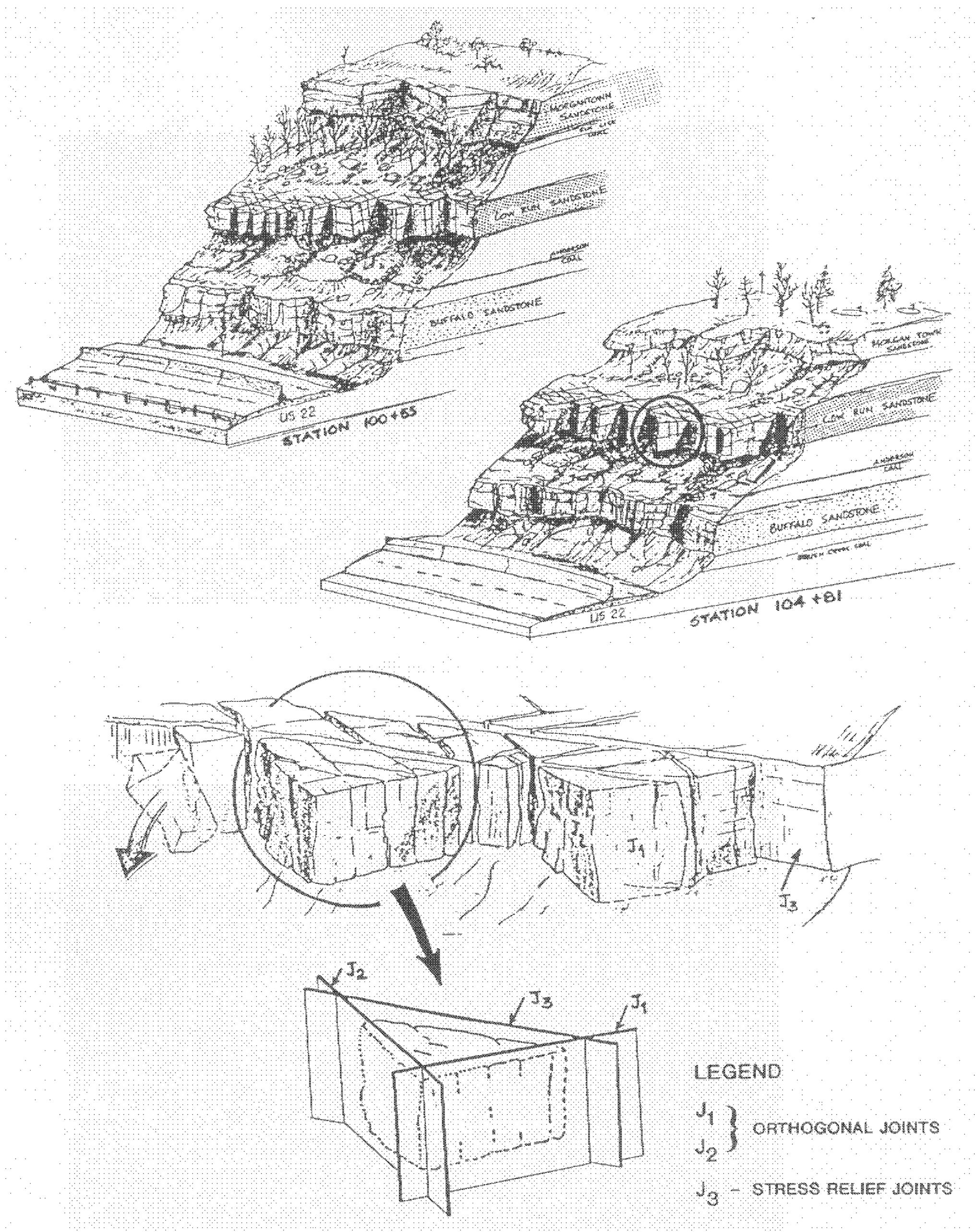


Figure 3.4: Generation of rock falls by the intersection of different types of discontinuities and by the process of undercutting (taken from Geiger, 1992).

plane, wedge, or toppling failures due to differential weathering before developing into falls (Shakoor and Weber, 1988).

3.2.1 Rockfalls

Rockfalls predominate where rock discontinuities form orthogonal blocks in competent strata, which are underlain by easily erodible incompetent strata. Undercutting by weaker layers allows loose blocks from the upper layer to fall under the influence of gravity. The frequency and size of rockfalls depend upon joint spacing within the competent unit and the extent by which it has been undercut. However, undercutting is not always required for rockfalls to occur. Closely jointed rocks can lead to rockfalls even if there is no undercutting involved (Shakoor, 1995).

There are many causes of rockfalls such as rain, freeze-thaw action, differential erosion, and root wedging, just to name a few. McCauley and others (1985) performed a comprehensive study of rockfalls that have occurred along California state highways. Fourteen causes of rockfalls are cited (Table 3.1) in that study and 68% of those are found to be water related.

One of the earliest studies of rockfalls was made by Ritchie (1963) whose empirical work was later converted into design charts relating slope dimensions (slope height, slope angle) to size (width and depth) and shape of the catchment ditch (Figure 3.5). Starting in the 1980's a number of computer programs were developed to simulate the behavior of rockfalls as they roll and bounce down slope faces (Piteau, 1980; Wu, 1984; Descoeudres and Zimmerman, 1987; Spang, 1987; Hungr and Evans, 1988,

Table 3.1: Causes of rock fall occurrence in California and their relative significance (taken from McCauley et al., 1985).

Causes of Rock Falls on Highways in California	
Cause	Percentage of Total
Rain	30
Freeze-thaw	21
Fractured rock	12
Wind	12
Snowmelt	8
Channeled runoff	7
Adverse planar fracture	5
Burrowing animal	2
Differential erosion	1
Tree roots	0.6
Springs or seeps	0.6
Wild animals	0.3
Truck vibrations	0.3
Soil decomposition	0.3

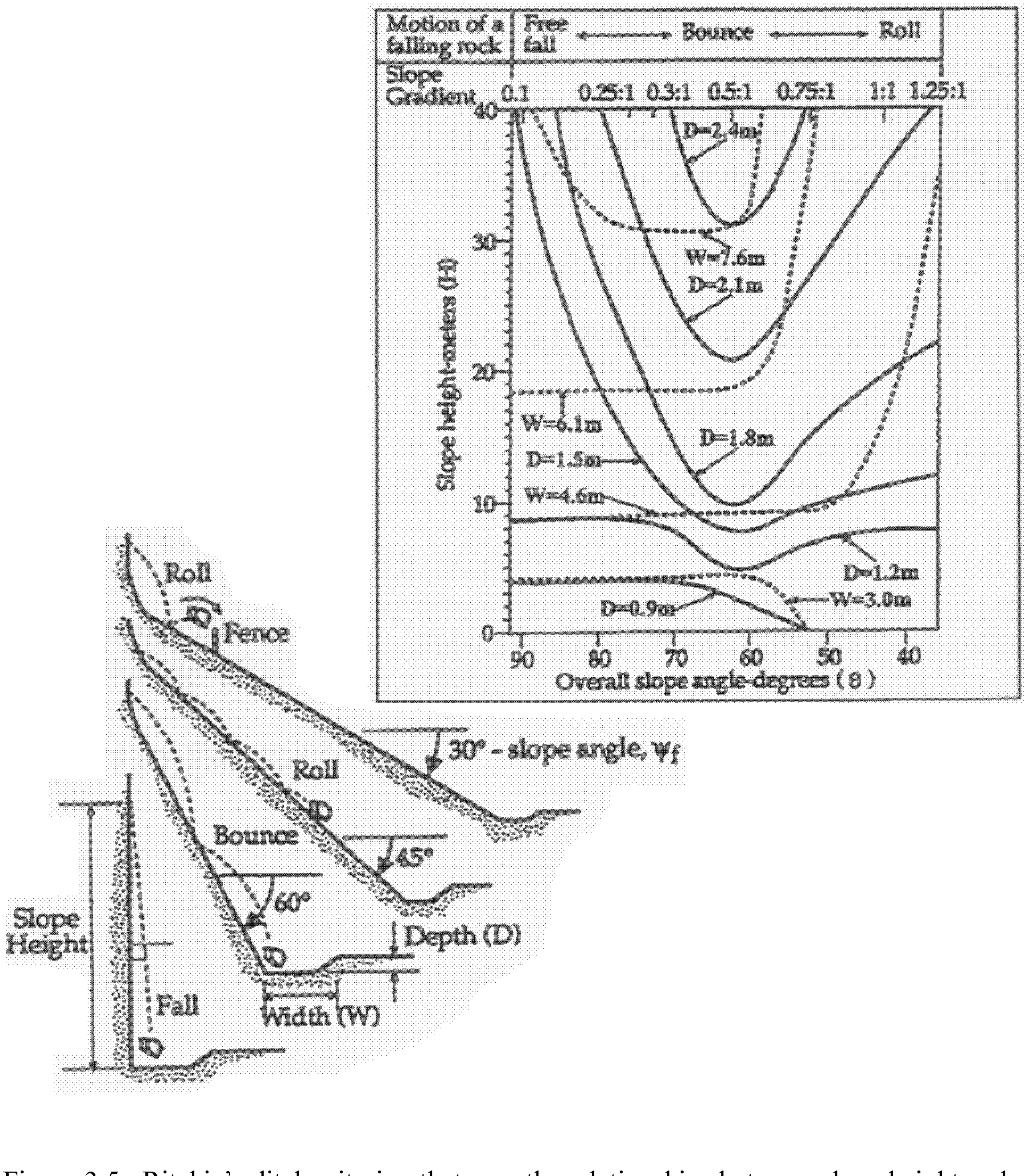


Figure 3.5: Ritchie's ditch criterion that uses the relationships between slope height and slope angle to obtain effective ditch widths and depths (taken from NYDOT, 1996).

Pfeiffer and Bowen, 1989; Pfeiffer et al., 1990; Guzzetti et al., 2002). One of the most widely used computer programs is the Colorado Rockfall Simulation Program (Pfeiffer, 1990; Jones et al., 2000).

3.2.2 Planar Failures

A plane failure or translational slide involves a downward and outward movement along a more or less planar or gently undulating surface of failure. Two conditions must be met for sliding to occur. First, the discontinuity must have a dip angle that is steeper than its friction angle. Second, the discontinuity must dip in the same general direction as the slope face (± 20° of the dip of the slope face), but less steeply than the dip of the slope (Markland, 1972). The condition describing the relationship can be represented on a dip vector stereoplot as shown in Figure 3.6. A dip vector is the mid point of a great circle representing a discontinuity. It represents the direction as well as the amount of dip of the discontinuity. Discontinuity dip vectors that lie within ± 20° of the direction of dip of the slope and are less steep than the slope face satisfy the Markland's criterion for a plane failure (Markland, 1972; Hoek and Bray, 1981; Wyllie and Norrish, 1996; Watts et al., 2000). An example of a plane failure can be seen in Figure 3.7.

3.2.3 Wedge Failures

Wedge failures result when rock masses slide along two intersecting discontinuities both of which dip out of the cut slope at oblique angles to the cut face, forming a wedge shaped block. Rock masses with well-defined orthogonal joint sets, in

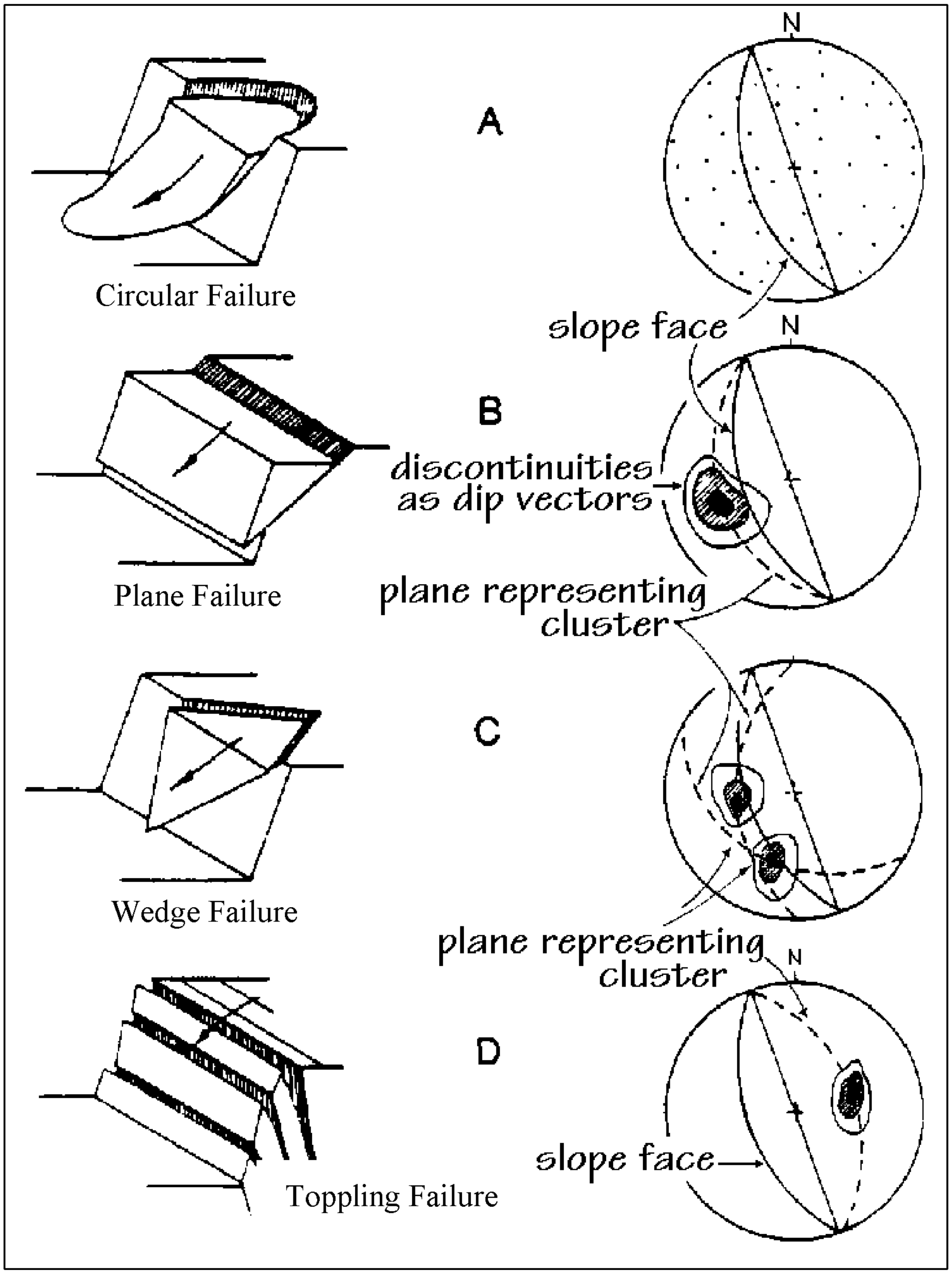


Figure 3.6: Types of slope failures with associated dip vector stereoplots illustrating the identification of each failure type: (A) circular failure, (B) plane failure, (C) wedge failure, and (D) toppling failure (taken from Watts et al., 2000).

Figure 3.7: Example of a plane failure found in Ohio along State Route 7 at a site designated as JEF-7-14.4b. The large block first failed along the valley stress relief joint as a plane failure before tilting.

addition to bedding, generally are favorable situations for wedge failures to occur (Piteau, 1971).

Stereonet analyses for potential wedge failures are similar to the stereonet analyses for plane failures. In order for a wedge failure to occur, the line made by the intersection of the planes creating the wedge must plunge more steeply than the friction angle and less steeply than the dip of the slope face, and should be inclined in a direction such that it daylights on the slope face (Markland, 1972; Hoek and Bray, 1981; Wyllie and Norrish, 1996). The condition illustrating the intersection of two discontinuities that satisfies the requirement of a wedge failure can be seen in Figure 3.6.

Differential weathering can cause wedge failures to occur in more competent layers even when the lines of intersection do not initially daylight on the slope face i.e., the points of intersection do not fall within the critical zone (Shakoor and Weber, 1988). When the line of intersection is steeper than the slope face, the wedge has a greater tendency to move downward than outward. When the line of intersection is nearly vertical, which will be the case for a wedge formed by near vertical discontinuities, the wedge could fail only by downward movement. Such movement can occur only if the underlying rock is removed through the process of differential weathering (undercutting). The term "wedge falls" has been proposed to describe such combinations of wedge failures and rockfalls by Shakoor and Weber (1988). An example of wedge-fall failures caused by undercutting can be seen in Figure 3.8

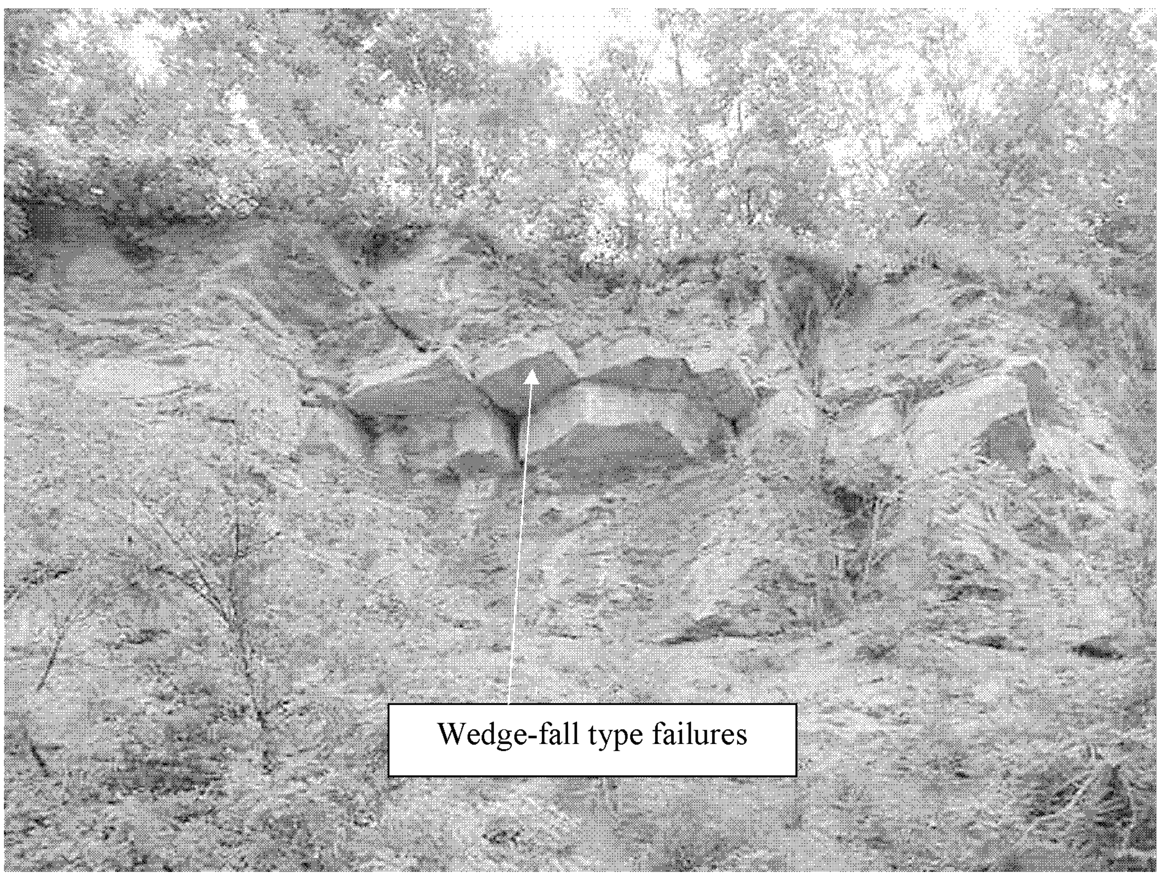


Figure 3.8: Example of a potential wedge failure caused by undercutting at site designated as WAS-7-19.

3.2.4 Toppling Failures

Toppling failure involves the forward rotation about a pivotal point below the base of the block and it occurs under the influence of gravity in addition to the forces exerted by adjacent blocks. The type of toppling found in Ohio can be described as secondary toppling as defined by Goodman and Bray (1976). Secondary toppling is initiated by some undercutting of the toe of the block by processes such as erosion or differential weathering. The primary mode of failure involves sliding or physical breakdown of the rock and toppling is induced in some part of the slope as a results of this primary failure (Goodman and Bray, 1976; Hoek and Bray, 1981; Wyllie and Norrish, 1996).

Goodman (1980) discusses a stereonet procedure for kinematically identifying potential toppling failures. He states that interlayer slip must occur before large flexural deformations can develop. If the interlayer slip is controlled by friction angle, toppling will occur if stresses normal to the toppling layers are inclined less steeply than a line inclined at an angle equal to the friction angle above the plane of the slope. In addition, toppling will occur only if the layers strike nearly parallel to the strike of the slope, typically within 30 degrees (Wyllie and Norrish, 1996; Watts et al., 2000). Figure 3.6 illustrates the relationship between the orientation of the slope face and discontinuities where toppling failures may exist.

3.3 Characteristics of Discontinuities

As described by Hoek and Bray (1981), there are seven aspects of discontinuities that are important in assessing rock slope stability. They include geometry, continuity, spacing, surface irregularities, physical properties of adjacent rock, nature of infilling material, and ground water. The nature and the role of these aspects in rock slope stability are discussed below.

3.3.1 Geometry

The geometry of discontinuities deals with the orientation of discontinuities in space and in relation to a slope face. In rock slope stability, Markland failure criterion (1972) is used to determine if there is a kinematic potential for a failure to occur along a discontinuity or an intersection of two discontinuities. Markland failure criterion is used to identify the potential for plane and wedge failures.

Ohio is characterized by the presence of horizontal or nearly horizontal bedding planes, orthogonal joint sets that dip nearly vertical and valley stress relief joints that also dip nearly vertical. Figure 3.9 shows the presence of bedding planes and orthogonal joints at a typical site (WAS-7-39.5) along with the associated stereonet. Traditional use of Markland failure criterion (1972) initially indicates that there are no kinematically possible modes of failure. However, undercutting of the more durable units by less durable units can lead to daylighting of the more or less vertical joints, promoting plane or wedge failures (Shakoor and Rodgers 1992). In this case Markland failure criterion needs to be adjusted to identify failure modes. The adjustment to visualize the failure

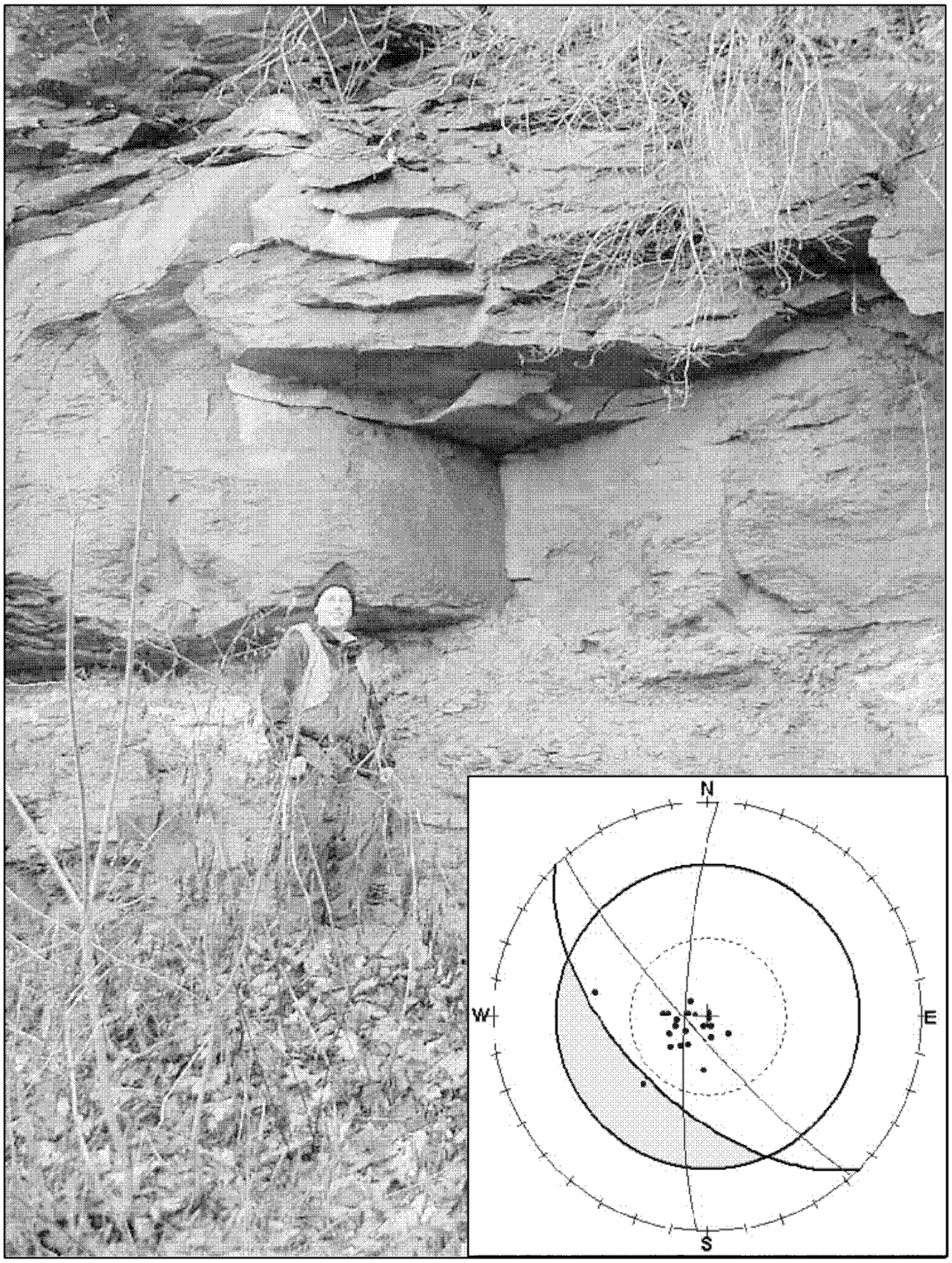


Figure 3.9: Example of a typical road cut, from site designated as WAS-7-39.5, with its associated dip vector stereoplot. Notice that neither plane failures nor wedge failures can be identified through the conventional use of Markland failure criterion as almost all of the dip vectors fall outside the critical zone.

modes defined by Markland can be seen by adjusting the slope angle to a vertical slope. This is done to approximate the daylighting of the high angle discontinuities due to the undercutting. In essence this increases Markland's "critical zone" to identify potential the different failure modes.

3.3.2 Continuity

The term continuity indicates the extent of the discontinuity, or how through going the discontinuity is. Taking the total length of the intact portions of the discontinuity and dividing it by the length of the discontinuity can quantify it. A less continuous discontinuity indicates a failure surface with intact rock along the fracture. The presence of intact rock along a failure surface gives added resistance to shearing, as the intact rock must be sheared through for the failure to occur. Conversely, if a discontinuity is continuous the shearing resistance depends only upon the shear strength of the fractured surface (Hoek and Bray, 1981). It should be noted that discontinuities such as valley stress relief joints can extent through lithologic unit or may be contained within a single unit, such as with a bedding plane.

Both bedding planes and orthogonal joint sets found in Ohio may be considered continuous. Orthogonal joint sets are present throughout the slope, becoming more frequent in weaker strata such as shale units. Generally, valley stress relief joints are smaller and more closely spaced in less competent rocks such as clayey shales, claystones, and coal than in the more competent units such as sandstones and limestones

(Gray et al., 1979). However, valley stress relief joints can be traced throughout the entire slope where the slope parallels a stream valley.

In order to estimate how continuous the potential failure surfaces are, a classification suggested by Watts and others (2000) can be used. It uses three categories to classify continuity; zero percent intact rock along discontinuity, zero to five percent, and greater than five percent. Watts and others (2000) state that even the addition of minor amounts of intact rock can significantly increase the shear strength of a discontinuity. Continuity can also be described by definitions by Pierson (1991) in which a continuous discontinuity are those greater than ten (10) feet (3 m) in length and discontinuous if shorter.

3.3.3 Joint Spacing

Spacing of the discontinuity is significant in rock slope engineering because it controls rock mass strength, size of the failures, and pore pressure development (Hoek and Bray, 1981). Rock slopes that have a small spacing between discontinuities generally exhibit failures that are comprised of smaller blocks, whereas slopes that have widely spaced joints generally have larger blocks comprising the failure (Figure 3.10). Quantification of discontinuity spacing can be done according to the classification proposed by Deere and Miller (1964) and provided in Table 3.2. In Ohio, discontinuity spacing is highly variable, ranging from less than 2 inches (5 cm) to greater than 100 feet (30 m).

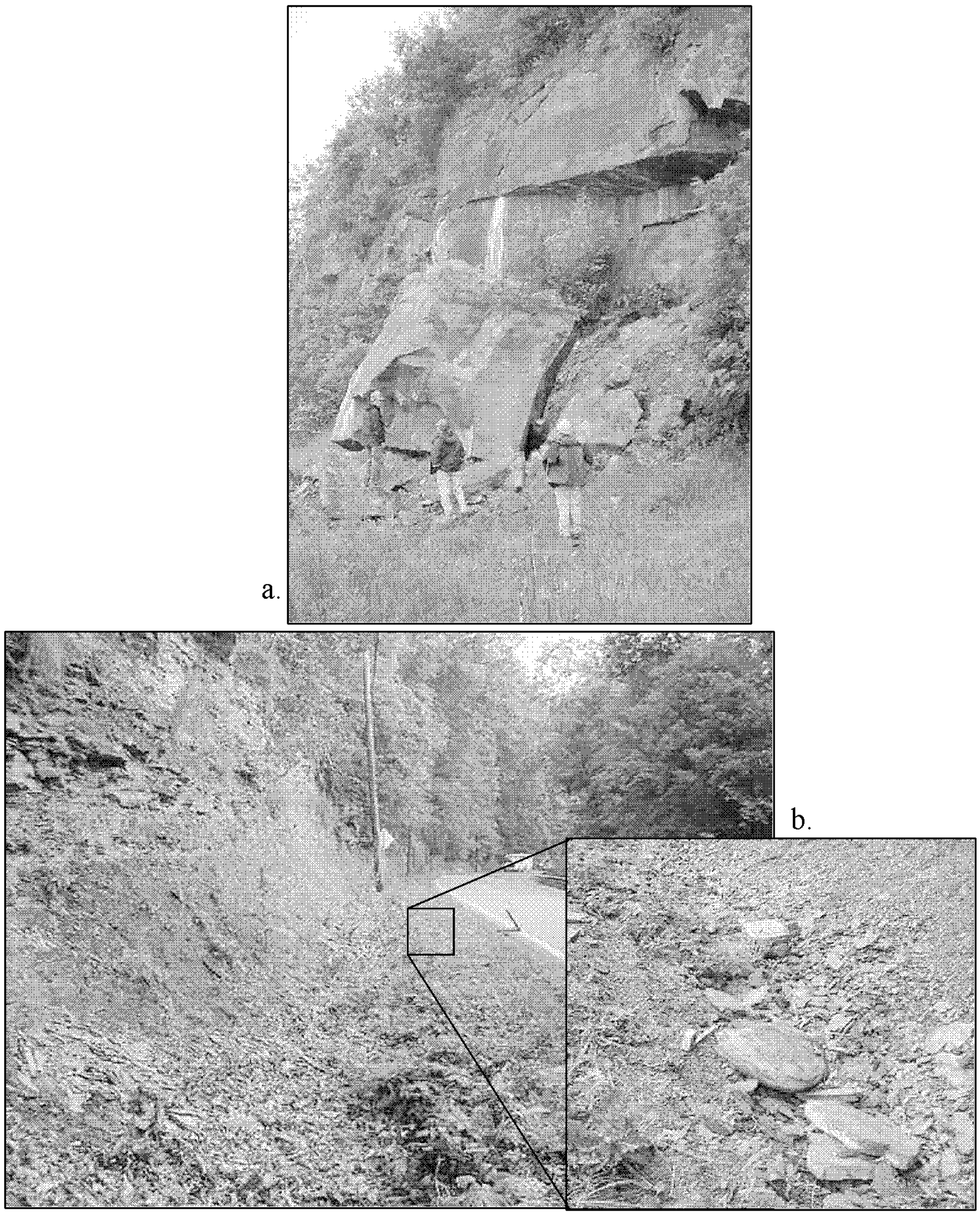


Figure 3.10: Effect of joint spacing on size of failure (a) large joint spacing promoting large block failures and (b) small joint spacing promoting development of small failures.

Table 3.2: Classification of discontinuity spacing according to Deere and Miller (1964).

Descriptive Classification of Discontinuity Spacing (Deere, 1964)			
Bedding	Spacing		Joints
very thin	< 2"	< 5cm	very close
thin	2" - 1'	5 - 30cm	close
medium	1' - 3'	30cm - 1m	moderately close
thick	3' - 10'	1m - 3m	wide
very thick	> 10'	> 3m	very wide

There is also a relationship in the Ohio strata between joint spacing and rock type. In general, the more competent the rock layer the greater the joint spacing. Bedding thickness is also an indicator of joint spacing, the greater the bedding thickness the greater the joint spacing. Joint spacing is much smaller within less durable mudrocks.

3.3.4 Surface Irregularities

An irregular discontinuity surface can provide resistance to sliding due to increased friction (Patton, 1966; Landanyi and Archambault 1970; Barton, 1973). According to Barton (1973), surface irregularities can increase the friction angle from a residual value of 30-35° to a maximum of 70°. Commonly, the increase in the friction angle value is only on the order of 15 to 20° (Hoek and Bray, 1981). The increased friction is determined by summing the basic friction angle and the average angle of surface irregularities (i) (Patton, 1966). Barton (1973) developed a method to estimate joint roughness by using a joint roughness coefficient (JRC). This is accomplished by a comparison of the discontinuity surface profile with the profiles shown in Figure 3.11.

Most discontinuities in Ohio are generally smooth or slightly undulating, with a maximum joint roughness coefficient of 5 or 10, or an i value near zero. In Ohio, both the tectonic joints and the valley stress joints, which promote most of the failures in the state, dip in excess of this maximum angle of 70°. Therefore, a detailed examination of surface irregularities is not critical for analysis of slope failures.

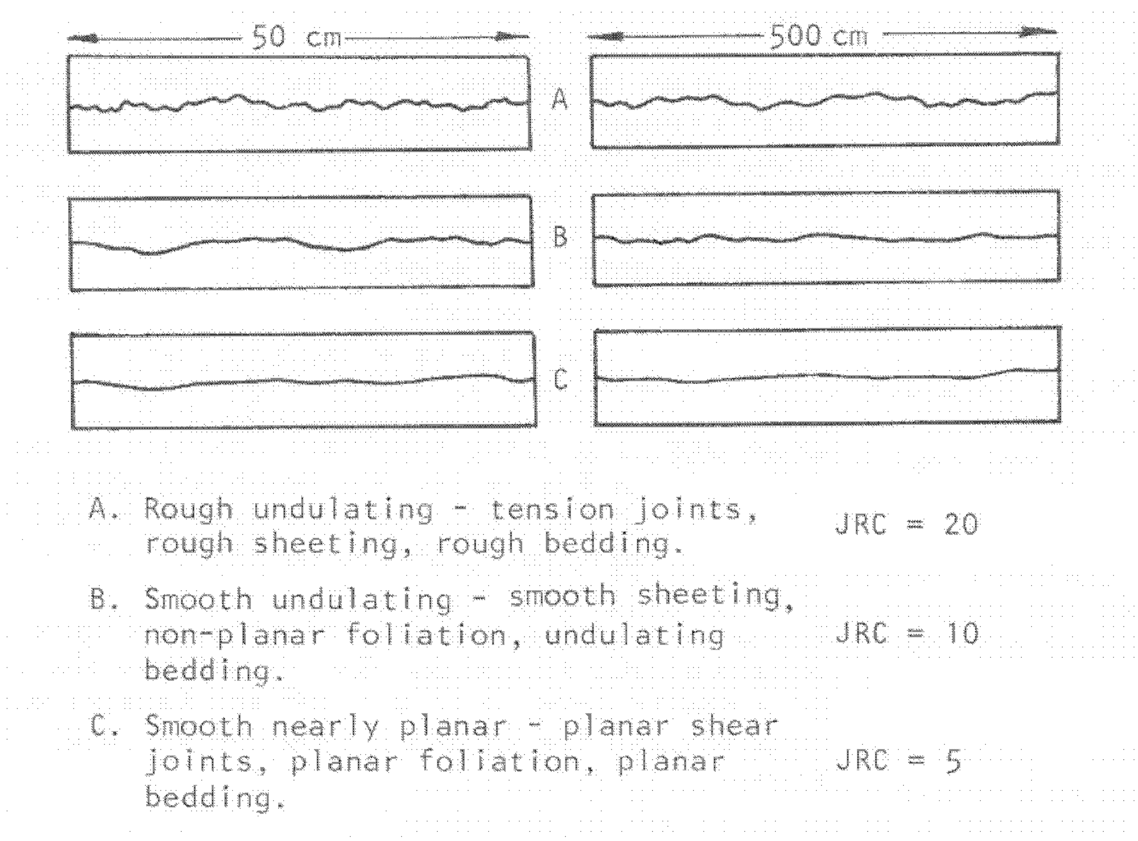


Figure 3.11: Barton's definition of joint roughness coefficient JRC (taken from Hoek and Bray, 1981.

3.3.5 Physical Properties of Adjacent Rocks

Physical properties of adjacent rocks generally affect shearing resistance of a failure surface (Hoek and Bray, 1981). For instance, a contact between two sandstone blocks will generally have a greater friction angle than that between sandstone and shale. Again, the discontinuities that control failures in Ohio dip at angles significantly greater than the differences in strength attributable to any increase or decrease of the friction angle between two adjacent lithologies. Therefore, this aspect of discontinuities is not critical with respect to failures in Ohio. In Ohio, it is the durability of adjacent rock units that is of grater importance. Undercutting of more durable layers by less durable layers will either result in daylighting of the nearly vertical joints or enough undercutting to cause a tensional failure of the rock mass (Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Shakoor, 1995).

3.3.6 Infilling Material

Infilling material includes all soil-like material that occurs between the walls of a fracture as well as some mineral deposits. The infilling material generally decreases the shear strength along a discontinuity, except in some cases where mineral deposits may actually increase the shear strength (Goodman, 1970; Barton, 1974; Hoek and Bray, 1981). In Ohio, however, since the discontinuities are nearly vertical, the change in the shear strength due to infilling material has little effect on the overall stability of the slope. There are some localities in Ohio where infilling material is present, but its effect on slope stability in general is negligible (Rauber, 2000).

3.3.7 Ground Water

The California Department of Transportation (Caltrans) initiated a study to understand the factors that promote rockfalls (McCauley et. al., 1985). It was determined from this study that there were fourteen common factors that initiated rockfalls. Of the fourteen factors, seven deal directly or indirectly with water (Table 3.1). The other factors that affect slope stability, according to McCauley and others (1985), are the geologic conditions present at the site including the rock type, nature of discontinuities, and soil condition. Between water conditions and geologic factors, 85% of the causes of rockfalls can be identified (Wyllie and Norrish, 1996).

Ground water increases the driving force due to build up of pore pressure (Hoek and Bray, 1981). Ground water is also an erosional agent. It can cause erosion either through the processes of freeze and thaw or by removal of material due to water pressures. In Ohio, water is a major role player in rock slope stability. It is the primary agent that causes the slaking of a less durable layer leading to undercutting of a more durable layer. The more competent layers present in Ohio (sandstones and carbonates) are more permeable than the less durable mudrocks and, therefore, any water entering the slopes flows along the contacts between the layers. As water exits the slopes it weakens the less durable layers and removes the broken down material. Surface water also causes differential weathering resulting in undercutting (Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Shakoor, 1995).

3.4 Role of Undercutting by Weak Rocks in Promoting Slope Failures

The weaker rocks that alternate with stronger rocks in Ohio can be termed "mudrocks". The term mudrocks is used to include all fine-grained argillaceous rocks such as shales, claystones, mudstones, siltstones, and argillites. Mudrocks in Ohio are most commonly found interbedded with harder, more durable, units such as sandstones and limestones. This type of stratigraphy is prone to differential weathering (Shakoor, 1995), whereby the softer, less durable, layers erode more quickly than the harder, more durable, layers. When the weaker layers are situated underneath the more durable layers, undercutting of the harder units occurs.

As undercutting proceeds, vertical support of the resistant layer diminishes and the jointed blocks comprising the resistant layer become unstable. As previously described, undercutting can lead to a variety of slope movements including rockfalls, plane failures, wedge failures, and toppling failures (Fookes and Sweeney, 1976; Rib and Liang, 1978; Young and Shakoor, 1987; Shakoor and Weber, 1988; Shakoor, 1995).

The extent to which differential weathering occurs depends on the engineering properties of the weak units and the slope characteristics. Engineering properties that affect the degree of weathering of a mudrock includes slake durability, freeze-thaw resistance, unconfined compressive strength, type and amount of clay minerals, and rock fabric (Spears and Taylor, 1972; Russell and Parker, 1979; Oakland and Lovell, 1985; Shakoor and Brock, 1987; Taylor, 1988; Dick and Shakoor, 1992; Shakoor, 1995; Greene and Schaffer, 1997). Slope characteristics that affect the degree of weathering include slope aspect, slope vegetation, surface runoff, ground water seepage, talus accumulation, and fracture frequency of the weak unit (Sowers and Royster, 1978; Rib and Lang, 1978; Shakoor and Rodgers, 1992; Shakoor, 1995).

Undercutting cannot be considered a static condition for rock slopes. Undercutting is a process that continually changes slope conditions, usually for the worse. Most slopes consisting of interbedded more and less durable strata such as prevalent in Ohio will become completely different in five to ten years of existence. Therefore, not only the amount of undercutting but also the rate of undercutting becomes important in examining the slopes in Ohio. Shakoor (1995) states that the time between the excavation of a road cut in such a geologic setting and the initiation of undercutting-induced failures will depend upon the rate at which the mudrocks weather and erode. According to the study by Shakoor and Rodgers (1992), the second-cycle slake durability index can be used to predict the approximate rate of undercutting along Ohio roadways and, therefore, time of initiation of rockfalls and other types of failure from the date of excavation of a given road cut. Figure 3.12 shows the relationship between the second-cycle slake durability index and the rate of undercutting, as developed by Shakoor and Rodgers (1992).

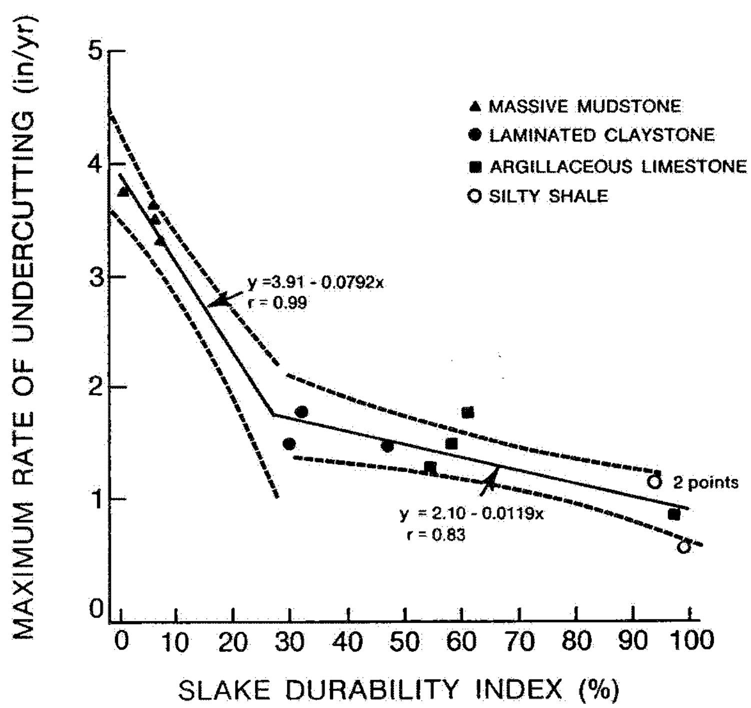


Figure 3.12: Correlation between maximum rate of undercutting and slake durability index values from Shakoor and Rodgers, 1992.

CHAPTER 4

RESEARCH METHODS

4.1 Site Selection

Each of ODOT's 12 district offices was asked to compile a list of all known rockfall sites within their district. Along with the list, district offices were asked to prioritize the sites into one of three categories, namely high-priority (high hazard potential), medium-priority (medium hazard potential), and low-priority (low hazard potential) sites. During the site selection process, every effort was made to ensure the sites selected were representative of the geological and hydrological conditions that exist in the state as well as the types and spatial distributions of slope movements. After completion of a districts list, sites were visited with district office personnel to determine their location, understand the districts' opinion about them, and verify the prioritization given to each site. The district offices were asked to help in the site selection process because of their familiarity with the history of each site.

Each district was asked to select three high-priority, three medium-priority, and three low-priority sites that would ideally result in a total of 108 sites. However, each district did not report the requested nine (9) sites and several reported no rockfall sites at all. To account for the districts without the required rockfall sites, additional sites from districts with greater than nine (9) sites were selected. Figure 4.1 shows the locations of the study sites.

4.2 Field Investigations

4.2.1 General Slope Information

Before any detailed information was gathered at a particular site, general slope information was obtained. A copy of the slope information data sheets can be found in Appendix A. The information included site location, trend of the road (north-south or east-west road), and direction of slope facing (north, south, east or west). A site designation was applied that followed methods used by the Ohio Department of Transportation where each location is defined by its county, route number, and mile marker. For example, a site within Summit County on State Route 800 at mile marker 1 would be designated as SUM-800-1. Also, a description to aid in site location such as "just south of Steubenville" and physical descriptions of roadway conditions such as grading of roadway were included.

The slopes were then classified into one of three slope configurations with respect to angle and presence or absence of benches: single-angle, multiple-angle, or benched slope. A single-angle slope is a slope in which the cut makes only one angle, a multiple-angle slope is a slope in which the cut has more than one angle, and a benched slope is a slope that contains benches. Figure 4.2 illustrates each slope classification.

For all slopes, the back slope condition was noted. Back slope is the part of the slope above the man-made cut (New York DOT, 1996). Since this portion of the slope is

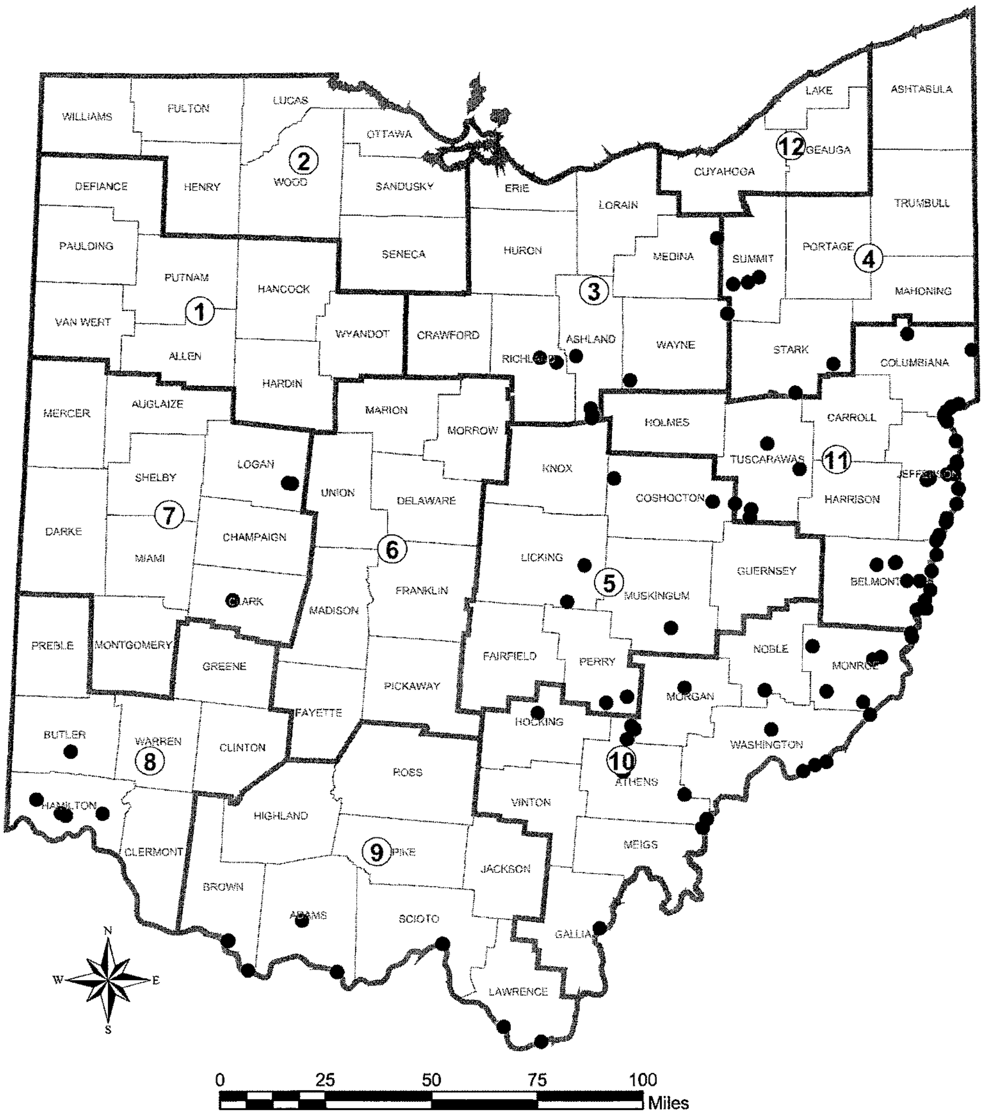
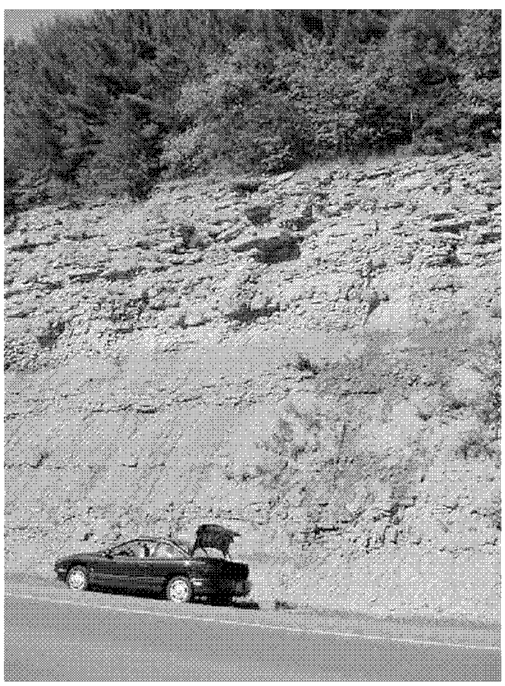
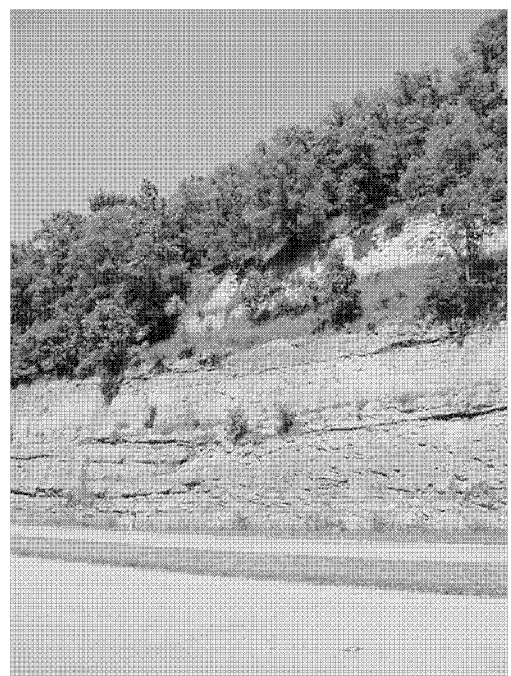


Figure 4.1: Map of Ohio showing the locations of the study sites. Lighter lines delineate county boarders, whereas darker lines define Ohio Department of Transportation districts.

(a)



(b)



(c)

Figure 4.2: Slope classification: (a) single-angle slope with back slope, (b) multiple-angle slope, and (c) benched slope.

natural, it does not lend itself to the analysis laid out in this study. However, in many road cuts throughout Ohio, the back slope area is a major source of rocks and debris that may fall and enter the roadway (Figure 4.3). The angle, amount of vegetation, and/or type of material comprising the back slope were recorded as well as possible sources of falling rock material, where applicable.

4.2.2 Slope Geometry

The geometry of a slope greatly influences the trajectory of a rockfall into the catchment area and possibly the roadway. A number of parameters were used to characterize slope geometry. These included: orientation, height, length, and amount and direction of dip for the cut slope as well as the upper natural slope. The catchment area is designed to catch most rocks that fall from the slope. Geometry of the catchment area affects the impact trajectory and rollout distances of rockfalls (Ritchie, 1963; Pierson et al., 1994; Pierson et al., 2001). Geometry of the catchment area was described by its width, depth, and angle toward the roadway. Each of these parameters was measured in the field by the methodologies described below.

Slope Height

Slope height is the vertical measurement of the slope and not a measure of the distance over which a rock could travel. Since the potential energy of a rock on a high slope is much greater than that on a low slope, the potential hazard of rockfalls would be more for higher slopes. In order to estimate the vertical slope height, the relationships in Figure 4.4, modified from the Oregon Rockfall Hazard Rating System (Pierson, 1991),

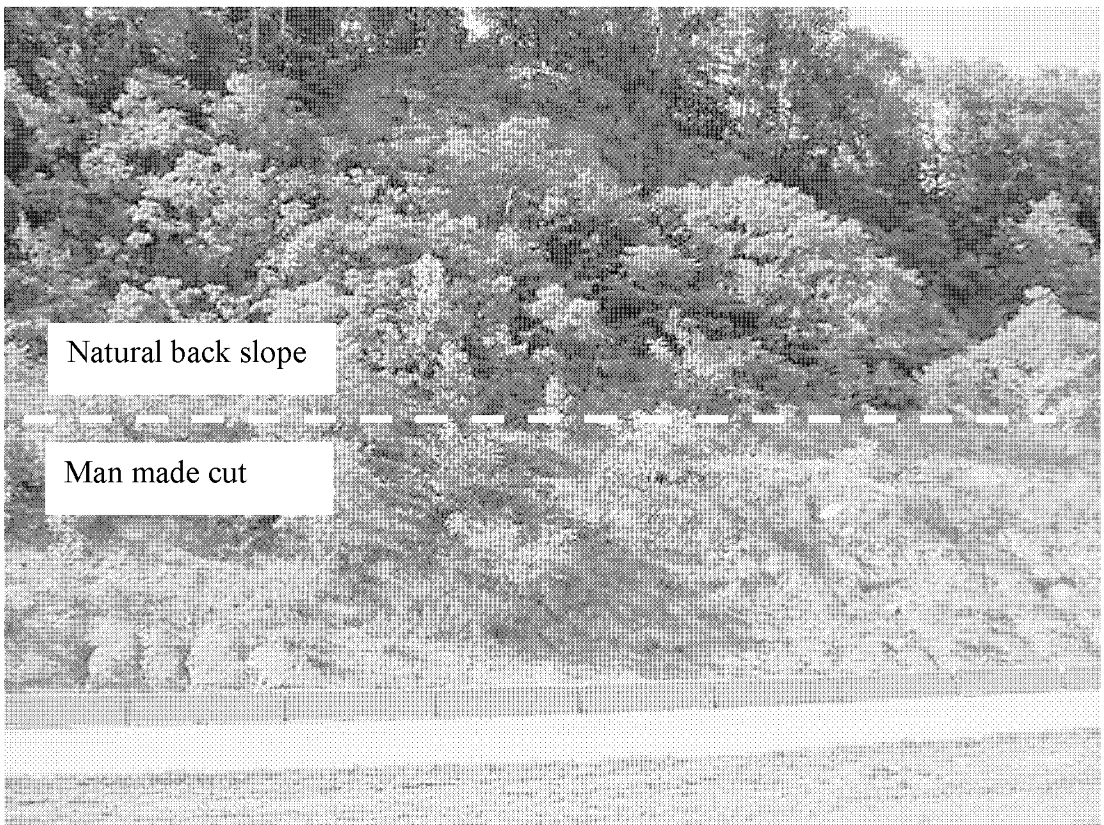


Figure 4.3: Example of a natural back slope above an engineered rock cut where rock falls can be generated from the material accumulating on the back slope.

were used. The angles θ and β in Figure 4.4 were measured with a brunton compass, an inclinometer, or a transit.

Five measurements of each of these two angles were taken and averaged. Measurements of slope heights were made at the highest vertical locations where rockfalls could generate on the slope. Mid-slope vertical heights were also obtained using this methodology. Examples of mid-slope heights include bench locations and elevations of changes in lithologic units.

Slope Angle

The overall slope angle was measured using a brunton compass or inclinometer. In the case of a single-angled slope, the slope face or, in some cases, the pre-split drill hole markings were used as a guide for the brunton or inclinometer to measure the slope angle. If a slope had multiple angles or was benched, the slope angle was approximated from the toe of the slope to the highest located rockfall generating area. In some rare cases, where the slope top was accessible, measurements of slope heights and angles were confirmed with alternate methods (i.e., the use of altimeters, tape measures, and shooting of angles from the top of the slope downward). The combination of slope angle and slope height data was used to create slope profiles. Slope profiles, or weathered profiles, were later used to prepare the stratigraphic sections.

Ditch Parameters

Ditch parameters include ditch width (dw), ditch depth (dd), and location of the deepest part of the ditch (ld). In order to determine the ditch parameters, a total of five

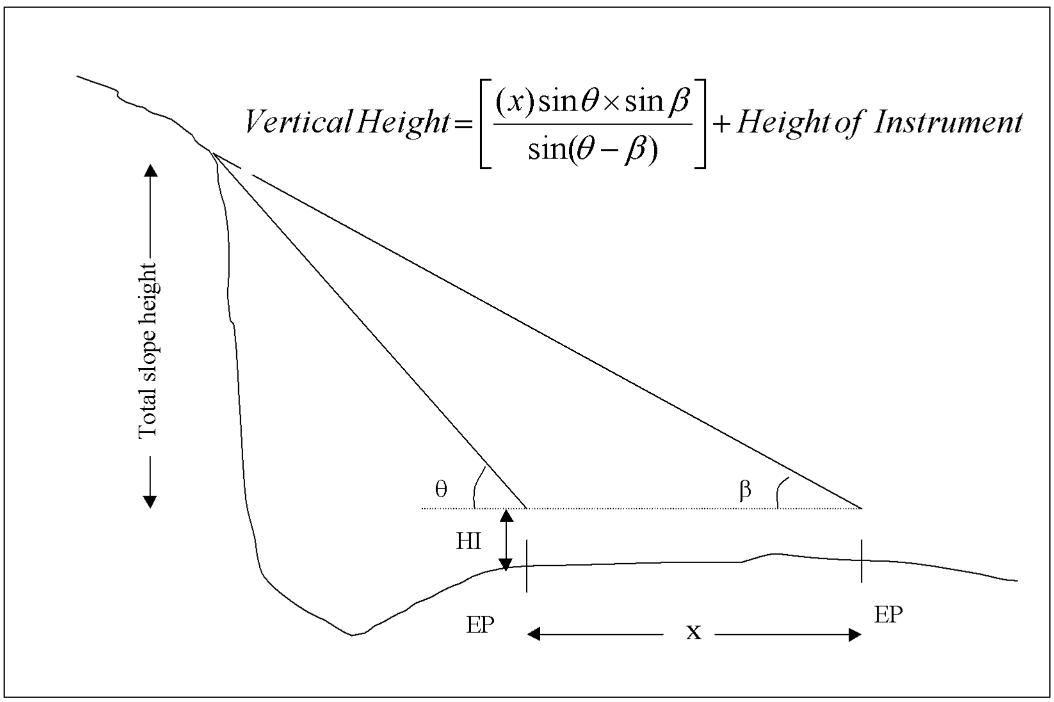


Figure 4.4: Relationship between slope height and geometrical parameters (HI=height of instrument, x= distance between the two points used for measurement of angles (θ and β= angles measured from horizontal, EP= edge of pavement)(adapted from Pierson et al., 1991).

measurements of width, depth, and location of maximum depth were taken and averaged at each site (Figure 4.5). Before taking these measurements, the length of the slope was measured and divided into four equal sections. The beginning and end points of a road cut were chosen by the extent of the area over which rockfalls were likely to occur, or by changes in the road cut. Changes included the cut's aspect to the roadway or geomorphic changes. The slope length was measured by walking a measuring wheel along the shoulder of the road. Within each of the four sections, measurements of ditch depth and width were taken as well as the location of the deepest part of the ditch. One additional measurement was taken directly down from the highest point on the slope to account for the worst conditions. The final ditch width, ditch depth, and location of the deepest part of the ditch were taken as the average of the five measurements of these parameters.

Bench Characteristics

On benched slopes, the number of benches, bench heights, and bench widths were recorded during the development of the slope profile. In addition to the geometric aspects of benches, the condition of each bench was noted. Bench conditions include the extent to which benches are covered with talus and growth of vegetation, extent to which benches are likely to serve as launching pads for rockfall trajectories, or other such observations. Each slope with benches was qualitatively assessed for the condition of the benches.

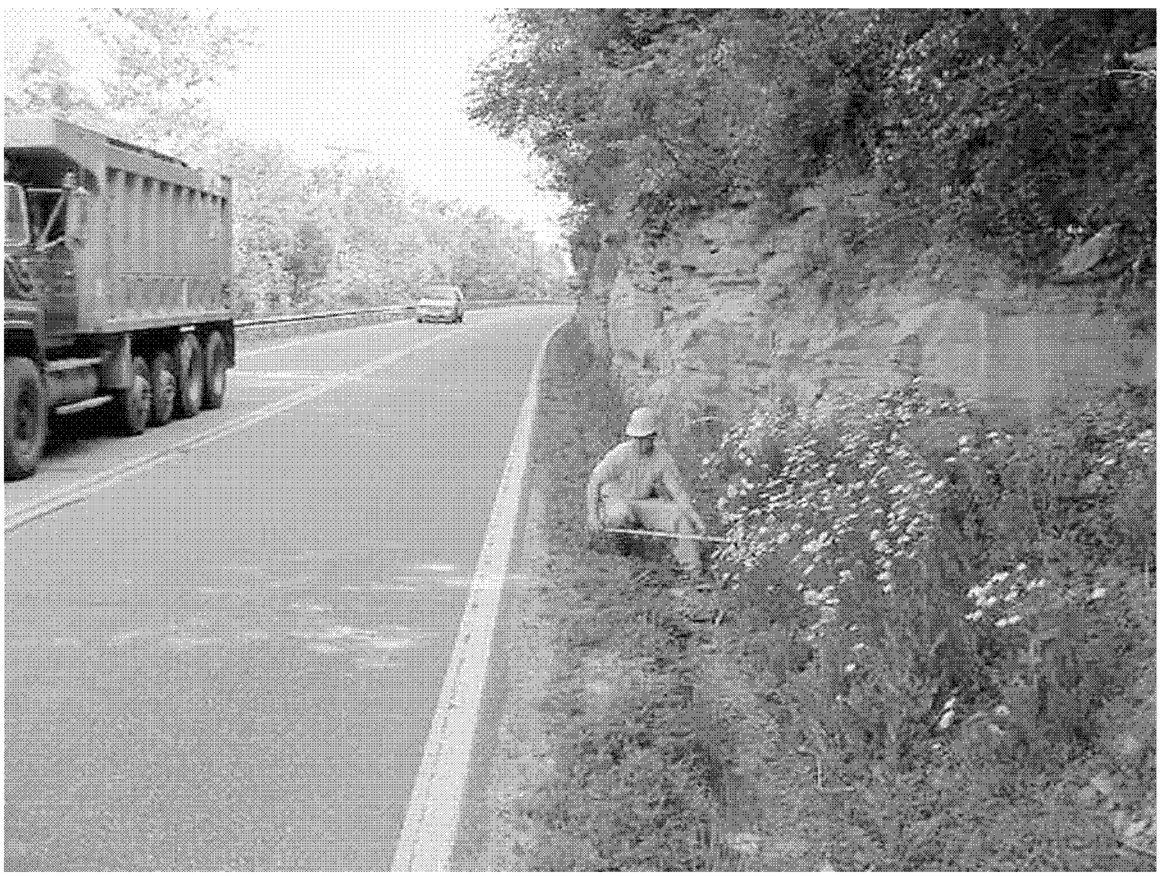


Figure 4.5: Measurement of ditch width, depth, and angle.

Back slope

Back slope is described in the New York State Rock Slope Rating System (1996) as the natural slope above the man-made road cut. NYDOT differentiated the back slope using such parameters as the amount of vegetation, angle of the slope, and the generation of rockfalls. In this study, the back slope was defined as the natural slope above the cut slope and the angle of the back slope was measured in a similar manner as slope angle. Notes concerning vegetation and possible rockfall generating areas from the back slope were recorded. There are many places within the state of Ohio where rockfalls are generated from the back slope, especially along the Ohio River. In some localities, rockfall problems are entirely associated with the back slope, and have nothing to do with the man-made cuts.

4.2.3 Slope Geology

Compared to the other states where rating systems were created (Oregon, New York, and Washington), the geology in Ohio is relatively simple, consisting of alternating sequences of more and less durable, relatively flat lying, sedimentary rock units. Therefore, the rating system for Ohio needs to focus on differential weathering, undercutting, and hydrologic conditions present at the rock cut.

Frequency and size of rockfalls in the state of Ohio are greatly affected by the spacing of discontinuities. Whether a rockfall initiates as a fall, a slide, a wedge or a toppling failure, it is the joint spacing that determines its size. Undercutting of more durable units by weaker mudrock units can also allow daylighting of joint intersections or of single discontinuities such as valley stress relief joints that are so prevalent along the

Ohio River. In conjunction with the rate of weathering of weaker layers, joint spacing plays an important role in determining how frequently a fall will occur. For example, the closer the joint spacing the less the amount of undercutting needed to promote rockfalls and the wider the joint spacing the more the amount of undercutting required for rockfalls.

The general stratigraphy at each site was described in terms of a stratigraphic cross-section (Appendix B). This included information regarding geologic ages, lithologic descriptions, thicknesses of various rock units, residual soil, etc. The discontinuities at each site were measured and described using the detailed line survey method developed by Piteau and Martin (1977). This method includes examination of discontinuity orientation, spacing, surface irregularities, infilling material, and water conditions.

Measurements of the undercutting were taken at the horizon with the greatest amount of undercutting. Ideally this horizon is found near the base of the slope. In this case direct measurements of undercutting were made and the average and maximum amounts of undercutting were recorded according to procedures described by Shakoor and Rodgers (1992). The average amount of undercutting was measured from the edge of the overlying unit inward to the underlying shale unit. A number of measurements were taken and the average was used as the average amount of undercutting. If the horizon was inaccessible, generally due to height on the slope, estimations were made to quantify the average and maximum amount of undercutting. Unsuccessful attempts were also made to compare maximum depth of undercutting to minimum fracture spacing within the overlying layer due to inconsistent visibility of overlying layers. Sampling of the weaker, less resistant rock units (claystones, mudstones, shales, etc.) was also done for determination of second-cycle slake durability index values (ASTM D4644). The maximum amount of the undercutting and the average amount of undercutting values may be used to approximate the amount of weathering of a particular cut (Shakoor and Rodgers, 1992; Shakoor, 1995).

Detailed line survey

A detailed line survey, as described by Piteau and Martin (1977), was performed on a more resistant layer at each site. The more resistant layers were chosen because they are the source of the rockfalls. To perform the detailed line survey, a tape measure was stretched across the slope (Figure 4.6). When a discontinuity crossed the tape, its distance on the tape, orientation, and spacing were recorded. The aspects of discontinuities such as roughness, infilling material, and water conditions were assessed according to procedures outlined in the ROCKPACK III beta users manual (Watts et al., 2000).

Size of rock blocks

Sizes of the rock blocks were initially determined through methods described by the Oregon Rockfall Hazard Rating System (Pierson, 1991), New York Rock Slope Rating Procedure (New York DOT, 1996), and Colorado RockFall Simulation Program Manual (Pfeiffer and Higgins, 1990). These methods direct the field investigator to first

Figure 4.6: Measurement of discontinuities in accordance with the detailed line survey method.

look in the ditch and measure the largest of the blocks found in the ditch. A comparison is then made between those measurements and an estimate of the largest size block that could possibly fall from the slope. The block sizes were used to compute their volumes. Since different rock shapes were used in the CRSP investigation (spherical, cylindrical, and discoidal), the weight of the block was recorded in the data set rather than the diameter of a block for a consistent measure between different shapes. The weight was determined by using the volume measured in the field and generally accepted estimated unit weight values (e.g. limestone, 165 pcf and sandstone, 150 pcf).

Hydrogeologic Conditions

According to McCauley and others (1985), water is a major contributor to rockfall generation. In most of the previous systems the value for the water condition was subjectively determined. For example, in the Oregon Rockfall Hazard Rating System the rater chooses one of four descriptions such as "moderate precipitation or short freezing periods or intermittent water on slope," to assess water conditions (Pierson, 1991). To limit the amount of subjectivity, a new methodology was developed to quantitatively assess water conditions. The basic premise was to define a recharge area that may contribute water to the rock slope in question. Knowing the size of the recharge area, the amount of rainfall expected per year, and the amount of surface runoff, a value of the potential amount of water flowing through the ground to the rock cut was computed. This value was termed the "hydrologic value".

In order to determine the hydrologic value, a recharge area was drawn using a polygon in the computer program ArcView®, which represented an area within which a falling raindrop would enter the ground, following the most likely subsurface path to the slope face (Figure 4.7). Annual rainfall and runoff values were obtained from the Ohio Division of Water Resources map of annual rainfall and runoff for the State of Ohio (Figure 4.8 and 4.9). Annual runoff was then subtracted from annual rainfall for the given area and converted to feet. The value designated as the hydrogeologic coefficient was defined by the equation 4.1.

$$\text{Hydrogeologic Coefficient}(ft^3) = \{\text{RechargeArea}(ft^2)\} * \{\text{Rainfall}(ft) - \text{Runoff}(ft)\} \quad \text{Eq. 4.1}$$

The above equation yields a volume of water in ft^3, which, even though it does not account for evaporation, is essentially the amount of water infiltrating into the ground and flowing underground toward a particular slope. This method takes into account groundwater only. It does not account for any surface water hitting the slope and, therefore, does not account for any erosion on the slope face caused by direct rainfall, wind, or surface runoff.

Rockfall History

According to many reports, the rockfall activity at a site is an indicator of future rockfall events (Brawner and Wyllie, 1975; Wyllie, 1987; Pierson et al., 1990; New York DOT, 1996; Wyllie and Norrish, 1996). For this reason, all previous relative slope-rating systems incorporate the rockfall history of a site. The Oregon RHRS, for example, has the rater subjectively assign a value for rockfall history according to four descriptive categories. The categories include the descriptions of a few falls, occasional falls, many

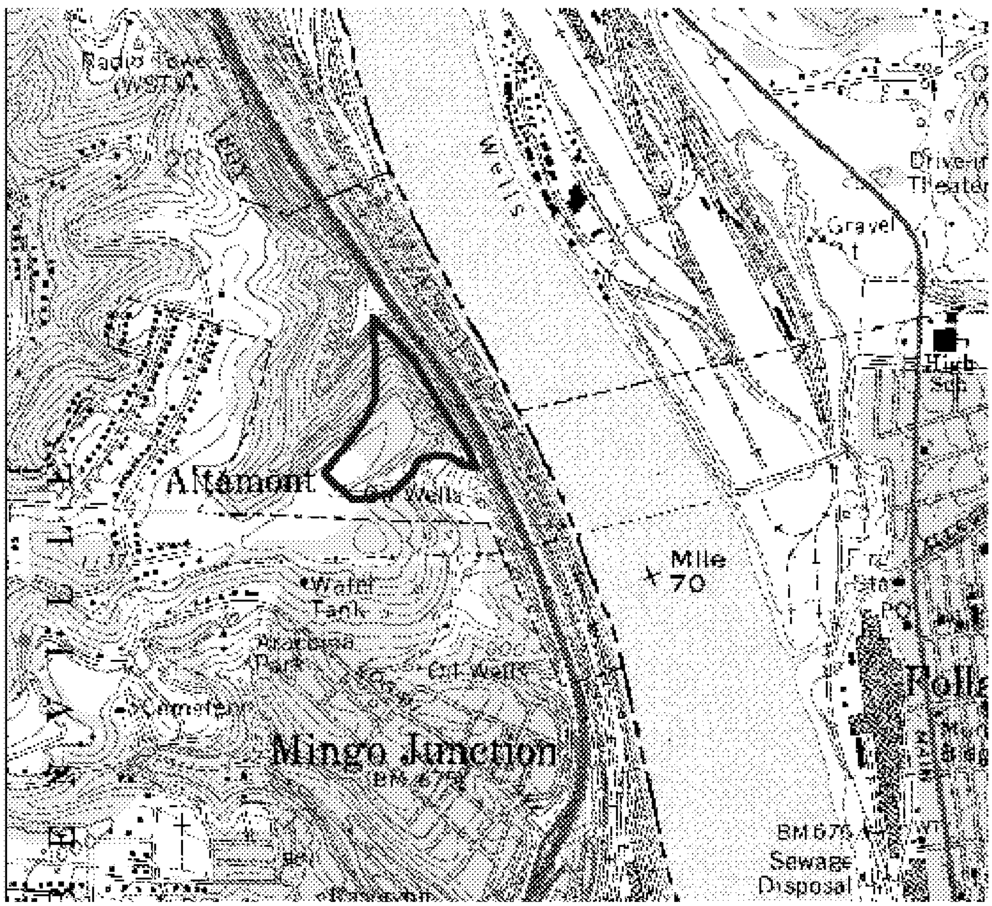


Figure 4.7: Example of a delineated watershed that most likely contributes groundwater to road cut.

Figure 4.8: Average annual precipitation in Ohio (Ohio Department of Natural Resources, Division of Water; Harstine, 1991)

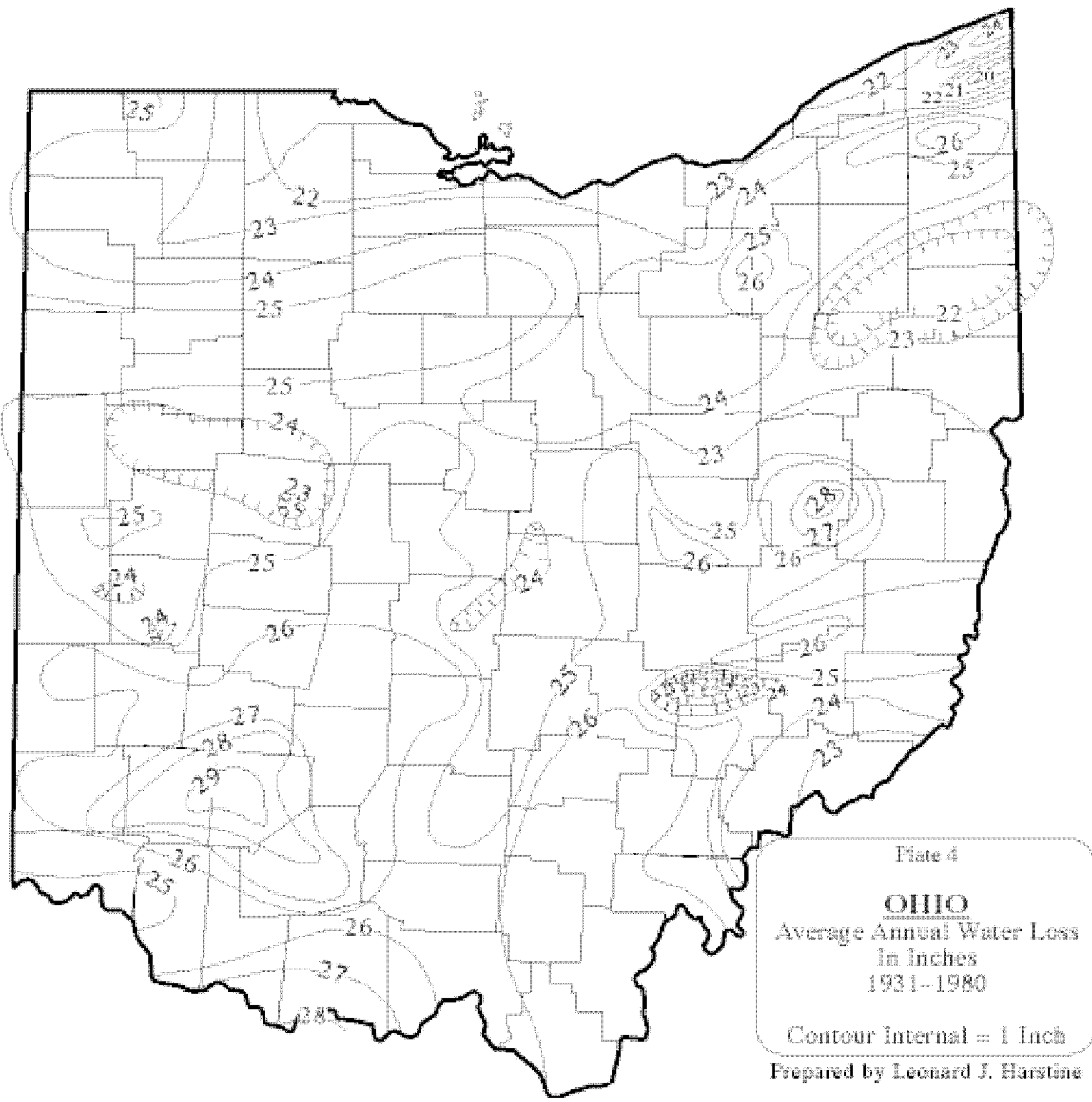


Figure 4.9: Average annual water loss in Ohio (Ohio Department of Natural Resources, Division of Water; Harstine, 1991).

falls, and constant fall (Pierson, 1991). It is also noted that information can be obtained from maintenance personnel or, where no history is available, maintenance costs may reflect rockfall activity (Pierson, 1991). The value selected in the Oregon system is an approximated value within the scale form 3 to 81 points. In case of the New York DOT Rock Slope Rating Procedure, a value is obtained by the category that most closely describes site conditions (New York DOT, 1996).

In order to assess the rockfall history for sites along Ohio roadways, a qualitative assessment was made according to the Oregon and New York procedures. Observations were made concerning the amount of rock debris found in the catchment area, the volume of the blocks, and their potential rollout distances. Remarks were also made if catchment areas had recently been cleaned or if barriers had been placed on the shoulder of the roadway. The performance of the barriers was also noted.

Slope Orientation

The orientation of a slope can be defined in terms of the dip direction of the road cut. For example, if the road traveled from north to south and the road cuts were parallel to it, facing due east, the slope orientation for that slope would be 90^{o} (azimuth compass). Slope orientation may reflect certain trends with respect to rockfall history. For example, south facing slopes are exposed to more changes in temperature (they get more sun) and are potentially more prone to weathering processes and, consequently, rockfalls.

Stratigraphic Section

A weathered profile, with associated stratigraphy, was created for each site (Figure 4.10). The location of the stratigraphic section was taken at the highest point along the slope where rockfalls could generate. Information useful to other aspects of the study, including the Colorado Rockfall Simulation Program, was also taken at this time. During development of the stratigraphic section, joint spacing, bedding thickness, amount of undercutting, and any other notes pertaining to geology of each site were recorded. The stratigraphic sections for individual sites are included in Appendix B.

4.2.4 Human Interaction

The risk of a rockfall impacting a vehicle increases as the time a vehicle being in proximity to a rock slope increases. To account for human interaction, parameters such as the overall slope length, posted speed limit, average daily traffic (ADT), and decision sight distance (DSD) were recorded. In the Oregon Rockfall Hazard Rating System, the following relationship is used to approximate how long a car is exposed to a rock slope.

$$\left[\frac{ADT * Slope\ Length / 24}{Posted\ Speed\ Limit}\right] * 100\% \qquad \text{Eq. 4.2}$$

The above relationship gives an approximation of how often and how long a vehicle is likely to be in contact with the slope (Pierson, 1991). The longer the length of a slope, the greater the time and distance a vehicle may encounter a rockfall and, therefore, greater the potential for a rockfall to impact a vehicle. The value for the average daily traffic (ADT) was obtained from a database provided by the Ohio Department of

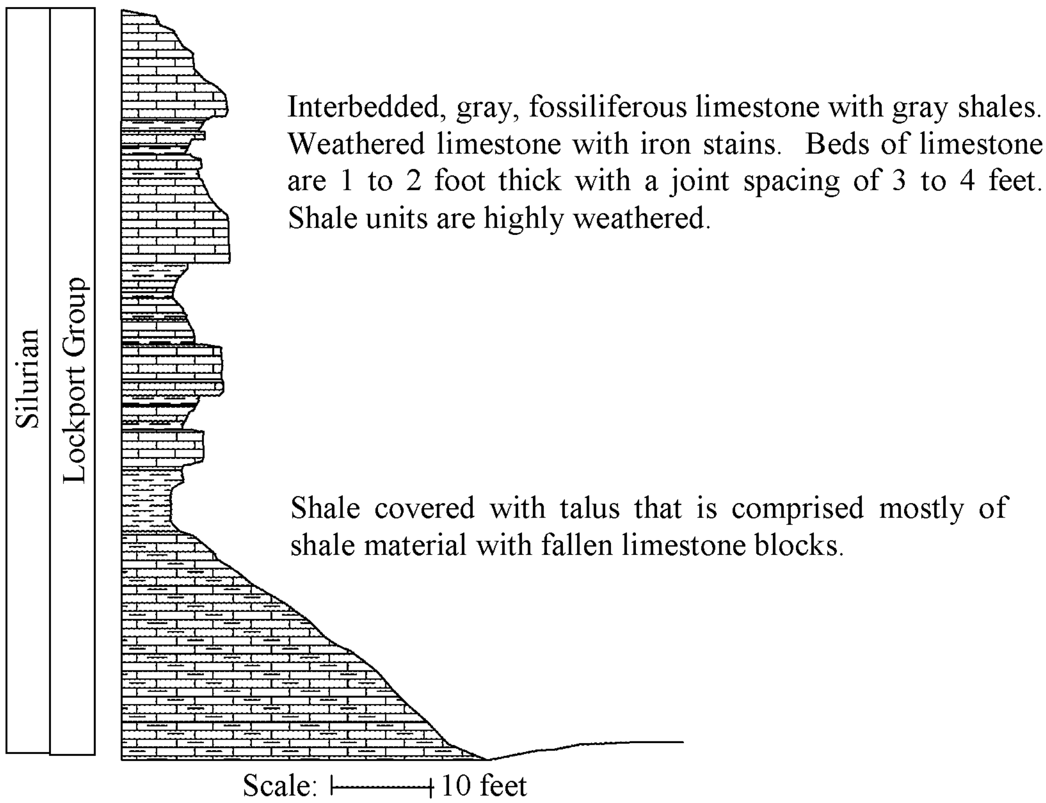


Figure 4.10: Example of a stratigraphic section for the site located at ADA-41-16.1.

Transportation. The posted speed limit of the road was recorded at the site, and the slope length was determined while measuring the geometry of the ditch.

Average Daily Traffic

Average Daily Traffic (ADT), which includes all vehicles, was indirectly measured in this project. The information was obtained from data provided to us by ODOT for all road segments throughout the state. In conjunction with speed limit and length of the slope, a value for how many cars are proximal to the road cut was calculated (equation 4.2).

Slope Length

Slope length is a measure of the extent of the rock slope along the roadway. Slope length can be a factor in both the geometric parameters of the cut as well as the hazard potential. The longer the slope the more the time a vehicle is potentially in contact with an area from which a rock can fall and enter the roadway. The beginning and end points of a road cut were estimated as the portion of the slope that characteristically would have similar rockfall trajectories or rockfall generation sources. The divisions between road cuts included: (i) changes in a cut's aspect to the roadway, (ii) natural breaks in the cut (e.g. tributary valleys), and (iii) large topographic changes that present different slope geometries.

Posted Speed Limit

The designated road signs indicated the speed limit for the segment of roadway proximal to the road cut. Speed limit is used in all methods of evaluating roadway hazards including decision site distance and Oregon Vehicle Risk (Pierson, 1991; New York DOT, 1996).

Roadway Width

Roadway width or pavement width is a direct measure of the distance perpendicular to the trend of the roadway and road cut, and is ideally a measure from edge-to-edge of the pavement. In certain circumstances obtaining edge-to-edge measurement was difficult such as where there was a barrier in the middle of the road. In this case the Roadway width was taken as the edge of road to barrier. Usually this value was also used as the "x" variable (Figure 4.4) in calculating slope heights with an inclinometer. Pavement width can play a role in the maneuverability of a vehicle around a rockfall event.

Percent Decision Sight Distance

The percent decision sight distance (%DSD) is a ratio between the decision sight distance (a design criteria) and the actual sight distance measured at a sight. The actual sight distance is the shortest distance along a roadway over which a six (6) inch (.15 m) object is continuously visible to the driver (height of 3.5 feet or 1 m), and was obtained according to the Oregon Rockfall Hazard Rating System manual (Pierson and Van Vickle, 1990). This was accomplished by placing a cone or hardhat near the edge of the road and measuring the distance away from that object to a point from where it could no longer be seen at the 3.5 foot (1m) height. This measure indicates the distance to which a driver first can see an object, such as a rock in the road, and react to avoid the object.

The Decision Sight Distance (DSD) is a value determined by the Department of Transportation for a certain section of the road. This value is obtained from a chart that considers speed limit, use and type of roadway, and, in some circumstances, the curvature and grade of the road. The values for this project were obtained from the New York DOT values published in their rockfall rating system guide (1996). The value for the percentage DSD used in this study is the ratio of the ASD divided by the DSD. In most cases the percent decision sight distance was found to be so large (greater than 100%) that a driver should have more than enough time to stop.

4.3 Use of the Colorado Rockfall Simulation Program

The Colorado Rockfall Simulation Program (CRSP) uses slope geometry, slope height, slope surface roughness, normal coefficient of restitution (a measure of the degree of elasticity of a rock colliding normal to the slope), tangential coefficient of frictional resistance (a measure of frictional resistance parallel to slope), and physical characteristics of rock (size, shape, and unit weight) as the controlling variables to limit rock behavior (Barrett and White, 1991). The output of CRSP provides rockfall trajectories, bounce heights, and velocities over the entire slope. CRSP was applied to 100 of the study sites in this project. An example of a CRSP output is provided in Figure 4.11.

The methodologies described in the CRSP 4.0 manual (Jones et al., 2000) for determining the normal and tangential coefficients left much to interpret due to the broad descriptions given for the ranges of values to be used. Table 4.1 shows the ranges of scores and descriptions given in the CRSP users manual (Jones, 2000). For this project,

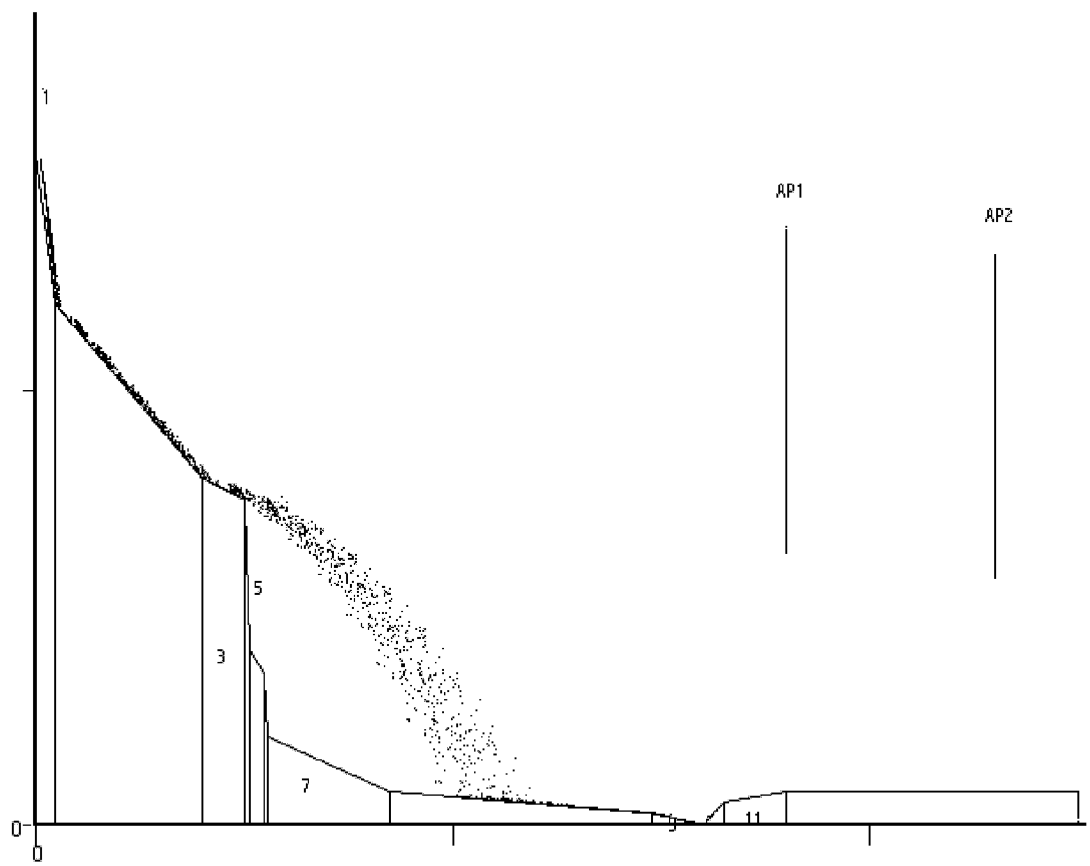


Figure 4.11: Example of a CRSP output profile.

Table 4.1: CRSP coefficient guide for normal and tangential coefficient. Note the wide range of values for each description (Jones, 2000).

Description of Slope	Normal Coefficient (Rn)	Remarks
Smooth hard surfaces and paving	0.60- 1.0	-For short slopes try lower values in applicable range. - If max. velocity /KE* are design criteria, use lower values in range; if avg. velocity/KE* are design criteria, use higher values in range.
Most bedrock and boulder fields	0.15- 0.30	
Talus and firm soil slopes	0.12- 0.20	
Soft soil slopes**	0.10- 0.20	

* KE= kinetic energy

**Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

Description of Slope	Tangential Coefficient (Rt)	Remarks
Smooth hard surfaces and paving	0. 90- 1.0	-Rt is not very sensitive compared to Rn, but may be important for hard or significantly vegetated slopes. -Use lower Rt as the density of vegetation on the slope increases.
Most bedrock and boulder fields	0.75- 0.95	
Talus and firm soil slopes	0.65- 0.95	
Soft soil slopes*	0.50- 0.80	

*Soft soil slope coefficients were extrapolated from other slope types due to lack of data.

the definitions of the coefficients were further refined to create a greater consistency between raters in applying the coefficient values. The refinements were accomplished by assigning coefficient values to the soil and rock hardness descriptions from Piteau (1971). Table 4.2 shows the easy to identify field tests for hardness by Piteau with the associated normal and tangential coefficient values used in this study. These refinements of the CRSP coefficients were made to simplify and standardize their application and are not supported by any new data set.

4.4 Use of Ritchie Ditch Criteria

Ritchie (1963) used the slope height and gradient to design an effective catchment ditch. The results of this study can be seen in Figure 3.5. In order to evaluate the effectiveness of catchment areas, the New York rating procedure compares the actual field measurements of ditches to the requirements suggested by Ritchie (NYDOT, 1996). Note, the Ritchie chart in Figure 3.5 is in metric units and conversion of those units should be made prior to use. If a catchment ditch satisfies Ritchie's criteria it is expected to reduce the number of rocks escaping the catchment area to a maximum of 15 percent (Pierson et al., 2001). For this project, the methods described in the New York procedure (New York DOT, 1996) were used to obtain a value referred to as the Ritchie score. The Ritchie score, developed by the New York DOT (1996), is a mathematical comparison of the prescribed Ritchie values compared to the actual ditch measurements, as indicated below.

$$Ritchie\ Score = \frac{Ritchie\ Depth + Ritchie\ Width}{Actual\ Depth + Actual\ Width} \qquad \text{Eq. 4.2}$$

Table 4.2: Chart showing the relationships between the hardness guide (Piteau, 1971) and the coefficients used in the CRSP computer program.

Hardness Reference Guide with CRSP Coefficient Values				
Hardness input code	Consistency	Field Identification	Normal Coefficient Values (Rn)	Tangential Coefficient Values (Rt)
1	very soft	Easily penetrated several inches by fist	0.10	0.50
2	soft	Easily penetrated several inches by thumb	0.10	0.55
3	firm	Can be penetrated several inches by thumb with moderate effort	0.15	0.65
4	stiff	Readily indented by thumb but penetrated only with great effort	0.15	0.70
5	very stiff	Readily indented by thumbnail	0.20	0.75
6	hard	Indented with difficulty by thumbnail	0.20	0.80-.85
7	extremely soft rock	Indented by thumbnail	0.15	0.75
8	very soft rock	Crumbles under firm blows with point of geological pick, can be peeled by a pocket knife	0.15	0.75
9	soft rock	Can be peeled by a pocket knife with difficulty, shallow indentations made by firm blow of geological pick	0.20	0.80
10	average rock	Cannot be scraped or peeled with pocket knife, specimen can be fractured with single firm blow of hammer end of geological pick	0.25	0.85
11	hard rock	Specimen required more than one blow with hammer end of geological pick to fracture it	0.25-0.30	0.90
12	very hard rock	Specimen required many blows of hammer end of geological pick to fracture it	0.25-0.30	0.95-1.0
13	extremely hard rock	Specimen can only be chipped with geological pick	0.25-0.30	0.95-1.0

If this ratio has a value of 1 or less, it indicates that the catchment area at a site exceeds the recommended dimensions of Ritchie's ditches. As the score increases beyond a value of 1 it indicates that the catchment area is less and less adequate to contain potential rockfalls. The Ritchie score was computed for all 108 sites and used as the geometric parameter in development of the rating matrix.

Ritchie (1963) states in his paper that the ditch criteria presented is applicable to benched and multiple angle slopes. He also states that the overall angle from toe of slope to top of slope should be used as the overall slope angle. It should be noted, however, that this statement has not been researched.

4.5 Laboratory Investigations

4.5.1 Slake Durability Testing

Slake durability is the resistance of a rock to weathering. The slake durability test is especially useful to evaluate the resistance of mudrocks to breakdown by alternating wetting and drying. Samples of mudrocks were collected from all road cuts where they were exposed. Attempts were made to collect samples from horizons of greatest amount of undercutting. If that horizon was inaccessible, samples were collected from an accessible horizon with the next greatest amount of undercutting. A minimum of 30 pounds of sample was collected at each site. Each sample was sealed in two plastic bags to preserve the natural water content.

The slake durability of mudrock units was determined as the second-cycle slake durability index according to the American Society for Testing and Materials (ASTM) method D-4644 (ASTM, 1996). For each field sample, three second-cycle tests were performed to ensure testing consistency. The average of the three tests was used to characterize the slake durability. The raw data for the second-cycle slake durability index can be found in Appendix C.

Slake durability index can indirectly be used as a measure of the rate of undercutting for slopes with an interbedded sequence of durable and non-durable rocks (Gray et al., 1979; Young and Shakoor, 1987; Shakoor and Weber, 1988; Shakoor and Rodgers, 1992; Geiger et al., 1992; Shakoor, 1995). One problem with using slake durability was that not all sites studied contained mudrock units; therefore, some slopes did not have a direct value of slake durability index. For slopes that did not have mudrock units, a default slake durability index value of 100% was assigned in statistical analyses.

CHAPTER 5

STATISTICAL ANALYSIS OF VARIABLES INFLUENCING ROCKFALL HAZARD POTENTIAL

The variables used in statistical analysis and eventual development of the rating matrix were divided into three distinct groups representing the geologic, slope geometric, and traffic conditions that influence rockfall hazard potential. The geologic conditions (slake durability index, maximum amount of undercutting, average amount of undercutting, rock block size, hydrologic value, and slope orientation) include variables that indicate the potential for rockfall occurrence and the size of the rockfall. If a rockfall is geologically possible, then the slope geometric conditions (slope height, slope angle, back slope angle, ditch geometry, and Ritchie score) may suggest whether or not a falling rock may enter the roadway. The traffic conditions (roadway width, average daily traffic, speed limit, Oregon vehicle risk rating, and the percent decision sight distance) consider the hazard posed to vehicles. The field data and laboratory test results representing the three groups stated above, and subjected to statistical analysis, can be found in Appendix C.

The statistical analyses performed on each group of variables included univariate, bivariate, and cluster analyses. Univariate statistics include checks for normalcy and dispersion, bivariate statistics examine correlations between variables, and the cluster analysis explores multi-variate relationships. All three groups of variables were subjected independently to both univariate and bivariate analyses. Cluster analysis involved an examination of variables belonging to individual groups as well as combinations of variables from different groups. Table 5.1 summarizes various statistical analyses performed, their purpose, and conclusions drawn from each analysis.

5.1 Univariate Statistical Analysis

Univariate statistical analysis was performed on each variable with two goals in mind: (i) checking the data set for possible outliers and errors, and (ii) checking whether or not each variable was normally distributed. The first step was to plot the frequency distribution histograms and QQ-plots for each variable. Both of these plots give a visual representation of the data from which the type of distribution can be studied. These plots can be used to identify outliers in the data set. An outlier is a point in the data that falls so far from the mean that it is unlikely to be from that distribution. Outliers are indications of potential errors in the data set. An example of a discovered error can be found in Figure 5.1a that shows the frequency distribution histogram of the initial roadway widths. The histogram shows some roadway widths are greater than 50 feet (15 m), slightly skewing the data to the left. This width in reality would indicate a measurement of a roadway width from across four lanes of traffic. Since no field measurements involved more than two lanes of traffic, this represents a possible error in the data. After reviewing the field notes for those particular sites, it was discovered there was an error in data entry. The corrected roadway width values can be seen in Figure 5.1b that shows that the distribution is no longer skewed to the left and is visually more

Table 5.1: Summary of statistical analyses performed and conclusions drawn.

Statistics Performed	Purpose	Conclusions
Divide into groups	Examine different slope mechanics	Geology Geometry Traffic
Univariate Statistics Frequency-distribution histograms QQ-plots Summary statistics	-Check for outliers (errors in data). -Test for normality	Raw or natural log data indicate normality
Bivariate Statistics x-y scatter plots Correlation coefficients (R^2)	-Check for outliers (reapply Univariate Statistics). -Identify variables that provide independent information	Cleaned data rechecked through univariate statistics. Some data provided similar information (maximum and typical amount of undercutting)
Cluster Analysis K-means Analysis of variance	-Determine significant variables. -Group or cluster data	Significant variables obtained for geology and geometry

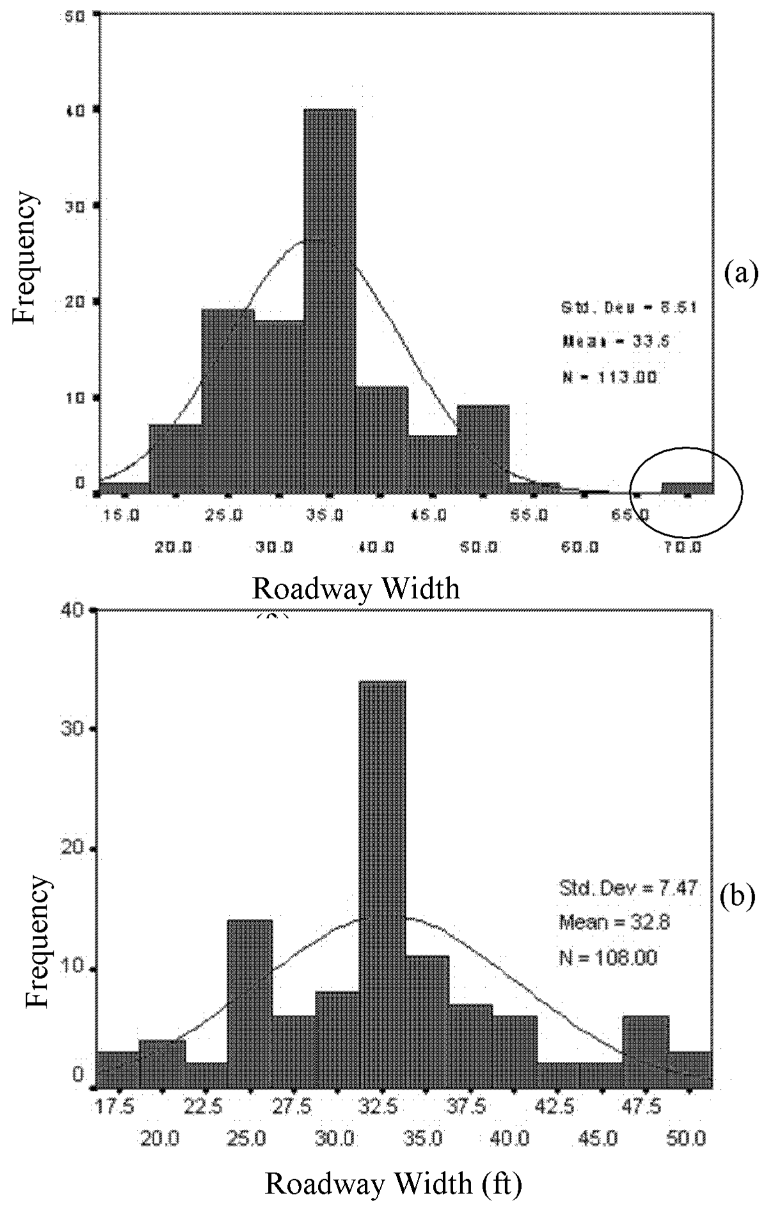


Figure 5.1: Example of outliers found in frequency distribution histograms:
(a) initial roadway width data with data indicating widths beyond 50 feet (15 m), and (b) corrected roadway width data.

normally distributed. Each variable in the data set was taken through this process to ensure accuracy of the data set.

Summary statistics analysis was also employed to determine coefficient of variation, standardized skewness, and standardized kurtosis. These statistics were used to further check if the data was normally distributed. The coefficient of variation is the ratio of the standard deviation to the mean and is a measure of relative dispersion. The use of coefficient of variation lies partly in the fact that the mean and standard deviation tend to change together in many experiments. If the values for the coefficient of variation are more than 0.5, or 50%, it suggests lack of control in data or process. The larger the coefficient of variation the less the control exhibited by in the data set. If the coefficient of variation is greater than 0.5 or 50%, a transformation of the variable may help in improving the normality.

Skewness and standardized skewness measure how symmetric the data is. Data from a normal distribution will have a skewness value around zero and will appear symmetric to the left and right of the center of a frequency-distribution histogram. Data with a long upper tail will have a positive value of skewness (shift to left), while data with a long lower tail will have a negative value (shift to right). The standardized skewness can be used to determine whether the observed skewness is consistent with the hypothesis that the data came from a normal distribution. For a large sample size, standardized skewness is obtained by dividing the skewness by $(6/n)^{0.5}$, where n is the sample size. If the data came from a normal distribution, the standardized skewness should fall within the range (-2, 2) indicating that the true values lie within two standard errors. If the standardized skewness falls outside the specified range, a transformation of the data may be helpful.

Kurtosis and standardized kurtosis measure the peakedness of a distribution. Data from a normal distribution will have a kurtosis value around zero. Data from a distribution with a sharper peak than the normal will tend to have a positive value (leptokurtic), while data from a distribution with a flatter peak will tend to have a negative value (platykurtic). The standardized kurtosis can also be used to determine whether the observed kurtosis is consistent with the hypothesis that the data came from a normal distribution. For large sample size, standardized kurtosis is obtained by dividing the kurtosis by $(6/n)^{0.5}$, where n is the sample size. If the data came from a normal distribution, the standardized kurtosis should fall within the range (-2, 2) indicating that the true values lie within two standard errors. Similar to standardized skewness if the standardized kurtosis falls outside the specified range, it may be helpful to transform the data.

If a variable was not found normally distributed by one or both of the previously mentioned methods (standardized skewness and kurtosis), the data was transformed (commonly using a natural log transformation) and re-investigated for normality to characterize the data.

5.1.1 Univariate Analysis of Geologic Variables

The variables included in the geology group are slake durability index, maximum amount of undercutting, average amount of undercutting, block weight, hydrologic value, and slope orientation. The frequency-distribution histograms and QQ-plots for the geologic variables can be found in Appendix D. The summary statistics for the geology variables are shown in Table 5.2. In examination of the summary statistics, all of the geologic variables have problems with respect to either normality or dispersion.

The second-cycle slake durability index data shows that it is both skewed (standardized skewness= -8.2) and leptokurtic (standardized kurtosis= 7.2). This may be explained by the data not coming from one population of data but multiple populations. As explained in section 4.3.1, sites that did not contain weak rocks were assigned a default value of 100% for slake durability index. This indicates that there area at least two population within the slake durability data; weak rocks with percentages less than 100% and non-weak rocks with slake durability index values at 100%.

The raw data for the maximum amount of undercutting shows a slightly higher than desired coefficient of variation (0.75). However, the standardized skewness and kurtosis are well within the acceptable ranges. This indicates that a transformation may help to normally distribute the data. The histograms of the raw and transformed (natural log transformation) data can be seen visually in Figure 5.2. In examining the histogram of the untransformed data, the data as a whole seems normally distributed except for the far left column designated zero feet. The data set appears to be truncated or has the appearance of continuing beyond the end of the data set. This skewness in the data may be due to the absence of undercutting at a limited number of the slopes, which were assigned a value of zero feet. In regard to raw data distribution, it should be noted that negative values for undercutting are reasonable. This is logical because the opposite of undercutting is ledging and, therefore, the data shows the natural variability in the slope

Table 5.2: Summary statistics of the geological Variables. The highlighted values indicate departure from normalcy.

Statistical Measures	Slake Durability Index (%)	Max. Amt. of Undercut. (ft)	log Max. Amt. of Undercut. (ft)	Avg. Amt. of Undercut. (ft)	log Avg. Amt. of Undercut. (ft)	Block Size (lbs)	log Block Size (lbs)	Hydro. Value (ft^3)	log Hydro. Value (ft^3)	Slope Orientation (degrees)
Mean	82	2.7	0.47	1.3	0.13	718	4.76	9.85E+05	13.38	120
Standard Deviation	24	2.1	0.26	1	0.28	3105	1.57	1.05E+06	0.95	87
Skewness	-1.93	0.27	-0.87	0.49	-0.55	6.84	0.72	2.85	-0.11	0.66
Kurtosis	3.4	-0.8	0.37	-0.8	-0.29	47.50	1.90	11.2	0.10	-0.2
Coefficient of Variation	0.3	0.75	0.57	0.8	2.23	4.32	0.33	1.07	0.07	0.72
Standardized Skewness	-0.82	1.2	-3.6	2.0	-2.4	29.2	3.1	12.2	-0.5	2.8
Standardized Kurtosis	7.2	-1.8	0.8	-1.6	-0.7	100.3	4.0	23.9	0.2	-0.4

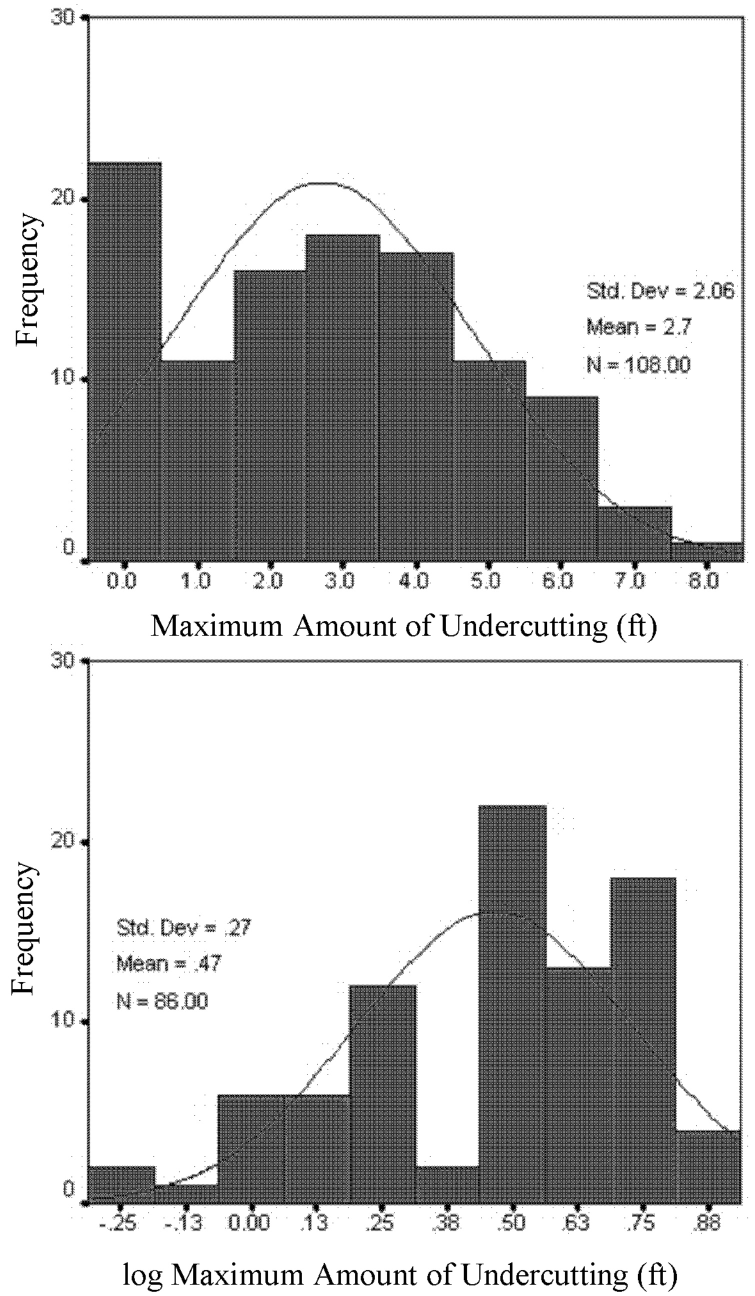


Figure 5.2: Frequency histogram of maximum amount of undercutting data; (top) raw data, (bottom) transformed data. The raw data appears to be more normally distributed than the transformed data.

morphology. The histogram, therefore, shows an unnatural cutoff of the data caused by the data collection methodology. Otherwise the data appears to be normally distributed and transformation of data is not needed.

As with the maximum amount of undercutting, the average amount of undercutting is also found to be truncated, meaning the data seems to be cut off from a typical bell-shaped curve. However, in the case of the average amount of undercutting the transformed data drastically enlarges the coefficient of variation indicating that the use of untransformed data is more appropriate.

The summary statistics of the block weight indicate many problems with normalcy. After a natural log transformation, there is more control in the data and the standardized skewness and kurtosis values fall closer to acceptable ranges. Therefore, the natural log of block weight was used in further analysis.

The hydrologic value had issues with all three summary statistics. The natural log transformation greatly improved the coefficient of variation, standardized skewness and standardized kurtosis values (Table 5.2).

Slope orientation is a difficult variable to deal with in this data set due to the fact that it is a compass measure on a 360^{o} scale as opposed to a linear scale. This creates problems with respect to statistical handling of slope orientation data. However, slope orientation data was also kept for further analysis.

5.1.2 Univariate Analysis of Geometric Variables

Slope geometry includes the variables of slope height, slope angle, back slope angle, ditch width, ditch depth, and Ritchie score. After checking the data for possible errors and nature of distribution, slope angle and ditch width were found to be normally distributed (Table 5.3). Slope height and back slope angle were easily normalized with a natural log transformation. The reason for the elevated coefficient of variation for the log of back slope angle (Table 5.3) is similar to that for the undercutting related geologic variables. There is a truncation of the data at zero degrees (horizontal back slope), which was frequently encountered along Ohio roadways. The frequency distribution histogram of ditch depth (Figure 5.3) appears to be slightly leptokurtic in shape. However, the standardized kurtosis value (0.3) indicates a distribution that falls within an acceptable range.

Both the raw and transformed data for the Ritchie score showed departures from normal distribution. This may be the result of how the Ritchie score is calculated or the manner in which ditches in Ohio are designed. This value is determined by a ratio between two field-collected variables and two variables obtained from non-linear relationships off a graph (Figure 3.5). Theoretically, this is a very complicated structure to deal with statistically. Since the data set contains all the field variables used to determine the Ritchie score (slope height, slope angle, ditch depth, and ditch width) and since this variable presents difficulties with respect to statistics, it was not continued through the cluster analysis. However, the Ritchie criteria has proven to be a useful tool in the construction of catchment areas and other rating systems (NYDOT, 1996; Pierson et al., 2000) and may still be useful in the final matrix.

Table 5.3: Summary statistics of the geometric variables. The highlighted values indicate departures from normalcy

Statistical Measures	Slope Height (ft)	log Slope Height (ft)	Slope Angle (degrees)	Back slope Angle (degrees)	log Back slope Angle (degrees)	Ditch Depth (ft)	Ditch Width (ft)	Ritchie Score
Mean	85	4.19	61	17	2	1.4	18.3	1.49
Standard Deviation	62.54	0.71	13.80	17.56	1.49	0.86	7.86	0.89
Skewness	1.39	0.10	0.24	0.86	-0.37	2.31	0.15	3.11
Kurtosis	1.69	0.10	0.25	0.86	-0.35	2.28	0.15	3.11
coefficient of variation	0.74	0.17	0.23	1.03	0.72	0.61	0.43	0.60
standardized skewness	6.00	0.40	1.10	3.70	-1.50	9.70	0.60	13.30
standardized kurtosis	3.60	0.20	0.50	1.80	-0.70	4.90	0.30	6.60

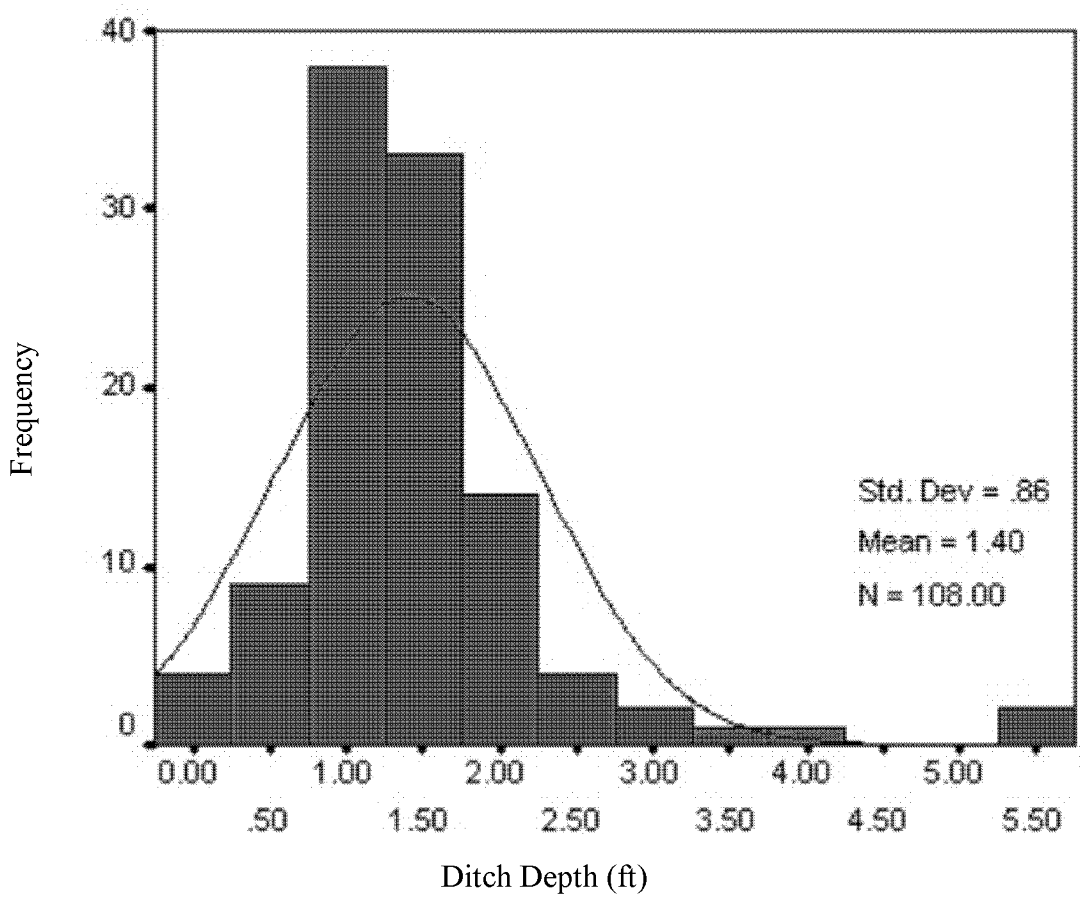


Figure 5.3: Frequency distribution histogram of ditch depth data. Note the possible outliers to the far right of the graph.

5.1.3 Univariate Analysis of Traffic Variables

The variables pertaining to the traffic group include roadway width, average daily traffic (ADT), posted speed limit, Oregon vehicle risk (OVR), decision sight distance (DSD), and slope length. Of these variables, roadway width was the only variable found to be normally distributed (Table 5.4). Slope length was normalized with a natural log transformation and the average daily traffic fell closer to a normal distribution after log transformation.

Posted speed limit had issues with both standardized skewness and kurtosis. One explanation for this is that the posted speed limit is a value with discrete numbers, commonly 45, 55 and 65 miles per hour (mode equaling 55 mph). A data set of discrete values can naturally result in a leptokurtic distribution, and this creates a problem in dealing with engineered values that tend to be discrete in nature.

The Oregon vehicle risk value, a combination of the average daily traffic, posted speed limit, and slope length, originally was found not normally distributed until a natural log transformation was performed which resulted in a distribution that was found to be slightly skewed. However, this variable contains variables that do have some theoretical issues with respect to normalcy.

Percent decision sight distance also presented some problems with respect to normality. According to the summary statistics, the percent decision sight distance was found to have an acceptable range for the coefficient of variation but showed a significant skewness and variability. Further examination of the percent decision site distance revealed that only 5 out of the 108 sites in this study contained values less than 100%. If

Table 5.4: Summary statistics for the traffic variables. The highlighted values indicate issues with normalcy

Statistical Measures	Roadway Width (ft)	log Average Daily Traffic (cars/day)	Posted Speed Limit (mph)	log Posted Speed Limit (mph)	Oregon Vehicle Risk	log Oregon Vehicle Risk	Percent Decision Sight Distance	Slope Length (ft)	log Slope Length (ft)
Mean	33	9.01	55	4	223	4.51	98	1025	6.65
Standard Deviation	7.5	1.18	7.2	0.16	324	1.5	11.8	899	0.73
Skewness	0.33	-0.68	-2.02	-3.29	2.8	-0.5	-5.58	2.29	0.36
Kurtosis	0.10	0.99	6.97	15.36	8.9	0.07	31.20	6.63	-0.18
Coefficient of Variation	0.23	0.13	0.13	0.04	1.45	0.33	0.12	0.88	0.11
Standardized Skewness	1.40	-2.80	-8.60	-14.00	12.00	-2.00	-23.80	9.80	1.60
Standardized Kurtosis	0.20	2.10	14.90	32.80	19.10	0.30	66.60	14.10	-0.40

this variable was kept, it could skew the results of cluster analysis and blur the identification of other more continuous variables. The lack of sites with lower than 100% percent DSD values is a function of the size of the data set and, therefore, the importance of this variable should not be completely ignored. However, due to the problems it may cause in the cluster analysis, percent DSD was not considered in the cluster analysis.

5.2 Bivariate Statistical Analysis

Bivariate statistical analysis examines how each variable relates to the other variables. In this study all variables in a group (geologic variables, geometric variables, and traffic related variables) were compared to each other using x-y scatter plots (Appendix E). Scatter plots suggest possible relationships. The closer the data points plot to a straight line, the higher the correlation in magnitude between the two variables, or the stronger the relationship.

A correlation coefficient (r) is a number between -1 and 1 that measures the degree to which two variables are linearly related. If there is a perfect linear relationship with a positive slope between the two variables, it has a correlation coefficient of 1. A positive correlation between the two variables indicates that whenever one variable has a higher or lower value, so does the other. If there is a perfect linear relationship with a negative slope between the two variables, the relationship has a correlation coefficient of –1. A negative correlation between the variables indicates that whenever one variable has a higher or lower value, the other has a lower or higher value, respectively. Having a correlation coefficient of 0 means there is no linear relationship between the two variables.

The x-y scatter plots were also used to identify potential outliers in the data sets. An example of a potential outlier can be seen in Figure 5.4, which is an x-y scatter plot of the slope angle versus ditch depth. On this plot two sites have ditch depths greater than 5 feet (1.5 m), which is much more than expected. Again, the field notes were reviewed and these particular sites were found to contain ditches that were dug at the location of the catchment areas. Therefore, these outliers were considered correct and were kept in the data set.

The purpose of bivariate statistics was to establish if any two variables provide the same information. If there were a strong correlation between two variables, it would indicate that one variable could be used to predict the other. In that case it would be justified to use only one of the two variables in the final stage of analysis. This is of vital importance for this project due to the high number of variables considered and relatively low site population. It is also of economic significance, as collecting data about more variables requires more time and resources.

5.2.1 Bivariate Analysis of Geologic Variables

The correlation coefficient values (r) for the geology group can be seen in Table 5.5. According to the correlation coefficient values, slake durability index (SDI) provides independent information due to the r-values being near zero. However, the x-y scatter plot (Figure 5.5) containing SDI exhibits truncation of the data. This is due to the fact that many slopes in Ohio do not contain weak rocks. For those particular cuts made of more durable rocks, such as limestone, the SDI value could be as high as 10 to 100 times that of mudrocks. However, since the slake durability test is not designed to

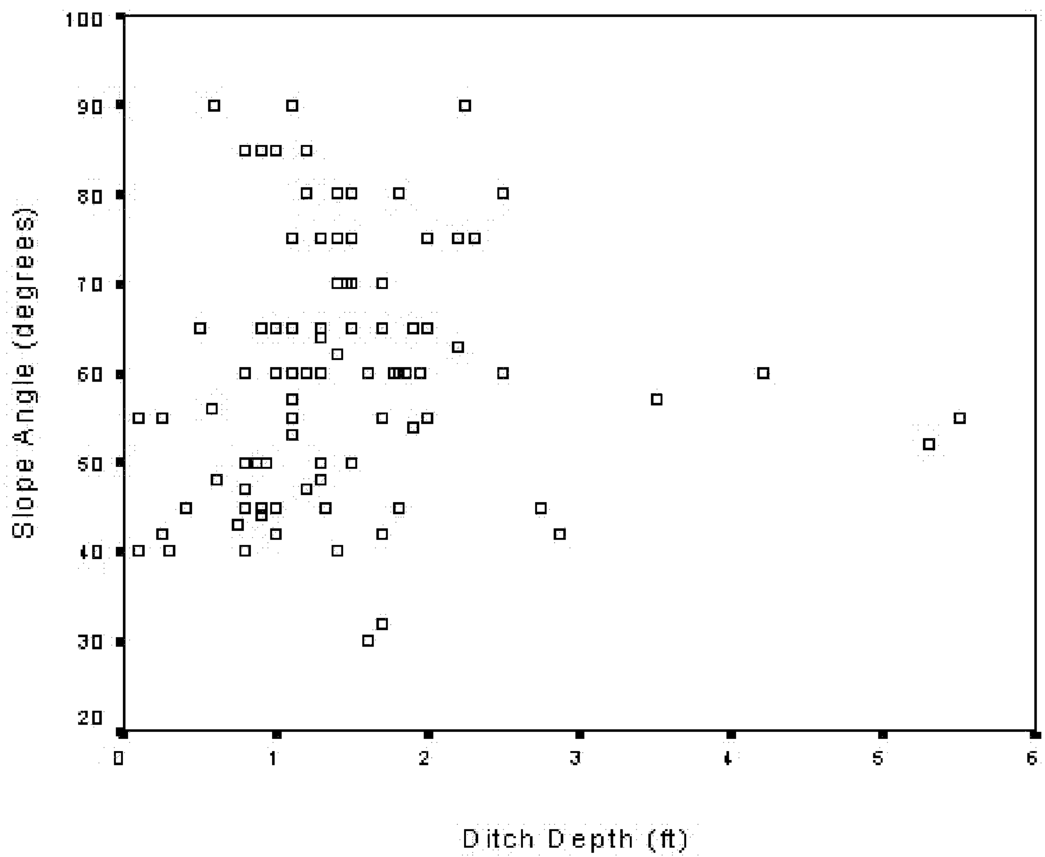


Figure 5.4: An x-y scatter plot of slope angle versus ditch depth.

Table 5.5: Correlation coefficient (r^2) values for geologic variables.

Variables	Slake Durability Index (%)	Max. Amt. of Undercutting (ft)	log Max. Amt. of Undercutting (ft)	Avg. Amt. of Undercutting (ft)	log Avg. Amt. of Undercutting (ft)	log Block Size (lbs)	log Hydro. Value (ft^3)	Slope Orient. (degrees)
Slake Durability Index (%)	1							
Max. Amt. of Undercutting (ft)	-0.06	1						
log Max. Amt. of Undercutting (ft)	-0.04	0.89	1					
Avg. Amt. of Undercutting (ft)	-0.03	0.82	0.65	1				
log Avg. Amt. of Undercutting (ft)	-0.01	0.70	0.78	0.90	1			
log Block Size (lbs)	0.00	0.03	0.04	0.03	0.04	1		
log Hydrologic Value (ft^3)	0.00	-0.01	0.00	-0.01	0.00	0.08	1	
Slope Orient. (degrees)	0.00	0.00	0.00	0.01	0.00	0.00	0.00	1

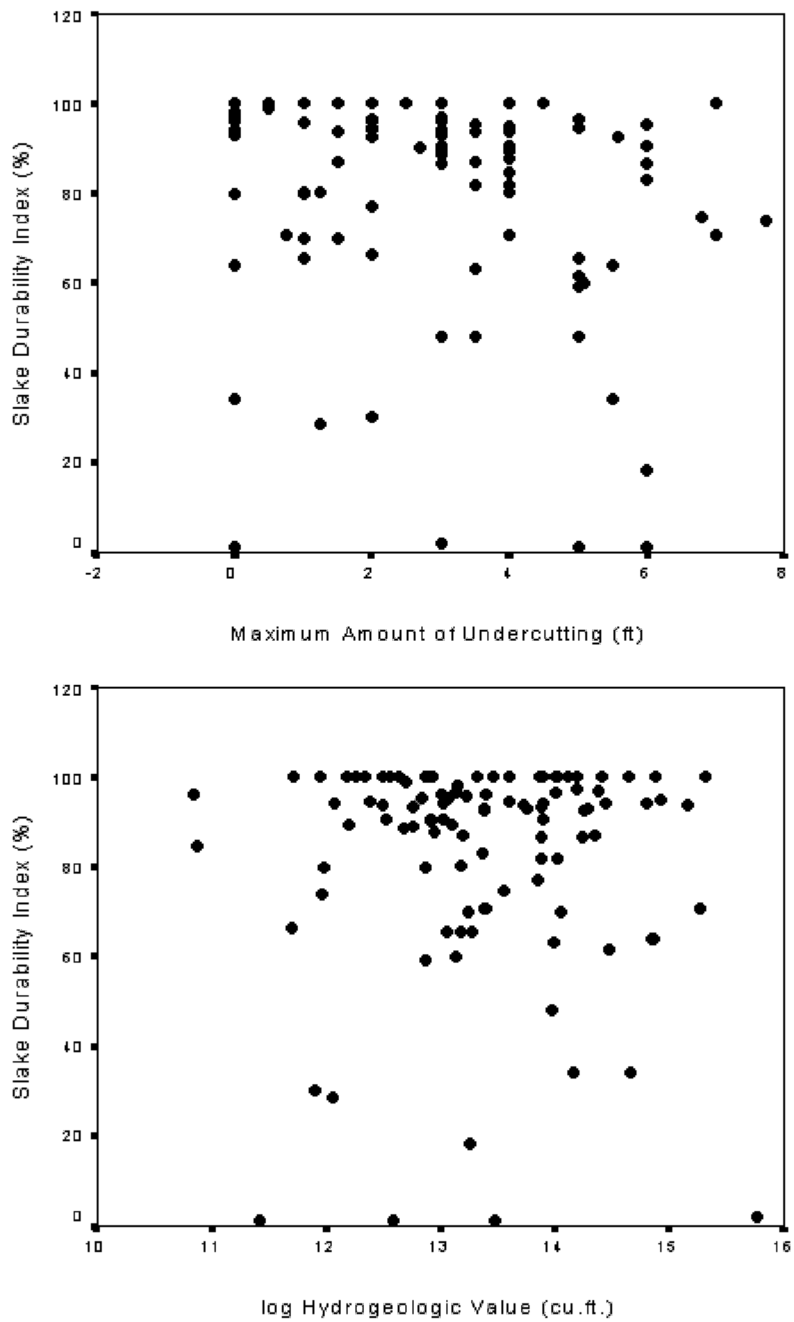


Figure 5.5: Relationship of slake durability index with: (top) maximum amount of undercutting and (bottom) log of hydrologic value. Note the truncation or stopping of continual reporting of the slake durability index values beyond 100%.

examine those particular lithologies, a default value of 100% was assigned. According to the statistics, SDI values for those slopes that were assigned 100% values should actually have greater values for the truncation not to occur.

The geologic variables (slake durability, maximum amount of undercutting, average amount of undercutting, block size, hydrologic value and slope orientation) all provide useful information for examining different geologic settings in Ohio, and their potential for rockfall generation and falling block size. Both the natural log of hydrologic value and the natural log of block weight variables provide independent information and were included in the further statistical analysis. Only the maximum amount of undercutting and the average amount of undercutting show a strong correlation ($r = 0.82$) with each other (Figure 5.6). Since both undercutting variables indicate the amount of erosion at a particular site, it makes sense that there is a strong correlation between them. Also, since both undercutting measures provide the same information and since statistical tests do not indicate which of these two variables should be carried on to the cluster analysis, a choice between the two was necessary. The maximum amount of undercutting was chosen due to its ease in measuring in the field. An attempt was made to correlate the maximum amount of undercutting with the SDI but no strong relationship was found between the two variables.

Based on the assumption that south-facing slopes should have a greater exposure to sunlight and, therefore, a possibility of a greater number of freeze-thaw events than a north-facing slope, a relationship between slope orientation and amount of undercutting was anticipated. However, such a relationship was not found. Since there is no

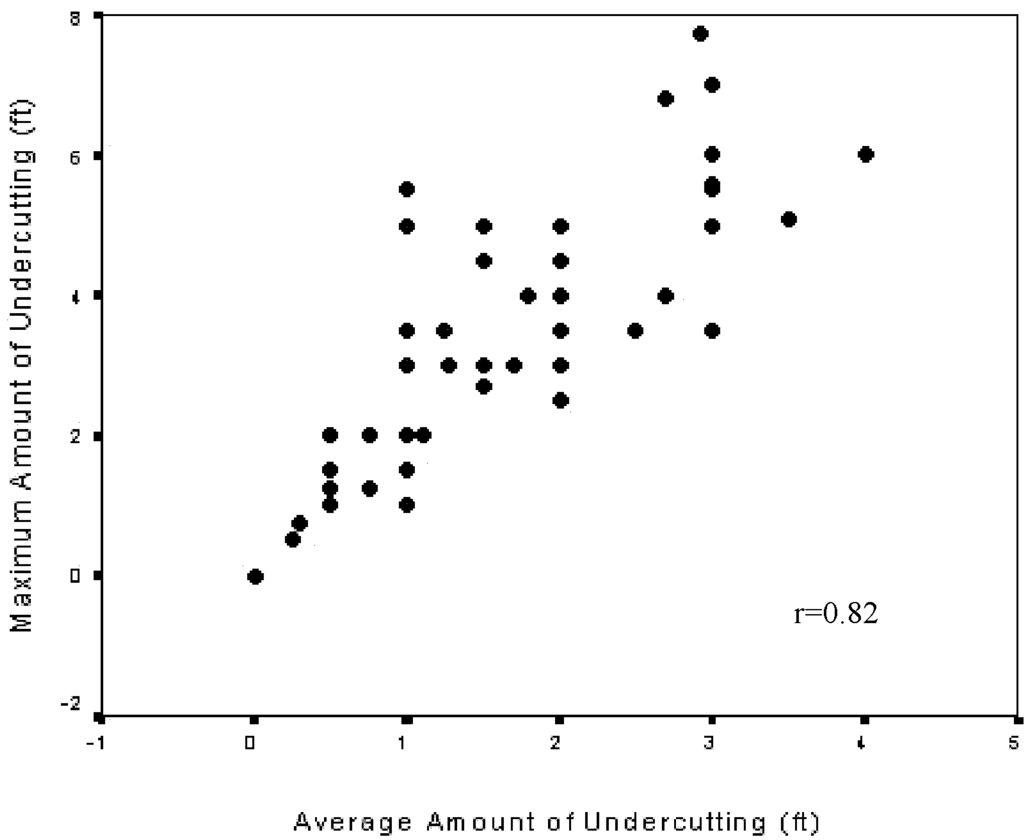


Figure 5.6: Relationship between maximum amount of undercutting and average amount of undercutting. Note the strong relationship (r=0.82) between the two variables.

relationship between slope orientation and the amount of undercutting, and since slope orientation is a compass direction that causes problems in using it in this statistical analysis, slope orientation was removed from the data set used in cluster analysis. This leaves slake durability index, maximum amount of undercutting, natural log of block size, and natural log of hydrologic value to be used in the cluster analysis.

5.2.2 Bivariate Analysis of Geometric Variables

Table 5.6 shows the correlation coefficients for both the raw and some transformed data sets pertaining to slope geometry. During the univariate statistical analysis for slope geometry, natural log of slope height, slope angle, natural log of back slope angle, ditch depth, ditch width, and Ritchie score were examined. Table 5.6 indicates that only two variables, namely the ditch width and Ritchie score, show a weak relationship with each other (r=0.29). This weak relationship is quite logical because ditch width is used to calculate the Ritchie score. Due to the relationship between ditch width and Ritchie score, the previously mentioned problems with the Ritchie score, and that the raw data used to obtain the Ritchie score (slope height, slope angle, ditch width and ditch depth) are within this group, the removal of the Ritchie score from the data set is justified for the cluster analysis. All other variables show little correlations with each other and can be used in the cluster analysis.

5.2.3 Bivariate Analysis of Traffic Variables

As compared to the other groups of data, traffic variables show a relatively higher overall degree of correlation with each other (Table 5.7). For example, the natural log of

Table 5.6: Correlation coefficient (r) values for geometric variables.

Variables	log Slope Length (ft)	log Slope Height (ft)	Slope Angle (degrees)	log Back Slope (degrees)	Ditch Depth (ft)	Ditch Width (ft)	Ritchie Score
log Slope Length (ft)	1						
log Slope Height (ft)	0.07	1					
Slope Angle (degrees)	0.01	0.06	1				
log Back Slope (degrees)	0.03	0.02	0.00	1			
Ditch Depth (ft)	0.00	0.02	0.00	0.03	1		
Ditch Width (ft)	0.10	0.11	0.03	0.04	0.07	1	
Ritchie Score	0.04	0.02	0.01	0.01	0.1	0.29	1

Table 5.7: Correlation statistics (r) values for traffic variables.

Variables	Roadway width (ft)	log Average Daily Traffic (cars/day)	Posted Speed Limit (mph)	log Oregon Vehicle Risk	% Decision Site Distance	log Slope Length (ft)
Roadway width (ft)	1					
log Average Daily Traffic (cars/day)	0.38	1				
Posted Speed Limit (mph)	0.37	0.31	1			
log Oregon Vehicle Risk	0.40	0.89	0.26	1		
% Decision Site Distance	0.05	0.18	0.01	0.22	1	
log Slope Length (ft)	0.28	0.29	0.26	0.68	0.17	1

Oregon Vehicle Risk exhibits a strong correlation with the natural log of average daily traffic (r=0.89) and a moderately strong correlation with the natural log of slope length (r=0.68). This is expected because average daily traffic, slope length, and posted speed limit are used in calculating the Oregon Vehicle Risk. Other relatively weak relationships between variables in this data set are also present. Since the natural log of Oregon Vehicle Risk variable is a combination of the average daily traffic, slope length, and posted speed limit, it was used in the final cluster analysis. Since the log of the Oregon vehicle risk and roadway width were the only traffic variables that were normally distributed, and based on the above discussion, only the roadway width and natural log of Oregon Vehicle Risk were used in the final cluster analysis stage.

5.3 Cluster Analysis

Cluster analysis is used to classify a set of observations into two or more mutually exclusive, unknown, groups based on combinations of individual variables. The purpose of cluster analysis is to discover a system of organizing observations into groups where members of the groups share properties in common. It is cognitively easier to predict behavior or properties based on group membership, where members share similar properties. In this study the aim was to divide all the sites into slopes of similar characteristics, i.e., vertically short slopes with adequate catchment areas versus tall slopes with highly inadequate catchment areas and the in-between categories.

The cluster analysis attempts to identify relatively homogeneous groups of cases based on selected characteristics, using an algorithm that can handle a large number of cases. The computer program SPSS was used to perform the cluster analysis. One of the most well known clustering methods is k-means. In the k-means algorithm, observations are classified as belonging to one of the k-groups. Group membership is determined by calculating the centroid for each group (the multidimensional version of the means) and assigning each variable to the group with the closest centroid. However, the algorithm requires that the number of clusters be specified. In this study, three cluster centers were chosen.

Analysis of variance, or ANOVA, was used to test the null hypothesis. The null hypothesis in this case is that there is no difference between the means in the population or the data has come from the same population. If the null hypothesis is true it indicates there is no difference between the means of each of the k-groups and that the groups are the same. Conversely, if the null hypothesis is rejected, then there is a difference between the means and those variables are helping to define the groups. The null hypothesis is a term that statisticians often use to indicate the statistical hypothesis being tested. The purpose of most statistical tests is to determine if the obtained results provide a reason to reject the null hypothesis (sample means or groups are equal), that they are merely a product of chance factors. For example, in an experiment in which two groups of randomly selected subjects have received different treatments and have yielded different means, it is always necessary to ask if the difference between the obtained means is among the differences that would be expected to occur by chance whenever two groups are randomly selected. In this example, the hypothesis tested is that the two samples are from populations with the same mean. Another way to say this is to assert that the investigator tests the null hypothesis that the difference between the means of the populations, from which the samples were drawn, is zero. If the difference between the means of the samples is among those that would occur rarely by chance when the null hypothesis is true, the null hypothesis is rejected and the investigator describes the results as statistically significant. This was achieved by comparing the sample variance estimated from the group means to that estimated within the groups.

To test the null hypothesis, meaning that the means of the variables are the same, the F-test was utilized and the results were reported within ANOVA tables. The F-test is the ratio of the variance between all the variables tested and the variance of a particular variable. A large F-test ratio, with low probability, indicates that a particular variable has a variance significantly different and, therefore, is providing independent information. If the F-test ratio nears zero it indicates that the variable is not different than the mean and does not contribute independent information. While these statistics are opportunistic (the procedure tries to form groups that do differ), the relative size of the statistics provides information about each variable's contribution to the separation of the groups.

5.3.1 Cluster Analysis of Geological Variables

The slake durability index, maximum amount of undercutting, and the natural logs of both block weight and hydrologic value were initially examined using cluster analysis. Table 5.8 shows the associated ANOVA table from the cluster analysis where the computer program SPSS was asked to divide the data into three groups. In examining the ANOVA table (Table 5.8), there are two distinct groupings of the data. The slake durability index and the maximum amount of undercutting show large F-test values (greater than 1) and low significance ratios (less than 0.05). This implies that for these

Table 5.8: Initial ANOVA table for the cluster analysis of the geologic variables. Highlighted values indicate F-test and significance values at a range that those variables are not aiding in differentiation of slopes.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
Slake Durability Index (%)	27846.2	2	58.281	105	477.795	0
Max. Amt. of Undercutting (ft)	17.484	2	3.993	105	4.379	0.015
log Block Size (lbs)	2.25	2	2.478	105	0.908	0.406
log Hydro. Value (ft^3)	0.825	2	0.898	105	0.919	0.402

two variables the null hypothesis can be rejected and that these variables are helpful in distinguishing between the clusters.

Conversely, the variables of the natural logs of block weight and hydrologic value have very low F values and relatively high significance (probability) values suggesting that the null hypothesis is true and that there are similarities between the means. This indicates that these variables are not contributing to the differentiation of the clusters. Furthermore, it also indicates that perhaps the use of these variables may blur the differentiation of the clusters.

In order to further test this observation, the slake durability index and the maximum amount of undercutting were again subjected to the cluster analysis technique. Table 5.9 shows the results of this second cluster analysis and the associated ANOVA table. Comparing the results of this cluster analysis with those of the previous analysis shows no change in the cluster centers of the groups. This indicates that the slake durability index and the maximum amount of undercutting can be used to differentiate between slopes of similar geologic characteristics with respect to rockfall hazard potential.

A visual representation of the cluster analysis can be seen in Figure 5.7 which shows an x-y scatter plot of slake durability index versus the maximum amount of undercutting with the associated group assignments. An examination of Figure 5.7 shows the presence of three cluster groups based almost entirely on the slake durability index (SDI). The first cluster group contains slopes with high slake durability index values (>80%), the second cluster group contains slopes with low SDI values (<40%), and the

Table 5.9: ANOVA table for the cluster analysis of slake durability index and maximum amount of undercutting.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
Slake Durability Index (%)	27846.2	2	58.281	105	477.795	0
Max. Amt. Of Undercutting (ft)	17.484	2	3.993	105	4.379	0.015

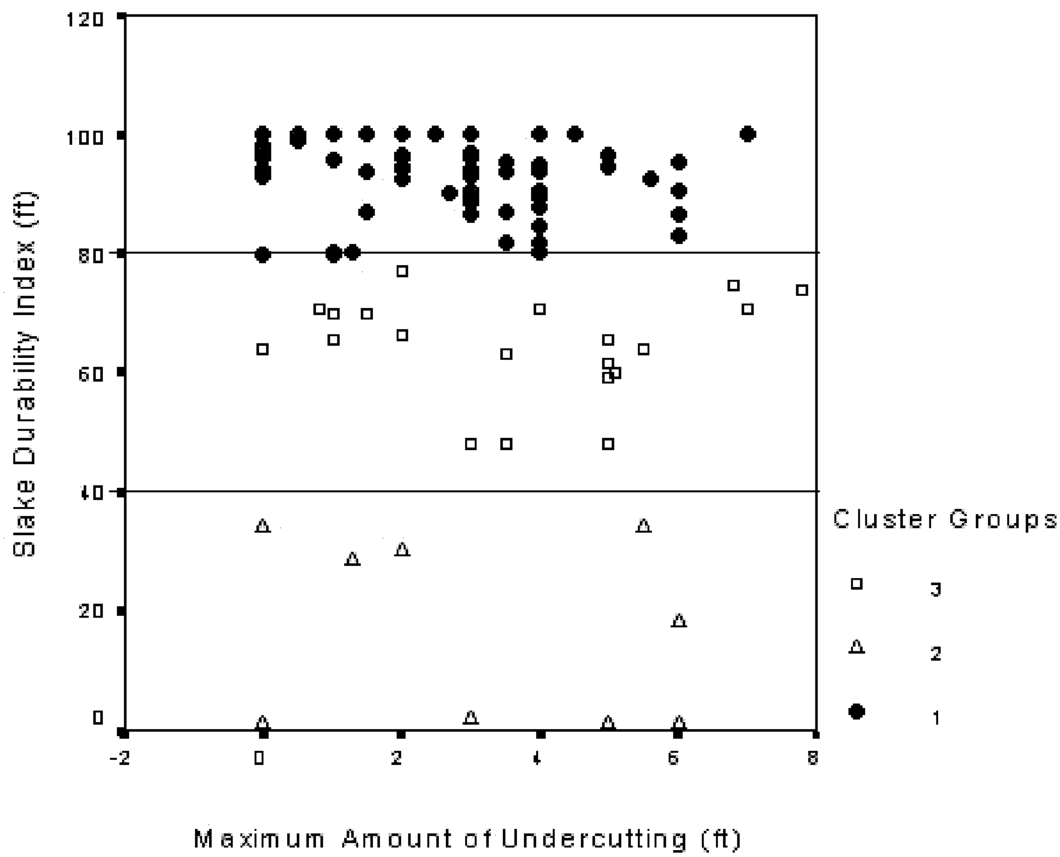


Figure 5.7: Cluster groupings for the geologic variables of slake durability index and maximum amount of undercutting. Note the group assignments are visually based on the slake durability index and not on the maximum amount of undercutting.

third group contains slopes with moderate SDI values (40-80%). In Table 5.9, the significantly greater F score for slake durability index (477) compared to that of the maximum amount of undercutting (4) supports the observation that the SDI values are more critical in differentiating the slopes than the maximum amount of undercutting.

5.3.2 Cluster Analysis of Geometrical Variables

The variables related to geometry, including slope height, slope angle, back slope angle, ditch depth, and ditch width, were used in the initial cluster analysis. Similar to the analysis of geological variables, the computer program SPSS was asked to divide the data into three groups. The results of cluster analysis, in the form of an ANOVA table, are shown in Table 5.10. As can be seen from the table, the F-test results and significance ratios indicate that only the slope height and slope angle are useful in differentiating the cluster groups. A second cluster analysis was run to see if only those two variables were helpful in distinguishing the clusters. Table 5.11 shows no change in the cluster groups and, therefore, only the slope height and slope angle are the variables that can be used to distinguish slopes on the basis of the geometry.

A visual representation of the cluster analysis can be seen in Figure 5.8 in the form of an x-y scatter plot of slope angle versus the slope height along with the associated group assignments. Similar to the geologic variables, the cluster groups for the geometric variables are dominated by one variable. In this case the slope angle appears to be much more dominant in differentiating groups. Evidence for this can also be seen in Table 5.11 where the F-test score for slope angle (363) is significantly greater than that for slope height (8.6). Slope angle can be used to visually differentiate the data

Table 5.10: Initial ANOVA table for the cluster analysis of the geometric variables. Highlighted values indicate F-test and significance values at a range suggesting that those variables are not aiding in differentiation of slopes.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
log Slope Height (ft)	3.818	2	0.443	105	8.618	0
Slope Angle	8898.8	2	24.536	105	362.684	0
log Backslope (angle)	0.285	2	2.248	105	0.127	0.881
Ditch Depth (ft)	0.65	2	0.737	105	0.881	0.417
Ditch Width (ft)	126.69	2	60.551	105	2.092	0.129

Table 5.11: ANOVA table for the cluster analysis of slope height and slope angle.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
log Slope Height (ft)	3.818	2	0.443	105	8.618	0
Slope Angle	8898.8	2	24.536	105	362.684	0

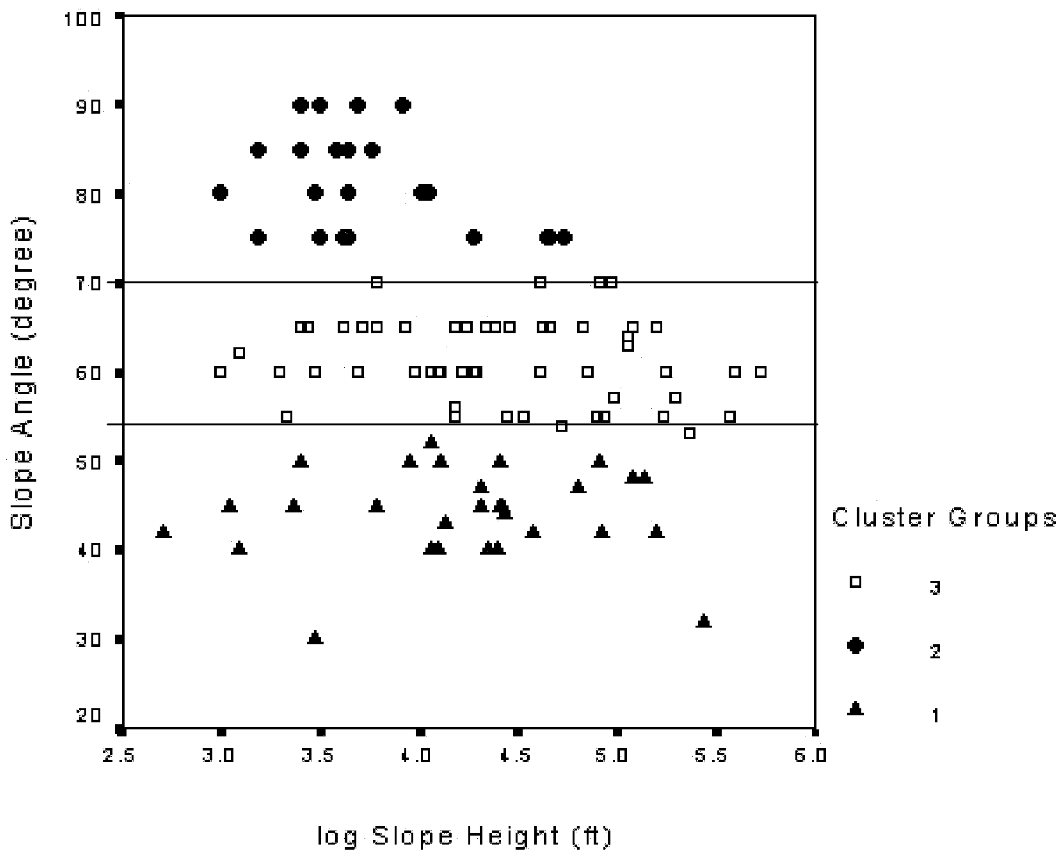


Figure 5.8: Cluster groupings for the geometric variables of slope angle and log of slope height. Group assignments listed above show the differences in the groups dominated by the slope angle.

set in to three groups: slopes with angles greater than 70 degrees, slopes with angles between 55 and 70 degrees, and slopes with angles less than 55 degrees.

5.3.3 Cluster Analysis of Traffic Related Variables

Even though there were concerns about performing a cluster analysis on the traffic related variables due to their discrete nature, the variables of roadway width, average daily traffic, posted speed limit, and slope length were analyzed. The results can be seen in the Table 5.12, which is the associated ANOVA table. The cluster analysis was performed to determine if one or more of these variables were significant in differentiating the slopes in the data set. As shown in Table 5.12, all four variables contribute significantly to the differentiating of slopes. This indicates that all of these variables need to be considered in the development of the final matrix.

5.3.4 Cluster Analysis of Geological and Geometric Variables Combined

In an attempt to find one set of groups or variables that can be used to identify the different slope clusters found in the data set, the remaining variables relating to geology and geometry (natural log of slope height, slope angle, slake durability index, and maximum amount of undercutting) were also examined through the use of cluster analysis (Table 5.13). The results of this clustering show that three of the four variables (natural log of slope height, slope angle, and slake durability index) significantly contribute to the identification of the cluster groups. The maximum amount of undercutting has a relatively low F-test score (.881) and a relatively large significance

Table 5.12: ANOVA table for cluster analysis grouping of traffic related variables. Note all the F-test and significance values indicate the ability to differentiate each of the three groups determined by the cluster analysis.

Variables	Cluster		Error		F-test	Prob $(F>F_{cutoff}/H_o)$
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
Roadway width (ft)	1702.49	2	24.365	105	69.873	0
Average Daily Traffic (cars/day)	7.377	2	1.267	105	5.821	0.004
Posted Speed Limit (mph)	2079.05	2	13.177	105	157.781	0
Slope Length (ft)	2.699	2	0.492	105	5.486	0.005

Table 5.13: ANOVA table for cluster analysis grouping of geologic and geometric variables. Highlighted values indicate F-test and significance values at a range suggesting that those variables are not aiding in differentiation of slopes.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
log Slope Height (ft)	4.389	2	0.432	105	10.154	0
Slope Angle	5906.073	2	81.54	105	72.431	0
Slake Durability Index (%)	22190.77	2	166.003	105	133.677	0
Max. Amt. of Undercut. (ft)	3.749	2	4.255	105	0.881	0.417

Table 5.14: ANOVA table for cluster analysis grouping log slope height, slope angle and slake durability index.

Variables	Cluster		Error		F-test	Prob ($F>F_{cutoff}/H_o$)
	Mean Square	Degrees of Freedom	Mean Square	Degrees of Freedom		
log Slope Height (ft)	4.389	2	0.432	105	10.154	0
Slope Angle	5906.073	2	81.54	105	72.431	0
Slake Durability Index (%)	22190.77	2	166.003	105	133.677	0

value (.417) indicating that it may not be as useful in distinguishing between the cluster groups as the other three variables (slope height, slope angle, and SDI).

A second cluster analysis was run with the removal of the maximum amount of undercutting variable. The ANOVA table (Table 5.14) shows little change in the cluster groups with the removal of the maximum amount of undercutting. This indicates that the influence of geology and geometry related variables contained in the database could be expressed using only three variables, namely slope height, slope angle, and slake durability index. A visual representation of this can be seen in Figure 5.9.

5.4 Summary of Statistical Analysis

The main purpose of performing the statistical analysis was to: (i) identify the variables that are important in defining the hazard potential, and (ii) ensure that there was no duplication of information being provided by different variables. The conclusions drawn from the statistical analysis can be summarized as follows:

- The slope height, slope angle, and second-cycle slake durability index are the most useful variables in differentiating between slope groups.
- The maximum amount of undercutting, block weight, and hydrologic value did lend independent information, but were not useful in differentiating between slope groups.
- The geometric variables of ditch depth and ditch width were not found to be statistically important in differentiating between slopes. This may be due to a consistency in catchment ditch construction.

- Engineered values, such as many of the traffic related variables, are primarily discrete in nature (not continual) and can not be subjected to the same type of cluster analysis as performed on geologic and geometric variables.

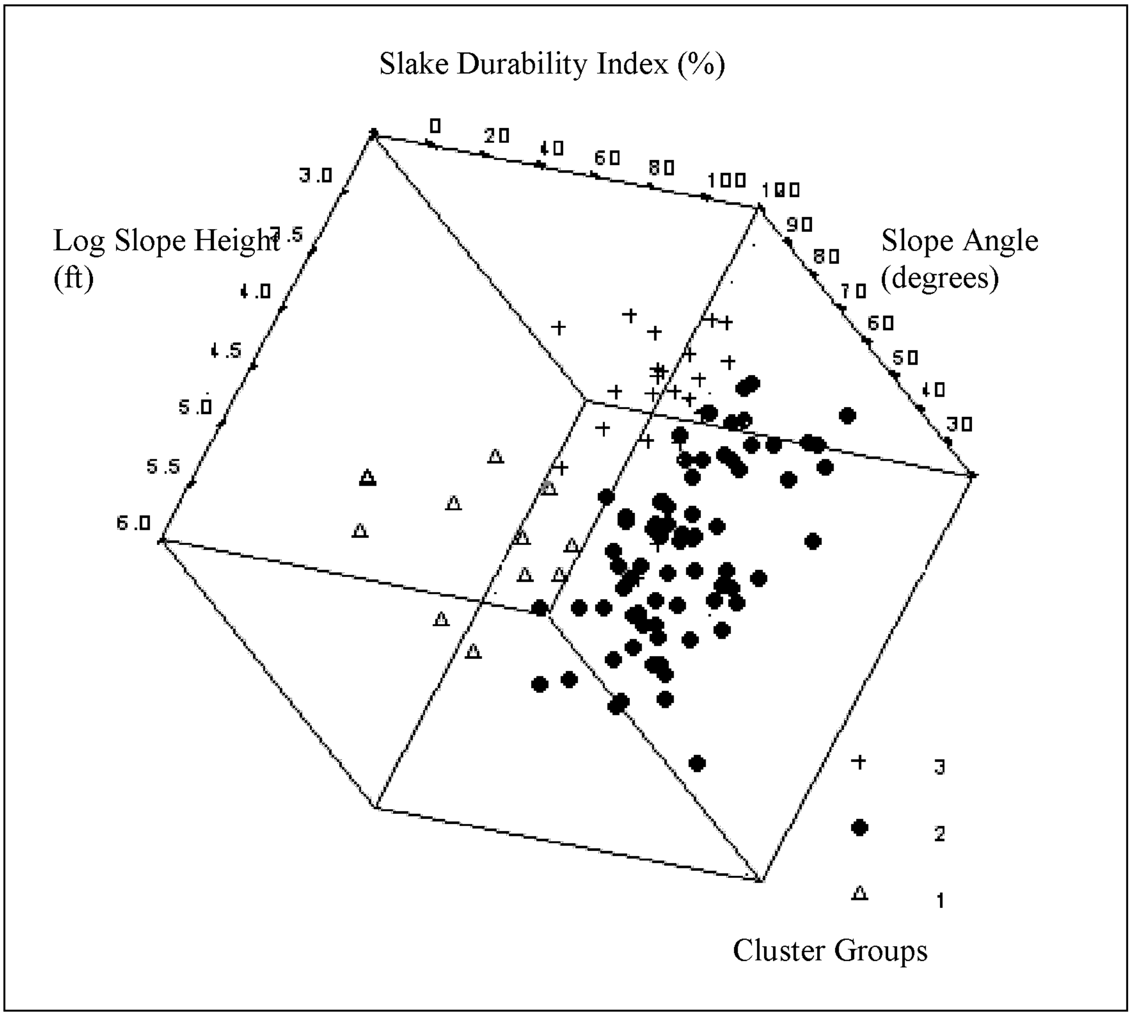


Figure 5.9: Illustration of the Differentiation of all 108 sites in three dimensions as a result of cluster analysis.

CHAPTER 6

DEVELOPMENT OF THE RATING MATRIX

For a rating system that is specifically developed for the geological conditions in Ohio to be practical and applicable, it must be able to perform the following three tasks: (i) evaluate the potential for a rockfall to occur, (ii) evaluate the adequacy of the catchment area, and (iii) evaluate the hazard rockfalls present to vehicles on the roadway. The following section describes the various parameters that need to be considered for the three categories of evaluation.

6.1 Evaluation Parameters

Based on the statistical analysis presented in Chapter 5, the following are the important parameters that should be considered in developing the matrix. It should be pointed out that the term "parameter" is used in this chapter in the same sense as the term "variable" in Chapter 5.

6.1.1 Parameters Required for Evaluation of Rockfall Potential

Two conditions control the occurrence of rockfalls in Ohio as described in Chapter 3: the presence of differential weathering and the role of discontinuities. The primary cause of rockfalls in the state of Ohio is the differential weathering of alternating series of durable and nondurable rocks. To account for differential weathering, the second-cycle slake durability index and the maximum amount of undercutting will be used in development of the matrix. The methodology used to obtain data regarding these two parameters can be found in Section 4.2.3. It should be noted that although statistical analysis revealed that slake durability index was more important than the maximum amount of undercutting in differentiating between slopes of differing rockfall potentials, both parameters should be included in the matrix. This is because at some sites, where the undercutting layers may be inaccessible, it may be difficult to obtain samples for the slake durability test. The maximum amount of undercutting, on the other hand, can be either directly measured or visually estimated for inaccessible layers.

The role of discontinuities in promoting rockfalls considers the shear strength, continuity, and orientation of the discontinuities in a similar manner as the Oregon Rockfall Hazard Rating System (Pierson, 1991). In order to evaluate the shear strength of joints, they are characterized by the joint roughness coefficient (JRC) developed by Barton (1974). The methodology for determination of JRC is described in Section 3.3.5 of Chapter 3. Continuity is characterized as continuous or discontinuous whereas orientation is described as favorable, random, or adverse. Since discontinuities in Ohio are generally either steeply dipping or nearly horizontal, aspects relating to shear strength (undulating, planar, etc.) are less important than the other aspects (continuity, orientation).

The types of rock as well as the amount of water present, both as groundwater flow and as surface runoff, control the extent of differential weathering at a given site. In order to account for the amount of water, a simplified qualitative approach of observing the number of water seeps on the slope (no water seeps, a few water seeps, many water seeps, numerous water seeps) will be used. The qualitative approach is chosen over the hydrologic value method developed in this study for two reasons. First, the statistical analysis showed that the hydrologic value, as developed in this study, was not a useful parameter in differentiating between slopes of differing hazard potential. Second, a simplified qualitative approach presents a more expedient method for data collection. The presence and amount of groundwater in the slope is greatly affected by the precipitation and snow/ice melt off. Both precipitation and melt off change drastically depending upon the season and recent local weather. The most conservative time of year to evaluate slope would be in the early spring due to the seasonal precipitation and snow melt. Evaluations done at other times of the year should take into consideration the drier conditions compared to the early spring.

Since a larger rockfall present a potentially greater hazard than a smaller rockfall, the size of the block or the volume of the rockfall event also needs to be evaluated. The characterization of this parameter, as described in the Oregon Rockfall Hazard Rating System (Pierson, 1991), appears to be equally applicable to the geologic conditions in Ohio (joint spacing, size of fallen blocks, etc.). Since it is simpler to estimate the diameter or volume of a rockfall event than to determine its weight, the size of the rockfall is expressed in terms of its diameter or volume in the matrix.

6.1.2 Parameters Required for Evaluation of Catchment Areas

The potential of a rock falling from the slope, leaving the catchment area, and entering the roadway is controlled by the geometry of the slope and size of the rockfall event. Statistical analysis showed the relative importance of slope angle and slope height in evaluating this parameter. The decreased importance of the ditch width and ditch depth can generally be attributed to the consistent construction techniques employed in catchment ditch design along Ohio roadways. However, it is the relationship between the slope and catchment area geometries that is needed to evaluate the ability of a catchment area to limit rockfalls from entering the roadway. Therefore, a technique that addresses both slope and catchment area geometries needs to be employed. For the matrix, a comparison of the actual ditch measurements to the prescribed Ritchie ditch criteria, designated as Ritchie score is recommended. The Ritchie ditch criteria have been tested by Pierson and others (2001) who found that the ditches designed in accordance with the Ritchie criteria were 85% to 95% effective in containing rockfalls. The methodology for obtaining Ritchie score can be found in Chapter 4, Section 4.4. This parameter has also been used in the Rock Slope Rating System of New York State (NYDOT, 1996).

6.1.3 Parameters Required for Evaluation of Traffic Hazard Potential

The statistical analysis indicated the importance of the average daily traffic, posted speed limit, slope length, percent decision site distance, and pavement width in evaluating the hazard posed to vehicles. In the matrix, this hazard will be evaluated by the use of three different parameters, the average vehicle risk, percent decision site distance, and roadway width. The average vehicle risk evaluates the percentage of cars in contact with the slope at a particular time and utilizes the average daily traffic, posted speed limit, and slope length. The percent decision site distance evaluates the reaction distance a vehicle may have to react to a rockfall event, and the roadway width evaluates the maneuverability of a vehicle around a rockfall event. The methodologies used to determine these parameters can be found in Chapter 4, Section 4.2.4.

6.1.4 Evaluation of Rating Scales

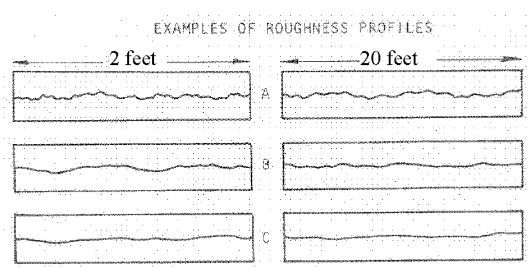
Two scales can be used to evaluate the parameters used in a matrix, a continual or linear scale (i.e., 1, 2, 3, 4…) and an exponential scale (3, 9, 27, and 81). Numerical scores were assigned to each parameter in accordance with both scales, with the lower scores indicating a lower potential for hazard and higher scores representing a higher potential for hazard. The exponential scale tends to accentuate the differences in slopes of differing hazard potential, because of which it has been the preferred scale of the previous hazard potential systems (Pierson, 1991; NYDOT, 1996; Lowell and Morin, 2000). In this study, both scales were evaluated before selecting the one that is more helpful in hazard potential categorization.

6.2 The Rockfall Hazard Rating Matrix

Table 6.1 shows the proposed rockfall hazard rating matrix for Ohio. It incorporates all the parameters mentioned in the previous sections and uses both the exponential and the continual scales. Table 6.2 is the accompanying scoring sheet for application of the proposed rating system to a specific site. The matrix considers four types of parameters: (i) geologic parameters, (ii) geometric parameters, (iii) traffic parameters, and (iv) rockfall history. The scores for each of these parameters are determined separately and then are added together to determine the overall score for the rock slope.

Table 6.1: The rock fall hazard rating matrix for Ohio.

EVALUATION PARAMETERS			RATING SCORES FOR DIFFERENT CATEGORIES OF EVALUATION CRITERIA			
			3 Point/(1)	9 Points/(2)	27 Points/(3)	81 Points/(4)
GEOLOGIC PARAMETERS						
Geologic Character	Differential Weathering	Slake Durability Index	90-100%	75-90%	50-75%	<50%
		Max. Amount of Undercutting	0-1 ft	1-2 ft	2-4 ft	>4 ft
	Discontinuity Role	Discontinuity Extent/Orient.	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
		Discontinuity Surface Features	Very rough JRC=20	Rough JRC=15	Undulating JRC=10	Smooth JRC=5
Block Size/Volume of Rock Fall			1 ft/ 3 yd^3	2 ft/ 6 yd^3	3 ft/ 9 yd^3	4 ft/ 12 yd^3
Hydrologic Conditions			No water seeps on slope	A few water seeps on slope	Many water seeps on slope	Numerous water seeps on slope
GEOMETRIC PARAMETERS						
Ritchie Score			<1	1-1.5	1.5-2.5	>2.5
TRAFFIC PARAMETERS						
ADT x Slope Length / 24 hrs / Posted Speed Limit 100%			25% of time (very low)	50% of time (low)	75% of time (medium)	100% of time (high)
% Decision Sight Distance			Adequate sight distance, ≥100%	Moderate sight distance, 75%	Limited sight distance, 50%	Very limited sight distance, <50%
Pavement Width			50 feet	40 feet	30 feet	20 feet
ROCKFALL HISTORY			No falls	A few falls	Many falls	Numerous falls



Joint Roughness Coefficient

A. Rough undulating - tension joints, rough sheeting, rough bedding. JRC = 20

B. Smooth undulating - smooth sheeting, non-planar foliation, undulating bedding. JRC = 10

C. Smooth nearly planar - planar shear joints, planar foliation, planar bedding. JRC = 5

Table 6.2: Scoring sheet for the rock fall hazard rating matrix.

GEOLOGIC PARAMETERS					
Differential Erosion					
SDI	______	(a)	Greater Value (c or f)*	______	(g)
Maximum Amount of Undercutting	______	(b)			
Total (a + b)	______	(c)*	Block size	______	(h)
Discontinuities Role			Hydrologic	______	(i)
Discontinuity Extent/Orientation	______	(d)			
Discontinuity Surface Features	______	(e)	Total (g+h+i)/4	______	(j)
Total (d + e)	______	(f)*			
GEOMETRIC PARAMETER					
Ritchie's Score	______	(n)			
TRAFFIC PARAMETERS					
AVR	______	(o)			
% DSD	______	(p)			
Pavement Width	______	(q)			
Total (o+ p+q)/3	______	(r)			
ROCK FALL HISTORY					
History	______	(s)			
OVERALL SCORE					
Lines (j+n+r+s)	______	(t)			

6.2.1 Geologic Parameters

The geologic parameters are divided into three different categories: geologic character, block size/volume of rockfall, and hydrologic conditions. The geologic character is subdivided into two different aspects, namely the differential weathering and role of discontinuities. The differential weathering aspect is further subdivided into two variables: slake durability index (SDI) and maximum amount of undercutting. The range of scores for SDI represents more durable rocks at higher values to less durable rocks at lower values. The amount of undercutting is assigned an increasing score with increasing amount of undercutting.

For the role of discontinuities within the geologic character category, the continuity and orientation of the discontinuities with respect to the slope face are evaluated in the same manner as in the Oregon Rockfall Hazard Rating System (Pierson, 1991). The terms used to describe orientation of discontinuities include adverse, random, and favorable. Adverse represents joint orientations that promote rockfalls, plane failures, wedge failures, and toppling failures. Random represents joint orientations that are likely to result in rockfalls and rarely any other type of failure. Favorable orientation indicates discontinuities that are likely to promote only a minimum number or rockfalls but none of the other types of failures. With respect to discontinuity extent, the term continuous refers to discontinuities that are greater than ten (10) feet (3 m) in length and the term discontinuous refers to shorter discontinuities.

In order to evaluate the frictional resistance along discontinuities, the use of the joint roughness coefficient (JRC), proposed by Barton (1974), is recommended. The JRC value is formed by comparing the joint roughness profile with the standard profiles developed by Barton with JRC values of 5, 10, and 20 degrees (Table 6.1). For surfaces with roughness profiles in-between the standard profiles the JRC values can be extrapolated.

The terminology used for representing block size is from the Oregon Rockfall Hazard Rating System (Pierson, 1991), as it is equally applicable to the geologic conditions in Ohio. The block size or volume of rockfall represents either the size of an individual block or the volume of the overall rockfall event. The measurement should be representative of either type of event that has already occurred or has the potential to occur.

The hydrologic parameter in the matrix is qualitatively evaluated in terms of the number of water seeps present, which in turn, is a manifestation of both the geologic and climatic conditions prevalent in the site area.

After the scores have been assigned to each category under the geologic parameters, the values for geologic character (the greater of differential weathering or role of discontinuity), block size/volume of rockfall, and hydrologic conditions are summed and divided by four. This will give a range of scores for the geologic parameters of 1 to 4 on the continual scale or 3 to 81 on the exponential scale.

A preliminary score for the geologic conditions can also be determined if the SDI value is unavailable for a particular site. In this case the scores for both SDI, in the differential weathering case, and frictional component, in the case of role of discontinuities, will not be considered. The three remaining variables (maximum amount of undercutting or orientation and continuity of discontinuities, block size, and hydrologic conditions) will be summed and divided by three. However, a note should be made for a slope rated in this manner within the database.

6.2.2 Geometric Parameters

The geometric condition is determined by assigning a score based on the comparison of actual ditch measurements to the prescribed Ritchie ditch criteria (Figure 3.5). The method for determining this value, referred to as Ritchie Score, can be found in Chapter 4, Section 4.4. A Ritchie score of one or less indicates a catchment area that is equal to or bigger than the prescribed dimensions. As the score increases, the effectiveness of the catchment area decreases. It may also be advisable to develop a graph of Ritchie score versus point values for the geometric parameters such as seen in Figure 6.1. From this graph, the scores to be used in Table 6.1 can be better defined between broader score values (3, 9, 27, 81), or, after the Ritchie score is determined, the equation of the line may also be used to determine the points to be allotted to a parameter (Figure 6.1). Using the graph or equation can greatly aid in differentiating between slopes that are found in the same range of scores. It should be noted that the largest Ritchie score found in Figure 6.1 is 3.5. A Ritchie score does have the potential of being greater than 3.5, in which case, the maximum point value of 81 should be used for the geometric parameter. This gives scores for the geometric parameter ranging from 1 to 4 on the continuous scale and 3 to 81 on the exponential scale.

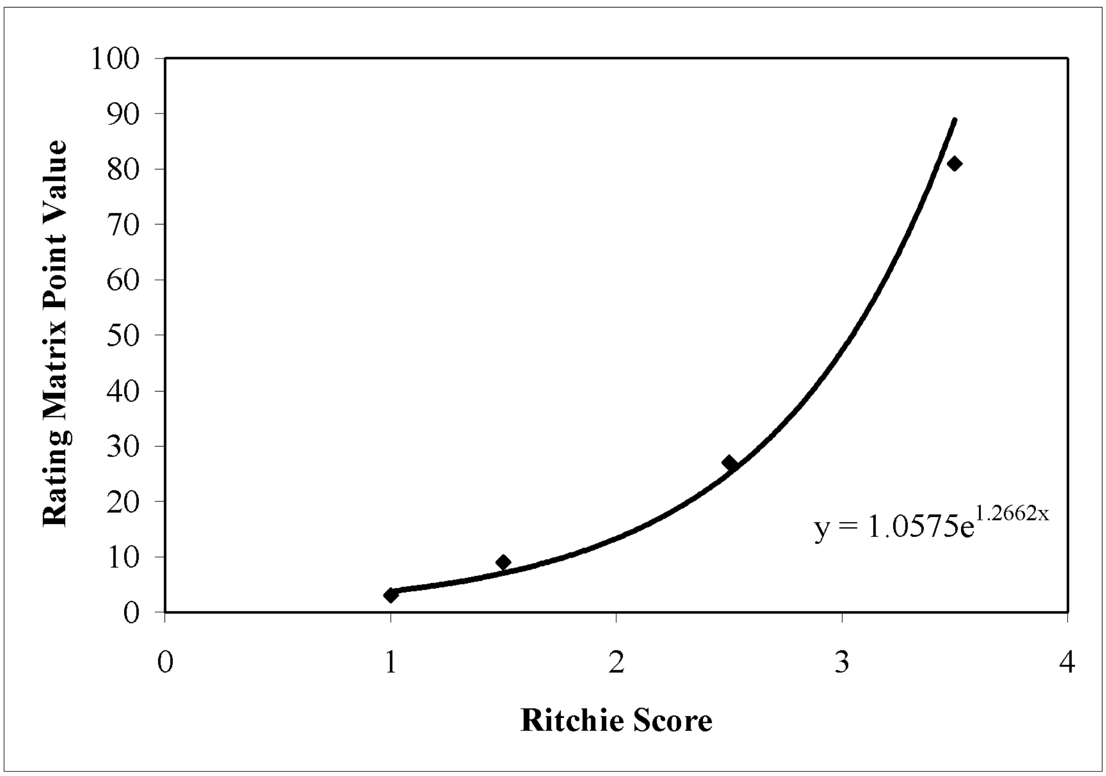


Figure 6.1: Relationship between the Ritchie score and point score for the rating matrix.

6.2.3 Traffic Parameters

Traffic parameters are evaluated using the average vehicle risk (AVR), percent decision sight distance (%DSD), and pavement width. In the univariate and bivariate statistical analyses of these parameters (Chapter 5), it was noted that these variables may provide important information. However, due to the nature of these variables (e.g. discrete number, low population of sites, etc.) problems arose with these variables during the cluster analysis, and some of them were subsequently discontinued from the final cluster analysis. However, since these variables do address traffic related concerns in the state of Ohio, they are used to assess the traffic parameters in the matrix. Their use for assessment of traffic parameters is also recommended by the Oregon Rockfall Hazard Rating System (Pierson, 1991). Summing up the scores for the three variables (average vehicle risk, percent decision sight distance, and pavement width) and dividing the sum by three gives the overall traffic parameters score. The potential scores for the traffic parameters then range from 1 to 4 on the continuous scale and 3 to 81 on the exponential scale.

6.2.4 Rockfall History

It is well established that a good understanding of the history of rockfall events for a particular rock slope gives important clues to its future rockfall activity. In other words, a slope that has had many rockfall events in the past is much more likely to continue to remain active in the future than a site with few falls in the past (Pierson, 1991; NYDOT, 1996). Due to the importance of this parameter, it has been added to the matrix even though no data on rockfall history was available for the study sites. Because of the non-availability of data regarding rockfall history, this parameter will not be used while applying the matrix to the study sites. However, it should be used for future evaluation once the rockfall history records have been compiled. An example of a rockfall history data sheet detailing important information about a rockfall event is provided in Appendix G.

6.2.5 Computation of the Overall Score

The overall score for the matrix can be determined by summing up the scores of the different parameters following Table 6.2, or using the following equation (Eq. 4):

$$OverallScore = \begin{pmatrix} Geo\log ic Parameters + \\ Geometric Parameters + \\ Traffic Parameteres + \\ Rock Fall History \end{pmatrix}$$

Overall scores can range from 4 to 16 on the continual scale and 12 to 324 on the exponential scale. Due to the absence of rockfall history data in the database for the present study, the rockfall history component was removed from the overall score, lowering the overall ranges of scores to 3 to 12 and 9 to 243 on the continual and exponential scales, respectively.

6.2.6 Application of the Matrix to an Individual Site

In order to demonstrate the application of the matrix, a site located in Muskingum County, S.R. 60 at mile marker 6.9 (MUS-60-6.9), is considered. This is a 1270-foot

(390 m) long, 30-foot (9 m) high, vertical cut comprised of mainly sandstone with some thin, interbedded, shale layers (Figure 6.2). At the base of the slope is a shale layer that undercuts the more durable sandstone with the maximum amount of undercutting being 5.6-feet (1.7 m). The undercutting shale unit was tested to have a second-cycle slake durability index of 92.5%. Above the sandstone is another thick shale layer creating a gently dipping back slope that is heavily vegetated. There are many water seeps found on the slope, and the joints are discontinuous and oriented favorably. The discontinuities are generally planar in nature. The size of the average rockfall is approximately 0.5 foot (.15 m) in diameter and the catchment area measures 4.5 foot (1.4m) wide and 0.6 feet (.18 m) deep. There are an average of 4866 vehicles per day passing the site with two lanes of maneuverability (33 foot or 10 m wide) and a posted speed limit of 55 mph (88 km/hr).

Using the matrix, the point-scores for the geologic character can be determined as follows:

1. Differential weathering:
    a. Second-cycle slake durability index (SDI) of 92.5% gives a score of 3 points on exponential and 1 point on the continual scale.
    b. Maximum amount of undercutting of 5.6 feet (1.7 m) gives a score of 81 on the exponential scale and 4 on the continual scale.
    c. Total points are 84 for the exponential scale and 5 for the continual scale.
2. Role of Discontinuities
    a. Discontinuous joints, favorable orientation – score: 3 (exponential scale); 1 (continual scale)

Figure 6.2: Rock slope located at MUS-60-5.3 and used in the rating matrix example.

b. JRC of 10- score: 27 (exponential scale); 3 (continual scale)

c. Total score – 30 (exponential scale); 4 (continual scale)

3. Block size/volume of rockfall – 0.5 foot diameter- score: 3 (exponential scale); 1 (continual scale)

4. Hydrologic condition – numerous water seeps on slope- score: 25 (exponential scale); 3 (continual scale)

Table 6.3 shows the scores used for this example recorded on the matrix scoring sheet. Since the sum of the scores for differential weathering (84 exponential scale; and 5 on continual scale) is greater than the scores for role of discontinuities (30 exponential scale; and 4 on continual scale), the differential weathering scores are placed in line (g) in Table 6.3. The differential weathering scores (line g.) are added to the scores for block size (line h.) and hydrologic condition (line i.) and divided by four to get the score for the geologic parameters of 28.5 on the exponential scale and 2.25 on the continual scale (line j.)

The slope height and slope angle are applied to Ritchie's chart (Figure 3.5), and when the ratio of prescribed ditch measurements are compared to actual ditch measurements a Ritchie score of 3.70 is obtained. This Ritchie score gives a maximum geometric parameters score of 81 on exponential scale and 4 on continual scale (line n. Table 6.3).

Following equation 4-2 for the average vehicle risk and using the above information provided above in site description, an AVR score of 89.1 is obtained. This value indicates that 89.1 percent of the time a car is exposed to this rock slope, and gives

Table 6.3: Scoring sheet for the rock fall rating matrix applied to MUS-60-6.9.

GEOLOGIC PARAMETERS					
Differential Erosion					
SDI	3	(a)	Greater Value (c or f)*	84	(g)
Maximum Amount of Undercutting	81	(b)			
Total (a + b)	84	(c)*	Block size	3	(h)
Discontinuities Role			Hydrologic	27	(i)
Discontinuity Extent/Orientation	3	(d)			
Discontinuity Surface Features	27	(e)	Total (g+h+i)/4	114/4= 28.5	(j)
Total (d + e)	30	(f)*			
GEOMETRIC PARAMETER					
Ritchie's Score	81	(n)			
TRAFFIC PARAMETERS					
AVR	50	(o)			
% DSD	3	(p)			
Pavement Width	27	(q)			
Total (o+ p+q)/3	80/3= 26.7	(r)			
ROCK FALL HISTORY					
History	n/a	(s)			
OVERALL SCORE					
Lines (j+n+r+s)	(28.5+81+26.7)/3=136.2	(t)			

an AVR score, according to Table 6.1, of 27 on the exponential and 3 on the continual scales. Further refinement of this value can be done through graphing the AVR versus matrix scoring, similar to the Ritchie score versus matrix score, as shown in Figure 6.3. From Figure 6.3, an exponential score of 50 is obtained (line o, Table 6.3). The decision sight distance is greater than the prescribed decision sight distance; therefore, low values of 3 (exponential scale) and 1 (continual scale) are applied (line p, Table 6.3). Since the pavement width measures 33-feet (10 m), it gives a matrix score of 27 (exponential scale) and 3 (continual scale) points (line q, Table 6.3). The score for the traffic conditions is the sum of these three parameters divided by 3, for a value of 28 (exponential scale) and 7 (continual scale) (line r, Table 6.3). The overall score for this slope is the sum of the three categories of parameters, resulting in a total score of 136.2 on the exponential scale and 8.6 on the continual scale (line t, Table 6.3).

6.3 Hazard Potential Evaluation of Individual Sites

The proposed matrix was used to assign rating scores to all 108 sites. Tables 6.4 (a and b) shows the scores given for each parameter according to both exponential and continual scales, as well as the total scores for each of the study sites. The exponential scores range from a high of 156.6 to a low of 22.5, with a mean score of 80.3 and a standard deviation of 29.9. The continual scale scores range from a high of 9.4 to a low of 4.9, with a mean of 7.0 and a standard deviation of 1.2. There are some minor differences in the rank ordering of sites with respect to the two scales. This is due to the use of equations to determine some scores on the exponential scale rating which were not used when employing the continual scale. In comparing the continual and exponential

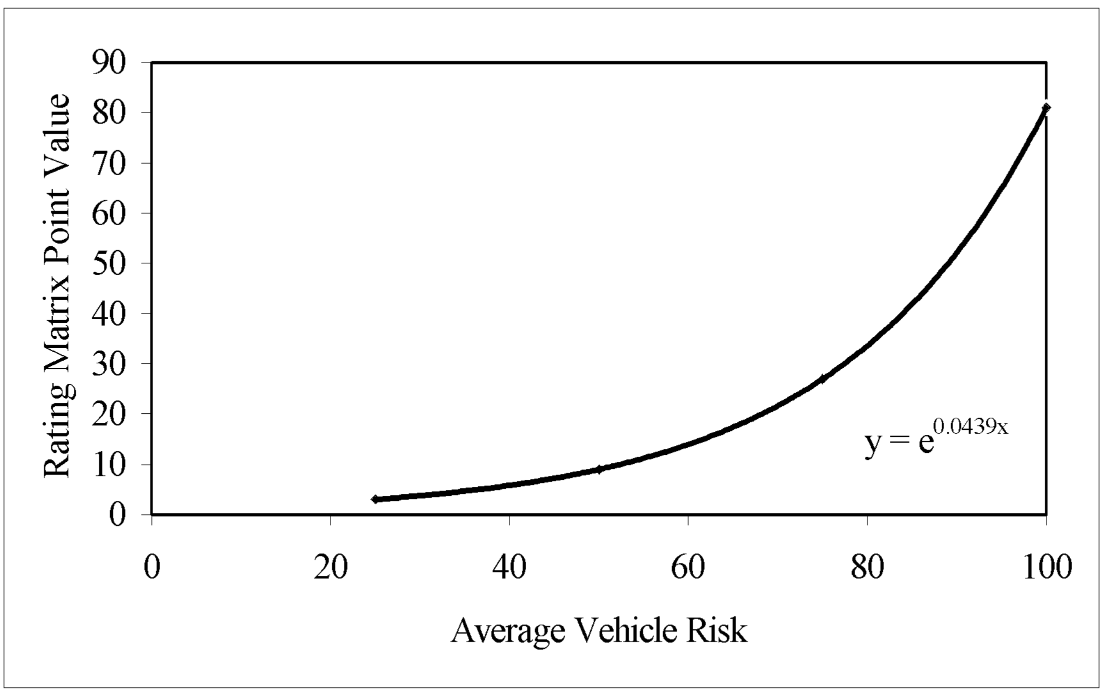


Figure 6.3: Relationship between the average vehicle risk and point score for the rating matrix.

Table 6.4a: Geologic parameter scores for all 108 study sites.

Site	Slake Durability Index			Max. Amt. of Undercut. (ft)			Block Size				Hydrologic/ Climatic				Geological Parameter Score			
	(%)	Exponential Scale	Continual Scale	(ft)	Exponential Scale	Continual Scale	Block Size	Diameter (ft)	Exponential Scale	Continual Scale	Hydro Value	Climate Rating	Exponential Scale	Continual Scale	sum exp	sum cont	Sum Exponential/4	Sum Continual/4
JEF-7-5B	90.5	3	1	6	81	4	649	2	27	3	1078860	81	81	4	192	12	48.0	3.0
COL-170-13.5	59.1	27	3	5	81	4	42	1	9	2	390113	27	9	2	144	11	36.0	2.8
JEF-7-14.4C	1	81	4	6	81	4	81	1	9	2	90333	27	3	1	198	11	49.5	2.8
MUS-60-6.9	92.5	3	1	5.6	81	4	40	0.5	3	1	1562500	25	81	4	112	10	28.0	2.5
JEF-7-5A	90.5	3	1	4	27	3	46	1	9	2	274398	27	9	2	66	8	16.5	2.0
JEF-7-34.5B	70.9	27	3	7	81	4	274	1.5	9	2	652330	81	27	3	198	12	49.5	3.0
WAY-3-2.4	100	3	1	0	3	1	9	0.4	3	1	193740	9	3	1	18	4	4.5	1.0
JEF-7-10.6	97.5	3	1	0	3	1	2191	3	27	3	1463750	60	81	4	93	9	23.3	2.3
JEF-7-34.5A	92.4	3	1	2	9	2	81	1	9	2	652330	27	27	3	48	8	12.0	2.0
JEF-7-33.3A	48.1	81	4	5	81	4	649	2	27	3	1170161	70	81	4	259	15	64.8	3.8
HAM-74-18.1	30.1	81	4	2	9	2	81	1	9	2	146500	15	3	1	114	9	28.5	2.3
WAS-7-39.5	63	27	3	3.5	27	3	81	1	9	2	1186929	81	81	4	144	12	36.0	3.0
BEL-7-23.1	93.6	3	1	4	27	3	68	0.9	3	1	266100	9	9	2	42	7	10.5	1.8
BEL-70-220.5	65.5	27	3	5	81	4	40	2	27	3	581016	27	27	3	162	13	40.5	3.3
JEF-7-28A	80	9	2	1	3	1	148	1.2	9	2	385277	70	9	2	91	7	22.8	1.8
STA-800-1	100	3	1	3	27	3	1	0.3	3	1	154881	25	3	1	58	6	14.5	1.5
SUM-76-23.5	100	3	1	0	3	1	10	1.8	9	2	1080000	9	81	4	24	8	6.0	2.0
JEF-7-33.3C	48.1	81	4	3.5	27	3	81	1	9	2	1170161	60	81	4	177	13	44.3	3.3
BEL-70-223	65.5	27	3	1	3	1	30	0.8	3	1	470283	30	9	2	63	7	15.8	1.8
TUS-36-0	94.5	3	1	5	81	4	40	0.5	3	1	800040	25	27	3	112	9	28.0	2.3
GAL-160-0.55	93.8	3	1	1.5	9	2	81	1	9	2	915561	15	27	3	36	8	9.0	2.0
JEF-7-22.6	86.8	9	2	3	27	3	274	1.2	9	2	1074865	60	81	4	105	11	26.3	2.8
ASD-97-4.1	81.9	9	2	4	27	3	28	1	9	2	1070000	27	81	4	72	11	18.0	2.8
COL-7-3.3	64.1	27	3	5.5	81	4	23864	7 4	81	4	2794155	27	81	4	216	15	54.0	3.8
JEF-7-28B	80	9	2	0	3	1	81	1	9	2	160499	81	3	1	102	6	25.5	1.5
TUS-77-60.9	18.3	81	4	6	81	4	10	1.5	9	2	572917	50	27	3	221	13	55.3	3.3
BEL-7-11	93.9	3	1	3.5	27	3	275	1.5	9	2	3818526	27	81	4	66	10	16.5	2.5
WAY-21-2.36	60.1	27	3	5.1	81	4	2190	3	27	3	504167	25	27	3	160	13	40.0	3.3
HAM-74-17.6	28.6	81	4	1.3	9	2	99	2.2	27	3	172500	20	3	1	137	10	34.3	2.5
HAM-74-9.4	84.5	9	2	4	27	3	46	1	9	2	52500	15	3	1	60	8	15.0	2.0
TUS-250-23	90.7	3	1	4	27	3	80	1	9	2	408512	27	9	2	66	8	16.5	2.0
HAM-71-10	66.2	27	3	2	9	2	243	1.5	9	2	120000	9	3	1	54	8	13.5	2.0
JEF-7-14.4B	1	81	4	5	81	4	81	1	9	2	292038	50	9	2	221	12	55.3	3.0
COL-7-0.5	1	81	4	0	3	1	10	0.5	3	1	709835	20	27	3	107	9	26.8	2.3
BEL-70-222.5	65.5	27	3	5	81	4	81	1	9	2	529860	9	27	3	126	12	31.5	3.0
JEF-7-33.3B	48.1	81	4	3	27	3	81	1	9	2	1170161	60	81	4	177	13	44.3	3.3

Site	Slake Durability Index			Max. Amt. of Undercut. (ft)			Block Size				Hydrologic/ Climatic				Geological Parameter Score			
	(%)	Exponential Scale	Continual Scale	(ft)	Exponential Scale	Continual Scale	Block Size	Diameter (ft)	Exponential Scale	Continual Scale	Hydro Value	Climate Rating	Exponential Scale	Continual Scale	sum exp	sum cont	Sum Exponential/4	Sum Continual/4
NOB-339-7.6	96.2	3	1	0	3	1	61	1.2	9	2	51025	20	3	1	35	5	8.8	1.3
COL-45-20.15	95.5	3	1	3.5	27	3	81	0.7	3	1	475549	50	9	2	83	7	20.8	1.8
LAW-7-2	1.9	81	4	3	27	3	1461	2.5	27	3	7066667	27	81	4	162	14	40.5	3.5
JEF-7-20.1	96.6	3	1	5	81	4	274	1.2	9	2	508333	75	27	3	168	10	42.0	2.5
JEF-7-6	61.5	27	3	5	81	4	649	2	27	3	1915151	60	81	4	195	14	48.8	3.5
BEL-149-1.8	88	9	2	4	27	3	81	2	27	3	419373	20	9	2	83	10	20.8	2.5
COS-715-6.5	93	3	1	0	3	1	81	1	9	2	1590000	9	81	4	24	8	6.0	2.0
ATH-13-9.2	94.6	3	1	2	9	2	82	0.9	3	1	238678	15	9	2	30	6	7.5	1.5
COL-7-3	34.1	81	4	5.5	81	4	649	2	27	3	1403117	27	81	4	216	15	54.0	3.8
SCI-52-25.5C	96.2	3	1	3	27	3	61	1.2	9	2	446570	9	9	2	48	8	12.0	2.0
MOE-78-24.5	94.2	3	1	3	27	3	1268	2.5	27	3	175713	20	3	1	77	8	19.3	2.0
ATH-33-15A	77	9	2	2	9	2	21304	6	81	4	1036306	6	81	4	105	12	26.3	3.0
LOG-292-2.6	100	3	1	0.5	3	1	78	0.9	3	1	265300	9	9	2	18	5	4.5	1.3
MOE-800-4.5	93	3	1	3	27	3	81	1	9	2	651996	9	27	3	48	9	12.0	2.3
TUS-77-63	95.3	3	1	6	81	4	42	0.8	3	1	373851	9	9	2	96	8	24.0	2.0
LAW-52-12	86.8	9	2	6	81	4	5194	4	81	4	1532042	9	81	4	180	14	45.0	3.5
BRO-62-9.0	80.4	9	2	4	27	3	160	2	27	3	533048	27	27	3	90	11	22.5	2.8
COL-7-5	64.1	27	3	0	3	1	274	1.5	9	2	2862477	81	81	4	120	10	30.0	2.5
ADA-41-16.1	74.7	27	3	6.8	81	4	68	2.2	27	3	766000	20	27	3	155	13	38.8	3.3
JEF-7-14.4A	82.9	9	2	6	81	4	80	1	9	2	635941	20	27	3	119	11	29.8	2.8
ASD-3-1.1	74	27	3	7.8	81	4	81	1	9	2	156250	20	3	1	137	10	34.3	2.5
COL-7-2.8	34.1	81	4	0	3	1	649	2	27	3	2341732	27	81	4	138	12	34.5	3.0
MOE-7-1.5	100	3	1	0	3	1	81	1	9	2	1050347	55	81	4	70	8	17.5	2.0
JEF-7-0	94.2	3	1	3	27	3	81	1	9	2	454300	27	9	2	66	8	16.5	2.0
BEL-7-18.6	100	3	1	0	3	1	274	1.5	9	2	806856	81	27	3	96	7	24.0	1.8
BEL-149-4.5	90	3	1	2.7	27	3	822	2	27	3	405699	27	9	2	84	9	21.0	2.3
MOE-537-1.7	88.5	9	2	3	27	3	81	1	9	2	320110	9	9	2	54	9	13.5	2.3
JEF-7-22.1	96.5	3	1	2	9	2	960	1.2	9	2	1201092	40	81	4	61	9	15.3	2.3
SCI-52-25.5B	89.5	9	2	3	27	3	122	1	9	2	199675	9	9	2	54	9	13.5	2.3
ATH-13-13.7	90.5	3	1	3	27	3	649	2	27	3	451888	15	9	2	72	9	18.0	2.3
LIC-70-135	100	3	1	0	3	1	197	1.5	9	2	306360	9	9	2	24	6	6.0	1.5
SUM-76-17	100	3	1	1.5	9	2	81	1	9	2	700000	27	27	3	48	8	12.0	2.0
RIC-30-12.5	100	3	1	4.5	81	4	81	1	9	2	122917	50	3	1	143	8	35.8	2.0
BEL-7-9	93.5	3	1	3	27	3	81	1	9	2	1069904	27	81	4	66	10	16.5	2.5
JEF-7-1.5	94.2	3	1	0	3	1	81	1	9	2	1863348	9	81	4	24	8	6.0	2.0
SCI-52-25.5A	94.2	3	1	2	9	2	40	0.5	3	1	1092100	9	81	4	24	8	6.0	2.0
BEL-7-14	95	3	1	4	27	3	81	1	9	2	3020655	81	81	4	120	10	30.0	2.5
ASD-30-2.25	100	3	1	2.5	27	3	61	0.8	3	1	284792	15	9	2	48	7	12.0	1.8
ASD-3-1.8	100	3	1	7	81	4	82	0.9	3	1	227600	3	9	2	90	8	22.5	2.0

Site	Slake Durability Index			Max. Amt. of Undercut. (ft)			Block Size				Hydrologic/ Climatic				Geological Parameter Score			
	(%)	Exponential Scale	Continual Scale	(ft)	Exponential Scale	Continual Scale	Block Size	Diameter (ft)	Exponential Scale	Continual Scale	Hydro Value	Climate Rating	Exponential Scale	Continual Scale	sum exp	sum cont	Sum Exponential/4	Sum Continual/4
BRO-52-23	70.9	27	3	0.8	3	1	40	0.7	3	1	4252000	40	81	4	73	9	18.3	2.3
PER-155-1.83	81.8	9	2	3.5		3	1268	4	81	4	1223708	27	81	4	117	13	29.3	3.3
JEF-22-8	70.8	27	3	4	27	3	81	1	9	2	635941	20	27	3	83	11	20.8	2.8
COS-36-28-30	100	3	1	0	3	1	437	1.8	9	2	1465333	15	81	4	30	8	7.5	2.0
BEL-7-26.8	87.1	9	2	3.5	27	3	81	1.5	9	2	1711823	27	81	4	72	11	18.0	2.8
ATH-78-22.5	95.9	3	1	1	3	1	40	0.5	3	1	557924	20	27	3	29	6	7.3	1.5
ATH-124-2	100	3	1	2	9	2	274	1	9	2	1808333	20	81	4	41	9	10.3	2.3
JEF-22-13.9	96.3	3	1	2	9	2	20	1.5	9	2	635941	81	27	3	102	8	25.5	2.0
PER-13-5.1	100	3	1	4.5	81	4	81	1	9	2	211458	9	9	2	102	9	25.5	2.3
WAS-7-33.2	100	3	1	0	3	1	81	1	9	2	1342457	27	81	4	42	8	10.5	2.0
BEL-7-5.9	93.1	3	1	0	3	1	10	0.5	3	1	938480	27	27	3	36	6	9.0	1.5
JEF-7-14.6	98.1	3	1	0	3	1	81	0.5	3	1	514234	3	27	3	12	6	3.0	1.5
JEF-22-13.2	96.3	3	1	0	3	1	30	1	9	2	635941	27	27	3	42	7	10.5	1.8
JEF-7-0.5	94.2	3	1	3	27	3	649	2	27	3	2658508	27	81	4	84	11	21.0	2.8
HOC-33-5	93.5	3	1	3	27	3	81	1	9	2	346382	20	9	2	59	8	14.8	2.0
MED-271-5.2	100	3	1	4	27	3	487	1.5	9	2	2900700	27	81	4	66	10	16.5	2.5
ATH-33-15B	86.9	9	2	1.5	9	2	649	2	27	3	539568	6	27	3	51	10	12.8	2.5
RIC-71-174	100	3	1	2	9	2	1096	2	27	3	409375	9	9	2	48	8	12.0	2.0
MRG-60-10	89.2	9	2	3		3	81	1	9	2	346929	9	9	2	27	9	6.8	2.3
MOE-7-28	69.9	27	3	1.5	9	2	20	1	9	2	1270563	40	81	4	85	11	21.3	2.8
CLA-68-7	100	3	1	0	3	1	81	1	9	2	4500000	9	81	4	24	8	6.0	2.0
BRO-62-9.1	80.4	9	2	1.3	9	2	46	1	9	2	533047	27	27	3	54	9	13.5	2.3
LOG-33-20.5	99.1	3	1	0.5	3	1	24	0.6	3	1	325500	9	9	2	18	5	4.5	1.3
TUS-250-12.3	89.3	9	2	4	27	3	2191	1	9	2	487987	27	9	2	72	9	18.0	2.3
SUM-76-20	100	3	1	2	9	2	42	0.8	3	1	2300000	9	81	4	24	8	6.0	2.0
LIC-16-28	100	3	1	1	3	1	81	1	9	2	385000	6	9	2	21	6	5.3	1.5
JEF-7-18.8	100	3	1	0	3	1	274	1.5	9	2	1218186	9	81	4	24	8	6.0	2.0
WAS-7-36.5	100	3	1	0	3	1	81	1	9	2	1220220	27	81	4	42	8	10.5	2.0
BEL-7-6.3	96.8	3	1	3	27	3	28	0.7	3	1	1749976	9	81	4	42	9	10.5	2.3
MEG-124-57.1	100	3	1	0	3	1	30	0.8	3	1	391375	9	9	2	18	5	4.5	1.3
BRO-62-9.2	80.4	9	2	1	3	1	8	0.4	3	1	533047	27	27	3	42	7	10.5	1.8
MOE-7-27	69.9	27	3	1	3	1	20	1	9	2	564312	20	27	3	59	9	14.8	2.3
COL-7-1.5	100	3	1	2	9	2	274	1.5	9	2	608333	27	27	3	48	8	12.0	2.0

Table 6.4b: Geometric and traffic parameter scores for all 108 study sites.

Site	Geometric Parameter Score			Oregon Vehicle Risk				% Decision Site Distance			Roadway Width				Traffic Parameter Score	
	Ritchie Score	Exp. Scale with Eq.	Continual Scale	AVR	In Oregon CR	Exp. Scale with Eq.	Continual Scale	Percent DSD	Exponential Scale	Continual Scale	Width (ft)	Exponential Score	Exp. Scale with Eq.	Continual Scale	Sum Continual/3	Sum Exponential/3
JEF-7-5B	2.3	70	3	280	81	81	4	100	3	1	33	81	31	4	3	38.3
COL-170-13.5	2.72	81	4	33	9	4	2	100	3	1	20	81	81	4	2	29.4
JEF-7-14.4C	1.8	51	3	208	81	81	4	100	3	1	33	81	31	4	3	38.3
MUS-60-6.9	3.7	81	4	89	81	50	4	100	3	1	33	81	31	4	3	28.0
JEF-7-5A	2.8	81	4	123	81	81	4	100	3	1	33	81	31	4	3	38.3
JEF-7-34.5B	2.3	70	3	47	9	8	2	100	3	1	33	81	31	4	2	14.0
WAY-3-2.4	5.1	81	4	6	3	1	1	26.9	81	4	28.5	81	58	4	3	46.6
JEF-7-10.6	2.3	70	3	499	81	81	4	100	3	1	33	81	31	4	3	38.3
JEF-7-34.5A	2.54	78	4	112	81	81	4	100	3	1	33	81	31	4	3	38.3
JEF-7-33.3A	1.6	41	3	79	81	32	4	100	3	1	35	27	24	3	3	19.6
HAM-74-18.1	1.56	39	3	717	81	81	4	100	3	1	27	81	71	4	3	51.6
WAS-7-39.5	1.6	41	3	191	81	81	4	71.7	9	2	32	81	36	4	3	41.9
BEL-7-23.1	2.3	70	3	136	81	81	4	100	3	1	33	81	31	4	3	38.3
BEL-70-220.5	1.72	47	3	41	9	6	2	100	3	1	24	81	81	4	2	30.0
JEF-7-28A	2.96	81	4	34	9	4	2	100	3	1	33	81	31	4	2	12.8
STA-800-1	6.7	81	4	48	9	8	2	100	3	1	30	81	47	4	2	19.4
SUM-76-23.5	2.52	78	4	1447	81	81	4	89.6	3	1	50	3	3	1	2	29.0
JEF-7-33.3C	1.9	55	3	45	9	7	2	100	3	1	35	27	24	3	2	11.3
BEL-70-223	2.5	77	3	22	3	3	1	100	3	1	30	81	47	4	2	17.5
TUS-36-0	2.1	63	3	76	81	28	4	100	3	1	35	27	24	3	3	18.0
GAL-160-0.55	2.32	71	3	75	81	27	4	100	3	1	29	81	54	4	3	27.9
JEF-7-22.6	1.6	41	3	131	81	81	4	100	3	1	33	81	31	4	3	38.3
ASD-97-4.1	1.8	51	3	5	3	1	1	22	81	4	35	27	24	3	3	35.3
COL-7-3.3	1.5	36	2	30	9	4	2	100	3	1	33	81	31	4	2	12.6
JEF-7-28B	2.1	63	3	34	9	4	2	100	3	1	33	81	31	4	2	12.8
TUS-77-60.9	1.1	11	2	114	81	81	4	100	3	1	38	27	16	3	3	33.2
BEL-7-11	1.64	43	3	808	81	81	4	100	3	1	33	81	31	4	3	38.3
WAY-21-2.36	1.27	23	2	397	81	81	4	100	3	1	36	27	21	3	3	34.8
HAM-74-17.6	1.1	11	2	393	81	81	4	100	3	1	27	81	71	4	3	51.6
HAM-74-9.4	1.4	31	2	418	81	81	4	100	3	1	27	81	71	4	3	51.6
TUS-250-23	1.8	51	3	105	81	81	4	100	3	1	48	9	4	2	2	29.3
HAM-71-10	1.4	31	2	1660	81	81	4	100	3	1	27	81	71	4	3	51.6
JEF-7-14.4B	1	4	1	155	81	81	4	100	3	1	35	27	24	3	3	35.9
COL-7-0.5	1.4	31	2	122	81	81	4	100	3	1	34	27	27	3	3	37.0
BEL-70-222.5	1.43	32	2	37	9	5	2	100	3	1	24	81	81	4	2	29.7
JEF-7-33.3B	1.4	31	2	75	27	26	3	100	3	1	35	27	24	3	2	17.6

Site	Geometric Parameter Score			Oregon Vehicle Risk				% Decision Site Distance			Roadway Width				Traffic Parameter Score	
	Ritchie Score	Exp. Scale with Eq.	Continual Scale	AVR	ln Oregon CR	Exp. Scale with Eq.	Continual Scale	Percent DSD	Exponential Scale	Continual Scale	Width (ft)	Exponential Score	Exp. Scale with Eq.	Continual Scale	Sum Continual/3	Sum Exponential/3
NOB-339-7.6	1.9	55	3	2	3	1	1	100	3	1	21	81	81	4	2	28.4
COL-45-20.15	1.775	50	3	76	81	28	4	100	3	1	32.5	81	33	4	3	21.4
LAW-7-2	1.16	16	2	120	81	81	4	100	3	1	36	27	21	3	3	34.8
JEF-7-20.1	1.17	16	2	94	81	63	4	100	3	1	33	81	31	4	3	32.4
JEF-7-6	0.98	3	1	458	81	81	4	100	3	1	33	81	31	4	3	38.3
BEL-149-1.8	1.14	14	2	114	81	81	4	100	3	1	24	81	81	4	3	55.0
COS-715-6.5	1.7	46	3	35	9	5	2	45.6	27	3	25	81	81	4	3	37.6
ATH-13-9.2	1.3	25	2	110	81	81	4	100	3	1	22	81	81	4	3	55.0
COL-7-3	1.2	18	2	52	27	10	3	100	3	1	33	81	31	4	3	14.5
SCI-52-25.5C	1.2	18	2	266	81	81	4	100	3	1	24	81	81	4	3	55.0
MOE-78-24.5	1.77	49	3	7	3	1	1	100	3	1	30.5	81	44	4	2	16.0
ATH-33-15A	0.8	3	1	116	81	81	4	99	3	1	21	81	81	4	3	55.0
LOG-292-2.6	1.8	51	3	3	3	1	1	100	3	1	24	81	81	4	2	28.4
MOE-800-4.5	1.6	41	3	7	3	1	1	100	3	1	18	81	81	4	2	28.5
TUS-77-63	1.3	25	2	138	81	81	4	100	3	1	38.5	27	15	3	3	32.9
LAW-52-12	1	4	1	904	81	81	4	100	3	1	41	27	10	3	3	31.4
BRO-62-9.0	1.66	44	3	39	9	5	2	100	3	1	33	81	31	4	2	13.2
COL-7-5	1.1	11	2	1222	81	81	4	100	3	1	33	81	31	4	3	38.3
ADA-41-16.1	1.33	27	2	30	9	4	2	100	3	1	33	81	31	4	2	12.6
JEF-7-14.4A	1.1	11	2	641	81	81	4	100	3	1	35	27	24	3	3	35.9
ASD-3-1.1	1.4	31	2	11	3	2	1	100	3	1	33	81	31	4	2	11.9
COL-7-2.8	1.4	31	2	70	27	22	3	100	3	1	43	9	8	2	2	10.9
MOE-7-1.5	1.2	18	2	127	81	81	4	100	3	1	32	81	36	4	3	39.9
JEF-7-0	0.8	3	1	104	81	81	4	100	3	1	25	81	81	4	3	55.0
BEL-7-18.6	0.6	3	4	115	81	81	4	100	3	1	29	81	54	4	3	45.9
BEL-149-4.5	1.12	13	2	80	81	33	4	100	3	1	24	81	81	4	3	39.0
MOE-537-1.7	1.4	31	2	1	3	1	1	100	3	1	18	81	81	4	2	28.4
JEF-7-22.1	1.2	18	2	315	81	81	4	100	3	1	33	81	31	4	3	38.3
SCI-52-25.5B	0.7	3	1	142	81	81	4	100	3	1	24	81	81	4	3	55.0
ATH-13-13.7	1.3	25	2	7	3	1	1	100	3	1	21	81	81	4	2	28.4
LIC-70-135	1.5	36	2	613	81	81	4	100	3	1	50	3	3	1	2	29.0
SUM-76-17	0.92	3	1	276	81	81	4	100	3	1	23	81	81	4	3	55.0
RIC-30-12.5	0.9	3	1	576	81	81	4	100	3	1	45	9	6	2	2	30.0
BEL-7-9	1.1	11	2	444	81	81	4	100	3	1	33	81	31	4	3	38.3
JEF-7-1.5	0.8	3	1	346	81	81	4	100	3	1	17	81	81	4	3	55.0
SCI-52-25.5A	0.6	3	1	562	81	81	4	100	3	1	24	81	81	4	3	55.0
BEL-7-14	0.9	3	1	404	81	81	4	100	3	1	43	9	8	2	2	30.6
ASD-30-2.25	1.18	17	2	105	81	81	4	100	3	1	36.5	27	19	3	3	34.4

Site	Geometric Parameter Score			Oregon Vehicle Risk				% Decision Site Distance			Roadway Width				Traffic Parameter Score	
	Ritchie Score	Exp. Scale with Eq.	Continual Scale	AVR	ln Oregon CR	Exp. Scale with Eq.	Continual Scale	Percent DSD	Exponential Scale	Continual Scale	Width (ft)	Exponential Score	Exp. Scale with Eq.	Continual Scale	Sum Continual/3	Sum Exponential/3
ASD-3-1.8	1.2	18	2	10	3	2	1	100	3	1	28	81	62	4	2	22.1
BRO-52-23	0.65	3	1	207	81	81	4	100	3	1	31	81	41	4	3	41.6
PER-155-1.83	0.92	3	1	16	3	2	1	100	3	1	24	81	81	4	2	28.7
JEF-22-8	1.26	22	2	86	81	43	4	100	3	1	48	9	4	2	2	16.8
COS-36-28-30	1.23	20	2	108	81	81	4	100	3	1	40	27	12	3	3	32.0
BEL-7-26.8	0.6	3	1	1725	81	81	4	100	3	1	33	81	31	4	3	38.3
ATH-78-22.5	1.5	36	2	4	3	1	1	100	3	1	31	81	41	4	2	15.0
ATH-124-2	1.22	20	2	5	3	1	1	100	3	1	26	81	81	4	2	28.4
JEF-22-13.9	0.7	3	1	326	81	81	4	100	3	1	48	9	4	2	2	29.3
PER-13-5.1	0.82	3	1	17	3	2	1	100	3	1	24	81	81	4	2	28.7
WAS-7-33.2	1.4	31	2	54	27	11	3	100	3	1	33	81	31	4	3	14.9
BEL-7-5.9	1.02	5	2	164	81	81	4	100	3	1	31	81	41	4	3	41.6
JEF-7-14.6	1.1	11	2	255	81	81	4	100	3	1	32	81	36	4	3	39.9
JEF-22-13.2	1.13	14	2	140	81	81	4	100	3	1	48	9	4	2	2	29.3
JEF-7-0.5	0.97	3	1	31	9	4	2	100	3	1	25	81	81	4	2	29.3
HOC-33-5	0.9	3	1	137	81	81	4	100	3	1	36	27	21	3	3	34.8
MED-271-5.2	0.9	3	1	270	81	81	4	100	3	1	44	9	7	2	2	30.3
ATH-33-15B	0.89	3	1	175	81	81	4	100	3	1	37	27	18	3	3	34.0
RIC-71-174	0.95	3	1	495	81	81	4	100	3	1	39	27	14	3	3	32.5
MRG-60-10	1.4	31	2	23	3	3	1	100	3	1	38	27	16	3	2	7.1
MOE-7-28	0.7	3	1	69	27	21	3	100	3	1	33	81	31	4	3	18.2
CLA-68-7	0.85	3	1	443	81	81	4	100	3	1	38	27	16	3	3	33.2
BRO-62-9.1	1.14	14	2	35	9	5	2	100	3	1	33	81	31	4	2	12.9
LOG-33-20.5	0.98	3	1	153	81	81	4	100	3	1	39	27	14	3	3	32.5
TUS-250-12.3	0.82	3	1	89	81	49	4	100	3	1	48	9	4	2	2	18.8
SUM-76-20	0.93	3	1	536	81	81	4	100	3	1	47	9	5	2	2	29.5
LIC-16-28	0.9	3	1	90	81	51	4	100	3	1	32	81	36	4	3	29.9
JEF-7-18.8	0.9	3	1	630	81	81	4	100	3	1	50	3	3	1	2	29.0
WAS-7-36.5	1.1	11	2	45	9	7	2	100	3	1	32	81	36	4	2	15.3
BEL-7-6.3	1	4	1	82	81	36	4	100	3	1	39	27	14	3	3	17.6
MEG-124-57.2	1.05	8	2	25	3	3	1	100	3	1	32	81	36	4	2	13.9
BRO-62-9.2	0.91	3	1	28	9	3	2	100	3	1	33	81	31	4	2	12.5
MOE-7-27	0.71	3	1	14	3	2	1	100	3	1	38	27	16	3	2	6.8
COL-7-1.5	0.62	3	1	40	9	6	2	100	3	1	39	27	14	3	2	7.5

scales, the exponential scale provides a better differentiation of the scores than the continual scale due to its larger range of scores and is, therefore, recommended for future use.6.4 Hazard Potential Categorization of Sites

Table 6.5 represents a relative hazard potential rating for all 108 sites examined in this study. The sites with greater overall scores represent sites with a greater potential of rockfall hazard. It is also common to broadly assess the ratings in terms of group membership, i.e. categorize the sites as high hazard, moderate hazard, and low hazard sites. For this study, all sites with rating scores greater than 100 are considered as high hazard potential sites, those with scores between 50 and 100 as moderate hazard potential sites, and those with scores less than 50 are included in the low hazard potential category. The high hazard potential sites (greater score than 100) have a relatively high average score (33 points) for all three categories of evaluation parameters. Moderate hazard potential sites generally have only one category of parameters that may carry high scores, but the other parameter categories get relatively low scores, and low hazard potential sites represent slopes that are relatively safe with respect to all three categories of parameters. In this study, 26 of the 108 sites are rated as having high hazard potential for rockfalls, 51 as moderate hazard potential, and 31 as low hazard potential.

Table 6.5 also lists the original (preliminary) rating of the study. Notice that some of the study sites were not assigned any preliminary rating. The comparison of the original and final ratings show that of the 42 percent of the slopes originally ranked as being a high hazard potential were eventually ranked as a high hazard according to the matrix. Also, 86% of the moderate and 36% of the low hazard potential sites had

Table 6.5: Hazard Potential Evaluation of Individual Sites

Site	Original Rating	Overall Rating	Site	Original Rating	Overall Rating	Site	Original Rating	Overall Rating
High Hazard Potential			JEF-7-33.3B	*	93	BEL-7-14	*	64
JEF-7-5B	*	157	NOB-339-7.6	H	92	ASD-30-2.25	M	63
COL-170-13.5	M	146	COL-45-20.15	L	92	ASD-3-1.8	L-M	63
JEF-7-14.4C	H	139	LAW-7-2	M	91	BRO-52-23	L-M	63
MUS-60-6.9	H	137	JEF-7-20.1	*	91	PER-155-1.83	M	61
JEF-7-5A	*	136	JEF-7-6	*	90	JEF-22-8	Low	60
JEF-7-34.5B	*	134	BEL-149-1.8	M	90	COS-36-28-30	M	60
WAY-3-2.4	*	132	COS-715-6.5	L	90	BEL-7-26.8	*	59
JEF-7-10.6	H	132	ATH-13-9.2	H	87	ATH-78-22.5	*	58
JEF-7-34.5A	*	129	COL-7-3	M	87	ATH-124-2	M	58
JEF-7-33.3A	*	126	SCI-52-25.5C	H	85	JEF-22-13.9	M	58
HAM-74-18.1	L	119	MOE-78-24.5	M	85	PER-13-5.1	M	57
WAS-7-39.5	*	119	ATH-33-15A	L	84	WAS-7-33.2	*	56
BEL-7-23.1	*	119	LOG-292-2.6	L-M	84	BEL-7-5.9	*	56
BEL-70-220.5	H	118	MOE-800-4.5	L-M	82	JEF-7-14.6	*	54
JEF-7-28A	*	117	TUS-77-63	*	82	JEF-22-13.2	M	53
STA-800-1	L-M	115	LAW-52-12	*	80	JEF-7-0.5	*	53
SUM-76-23.5	M	113	BRO-62-9.0	M	80	HOC-33-5	H	53
JEF-7-33.3C	*	111	COL-7-5	*	80	MED-271-5.2	M-H	50
BEL-70-223	H	110	ADA-41-16.1	M	78	ATH-33-15B	L	50
TUS-36-0	*	109	JEF-7-14.4A	H	77	Low Hazard Potential		
GAL-160-0.55	H	108	ASD-3-1.1	L	77	RIC-71-174	L-M	48
JEF-7-22.6	*	106	COL-7-2.8	M	76	MRG-60-10	H	45
ASD-97-4.1	H	104	MOE-7-1.5	*	76	MOE-7-28	L	42
COL-7-3.3	H	103	JEF-7-0	*	75	CLA-68-7	L	42
JEF-7-28B	*	101	BEL-7-18.6	*	73	BRO-62-9.1	M	41
TUS-77-60.9	*	100	BEL-149-4.5	L	73	LOG-33-20.5	L	40
Moderate Hazard Potential			MOE-537-1.7	H	73	TUS-250-12.3	H	40
BEL-7-11	*	98	JEF-7-22.1	*	72	SUM-76-20	L	39
WAY-21-2.36	M	98	SCI-52-25.5B	*	72	LIC-16-28	L	38
HAM-74-17.6	L	97	ATH-13-13.7	H	71	JEF-7-18.8	*	38
HAM-74-9.4	L	97	LIC-70-135	M	71	WAS-7-36.5	*	37
TUS-250-23	*	97	SUM-76-17	L	70	BEL-7-6.3	*	32
HAM-71-10	M	96	RIC-30-12.5	M	69	MEG-124-57.2	L	26
JEF-7-14.4B	H	95	BEL-7-9	*	66	BRO-62-9.2	L	26
COL-7-0.5	*	94	JEF-7-1.5	*	64	MOE-7-27	L	25
BEL-70-222.5	H	94	SCI-52-25.5A	H	64	COL-7-1.5	*	23

Original Rating: H=High, M=Moderate, L=Low hazard. Original ratings are based on low to high scale assessment by ODOT District personnel. If ratings are not provided that site was not identified by district.

corresponding ratings to the original rating. The overall percentage of like ratings was 55%.

Figures 6.4 through 6.7 shows the distribution of the sites belonging to different hazard potential categories across the state. Examples of high, medium and low hazard potential sites are presented in Figures 6.8, 6.9, and 6.10, respectively.

6.4 Preliminary Ratings

It may be prudent to limit the number of slopes to be evaluated by the matrix developed in this study to those with a possibility of releasing a consequential rockfall. This can be accomplished by assigning a preliminary rating to all slopes. Table 6.6 shows a proposed preliminary rating matrix. It is based on two categories of evaluation, rockfall history and rockfall potential, which are subjectively assessed and ranked according to the following descriptions.

Table 6.6: Preliminary slope rating matrix.

	Rock Fall History	Rock Fall Potential
High	3	3
Moderate	2	2
Low Hazard	1	1

6.4.1 Rockfall History

A good indicator of the future performance of a road cut is it's the past behavior. The rockfall history for a site can be subjectively assessed through discussions with

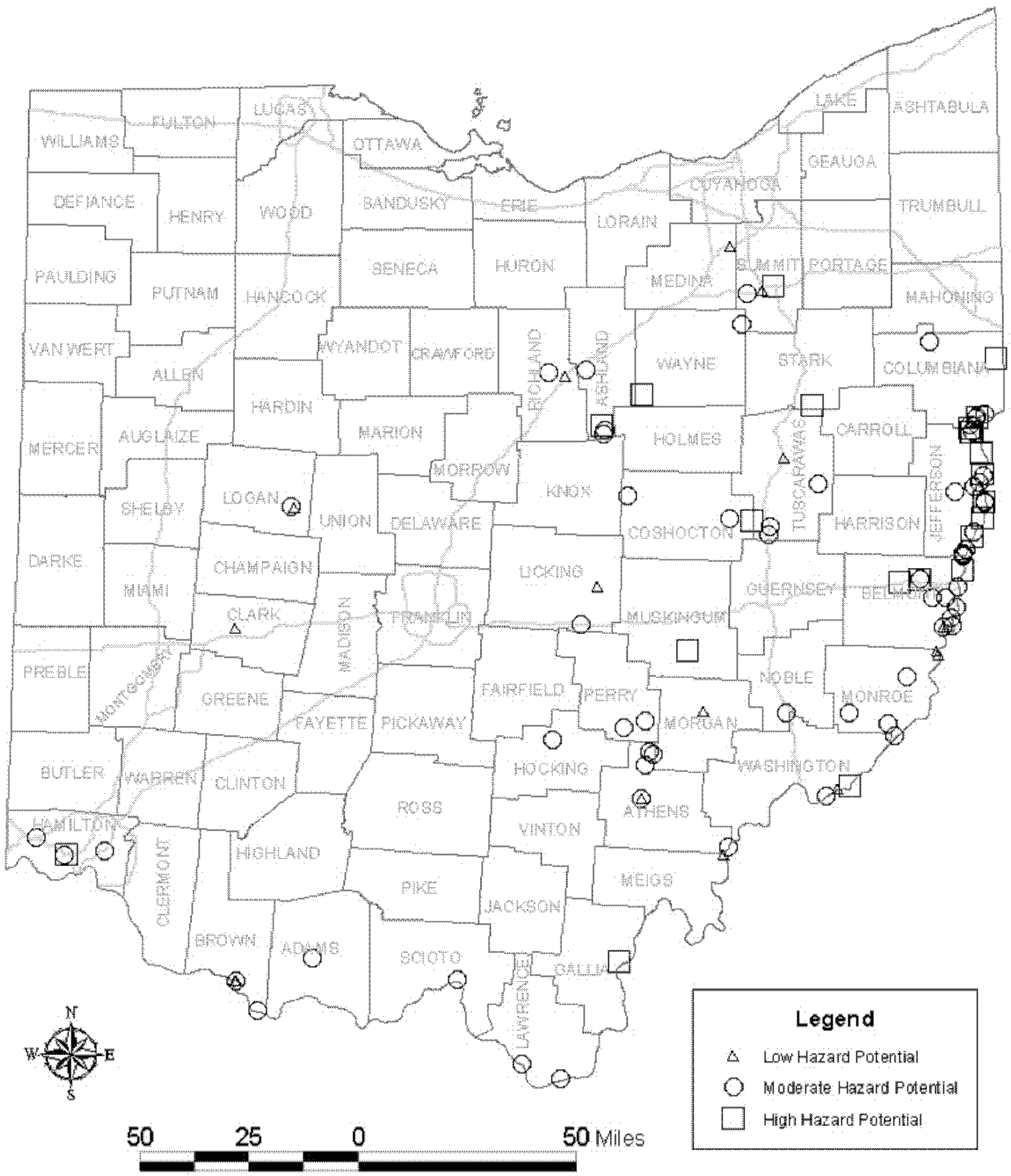


Figure 6.4: Distribution of study sites rated as high, moderate, and low hazard potential.

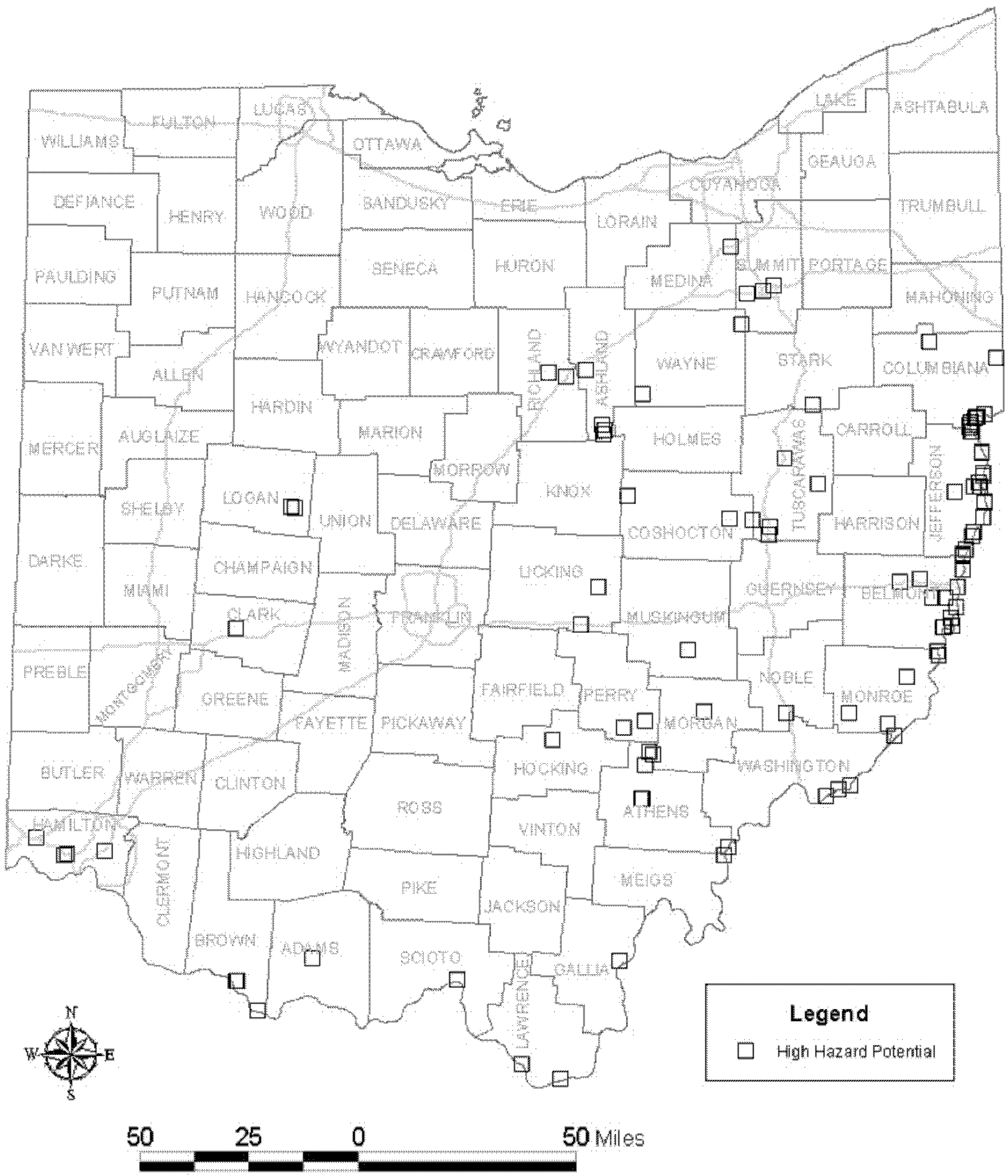


Figure 6.5: Distribution of study sites rated as having a high hazard potential.

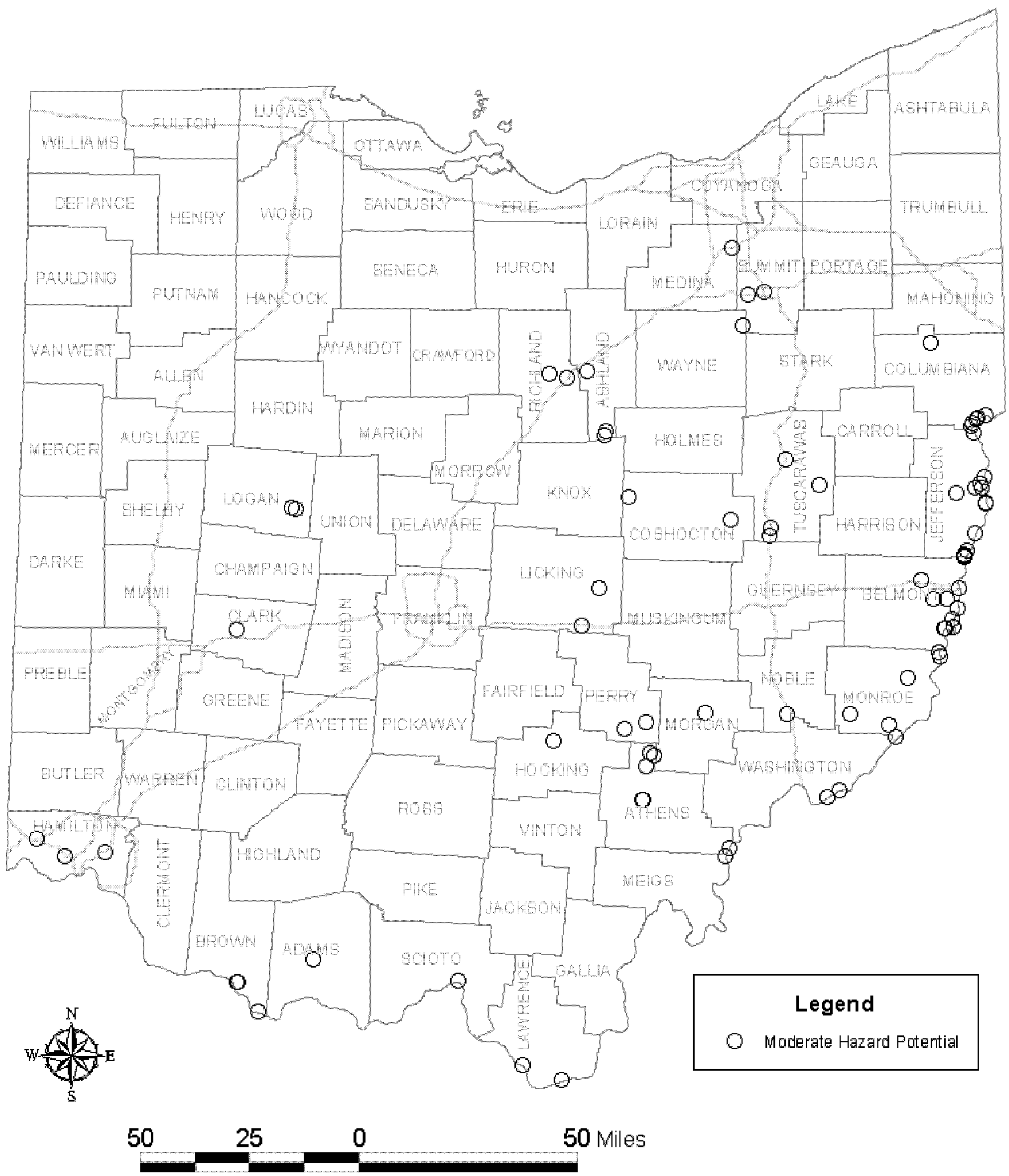


Figure 6.6: Distribution of study sites rated as having a moderate hazard potential.

Figure 6.7: Distribution of study sites rated as having a low hazard potential.

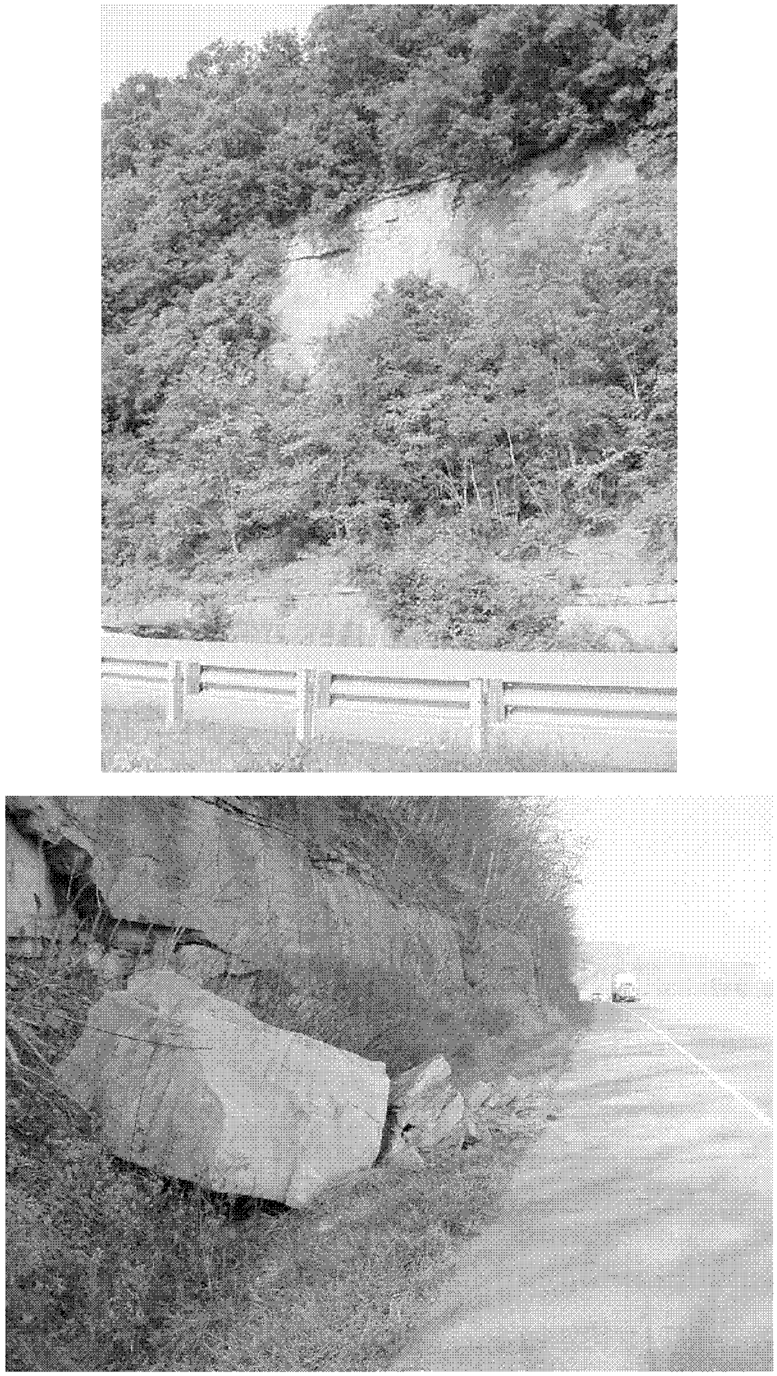


Figure 6.8: Example of a high hazard potential site located at JEF-7-5A: (top) view of entire slope; (bottom) presence of a narrow catchment ditch for large-size rock falls.

Figure 6.9. Example of a moderate hazard potential site located at JEF-7-22.1.

Figure 6.10: Example of a low hazard potential site located at MOE-7-27.

district personnel, review of maintenance records, and/or field observations. The rankings should be based on the descriptions listed below:

- High Ranking (3): frequent rockfalls; number of rocks in past reached the roadway.
- Moderate Ranking (2): rare to frequent rockfalls; some rockfalls reached the roadway.
- Low Ranking (1): infrequent to no rockfalls; no rocks known to reach the roadway.

6.4.2 Rockfall Potential

The rockfall potential present at a site can be is used to assess the possibility of future rockfalls and their potential to enter the roadway. This is accomplished by examination of the extent of differential weathering and a subjective assessment of the potential of a rockfall to enter the roadway. The rockfall potential should be assessed as follows:

- High Ranking (3): numerous undercuts with jointed overhanging rock with joints present; imminent potential for rockfalls; high potential for rockfalls to reach the roadway.
- Moderate Ranking (2): undercuts with jointed overhanging rock present with some potential for rockfalls; some potential for rockfalls to reach the roadway.
- Low Ranking (1): undercuts with jointed overhanging rock either absent or infrequent; no imminent potential for rockfalls entering the roadway.

6.4.3 Preliminary Rating

Each slope can be assigned a score on the basis of its rockfall history and rockfall potential ranging from 1 to 3. The sum of the two scores gives the preliminary rating for the slope, which ranges from scores of 2 to 6. The preliminary hazard potential category can then be assigned to each slope with scores of five 5 to 6 indicating a high hazard potential rating, scores of 3 to 4 a moderate hazard potential, and a score of 2 indicating a low hazard potential rating.

An example of the preliminary rating can be illustrated by the rock slope located on Route 52 in Lawrence County (LAW-52-12), which is shown in Figure 6.11. This slope is nearly 200 feet tall and contains two significant benches at 70 feet and 140 feet. There are numerous overhangs and potential for significant sized blocks to dislodge from the cut. However, this cut does posses a wide catchment area with a barrier placed at the edge of the road. Because there are frequent rockfalls and without the barrier a potential for rockfalls to enter the roadway the rockfall history score can be given a score of 2. Furthermore, a potential for future rockfalls does exist to break through the barrier and enter the roadway. But the potential is not as great as if this slope did not have a barrier in place, therefore a preliminary rockfall potential score of 2 is given. This gives a preliminary rating for this slope of a 4, or a moderate hazard potential. This indicates that this slope should be rated with the full rock slope rating.

The preliminary rating can be used to decrease the number of sites to be evaluated by the application of the full rating system (section 6.2). ODOT can allocate resources to perform full ratings on slopes with higher preliminary ratings. For rock slopes with low

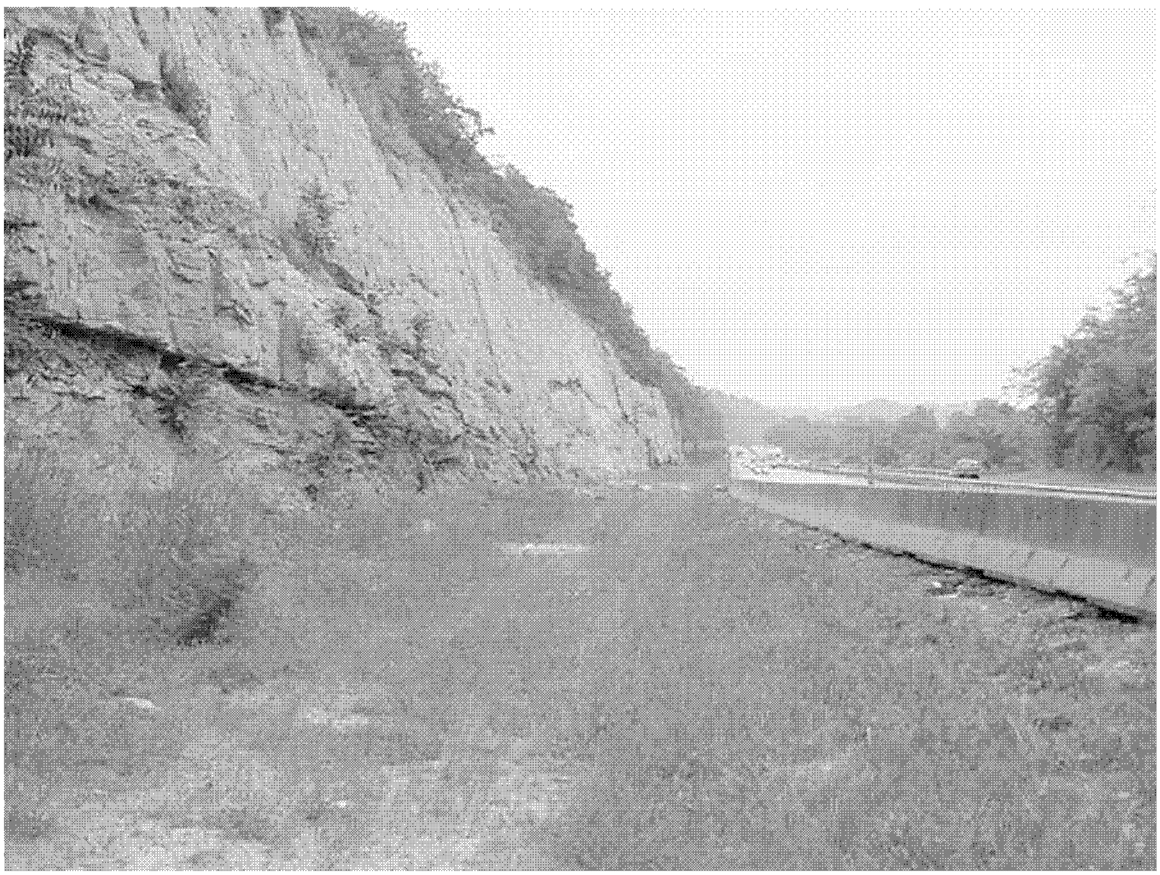


Figure 6.11. Example of the preliminary rating applied to a site located at LAW-52-12.5.

preliminary ratings, the effort to perform a full rating may not be necessary. The justification for this approach is that sites which have an obviously low potential for rockfalls and the associated hazard will most likely receive the low hazard potential rating even when a more comprehensive rating system is applied and the removal of these sites from the evaluation lists will allow the evaluator to allocate their time effectively towards more problematic slopes.

6.5 Limitations and discussion of the Rockfall Hazard Rating Matrix

Relative rating and classification systems are not designed to account for every situation they are applied to. Therefore, it is essential to understand the limitations of these systems. The following are some of the limitations of the proposed Ohio matrix.

6.5.1 Geologic Parameters (Differential Weathering)

It has been stated previously that differential weathering is the mechanism that controls rockfalls at the sites examined in this study. Also, according to the statistical analysis, the variable that aided in differentiating most of the slopes in terms of rockfall hazard potential is the slake durability index. This is because the slake durability index is an inherent property of the rocks that is controlled by their geology and does not change with time. However, the maximum amount of undercutting can change with time. If an evaluation of a particular site is made ignoring both the slake durability index and the joint roughness coefficient, the hazard potential may not be fully evaluated. For example, if a slope constructed in the 1950's, that contains differentially erodable strata, a problem could arise if it is evaluated by a rater who is not sure if the maximum amount of

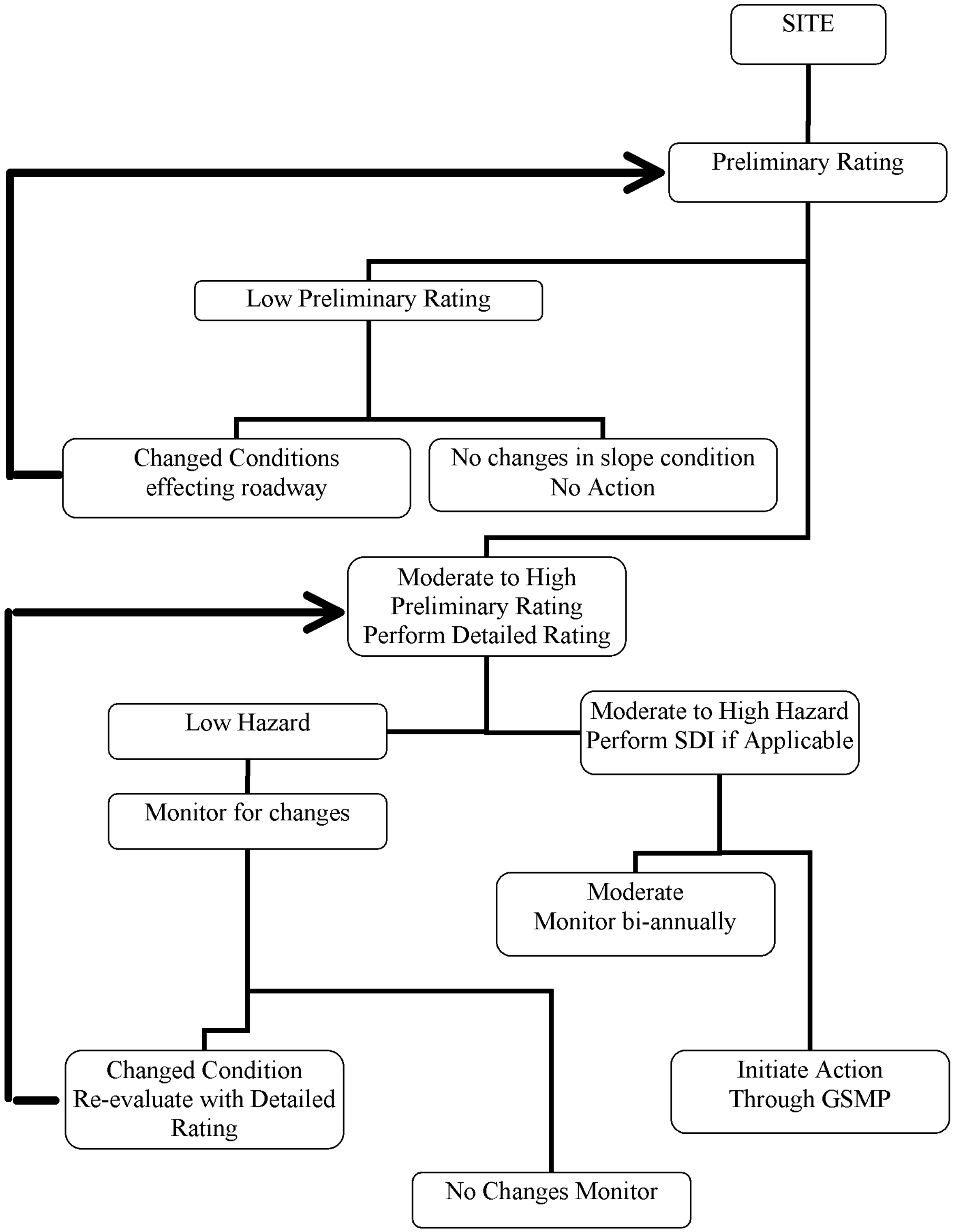


Figure 6.12. Sample Organizational Chart.

undercutting being recorded is the true amount of undercutting since excavation. For instance, if the undercut layer failed in the recent past, an underestimation of the amount of undercutting and, therefore, a lower rockfall hazard potential could be assigned. On the other hand, if a new cut is made in the same type of geology using the same design as the 1950's cut, the weathering and erosion processes will not have had time to occur. In this second case, although the geology is the same, the undercutting will be either absent or minimal. In this case the rater will not be able to predict the changes in the slope over time and will underestimate the potential for rockfalls if the evaluation was based entirely on the basis of the amount of undercutting and if slake durability was not taken into account. The usefulness of the proposed matrix lies not only in its ability to evaluate the present state of rockfall hazard but also the future potential so that the hazard can be prevented before it occurs.

6.5.2 Geologic Parameters (Role of Discontinuities)

In developing the rating matrix for Ohio, the mechanism that is considered to control the occurrence of most rockfalls in Ohio is differential weathering. However, the mechanism concerning the role of discontinuities was added to broaden the applicability of the rating matrix. The descriptions of the discontinuity extent and orientation as well as the frictional component are based on the experience gained through the application of existing rating systems and associated research.

6.5.3 Geometric Parameters

The Ritchie score was chosen as a parameter for the proposed matrix due to its successful longevity in slope design. However, this parameter does have some shortcomings when applied to the conditions prevalent in the state of Ohio. The Ritchie ditch criterion was developed for single-angled slopes and may not be completely accurate for the slopes in Ohio, many of which contain mid-slope benches and multiple angles. Also, the Ritchie ditch criterion is only applicable to slopes reaching a maximum of 120 feet (40 m) in height. In Ohio there are some slopes that are greater than 250 feet (80 m) in height.

However, the other methods that can be used to evaluate catchment ditches also have their limitations. The recently developed catchment ditch design proposed by Pierson and others (2001) is also limited to single-angled slopes with a maximum height of 80 feet (25 m). The Colorado Rockfall Simulation Program (CRSP) has been recommended, by Pierson and others (2001) for slopes of greater heights. However, the developers of this program caution about the indiscriminate use of CRSP due to the uncertainties associated with the input parameters (Higgins, 2001). The use of subjective ratings, such as in the Oregon Rockfall Hazard Rating System (Pierson, 1991), is yet another method that is commonly used to evaluate catchment area. But, the ratings become inconsistent as the number of people using this method increases (Hopkins, 2000).

6.5.4 Record of Past Rockfalls

Prior to the use of rockfall history as an input parameter in the matrix, historical rockfall data needs to be collected for all the sites. Without a well-documented historical account of rockfall events, improper ratings may be assigned. It is highly recommended that ODOT starts to develop a database for rockfall history and accumulate sufficient data before using this parameter as a part of the matrix. Information regarding a rockfall event such as date of occurrence, size or volume of rockfall event, location of final resting place of rockfall, and damage done to roadway and vehicles should be included in the database. A suggested rockfall event data sheet can be found in Appendix G.

CHAPTER 7

ROCKFALL MITIGATION AND COST ANALYSIS

The hazards posed by rockfalls to roadway travelers may be mitigated by the installation of protection devices, use of slope stabilization techniques, or modification of a hazardous slope. Table 7.1 is a list of the commonly used techniques used to mitigate rockfall hazards (McCauley et al., 1985). It should be noted, however, that no matter what method or combinations of methods are used, the ability to entirely eliminate the hazard in some locations might not be achievable. This may be due to monetary constraints, environmental concerns, or temporal changes that will take place along a rock slope. Mitigation of rockfall hazards can be accomplished in a number of ways. The following is a discussion of the commonly used techniques and their application in Ohio.

7.1 Rockfall Protection Measures

Rockfall protection measures include techniques used at the toe of the slope as well as on the slope face that control rockfalls or prevent rockfalls from entering the roadway. The most commonly used protection measures in Ohio are techniques employed at the toe of the slope. These include catchment areas and barriers placed at the toe of the slope to prevent falling debris from entering the roadway. To assess the adequacy of the methods employed at the toe of a slope, information about the trajectory and energy of a rockfall event is required.

Table 7.1: Examples of rock fall mitigation measures (from McCauley et al., 1985).

Protection Measures	Stabilization Measures	Warning Measures
Relocate Roadway	Flatten Slope	Signs
Tunnel	Scale or Trim	Electric Fences and Wire
Rock Shed	Design to Geology	Monitoring
Bench	Controlled Blasting	Patrols
Catchment Ditch	Subsurface Drainage	
Widening at Grade	Rockbolts and Dowels	
Wire Mesh Fence	Shotcrete and Gunite	
Timber Lagging Walls	Anchored Wire Mesh	
Metal Guardrail	Cable Lashing	
Jersey Barrier	Concrete Buttresses	
Earth Berm	Retaining Walls	
Draped Mesh Net		

7.1.1 Catchment Ditches

A properly designed catchment ditch located between the toe of the slope and the roadway is often a cost-effective means of stopping rockfalls when there is adequate space (Wyllie and Norrish, 1996). As previously stated in this study, much work has been done on the requirements for catchment ditch design (Ritchie, 1963; Pierson et al., 1994; Pierson et al., 2001). The dimensions of the catchment ditch (width and depth and/or angle) are based on the height and slope angle of the rock cut. Design charts, such as those based on the Ritchie criteria (Figure 3.5) can be used to determine the appropriate widths and depths of the catchment areas.

It may be difficult to change the geometry of an existing catchment area due to the proximity of the road cut to the roadway. However, attempts can be made to deepen catchment zones. Pierson and others (2001) found moderate success in steepening the overall angles of catchment areas. The steepening of the catchment area increases the ability of the catchment area to prevent rockfalls from entering the roadway by reducing the rollout distances.

7.1.2 Barriers

A variety of barriers are available that can either improve the performance of catchment ditches or possibly create catchment areas at the toe or at midpoints within the slope (Wyllie and Norrish, 1996). The provision of a barrier along the catchment area has the same effect as deepening of the catchment area and is a viable option where limited space is available. The function of a barrier is to form a near vertical face to trap the rocks in the catchment area. Commonly used barriers include soil berms, gabions, concrete barriers, and rockfall fences. The type of barrier to use depends upon the energy and trajectory of the falling rocks. To determine the adequacy of each type of barrier for a specific site, it is suggested that a rockfall simulation program, such as CRSP, be employed to determine the trajectories and energies of the rockfalls. The various types of barriers are summarized below:

Earth Berm

An example of an earth berm used as a rockfall barrier can be seen in Figure 6.10. At this site (MOE-7-28), the ditch has been deepened and a berm placed closer to the road. In a limited space, as is the case with the example shown in Figure 6.10, the use of the soil berm essentially enlarges the catchment area and prevents rocks from rolling past the berm on to the roadway. The effectiveness of this technique depends on the first bounce location of the rockfall away from the slope face. If the first bounce location happens to be on the roadway side of the soil berm, the berm will be ineffective in containing rockfalls.

Gabions

Gabions are rock filled baskets, typically measuring 3-foot square (1 meter square) cross-sections with varying widths, constructed on site from waste rock (Wyllie and Norrish, 1996). Gabions stacked on top of each other can withstand significant impacts from falling rocks with diameters up to 2.5 feet (0.75 m) (Wyllie and Norrish, 1996). The advantage of gabions is their ease of construction; however, they can sustain damage from falling rocks and maintenance vehicles. Also, repair of gabions can be difficult and costly (Wyllie and Norrish, 1996).

Concrete "jersey" Barrier

A commonly used alternative to gabions is the use of concrete or jersey barriers. The impact resistance of jersey barriers is similar to that of gabions (Wyllie and Norrish, 1996). However, unlike gabions, jersey barriers can be easily replaced creating a lower cost alternative. The choice of a jersey barrier is restricted by its height of 2.5 feet (0.75 meters), which limits the rockfall trajectories it can contain.

Metal Guardrail

A metal guardrail modified with an additional horizontal bar placed lower on the slope side of the rail has been used by many departments of transportations for rockfall protection. The containment of smaller rock and shattered rock is limited with this system as well as its limited bounce height and energy absorption capacity.

Modified D-50 Wall

To account for rocks that have trajectories slightly higher than 2.5 feet (0.75 m) a commonly used concrete barrier in Ohio is the cast in place modified D-50 wall, which measures 50 inches tall (1.25 m). The modified D-50 wall, as seen in Figure 7.1, is also slightly thicker than the common jersey barrier (6 inches or 0.15 meters across the top of the wall), which suggests an ability to handle rockfall impacts with greater energies than the jersey barriers.

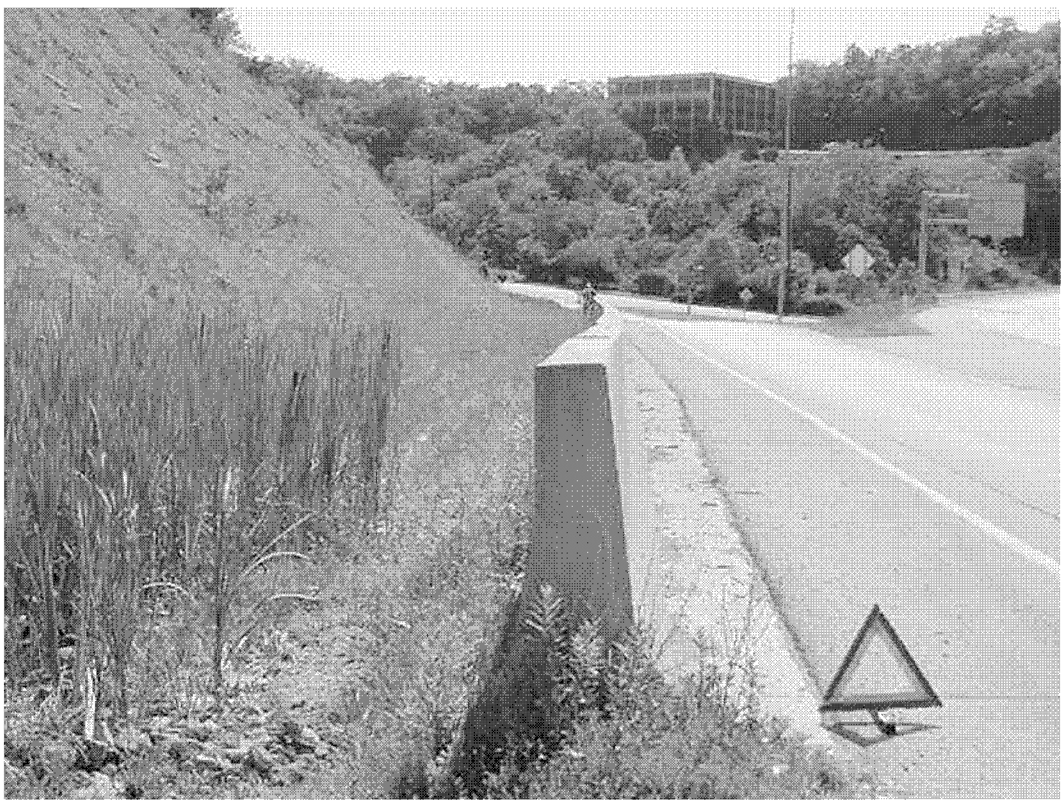


Figure 7.1: Example of a modified D-50 barrier.

Rockfall Fences

Rockfall fences are found in much less abundance than the barriers throughout Ohio. The most common rockfall fences used in the United States is a thick gabion-netting fence with mechanical breaking systems (Figure 7.2). The breaking systems allow the dissipation of impact energy from the rockfall allowing them to absorb a larger impact then either of the previously mentioned concrete barriers. These fences are also generally taller (height can reach 8 to 10 feet or 2.5 to 3 m) than a modified D50 concrete barrier making them a very useful remediation method for slopes producing rockfalls with larger bounce heights. Manufacturers of these fences include Geobrugg Fence®, CAN®, ELSA®, and X-cross®.

Another type of rockfall fence is also found within District 11 of ODOT and is shown in Figure 7.3. It has been designed by ODOT to contain many smaller rockfalls at a substantially lower price than the Geobrugg fence (Graham, 2000). However, it is a relatively new and has an unstudied design; therefore, its ability of containing significantly sized rockfalls is unknown.

7.1.3 Rockfall Protection Measures on the Slope

Benches

The most commonly used mid-slope rockfall protection measure used in Ohio is the use of benches (Figure 7.4). There are two purposes of providing benches: initially the bench acts as a catchment area for rockfalls generated from above and ultimately, as the slope weathers, the benches would fill in with eroded colluvial material to a natural angle of repose (Fookes and Sweeney, 1976). As a mid-slope catchment area, a bench

Figure 7.2: Example of a rock fall catchment fence with breaking system (photograph from www.geobrugg.com).

Figure 7.3: Simple rock fall fence employed by Ohio DOT shown parallel to roadway.

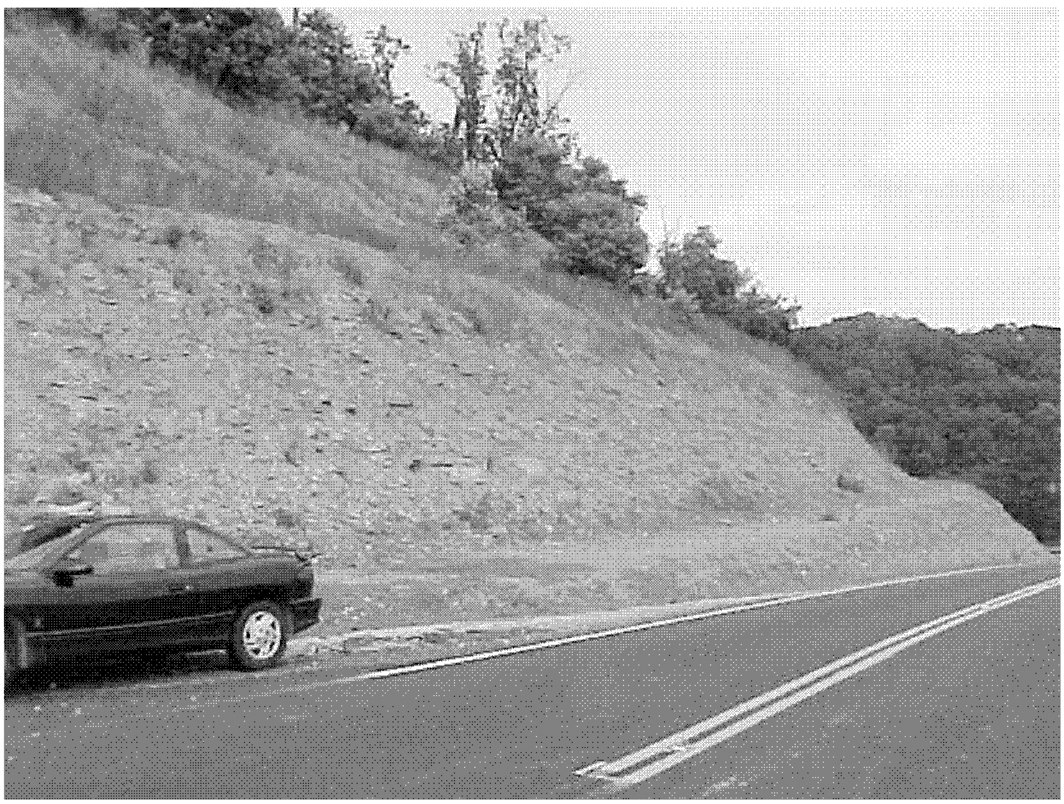


Figure 7.4: Mid-slope benches found at COS-715-6.

theoretically shortens the effective height of the slope resulting in the need for a smaller catchment area at the base of the slope. For instance, if a catchment bench was placed at an elevation of 50 feet (15 m) on a 100 foot (30 m) slope then the catchment areas, both at the mid-slope bench and toe of the slope, may only need to be designed for a 50 foot (15 m) tall slope rather than designing a catchment area at the toe for a 100 foot (30 m) tall slope.

A problem does exist, however, with allowing the colluvial material to build up on the mid-slope bench or benches. The build up of material can fill up the bench and diminish its ability to contain falling rocks. The filling of benches has sometimes created slope geometries which extend the trajectories of rockfalls away from the toe of the slope towards the roadway. This results in possibly making the catchment area at the toe of the slope inadequate at preventing rocks from entering the roadway (Wyllie and Norrish, 1996). It has also been recognized that if the crest of the bench is damaged due to inadequate construction (over blasting) or through erosion of the bench material, the effectiveness of the bench also decreases resulting in perhaps a more dangerous situation (Wyllie and Norrish, 1996). For these reasons, for a bench to work properly, it must first be designed properly as a catchment area as well as have a maintenance program initiated that periodically cleans the bench of the colluvial material. If a mid-slope bench (or benches) is determined not to be adequate at preventing falling rocks from moving beyond it (down slope) it may be modified by providing a rockfall barrier such as a rockfall fence along its edge.

Rockfall Attenuators and Draped Wire Mesh Netting

Other forms of mid-slope rockfall protection include rockfall attenuators and wire mesh netting. Rockfall attenuators can be placed in talus run out areas such as the back slope areas of road cuts. Various designs have been proposed (Smith and Duffy 1990; and Barrett and White, 1991) which are specifically based on the topography of the area as well as trajectory and energy of the rockfalls.

For slopes with a constant spalling of small rocks (1.5 foot diameter of 0.5 m), draped wire mesh netting can be employed. In this method, wire mesh is draped over the slope, anchored at the top by bolts, and effectively contains rockfalls between the slope and the mesh netting. The rock slowly works its way down the cut and gently falls into the catchment area where a maintenance crew can easily clean the catchment area. The wire mesh can also be anchored, proactively tightening the small loose blocks to the slope. If the wire mesh is anchored, care should be taken to not overburden the mesh netting with the build up of talus material.

7.2 Slope Stabilization

In cases of large isolated rock blocks that may lead to rockfalls, a reinforcement measure may be used to secure loose blocks on the slope face. These methods include rock bolts and dowels.

7.2.1 Rock Bolts

Rock bolts can be installed through a rock block, across potential failure surfaces, into sound rock beyond the block. The application of a tensile force on the bolt modifies the normal and shear forces acting along the discontinuities bounding the rock block in such a manner that the driving force is decreased and the resisting force is increased. The amount of tension force required to stabilize a block, which determines the number of bolts needed, depends upon the block size and the desired factor of safety (Wyllie and Norrish, 1996).

7.2.2 Dowels

Dowels are similar to rock bolts in that they are installed through a rock block into sound material beyond the block, but they are not tensioned. Therefore, dowels only act passively and any increase in the resisting force is only due to the shear resistance of the dowels.

7.2.3 Shotcrete

Applying a layer of shotcrete to the rock face can protect zones or beds of closely fractured or degradable rock. The shotcrete controls both the fall of small blocks of rock and the progressive raveling that will produce large, unstable overhangs on the face. However, shotcrete provides little support against sliding of large blocks, its primary function being surface protection. Shotcrete is pneumatically applied, fine-aggregate mortar (less than 13 mm aggregate size) that is usually placed in a 75 to 100 mm thick layer (American Concrete Institute, 1983).

The effectiveness of shotcrete depends to a large degree on the condition of the rock surface to which it is applied. The surface should be free of loose and broken rock, soil, vegetation, and ice. It should be damp to improve the adhesion between the rock and the shotcrete. It is important that drain holes be drilled thought he shotcrete face; the drain holes are usually about 0.5 m deep and are located on 1 to 3 m centers (Wyllie and Norrish, 1996). Shotcrete can be ineffective in areas with elevated or perched groundwater. Any installation of shotcrete should be done with weep holes to alleviate pore pressures.

Cable Lashing

A technique to contain isolated large blocks includes cable lashing. A series of cables are pined into the rock mass surrounding an isolated block and tightened to secure the block.

Retention Structures

Structures such as timber lagging walls, concrete buttresses, and other types of retaining structures can be constructed to contain or confine rockfalls. This action is commonly only performed in isolated areas where a structure is cost effective.

7.3 Slope Modification

7.3.1 Scaling and Trimming

Scaling and trimming, also referred to as dental work, is the removal of loose or hazardous rocks, soil and vegetation from the face of a slope (Wyllie and Norrish, 1996). This involves a number of techniques from controlled blasting to hand removal using scaling bars, shovels, hydraulic jacks, and chain saws.

The term trimming refers to the removal of large unstable blocks by controlled blasting. Controlled blasting involves drilling a series of closely spaced, parallel holes along a specified break line and minimizing the blast damage to the material left on the face (Wyllie and Norrish, 1996). The aim is to remove unstable masses, leaving a clean undamaged surface. A clean undamaged face of rock is less likely to develop into a rockfall generating area than a blast damaged face (Wyllie and Norrish and Norrish, 1996).

Scaling describes the removal of loose debris (rock, soil and vegetation) commonly using hand tools. Larger equipment may also be used to scale slope faces. For example, an excavator positioned at the top of a slope can reach below the crest of a slope and remove unstable material.

Due to the differential weathering commonly found in Ohio, the rock slopes are constantly changing and rockfall generating areas may develop just a few years after a slope may be deemed safe. With this in mind, scaling and trimming should be considered a part of a slope modification or maintenance program, where a slope may have to be trimmed every so often to decrease the rockfall hazard.

7.3.2 Slope Re-design

When a slope is highly prone to generating rockfalls or possibly global (large scale) failures, such as in the case of the site designated as JEF-7-14.6 (Figure 7.5), it may be more effective to re-design the slope. A slope may be re-designed by blasting away material in a new configuration, away from the roadway. There are two approaches that are commonly employed in Ohio for re-designing a slope: flattening the slope or placing benches strategically according to the geology of the slope.

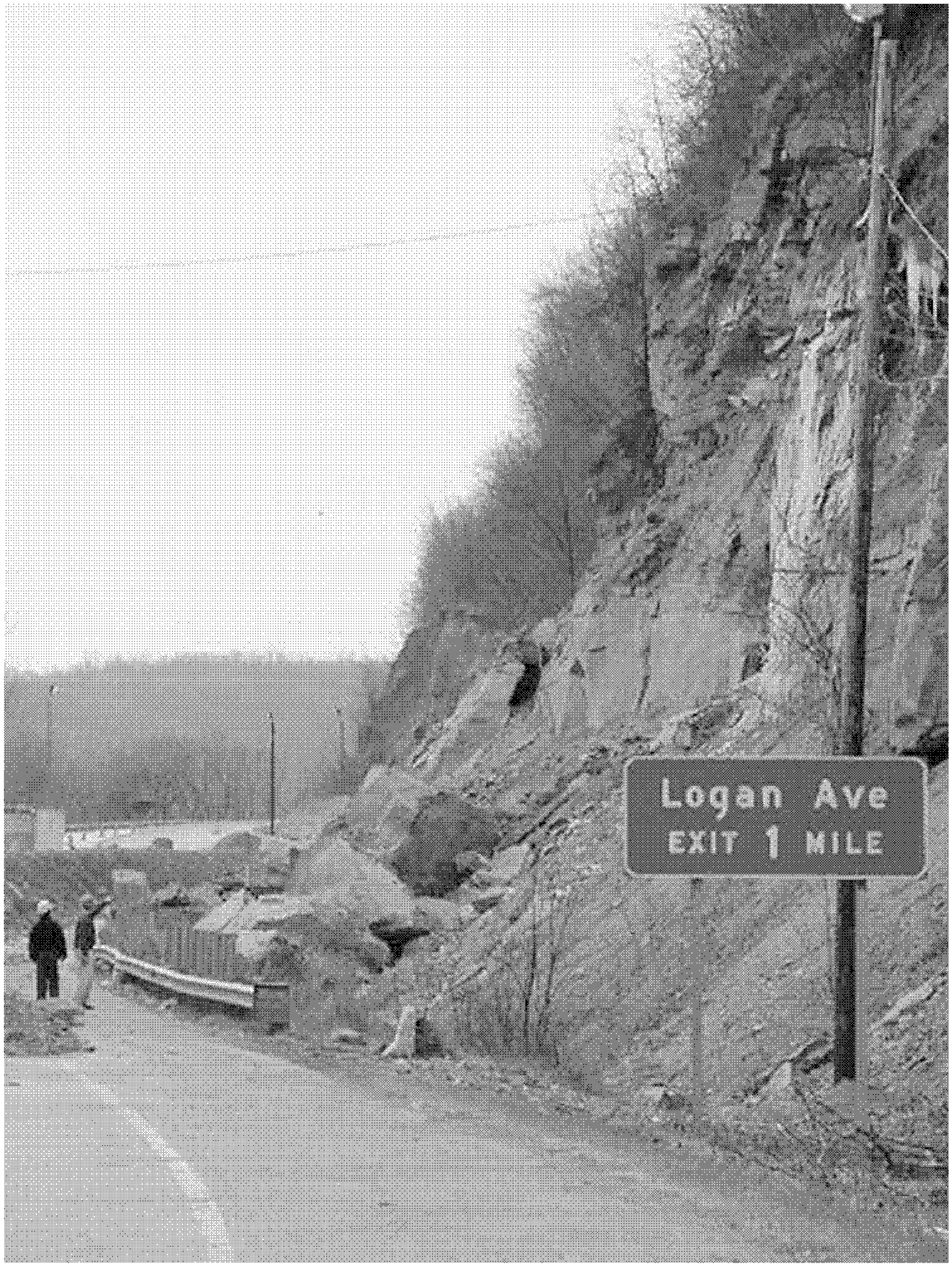


Figure 7.5a: Global failure of road cut located at JEF-7-14.6.

Figure 7.5b: Re-designed slope at JEF-7-14.6 with a geologically placed mid-slope bench

Flattening of a slope

If the material of the slope is so weak that it remains unstable at the present slope angle the slope may be flattened. For example, if a slope comprised of interbedded shales and limestones stands at a 0.5H: 1V (63°) and is unstable, changing the angle of the slope to a 1H: 1V (45°) or 2H: 1V (26°) may stabilize the slope. The decreased angle may retard the rate of undercutting or prolong the initiation of undercutting (Shakoor, 1995). Also, because of the gentler angles, the loose, failed material may remain on the slope which means a smaller catchment area will be required for that slope.

Geologically Placed benches

Placement of a horizontal bench along the contact between the incompetent and competent layers can be used to prolong the time by which the incompetent layer starts undercutting the competent layer (Shakoor, 1995). An example of this is at a site located just south of Steubenville, in Jefferson County (JEF-7-14.6). In this case, a 15 to 20 foot (5-7 m) bench is made in the weaker material (Figure 7.5). This delays the onset of undercutting of the more durable layer and if vegetation is allowed to grow on the bench, erosion of the weaker layer is decreased even more (Shakoor, 1995).

Subsurface Drainage

Some slope conditions exist where extremely high water tables greatly affect the stability of a cut face. The effects include increased pore water pressures, higher number of seep locations, and increased amount of undercutting. In some cases subsurface drainage can aid in slope stabilization. Drainage can be accomplished by a series of horizontal drains or even micro-tunnels designed to evacuate groundwater from behind the slope face.

Roadway Relocation

It may be more cost effective to relocate or restructure a roadway away from a problematic slope face then to attempt any of the previous mitigation techniques. Generally, this mitigation measure is very costly and attempts to mitigate slope conditions are considered first. These techniques can include tunneling or construction of a rock shed. However, the tunneling or rock shed options are not commonly considered in Ohio.

7.4 Cost Analysis

The cost analysis presented herein builds on a concurrent study conducted by Davis (2003) in which he evaluated the effectiveness of rockfall catchment ditches in the state of Ohio. In order to evaluate the catchment ditches, Davis (2003) utilized the Ritchie score (NYDOT, 1996), Colorado Rockfall Simulation Program (CRSP) (Jones, 2000), Oregon catchment ditch design (Pierson et al., 2001), and the Oregon rockfall hazard rating system rating (Pierson, 1991). As a result of his study, Davis (2003) categorized ditches as being adequate, marginally adequate, or inadequate as shown in Table 7.2 for sites located in Jefferson County, Ohio. The main remediation method that is recommended in Davis' study (Davis 2003), along with the cost estimates, is the placement of barriers along the roadway side of the catchment areas (concrete "jersey" barrier, modified D-50 wall, Geobrugg® fence). In addition to the use of barriers as a possible remediation method, the use of slope modification techniques is examined in this

Table 7.2: Rock fall hazard potential and ditch evaluation.

Site	Hazard Rating Score	Hazard Potential Category	Ditch Evaluation
JEF-7-5A	135.8	High	Inadequate
JEF-7-5B	156.6	High	Marginally Adequate
JEF-7-10.6	131.9	High	Inadequate
JEF-7-20.1	90.7	Moderate	Inadequate
JEF-7-22.6	105.9	High	Inadequate
JEF-7-28A	116.6	High	Marginally Adequate
JEF-7-28B	101.3	High	Inadequate
JEF-7-33.3A	125.7	High	Inadequate
JEF-7-33.3C	110.6	High	Inadequate
JEF-7-34.5A	128.5	High	Marginally Adequate
JEF-7-34.5B	133.7	High	Inadequate

study. These include the excavation of material to either flatten the slope or re-design the slope with benches placed at geologically suitable locations to delay the rate of undercutting.

7.4.1 Cost Estimates

To compare remediation costs of various remediation techniques, the unit cost for each technique was obtained from the Ohio Department of Transportation (Table 7.3). It should be noted that the total cost of a given remediation technique can be obtained by multiplying the unit cost (per linear foot) by the measured slope length parallel to the roadway. However, a more precise cost estimate for a particular cut slope can only be obtained by a detailed site-specific survey and by obtaining up-to-date unit prices from qualified contractors.

The various remediation techniques listed in Table 7.3 have been recommended, as appropriate, for sites rated as having a high hazard potential according to the rockfall hazard rating matrix developed in this study. The choice of a given method for a particular slope was made on the basis of its effectiveness and cost. The least costly alternatives are given in Table 7.4.

7.4.2 Placement of Barriers

Sites rated as having a high rockfall hazard potential as well as having inadequate catchment ditches, according to Davis (2003), were analyzed using the CRSP computer program, for rockfall trajectories and energies. Based on this analysis, the least expensive and the most effective barrier were selected for each site (Table 7.4). The

Table 7.3: Unit costs for different remediation options provided by Ohio DOT.

Remediation	Unit Cost
Barrier Type	
Jersey Barrier	$ 30/lft
D50 Wall	$ 65/lft
Geobrugg Fence	$ 230/lft
Excavation	
Soil	$5 /cu.yd.
Rock	$ 6/cu.yd.

Table 7.4(a): Rock Fall barrier recommendations and cost analysis based on heights for slopes rated high with inadequate catchment ditches.

Site	Max Bounce Ht. (ft)	Avg. Bounce Ht. (ft)	Road Cut Length (ft)	Recommended Barrier Type	Unit Cost** Per lin.ft.	Approx. Total Cost
WAY-3-2.4	0.11	0.03	215	Concrete Barrier	$ 30/lft	6,450
STA-800-1	2.33	1.59	510	D50 wall	$ 65/lft	33,150
MUS-60-6.9	0.2	0.02	1270	Concrete Barrier	$ 30/lft	38,100
ATH-13-9.2	0.03	0	1100	Concrete Barrier	$ 30/lft	33,000
GAL-160-.55	0.81	0.15	400	Concrete Barrier	$ 30/lft	12,000
MOE-78-24.5	9.50*	1.67	180	Geobrugg Fence	$ 230/lft	41,400
MOE-537-1.7	0.25	0.05	230	Concrete Barrier	$ 30/lft	6,900
WAS-7-39.5	2.45	2	2100	D50 wall	$ 65/lft	137,280
BEL-149-2	7.08	0.18	1000	Geobrugg Fence	$ 230/lft	230,000
COL-45-20.2	1.55	0.65	486	D50 wall	$ 65/lft	31,590
COL-170-13	4.88	0.75	660	Geobrugg Fence	$ 230/ ft	151,800
TUS-36-0	0.74	0.13	900	Concrete Barrier	$ 30/lft	27,000
TUS-77-63.3	1.13	0.21	725	Concrete Barrier	$ 30/lft	21,750
BEL-7-5.9	0.68	0.13	1900	Concrete Barrier	$ 30/lft	57,000
BEL-7-23.1	1.38	0.5	525	Concrete Barrier	$ 30/lft	15,750
JEF-7-5A	1.31	0.28	700	D50 wall	$ 65/lft	45,500
JEF-7-10.6	33.92*	18.42*	2153	Geobrugg Fence	$ 230/lft	495,190
JEF-7-20.1	0.4	0.09	400	Concrete Barrier	$ 30/lft	12,000
JEF-7-22.6	0.05	0	960	Concrete Barrier	$ 30/lft	28,800
JEF-7-28B	25.47*	14.46*	350	Geobrugg Fence	$ 230/lft	87,500
JEF-7-33.3A	0.23	0.04	645	Concrete Barrier	$ 30/lft	19,350
JEF-7-33.3C	0.6	0.21	370	Concrete Barrier	$ 30/lft	11,100

* Energies and bounce heights too large for all barrier choices

Table 7.4(b): Recommendation of slope re-design and associated costs for selected high hazard potential sites.

Site	Excavation Amount (cu. yd.)	Road Cut Length (ft)	Unit Cost	Cost of Excavation*
MOE-78-24.5	4712	180	$6.00/cu.yd.	$28,272
JEF-7-10.6	14980	2153	$6.00/cu.yd.	$89,880
JEF-7-28B	31431	350	$6.00/cu.yd.	$188,586

effectiveness of each barrier was determined by the height of the barrier with respect to the maximum bounce height of a rock as it passed the end of the catchment area and entered the roadway. The unit cost of the least expensive effective barrier was multiplied by the slope length (parallel to roadway) to estimate the total cost of remediation.

7.4.3 Excavation and Re-design of Slope

For some study sites, the size and energy of the potential rockfalls far exceed the anticipated ability of any barrier system to contain them. The particular sites in question include JEF-7-10.6, MOE-78-24.5, and JEF-7-24.5. For these sites it may be prudent to re-design the slopes to both minimize the occurrence of rockfalls and increase the ability of the catchment areas to contain potential rockfalls. Therefore, an approach involving excavation and re-design of slopes at these sites is recommended.

The approach utilizes the general guidelines for slope design in different materials outlined below:

- Thick sequences of durable strata, most commonly sandstone or limestones were re-designed to a 0.5H: 1V (63^{o}) cut slope.
- Less durable units, such as shales, claystones, mudstones and coals have erodability concerns as well as lower angles of internal friction than the more durable layers. Therefore, these units were re-designed at a 2H: 1V (26^{o}) slopes.
- If a thick non-durable layer such as a clay stone underlies a thick durable stratum such as a sand stone a 15 to 20 foot (4.5 to 6 m) weathering bench was placed at the top of the non durable layer as discussed in section 7.3.2.

- Thin interbedded sequences of more and less durable strata were graded at a 1.5H: 1V (33°) grading to minimize the effect of undercutting and potential for increased rockfall velocities.
- Catchment area widths and depths were approximated using the new overall slope height and angle along with the prescribed Ritchie Ditch criterion.

Using the above-listed guidelines and the stratigraphic cross-sections along with their weathered profiles provided in Appendix B of sites designated as JEF-7-10.6, MOE-78-24.5, and JEF-7-24.5, cross-sectional areas of the material to be excavated was determined. Figures 7.6, 7.7 and 7.8 show the modified slope designs, respectively, for the three sites. Multiplying the slope length (parallel to roadway) by the calculated cross-sectional area gave an approximate volume of total material to be excavated. The total cost of slope re-design, which are given in Table 7.4, were estimated by using the unit costs of excavation provided in Table 7.3.

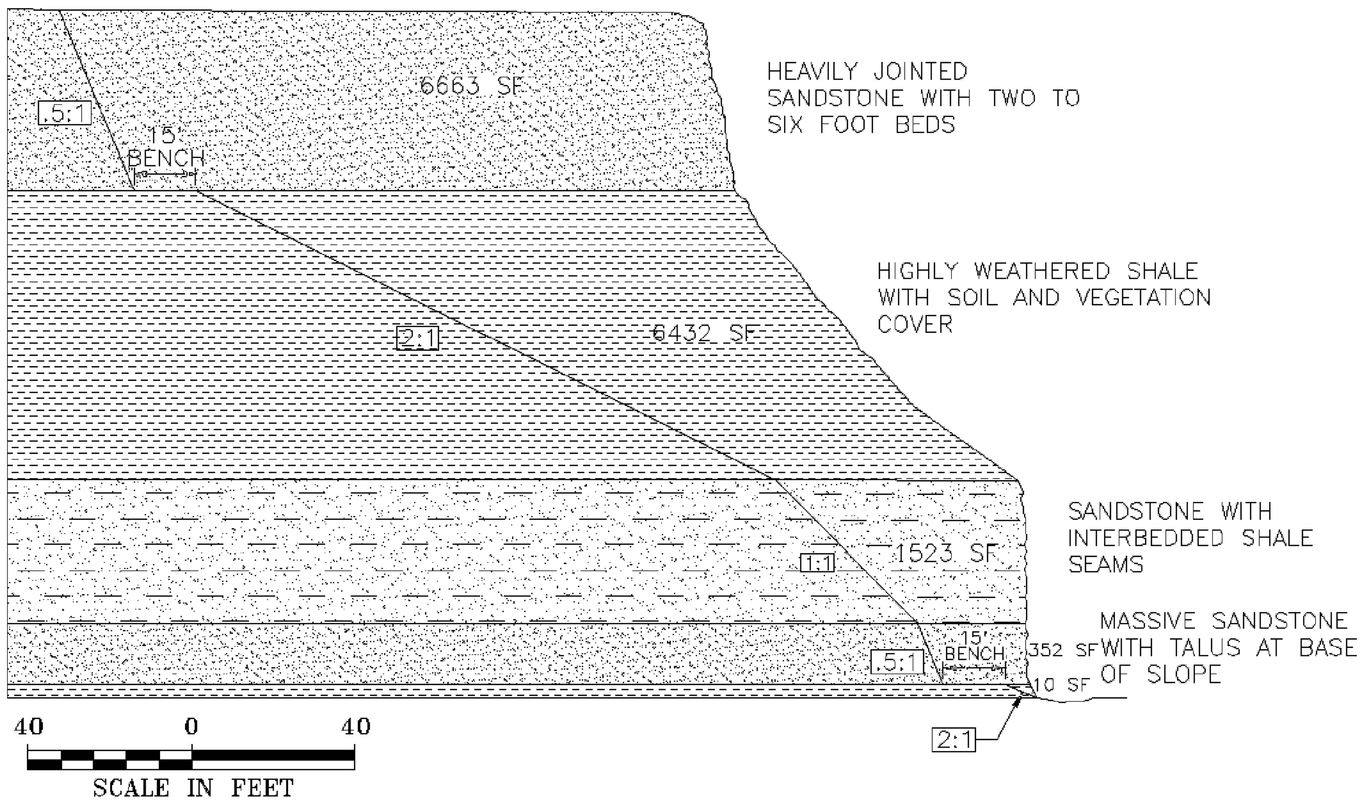


Figure 7.6: Re-designed slope at JEF-7-10.6 with excavation estimates.

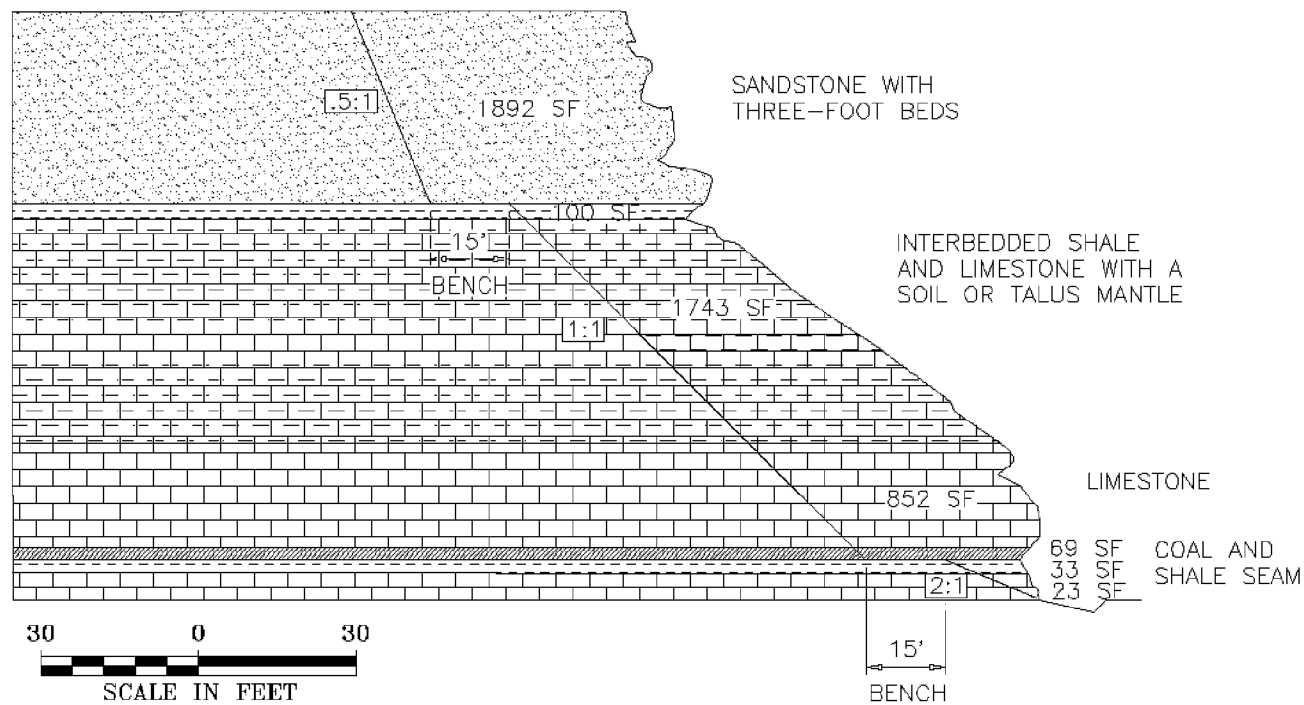


Figure 7.7: Re-designed slope at MOE-78-24.5 with excavation estimates.

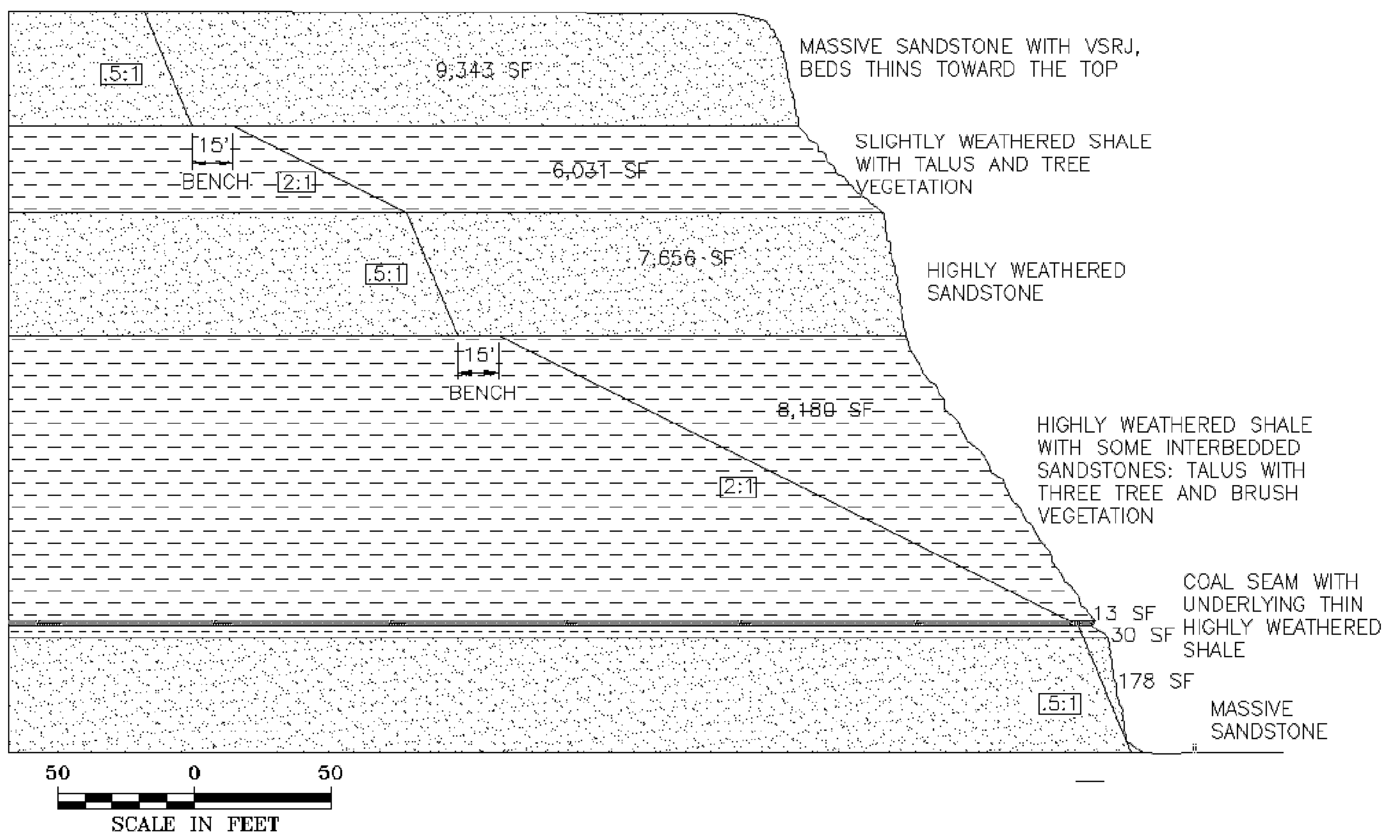


Figure 7.8: Re-designed slope at JEF-7-24.5 with excavation estimates.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The conclusions of the research can be summarized as follows:

1. Slake durability index, slope angle, and slope height are the most important variables in differentiating between slopes with respect to rockfall hazard potential. The maximum amount of undercutting, block weight, hydrologic value, ditch width, and ditch depth were not found to be statistically significant in differentiating between the slopes with varying degrees of hazard potential.
2. The matrix developed for Ohio is based on a number of parameters including those found significant in this study (slake durability index, maximum amount of undercutting, and Ritchie score) and those found important by previously developed rating systems (discontinuity extent/orientation, discontinuity roughness features, block size/volume of rockfall, hydrologic condition, vehicle risk, percent decision sight distance, pavement width, and rockfall history). The matrix is based on four categories of parameters, namely geologic parameters, geometric parameters, traffic parameters, and rockfall history. Each parameter is equally weighted so as to not skew the final ratings in favor of a given parameter

or group of parameters. The final rating score to assess rockfall hazard potential is determined by summing the weighted score for each parameter.

3. The primary mechanism that generates rockfalls in Ohio is the differential weathering of the interbedded strata of more durable and less durable rock units. To account for this mechanism, the use of maximum amount of undercutting in the matrix examines the present condition of each slope, whereas the slake durability index addresses the inherent property of the weaker rock units. The slake durability index is of vital importance because it is this property of the weaker rocks that helps evaluate how a slope will change with time, facilitating the generation of rockfalls.
4. A qualitative evaluation of hydrologic conditions present at a given slope is considered to be an appropriate approach as the quantitative approach, used in this study (hydrologic value), did not prove to be statistically significant.
5. Commonly used field and laboratory procedures can be employed to collect the data needed for the application of the rockfall hazard-rating matrix developed in this study. A combination of direct field measurements (maximum amount of undercutting, block size, slope height, slope angle, ditch width, ditch depth, and slope length), field observations (continuity/extent of discontinuities, joint roughness coefficient, hydrologic conditions, and posted speed limit), information from the Department of Transportation database (average daily traffic and posted speed limit) and laboratory analysis (slake durability index) is necessary to obtain the desired information.

6. Among the 108 sites evaluated in this study, 26 are ranked as high hazard potential sites, 51 as moderate hazard potential sites, and 31 as low hazard potential sites.
7. An exponential scale is more helpful in differentiating between slopes of varying degrees of hazard potential than a continual scale.
8. The remediation measures that are considered to be most feasible for the state of Ohio include rockfall barriers (jersey barriers, modified D-50 concrete walls, and rockfall fences) and slope modifications (cutting the slope back or cutting mid-slope benches according to the geology). Other remediation techniques such as the use of wire mesh netting or shotcrete may also be applicable and their application can be used on a case-to-case basis.

8.2 Recommendations for Future Research

1. The methods presently used to evaluate a catchment ditch have only limited application in Ohio. These methods either do not have the flexibility to address slopes with heights greater than 120 feet (40 m) (Ritchie ditch criteria and the Oregon catchment area design) or they do not address benched or highly vegetated slopes (Ritchie ditch criteria, Oregon catchment area design, and Colorado Rockfall Simulation Program). Further research needs to be done that more completely addresses the trajectories of rockfalls for slopes similar to those found in Ohio.

2. More information regarding the effect of vegetation, especially tree vegetation, on the trajectories of rockfalls is needed. Computer models do not presently address this issue.
3. A database of rockfall history at each site should be developed and maintained.
4. Further research is needed to develop a quantitative approach to assess both the hydrologic and climatic conditions at each site. An attempt was made in this study to quantify the hydrologic and climatic conditions at each site, but the results were not found to be statistically significant.

8.3 Recommendations for Implementation

1. For economical reasons the slake durability index (SDI) need only be performed on sites ranked as moderate or high potentially hazard. The low hazard sites may be ignored from the procedure due to lower risk.
2. Samples for SDI, as described in section 4.5.1, should be taken from the horizon with the greatest amount of undercutting. If this is not possible due to accessibility, then samples should be taken from the unit(s) with the greatest amount of undercutting that is safely accessible. Furthermore, no more than 1 sample per unit and 4 samples per site should be collected.
3. As historical rockfall data becomes available, the inclusion of this value into the geologic parameter should be considered.
4. The term slope length in this study is defined in section 4.2.4 and is the measure of the rock cuts extent along the roadway. The term section length can be used in place of this term. Also, a maximum slope length (section length) for data

collection should be set at 1 mile. Any cuts longer than this distance should be divided into multiple slopes.

5. It is recommended that road cuts be rated during the times of year when both water is generally at its highest and vegetation at its least. Ratings should ideally be performed during the spring and fall seasons.
6. A database should be flexibly constructed to allow for modifications to ratings due to observations. For example, if a slope was rated in the fall with little water effect and is seen in the spring with significantly greater seepage, the rating should be able to be modified.
7. Further variables may be included in the field forms for possible future inclusion such as; back slope area evaluation, presence and condition of benches and launching features, and presence of impedance features.
8. The geometric parameter should be considered to be revised due to the presence of, or potential use of remedial measures. Remedial measures should be considered in one of three types; (1) warning, (2) protection, or (3) stabilization. Examples of these three remediation types can be found in Table 7.1. To modify the ratings the geometric parameter may be modified with negative values added to the rated score based on the raters' judgment and the following general guidelines. Warning measures can have negative values ranging from 3 to 9 points, protection measures from 3 to 27 points, and stabilization measures from 3 to 81 points.

9. As noted in section 6.2.2 a graph of a parameter verses the rating score can greatly aid slope evaluations. It is advisable to create graphs for field use wherever possible.
10. The cost of maintenance should possibly be evaluated as a component of rockfall history.
11. A possible inclusion of a rockfalls potential impact to a structure for a site may be considered to be added to the traffic parameter. A structure may include a bridge, house or other man-made structure.

8.4 Additional Considerations

1. If desired, the catchment area evaluation developed by the Oregon Department of Transportation named the Oregon Catchment Area Design Manual, may be considered for use rather than the Ritchie ditch criteria. Exact values for scoring should be carefully considered.
2. The database should be constructed with the ability to use hidden weighting factors to be used to modify ratings as the DOT observes the ratings.
3. The preliminary method developed for the Missouri DOT might be considered as an optional preliminary rating method. This method includes the use of a video recording of slopes from a moving vehicle. This recording is examined in a computer program and scaled off to obtain geometric relationships. That, along with observations from the tape, facilitates a preliminary rating.

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