ABSTRACT

POLUGA, SARA LINDSAY, M.S. AUGUST 2017

GEOLOGY

ROCK MASS CHARACTERIZATION AND STABILITY EVALUATION OF MOUNT RUSHMORE NATIONAL MEMORIAL, KEYSTONE, SOUTH DAKOTA (352 pp.)

Thesis Advisor: Abdul Shakoor

This study was undertaken to characterize the rock mass at the Mount Rushmore National Memorial (MORU) site and to evaluate the stability of the presidential sculptures. Field investigations at MORU included detailed mapping of the discontinuities and the collection of rock samples for laboratory testing. The sculptures were not accessible during this study; therefore, LiDAR data and Split-FX software were used to determine the orientation of both the discontinuities and the slopes on the sculptures. Engineering properties of the granite and schist at MORU were determined in the laboratory. The second cycle slake durability results indicate a slight potential for undercutting between the schist and granite rock at MORU. Freeze-thaw durability results indicate that the intact granite at MORU is not subject to freeze-thaw damage, whereas the intact schist rock is. The rock mass characterization results, using both the Rock Mass Rating System and the Q-system, indicate the granite, schist, and pegmatite classify as fair to good rock. Stereonet analyses, using Dips software, were performed to determine the principal joint sets (PJS) and to complete kinematic analyses (KA). KA results indicate the potential for

planar sliding, wedge sliding, and toppling failure exists for various slopes on each of the sculptures. The factor of safety (FS) values against planar and wedge sliding ranged from 0.1-0.8 and 0.2-1.3, respectively. $FS < 1$ indicate unstable conditions, however failures have not been observed on the sculptures. This may be due to the fact that the FS calculations did not consider any cohesion that may be present along the discontinuities. Also, roughness and waviness of discontinuity surfaces may result in higher friction angles than used in the KA thereby giving rise to higher FS values. Furthermore, there may be intact rock segments along the discontinuities that have caused the slopes to remain stable. Sensitivity analyses completed for the slopes with $FS < 1$ indicate that a cohesion value $\leq 440 \text{ lb/ft}^2$ ($\leq 21 \text{ kPa}$) is required to increase the $FS > 1$. Sensitivity analyses also show that for the majority of the slopes, both cohesion and friction along the discontinuities are required for $FS > 1$. The KA and FS values together have identified several slopes on the Washington and Roosevelt sculptures which may benefit from further studies of the condition of the discontinuities to determine if monitoring is necessary. Using the Slide program, Overall Slope Probabilistic Analyses were performed with and without a seismic load coefficient applied to the entire slopes on which the MORU sculptures are located. For both the static and seismic conditions, the results indicate that the overall slopes of the sculptures are safe.

ROCK MASS CHARACTERIZATION AND STABILITY EVALUATION OF MOUNT
RUSHMORE NATIONAL MEMORIAL, KEYSTONE, SOUTH DAKOTA

A thesis submitted
To Kent State University in partial
Fulfillment of the requirements for the
Degree of Master of Science

by

Sara Lindsay Poluga

August 2017

© Copyright

All rights reserved

Except for previously published materials

Thesis written by

Sara Lindsay Poluga

B.A., Kent State University, 2006

B.S., Kent State University, 2013

M.S., Kent State University, 2017

Approved by

Abdul Shakoor, Advisor

Daniel Holm, Chair, Department of Geology

James L. Blank, Dean, College of Arts and Sciences

TABLE OF CONTENTS

ABSTRACT.....	i
LIST OF FIGURES	xii
LIST OF TABLES	xxvi
ACKNOWLEDGEMENTS.....	xxxv
CHAPTER 1 - INTRODUCTION.....	1
1.1 Background Information.....	1
1.2 Geologic Setting of the Black Hills, South Dakota	2
1.3 The Geology of Mount Rushmore National Memorial.....	2
1.4 Previous Investigations on the Stability of Mount Rushmore	9
1.5 Rock Block Monitoring System	11
1.6 Research Rationale.....	12
1.7 Study Objectives	12
CHAPTER 2 - RESEARCH METHODOLOGY	14
2.1 Site Selection	14
2.2 Field Investigations	14
2.2.1 Rock Description and Degree of Weathering	16
2.2.2 Discontinuity Data	16

2.2.3 Rock Quality Designation (RQD) Data	17
2.2.4 Sampling Procedure	18
2.3 Laboratory Investigations	19
2.3.1 Coring of the Rock Samples	19
2.3.2 Density Test	19
2.3.3 Absorption Test.....	20
2.3.4 Friction Angle Test	20
2.3.5 Unconfined Compressive Strength (UCS) Test.....	21
2.3.5.1 UCS Test by the Standard Test Method	21
2.3.5.2 Point Load Test	21
2.3.6 Tensile Strength	23
2.3.7 Slake Durability Test	23
2.3.8 Freeze-Thaw Test.....	24
2.3.9 Thin Section Analysis	25
2.3.10 SEM Analysis	25
2.4 Data Analysis	25
2.4.1 Extracting Discontinuity and Slope Orientations of the MORU Sculptures from LiDAR Data using SPLIT-FX	25
2.4.2 Statistical Analysis.....	26
2.4.3 In-Situ Hydraulic Conductivity Determination	27
2.4.4 Stereonet Analysis	27

2.4.5 Rock Mass Characterization	28
2.4.5.1 Rock Mass Characterization by Rock Mass Rating (RMR) System	28
2.4.5.2 Rock Mass Characterization by Quality System (Q-system)	29
2.4.6 Kinematic Analysis	30
2.4.7 Factor of Safety Calculations of the Potential Failures	36
2.4.7.1 Sensitivity Analyses for the Factor of Safety (FS) against Planar Sliding and Wedge Sliding (When $FS < 1$)	37
2.4.8 Rock Block Monitoring System in Light of the Kinematic Analysis Results and Factor of Safety (FS) Values.....	37
2.4.9 Overall Slope Probabilistic Analyses of the MORU Sculptures Considering both Static and Seismic Conditions	38
2.4.10 Comparison of the Results of this Study to the Results of RESPEC Study	42
CHAPTER 3 - DATA PRESENTATION AND RESULTS	44
3.1 Field Data.....	44
3.1.1 Rock Description and Degree of Weathering Data.....	44
3.1.2 Discontinuity Data	45
3.1.3 Rock Quality Designation (RQD) Data	47
3.1.4 Description of the Samples Collected from MORU	48

3.2 Laboratory Test Results	48
3.2.1 Density, Absorption, and Basic Friction Angle Test Results	48
3.2.2 Unconfined Compressive Strength (UCS) and Tensile Strength Results	49
3.2.3 Slake Durability Test Results.....	50
3.2.4 Freeze-Thaw Test Results.....	51
3.2.5 Thin Section Analysis Results	52
3.2.6 SEM Analysis Results.....	52
3.3 Data Analysis and Results	56
3.3.1 Discontinuity and Slope Orientation Data for the MORU Sculptures.....	56
3.3.2 Statistical Analysis.....	56
3.3.3 In-Situ Hydraulic Conductivity Data and Results	56
3.3.4 Stereonet Analysis	60
CHAPTER 4 – ROCK MASS CHARACTERIZATION OF MOUNT RUSHMORE	
NATIONAL MEMORIAL	63
4.1 Rock Mass Characterization Using the Rock Mass Rating (RMR) System Results ..	63
4.2 Rock Mass Characterization Using the Rock Mass Quality System (Q-system)	
Results.....	63
CHAPTER 5 – STABILITY EVALUATION OF MOUNT RUSHMORE NATIONAL	
MEMORIAL.....	66

5.1 Kinematic Analysis Considering the Principal Joint Set (PJS) Planes and Intersections	66
5.1.1 Washington Sculpture	67
5.1.2 Jefferson Sculpture	83
5.1.3 Roosevelt Sculpture	86
5.1.4 Lincoln Sculpture	90
5.2 Kinematic Analysis Considering All Discontinuity Planes and Intersections	93
5.2.1 Washington Sculpture	94
5.2.2 Jefferson Sculpture	104
5.2.3 Roosevelt Sculpture	107
5.2.4 Lincoln Sculpture	110
5.3 Factor of Safety Calculations of the Potential Failures Considering the Principal Joint Set Planes and Intersections	113
5.3.1 Washington Sculpture	113
5.3.2 Jefferson Sculpture	114
5.3.3 Roosevelt Sculpture	114
5.3.4 Lincoln Sculpture	117
5.3.5 Sensitivity Analyses for the Factor of Safety (FS) against Planar Sliding (When $FS < 1$)	119
5.3.6 Sensitivity Analyses for the Factor of Safety (FS) against Wedge Sliding (When $FS < 1$)	121

5.4 Rock Block Monitoring System in Light of the Kinematic Analysis Results and Factor of Safety Values (Considering the Principal Joint Set Planes and Intersections)	125
5.5 Overall Slope Probabilistic Analysis of the MORU Sculptures Considering both Static and Seismic Conditions	126
5.6 Comparison of the Results of this Study to the Results of RESPEC Study	128
CHAPTER 6 – DISCUSSION.....	134
6.1 Slake Durability Results and Undercutting Potential on the Sculptures.....	134
6.2 Freeze-Thaw Durability of the MORU Rock	134
6.3 Kinematic Analysis and Factor of Safety Calculations Indicating Unstable Slopes on the Sculptures.....	135
6.4 Effect of Vibrations due to Fourth of July Fireworks Celebrations on the Stability of the Mount Rushmore National Memorial Sculptures	135
CHAPTER 7 – CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS	136
7.1 Conclusions.....	136
7.2 Recommendations for Future Research	139
REFERENCES	140
APPENDICIES	148
APPENDIX A: PHOTOGRAPHS OF THE DISCONTINUITY DATA COLLECTION LOCATIONS WITHIN THE FOUR STUDY REGIONS AT MORU	149

APPENDIX B: CHARTS, TABLES, AND MAPS (WEATHERING CLASSIFICATION, JOINT ROUGHNESS COEFFICIENT, ROCK MASS RATING AND Q-SYSTEM CLASSIFICATIONS, USGS MAP OF PEAK GROUND ACCELERATION).....	183
APPENDIX C: ROCK DESCRIPTIONS AND WEATHERING DATA	190
APPENDIX D: DISCONTINUITY DATA.....	214
APPENDIX E: LABORATORY DATA (DENSITY, ABSORPTION, BASIC ANGLE OF FRICTION, UNCONFINED COMPRESSIVE STRENGTH, TENSILE STRENGTH, SLAKE DURABILITY, FREEZE-THAW DURABILITY).....	246
APPENDIX F: FAILED-SAMPLE PICTURES	254
APPENDIX G. HISTOGRAMS OF THE DISCONTINUITY DATA	261
APPENDIX H: STERONET ANALYSIS.....	282
APPENDIX I: KINEMATIC ANALYSIS CONSIDERING PRINCIPAL JOINT SET PLANES AND INTERSECTIONS	291
APPENDIX J: KINEMATIC ANALYSIS CONSIDERING ALL DISCONTINIUTY PLANES AND INTERSECTIONS	328
APPENDIX K: OVERALL SLOPE PROBABILISTIC ANALYSIS RESULTS	347
APPENDIX L: STERONET USING RESPEC DISCONTINIUTY DATA REPORTED IN BOYLE AND VOGT (1992).....	351

LIST OF FIGURES

Figure 1.1: Presidential sculptures of Mount Rushmore National Memorial (view to the northwest).	1
Figure 1.2: The location of Mount Rushmore National Memorial in the Black Hills of South Dakota. The Black Hills polygon is approximate (Google Earth Pro, 2013). Note: the legend is in terms of color not necessarily shape.....	3
Figure 1.3: The Black Hills dome structure, cross section, and location of Mount Rushmore (National Park Service, 2016; modified with Graham, 2008).	3
Figure 1.4: Pegmatitic sills and dikes traversing the Lincoln’s sculpture.	5
Figure 1.5: A schist band cutting through the bust area of the Washington’s sculpture.	5
Figure 1.6: Harney Peak Granite, looking northeast.....	6
Figure 1.7: Harney Peak Granite looking northwest (Photo courtesy of Eric Bilderback, NPS) ...	6
Figure 1.8: A close up view of Harney Peak Granite.	7
Figure 1.9: Pegmatitic area within the Harney Peak Granite.....	7
Figure 1.10: A schist outcrop at MORU looking northeast.	8
Figure 1.11: RESPEC measured 144 discontinuities daylighting on the surfaces of the sculptures (modified from Boyle and Vogt, 1992). For scale, the sculptures are roughly 59 ft. (18 m) from the bottom of the chin to the top of the head.....	10

Figure 1.12: Locations of the three critical blocks (W4, R16, L17) and the non-critical block (W1) (modified from RESPEC Inc., 2000). For scale, the sculptures are roughly 59 ft. (18 m) from the bottom of the chin to the top of the head.	11
Figure 2.1: Locations of the selected sites for discontinuity mapping at MORU. Each location (L) number represents the general area within each region where data were collected. The location numbers are not significant and were only used for recording purposes. Some locations have more than one pin; this only means that more than one GPS reading was taken during mapping. The red star is the approximate location of rock block 5 that is discussed in section 2.2.4 of this Chapter. The yellow polygon indicates the general area of the sculptures [Map created using the ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. Basemap source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community; Point locations were imported from Google Earth (Google Earth Pro, 2013)].	15
Figure 2.2: Planar sliding kinematic analysis (pole vector mode) (Rocscience, 2016b). The outer boundary (daylight envelope) of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. Pole vectors which fall within the red shaded critical area on the stereonet indicate potential planar sliding failures (Rocscience, 2016b).	30
Figure 2.3: Example of a wedge failure in the granite rock from Region 3 at MORU.	31

Figure 2.4: An example of a wedge failure in the granite from in Region 3 at MORU. This wedge is formed by the intersection of conjugate joints.	31
Figure 2.5: Wedge sliding kinematic analysis using the mean set plane intersections (principal joint set plane intersections) (Rocscience, 2016c). The inner boundary of the critical zone is the slope dip and the outer boundary is the friction angle of the discontinuity plane. Intersections which fall within the red shaded critical zone on the stereonet indicate potential wedge sliding failures (Rocscience, 2016c).....	32
Figure 2.6: Direct and oblique toppling analysis using the principal joint set plane intersections and principal joint set pole vectors (base planes) (Rocscience, 2016d). The red shaded area on the stereonet is the critical area for direct toppling (intersections and base plane poles). The yellow shaded area on the stereonet is the critical area for oblique toppling (intersections and base plane poles). The outer curved limit of the critical zone for direct toppling is constructed by taking 90 minus the slope angle (Rocscience, 2016d).	33
Figure 2.7: The three different zones that are used to describe the different criteria to be considered for direct and oblique toppling analyses (Rocscience, 2016d). Intersections that fall within zones 1 and 2 represent potential toppling blocks that may form. Intersections that fall within zone 3 represent oblique toppling blocks that have the potential to form. Poles that fall within zones 2 and 3 represent base planes that have the potential to act as release surfaces for the toppling blocks (Rocscience, 2016d).	34
Figure 2.8: Flexural toppling failure kinematic analysis (pole vector mode) (Rocscience, 2016e). Planes cannot topple if interlayer slip movement is not possible. Rocscience (2016e)	

states, “...for slip to occur, the bedding normal must be inclined less steeply than a line inclined at an angle equivalent to the friction angle above the slope. This results in a slip limit plane which defines the critical zone for flexural toppling”. The slip limit is constructed by taking the slope angle minus the friction angle. The dip direction of the slip limit is equal to the dip direction of the slope face. Pole vectors which fall within the red shaded critical area on the stereonet indicate potential flexural toppling failures (Rocscience, 2016e).	35
Figure 3.1: Granite 2 sample. Red arrow indicates a micro-fracture present in the sample. Note: not all micro-fractures are shown with arrows.	54
Figure 3.2: Granite 3 sample. Red arrow indicates an area where micro-fractures are present in the sample. Note: not all micro-fractures are shown with arrows.	54
Figure 3.3: Granite 4 sample. Red arrow indicates a micro-fracture present in the sample. Note: not all micro-fractures are shown with arrows.	55
Figure 3.4: Granite 5 sample. Red arrows indicate areas where micro-fractures are present in the sample. Note: not all micro-fractures are shown with arrows.	55
Figure 5.1: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Washington’s nose. The probability of planar sliding is low along this slope.	68
Figure 5.2: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Washington’s nose. There is no potential for planar	

sliding along this slope as none of the pole vectors fall within the critical zone for planar sliding.....	69
Figure 5.3 Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the front slope of Washington’s nose. The probability of planar sliding is low along this slope.	69
Figure 5.4: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Washington’s forehead. The probability of planar sliding is low along this slope.....	70
Figure 5.5: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Washington’s forehead. The probability of planar sliding is very low along this slope.....	70
Figure 5.6: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the center of Washington’s forehead. There is a risk for planar sliding on the center of Washington’s forehead. Set I has a planar sliding probability of 20% with respect to the principal joint set planes.	71
Figure 5.7: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington’s nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and E, and sets B and I) fall within the critical zone for wedge sliding.....	72

Figure 5.8: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.....	72
Figure 5.9: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the front of Washington's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.	73
Figure 5.10: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.	73
Figure 5.11: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.....	74
Figure 5.12: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the center of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.	74

Figure 5.13: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 75

Figure 5.14: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 76

Figure 5.15: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the front of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 76

Figure 5.16: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's forehead. There is a risk for oblique toppling as there are intersections between the principal joint set planes

which fall in the critical areas. There is no risk for direct toppling. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 77

Figure 5.17: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington’s forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 77

Figure 5.18: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Washington’s forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 78

Figure 5.19: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Washington’s nose. Principal joint set I has a 44% probability of failure with respect to the PJS planes in the set. 80

Figure 5.20: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Washington’s nose. There are 17 total critical principal

joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural
topples. 80

Figure 5.21: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling
along the front slope of Washington’s nose. There are 27 total critical principal joint set
planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.
..... 81

Figure 5.22: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling
along the slope on the right side of Washington’s forehead. There are 14 total critical
principal joint set planes (plotted as pole vectors on the stereonet) that may act as
potential flexural topples..... 81

Figure 5.23: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling
along the slope on the left side of Washington’s forehead. There are 16 total critical
principal joint set planes (plotted as pole vectors on the stereonet) that may act as
potential flexural topples..... 82

Figure 5.24: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling
along the central slope of Washington’s forehead. There are 24 total critical principal
joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural
topples. 82

Figure 5.25: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding
along the slope on the right side of Washington’s nose using the intersections of all of the
discontinuity planes in the file. In the primary (red) critical zone for wedge sliding,

wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 22% with respect to the total number of intersections. 96

Figure 5.26: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington’s nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 12% with respect to the total number of intersections. 97

Figure 5.27: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope on Washington’s nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 7% with respect to the total number of intersections. 97

Figure 5.28: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington’s forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 17% with respect to the total number of intersections. 98

Figure 5.29: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections. 98

Figure 5.30: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Washington's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 8% with respect to the total number of intersections. 99

Figure 5.31: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's nose. There is a 14% probability of direct toppling and an 18% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 100

Figure 5.32: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's nose. There is a 21% probability of direct toppling and 22% probability of oblique toppling with respect to the

total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 100

Figure 5.33: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Washington’s nose. There is a 21% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 101

Figure 5.34: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington’s forehead. There is an 11% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 101

Figure 5.35: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington’s forehead. There is a 21% probability of direct toppling and 22% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 102

Figure 5.36: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Washington’s forehead. There is a 21% probability of direct toppling and 19% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 102

Figure 5.37: Overall Slope Probabilistic Analysis considering the static condition for the entire slope on which the Washington sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters. 127

Figure 5.38: Overall Slope Probabilistic Analysis considering the seismic condition (0.14 horizontal and vertical seismic load coefficients) for the entire slope on which the Washington sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters. 127

Figure 5.39: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope of Washington’s right side of the forehead. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is no probability of planar sliding along the slope on the right side of Washington’s forehead. 130

Figure 5.40: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington’s forehead using the intersections of the principal joint set planes. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is no risk for wedge sliding along this slope. 131

Figure 5.41: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington’s forehead. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes). 131

LIST OF TABLES

Table 2.1: Rock block sample designations, rock type, and collection locations.....	19
Table 2.2: Random variables used in the probabilistic analyses.	42
Table 3.1: Summary of the degree of weathering (based on the charts by Dearman, 1976) of the different rock types encountered in the four regions at MORU. Listed are ranges with the highest frequency based on the histograms in Appendix G. Note: Pegmatite was not encountered or there was not sufficient data collected for this rock type in Regions 3 and 4.....	45
Table 3.2: Average discontinuity data for each region studied at MORU.....	46
Table 3.3: RQD values for each region at MORU. RQD values for the pegmatite rock type were not estimated for Regions 1, 3, and 4.....	47
Table 3.4: Laboratory results determined for each of the samples collected at MORU.....	49
Table 3.5: Average laboratory results for the schist and granite rock types studied at MORU. ..	49
Table 3.6: The strength values for each rock block sample collected from MORU. The values obtained by the standard test method represent the average of three specimens tested for each rock block sample (note: one specimen was tested for sample 1a because only one core was successfully obtained from the rock block). The fields listed with NA represent missing data due to insufficient samples meeting ASTM standards for testing. Note: 145 psi = 1 MPa.	50

Table 3.7: Average values of the unconfined compressive strength and tensile strength for the schist and granite rocks. Note: 145 psi = 1 MPa.....	50
Table 3.8: Slake Durability test results for the rock studied at MORU.....	51
Table 3.9: Average freeze-thaw durability test results.	52
Table 3.10: Approximate mineral percentages for the thin sections of the MORU rock blocks..	53
Table 3.11: Discontinuity orientation data for the sculptures obtained using LiDAR and Split-FX.	57
Table 3.12: Average slope orientations for the MORU sculptures obtained using LiDAR and Split-FX software (Split Engineering, 2014).	58
Table 3.13: Highest frequency data obtained from histograms of various discontinuity data.	59
Table 3.14: Hydraulic conductivity (k) and the average discontinuity values collected from Region 3 at MORU.	60
Table 3.15: Principal joint set data for the granite rock in each region studied at MORU.....	61
Table 3.16: Principal joint set data for the schist rock in each region studied at MORU.....	62
Table 3.17: Principal joint set data for the pegmatite rock in each region studied at MORU.....	62
Table 4.1: Rock Mass Rating (RMR) System parameter ratings and results.	64
Table 4.2: Rock Mass Quality (Q) System parameter ratings and results.	64
Table 5.1: Kinematic analysis results (considering the principal joint set (PJS) planes) for planar sliding on the slopes of the Washington sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).	71

Table 5.2: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Washington sculpture at MORU. “Set” refers to the PJS.....	75
Table 5.3: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Washington sculpture at MORU. “Set” refers to the PJS.....	79
Table 5.4: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Washington sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).....	83
Table 5.5: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).	84
Table 5.6: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS.....	84
Table 5.7: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS.....	85
Table 5.8: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).	86

Table 5.9: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).....	87
Table 5.10: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS.....	87
Table 5.11: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS.....	88
Table 5.12: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).....	89
Table 5.13: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).....	91
Table 5.14: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS.....	91
Table 5.15: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS.....	92

Table 5.16: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).....	93
Table 5.17: Kinematic analysis results for planar sliding on the slopes of the Washington sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	95
Table 5.18: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Washington sculpture at MORU. “All Planes” indicates all planes in the file.	99
Table 5.19: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Washington sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.3.....	103
Table 5.20: Kinematic analysis results for flexural toppling along the slopes of the Washington sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	104
Table 5.21: Kinematic analysis results for planar sliding on the slopes of the Jefferson sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	105

Table 5.22: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Jefferson sculpture at MORU. “All Planes” indicates all planes in the file.	105
Table 5.23: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Jefferson sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.7.....	106
Table 5.24: Kinematic analysis results for flexural toppling along the slopes of the Jefferson sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	106
Table 5.25: Kinematic analysis results for planar sliding on the slopes of the Roosevelt sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	108
Table 5.26: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Roosevelt sculpture at MORU. “All Planes” indicates all planes in the file.	108
Table 5.27: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Roosevelt sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.11.....	109

Table 5.28: Kinematic analysis results for flexural toppling along the slopes of the Roosevelt sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	110
Table 5.29: Kinematic analyses results for planar sliding on the slopes of the Lincoln sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	111
Table 5.30: Kinematic analyses results for wedge sliding (considering all intersections) on the slopes of the Lincoln sculpture at MORU. “All Planes” indicates all planes in the file.	111
Table 5.31: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Lincoln sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.15.	112
Table 5.32: Kinematic analysis results for flexural toppling along the slopes of the Lincoln sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.	112
Table 5.33: Factor of safety (FS) against planar sliding along the slopes of the Washington sculpture.	113
Table 5.34: Factor of safety (FS) against wedge sliding along the slopes of the Washington sculpture.	114
Table 5.35: Factor of safety (FS) against planar sliding along the slopes of the Jefferson sculpture.	115

Table 5.36: Factor of safety (FS) against wedge sliding along the slopes of the Jefferson sculpture.....	115
Table 5.37: Factor of safety (FS) against planar sliding along the slopes of the Roosevelt sculpture.....	116
Table 5.38: Factor of safety (FS) against wedge sliding along the slopes of the Roosevelt sculpture.....	117
Table 5.39: Factor of safety (FS) against planar sliding along the slopes of the Lincoln sculpture.	118
Table 5.40: Factor of safety (FS) against wedge sliding along the slopes of the Lincoln sculpture.	119
Table 5.41: Input data for the factor of safety calculations against planar sliding (considering the PJS planes). The numbers in the slope column are for reference and use in Table 5.42.	120
Table 5.42: Factor of safety (FS) against planar sliding and sensitivity analysis results (considering the PJS planes). c = cohesion, Φ = friction. The numbers in the slope column are for reference and use in Table 5.41.....	122
Table 5.43: Input data (excluding slope orientation) for the factor of safety calculations against wedge sliding (considering the PJS intersections).....	123
Table 5.44: Factor of safety (FS) against wedge sliding and sensitivity analysis results (considering the PJS intersections). c = cohesion, Φ = friction.....	124

Table 5.45: Slopes along the sculptures which had kinematic analysis results of 20% probability of failure or higher, factor of safety values less than one, and do not have any discontinuities monitored by the rock block monitoring system.	125
Table 5.46: Results of the Overall Slope Probabilistic Analysis for the MORU sculptures. The Slide program (Rocscience, 2016h) indicates which statistical distribution best fits the factor of safety distribution for the reliability index calculations, therefore only the results for the best fit statistical distribution are listed and the other is marked as NA.	128
Table 5.47: Principal joint sets determined using the RESPEC data [reported in the RESPEC report by Boyle and Vogt (1992)] as compared to the sets determined by the data in this study.	129
Table 5.48: Slope orientations determined by RESPEC [reported in the RESPEC report by Boyle and Vogt (1992)] and by this study.	130
Table 5.49: Kinematic analyses results for planar and wedge sliding on the right side of the forehead on the Washington sculpture using the RESPEC data and the data from this study.	132
Table 5.50: Kinematic analysis results for toppling on the right side of the forehead on the Washington sculpture using the RESPEC data and the data in this study.	132

ACKNOWLEDGEMENTS

I would like to extend a heartfelt thank you to my advisor, Dr. Abdul Shakoor for his guidance and support throughout the entirety of this project and my education. He has helped me to achieve goals that I never thought were possible. I would also like to thank my committee members Dr. Yonathan Admassu and Dr. David Hacker for their valuable contributions to this thesis. I would also like to thank Dr. Admassu for his guidance and assistance in the field at MORU.

I am grateful to Dr. Eric Bilderback, Bruce Weisman and all of the National Park Service staff for their time and help in the field. This project received a generous grant from the National Park Service, and I have Dr. Eric Bilderback to thank for facilitating that. Financial support was also provided by the Department of Geology at Kent State University, Sigma Gamma Epsilon (SGE), the Geological Society of America (GSA), and the Association of Environmental and Engineering Geologists (AEG). This project would not have been possible without all of these generous awards.

I would like to acknowledge everyone who provided software and laboratory assistance for this project. Those people include Brian Gary from Split Engineering, Dr. Skip Watts, the creator of Rockpack III, and Merida Keatts from Kent State University. I am grateful to CJ Lanning and Paul Horst Seiler at BASF in Beachwood, Ohio for allowing us to use their facility to complete the freeze-thaw durability tests. I would also like to thank my colleague and friend, Carl Jacklitch for assisting me in the rock prep lab at Kent State University.

Finally, I would like to thank all of my family and friends for the encouragement and support while I completed this project and degree. I am especially grateful to my husband, Dave Poluga, who not only assisted me in the field at MORU, but was a constant source of support and inspiration. I would not be where I am today without him.

CHAPTER 1 - INTRODUCTION

1.1 Background Information

Mount Rushmore National Memorial (MORU) represents the first 150 years of American history through the carvings of the four well-known presidents: George Washington, Thomas Jefferson, Theodore Roosevelt, and Abraham Lincoln (Figure 1.1) (Graham, 2008; Jones, 2011). Washington represents the foundation of America, Jefferson signifies the expansion of America as the Louisiana Purchase occurred during his presidency, Roosevelt symbolizes the development of America as he supported the establishment of the Panama Canal, and Lincoln represents the preservation of America due to his leadership and accomplishments during the Civil War (Jones, 2011; National Park Service, 2014a). Work on the sculptures, led by Gutzon Borglum, began on August 10, 1927 and finished on October 31, 1941 (Graham, 2008; Jones, 2011). MORU has become a symbol of America that attracts around two million visitors annually from all around the world (Jones, 2011; National Park Service, 2014b).

Figure 1.1: Presidential sculptures of Mount Rushmore National Memorial (view to the northwest).

1.2 Geologic Setting of the Black Hills, South Dakota

MORU is located in the Black Hills of South Dakota (Figure 1.2) (Graham, 2008).

Situated in the Great Plains physiographic province, “the Black Hills are the core of a prominent uplift associated with the Laramide Orogeny, a mountain-building episode that occurred about 65-45 million years ago (Ma)” (Graham, 2008). The Black Hills form a 124 x 65 mi. (200 x 105 km) dome structure that is elongated in a north-south direction (Figure 1.3) (Graham, 2008). The Precambrian core of the Black Hills dome is surrounded by concentric rings of Paleozoic and Mesozoic sedimentary rock (Figure 1.3) (Graham, 2008). The core is composed mainly of Precambrian metasedimentary, metavolcanic, and intrusive rocks (Dahl et al., 1993). The metasedimentary rocks, which were originally shales, greywackes, quartz sandstones, and iron formations, were deposited during Precambrian rifting of the Black Hills basin (Dahl et al., 1993). They were later subjected to deformation and low to medium grade regional metamorphism, which most likely occurred during the convergence of the Wyoming and Superior cratons between 1.88 and 1.72 billion years ago (Dahl et al., 1993). Around 1.7 billion years ago the Harney Peak Granite was emplaced into the country rock (National Park Service, 2005).

MORU is located in the southern half on the easterly dipping side of the Black Hills dome such that the foliation and remnant bedding in the rocks near the western boundary of the memorial dip about 30°E and near the eastern boundary they dip about 65°E (Powell et al., 1973; Graham, 2008). Mount Rushmore is 5,725 ft. (1,745 m) in elevation (Graham, 2008).

1.3 The Geology of Mount Rushmore National Memorial

The 59 ft. (18 m) high sculptures of the four presidents are carved in the Harney Peak Granite (RESPEC Inc., 1989; Graham, 2008). Within the main granite body are very coarse-

Figure 1.2: The location of Mount Rushmore National Memorial in the Black Hills of South Dakota. The Black Hills polygon is approximate (Google Earth Pro, 2013). Note: the legend is in terms of color not necessarily shape.

Figure 1.3: The Black Hills dome structure, cross section, and location of Mount Rushmore (National Park Service, 2016; modified with Graham, 2008).

grained granitic pegmatite sills and dikes, some of which can be seen as lighter-colored bands across the faces of the sculptures (Figure 1.4) (RESPEC Inc., 1989; Graham, 2008). Fractures that developed during the cooling of the main granite body were later exploited by molten magma, forming the pegmatitic sills and dikes (Graham, 2008). The other rocks within the memorial are mostly schists with some quartzite present as well (Powell et al., 1973). The schists are older than the granite, but are younger than 2.5 billion years (RESPEC Inc., 1989). Figure 1.5 shows a dark, horizontal band of schist above Washington's waist.

The granite within MORU is highly variable in its composition, but is mainly composed of potassium feldspar, albite, and quartz with smaller amounts of perthite and muscovite (Powell et al., 1973; Graham, 2008). The average grain size of the minerals in the granite is about 0.1 in. (3 mm), with the exception of perthite, which can be several centimeters or several meters long (Powell et al., 1973; Graham, 2008). Figures 1.6-1.8 show various views of the Harney Peak Granite. The primary minerals in the pegmatite are quartz, albite, microcline, and muscovite mica (Graham, 2008). Figure 1.9 shows an example of the pegmatite at MORU.

The schist rocks at MORU are also highly variable, but are primarily composed of quartz, biotite, and muscovite (Graham, 2008). The typical grain size in these rocks ranges from 0.01-0.04 in. (0.3-1.0 mm) (Graham, 2008). The schist cleaves easily (Powell et al., 1973). Figure 1.10 shows an example of a schist outcrop at MORU.

The Harney Peak Granite was fractured during the uplift associated with the Laramide Orogeny (Graham, 2008). Due to the presence of fractures and the weathered nature, varying amounts of granite had to be blasted away so that "good rock" could be exposed for the sculptures (RESPEC Inc., 1989). The rock conditions forced Gutzon Borglum to change his design a total of nine times (Powell et al., 1973; RESPEC Inc., 1989).

Figure 1.4: Pegmatitic sills and dikes traversing the Lincoln's sculpture.

Figure 1.5: A schist band cutting through the bust area of the Washington's sculpture.

Figure 1.6: Harney Peak Granite, looking northeast.

Figure 1.7: Harney Peak Granite looking northwest (Photo courtesy of Eric Bilderback, NPS)

Figure 1.8: A close up view of Harney Peak Granite.

Figure 1.9: Pegmatitic area within the Harney Peak Granite.

Figure 1.10: A schist outcrop at MORU looking northeast.

Wind, precipitation (rain and snow), chemical weathering, and frost wedging are the main causes of erosion at MORU (Graham, 2008). The Harney Peak Granite contains discontinuities that range from open joints to fine fractures (RESPEC Inc., 2000). Frost wedging may cause movement of the rock when the frozen water expands in the discontinuities (RESPEC Inc., 1989). Gutzon Borglum sealed the discontinuities to help prevent water from entering them with a mixture of linseed oil, white lead, and granite dust (RESPEC Inc., 1989). A silicon solution is used currently for this purpose (Graham, 2008).

1.4 Previous Investigations on the Stability of Mount Rushmore

A study by RESPEC Inc. (referred to as RESPEC herein) was conducted from 1989-1992 on the structural stability of the sculptures. Throughout the span of their study, RESPEC prepared multiple reports and papers including RESPEC Inc. (1989), Boyle and Vogt (1992), and RESPEC Inc. (2000), all of which are referenced in this document. The company mapped 144 discontinuities, traversing the sculptures, from field investigations as well as from maps and photographs (Figure 1.11) (Boyle and Vogt, 1992; RESPEC Inc., 2000). The orientations of these discontinuities were utilized in a key block analysis, which is a method that was developed by Goodman and Shi (1985) “for the geometrical analysis of rigid blocks” (Priest, 1993). A key block analysis identifies the key blocks for a given slope orientation (Priest, 1993). The analysis assumes that if the key blocks are stable, then the entire slope face is stable (Priest, 1993).

The study by RESPEC revealed twenty-two distinct rock blocks exposed on the sculptures’ surfaces. Ten of the twenty-two blocks were determined to be removable blocks, meaning the bounding discontinuities of the blocks are orientated such that the block is removable from the slope (Boyle and Vogt, 1992). Two of these blocks were identified as potential key blocks (the blocks are removable, but are considered stable due to sufficient friction along the bounding discontinuities) (Boyle and Vogt, 1992). There is also a block which is a thin sliver of rock that has the potential to be easily broken and requires special attention (Boyle and Vogt, 1992).

The first potential key block (Block R16) is located in the forehead and frontal hair area of Roosevelt’s sculpture, and the second potential key block (Block L17) is in the forehead and face of Lincoln’s sculpture. The block which is a thin sliver of rock (Block W4), is located on the southwestern side of the sculpture of Washington (RESPEC Inc., 2000). The locations of these

three blocks, as well as a fourth block (Block W1), located on the southwestern side of the head of Washington's sculpture, can be seen in Figure 1.12 (RESPEC Inc., 2000). The fourth block is not considered a potential key block, but it was monitored by the NPS prior to the study by RESPEC, therefore RESPEC concluded it was important to continue monitoring this block (RESPEC Inc., 2000).

Figure 1.11: RESPEC measured 144 discontinuities daylighting on the surfaces of the sculptures (modified from Boyle and Vogt, 1992). For scale, the sculptures are roughly 59 ft. (18 m) from the bottom of the chin to the top of the head.

Figure 1.12: Locations of the three critical blocks (W4, R16, L17) and the non-critical block (W1) (modified from RESPEC Inc., 2000). For scale, the sculptures are roughly 59 ft. (18 m) from the bottom of the chin to the top of the head.

1.5 Rock Block Monitoring System

A rock block monitoring system capable of measuring movements of less than 0.0001 in. (0.003 mm) was installed between 1998 and 1999 (RESPEC Inc., 2000; Graham, 2008). The rock block monitoring system monitors the three critical blocks along with the fourth non-critical block (RESPEC Inc., 2000). RESPEC anticipated that most of the movement would be due to cyclic responses to temperature changes (ranging from diurnal to annual) (RESPEC Inc., 2000). Graham (2008) confirms that only slight shifting has occurred due to temperature variations.

In September 2010, the NPS replaced the aging, lightning-prone electrical sensor system, which was installed in 1998, with an updated monitoring system based on fiber Bragg gratings

(Micron Optics Inc., 2010). This installation included 24 optical strain gages and 12 non-metallic temperature sensors (Micron Optics, Inc., 2010).

1.6 Research Rationale

The structural integrity of the MORU sculptures is of utmost importance. This study provides a detailed rock mass characterization and weathering description of the rock mass at the MORU site. In addition to orientation of discontinuities, the rock mass characterization takes into account all of the aspects of discontinuities (continuity, spacing, surface irregularities, nature of the infilling material, properties of the adjacent rock, and the presence of water). Discontinuity and slope orientation data, along with friction angle values determined in the laboratory, were used to conduct a kinematic analysis to determine the potential for planar, wedge, and toppling failures on the slopes of the MORU sculptures. Probabilistic Slope Stability analyses considering the Overall Slope method were conducted for each presidential sculpture to determine their overall slope stability. Static and seismic analyses were completed. The NPS is interested in the effect of vibrations, caused by Fourth of July fireworks, on the MORU sculptures. Because discontinuities are areas of weakness where movements of the rock blocks are most likely to occur, the impact of vibrations on the sculptures will depend on the response of discontinuities traversing the sculptures. Fireworks celebrations were not conducted during this study; therefore earthquake data were used in place of fireworks air blast data to conduct seismic stability analyses for the slopes of the MORU sculptures.

1.7 Study Objectives

The following are the main objectives of this study:

1. Determine the engineering properties of the rock at MORU including density, absorption, unconfined compressive strength, tensile strength, slake durability, freeze-thaw durability, and the basic friction angle.
2. Characterize the rock mass at the MORU site based on different aspects of the discontinuities, using both the Rock Mass Rating (RMR) system proposed by Bieniawski (1989), otherwise known as the Geomechanics Classification, and the Rock Mass Quality system (Q-system) developed by Barton et al. (1974).
3. Evaluate the potential modes of slope failure for the sculptures (planar, wedge, and toppling), and determine the factor of safety of the possible failures.
4. Perform static and seismic Overall Slope Probabilistic Analyses of the MORU sculptures to determine their global stability.

The stages of methodology set forth to accomplish the four objectives were field investigations, laboratory investigations, and data analysis.

CHAPTER 2 - RESEARCH METHODOLOGY

2.1 Site Selection

The area at MORU was divided into four “regions”, each with multiple locations where discontinuity data were collected (Figure 2.1). Three primary criteria were used to select the regions and the locations of data collection sites within each region. The first criterion was the accessibility. Discontinuity data were collected along slopes that were navigable and safe to climb. The second criterion was the rock type comprising the outcrop. The locations were selected to ensure that discontinuity data were collected within the three primary rock types (granite, schist, and pegmatite) present at MORU. The third criterion used to select region and data-collection sites was obtaining permission and an escort from the National Park Service (NPS) to enter the restricted areas at MORU. Areas at MORU that are within a certain proximity to the sculptures are restricted and require a NPS escort to traverse those grounds. Sites within the area of the MORU sculptures were restricted for discontinuity data collection during this study. Because of this restriction, LiDAR imagery provided by the NPS was used to obtain orientations of discontinuities within the sculptures. Appendix A provides photographs of locations where data were collected within each study region (excluding Location 28 in Region 3 due to lack of image).

2.2 Field Investigations

Field investigations began on July 7, 2014 and were completed on July 19, 2014. During this time, detailed mapping of the discontinuities exposed at the MORU site was completed and

Figure 2.1: Locations of the selected sites for discontinuity mapping at MORU. Each location (L) number represents the general area within each region where data were collected. The location numbers are not significant and were only used for recording purposes. Some locations have more than one pin; this only means that more than one GPS reading was taken during mapping. The red star is the approximate location of rock block 5 that is discussed in section 2.2.4 of this Chapter. The yellow polygon indicates the general area of the sculptures [Map created using the ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. Basemap source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community; Point locations were imported from Google Earth (Google Earth Pro, 2013)].

rock samples were collected for laboratory testing. During the mapping process, the parameters for both the RMR system (Bieniawski, 1989) and the Q-system (Barton et al., 1974) were measured.

2.2.1 Rock Description and Degree of Weathering

A detailed description of each rock type encountered at MORU was documented. This included the rock type, mineralogy, color, and texture. Structures present in the rock such as faults, folds, or any other distinctive features were also noted. The degree of weathering of the rocks at MORU was documented using the classification chart by Dearman (1976) (Figure B.1 in Appendix B). Based on this chart, the weathering of the rock mass is graded according to the following scale: I (fresh), II (slightly weathered), III (moderately weathered), IV (highly weathered), V (completely weathered), VI (residual soil).

2.2.2 Discontinuity Data

Discontinuity data within the four regions at MORU were collected using the window mapping method. This method entails mapping all of the discontinuities within defined areas or “windows” on the exposed rock face (Priest, 1993). The “window” dimensions are typically 10 m x10 m (Wyllie and Mah, 2004). This method reduces the orientation bias produced by linear sampling (Priest, 1993; Park and West, 2002). Park and West (2002) report that the linear sampling techniques, such as the detailed line survey method (Piteau and Martin, 1977) and borehole fracture mapping, are typically subject to bias because they miss discontinuities parallel to the sampling line. Utilizing the window mapping method at the various locations in the four MORU regions, a total of 695 discontinuity measurements were recorded. Of these measurements, 386 were recorded for granite, 279 for schist, and 30 for pegmatite.

The exposed discontinuities at MORU were mapped considering different aspects of

discontinuities including geometry (orientation), continuity, spacing, surface irregularities, nature of the infilling material, and the presence of water. The degree of weathering along discontinuities was also evaluated using the classification chart by Dearman (1976) (Figure B.1 in Appendix B). A Brunton compass was used to measure discontinuity orientations. These measurements were recorded in the field as dip and dip direction. The continuity of the discontinuities was based on visual inspection. Spacing of the discontinuities was determined by stretching a tape measure across the face of the slope and recording the distance between each discontinuity. The average spacing was calculated from these recordings. Surface irregularities were documented as Joint Roughness Coefficient (JRC) using the chart by Barton (1982), found in Singh and Goel (1999) (Figure B.2 in Appendix B). The JRC values range from 0–20 and are determined by assessing the amplitude of the asperities and the length of the joint profile (Singh and Goel, 1999). The asperities and length of the joint profile were based on visual inspection. Infilling material type (if present) was documented by visual inspection as well. Water presence within the discontinuity was recorded as completely dry, damp, wet, dripping, or flowing (following the RMR system parameters for groundwater).

2.2.3 Rock Quality Designation (RQD) Data

Deere et al. (1967) developed a modified NX core recovery procedure, which provides the Rock Quality Designation (RQD) (Johnson and DeGraff, 1988). The RQD is the percentage obtained by dividing the summed lengths of all core pieces equal to or greater than 4 in. (10 cm) long by the cored interval length (Johnson and DeGraff, 1988). RQD values indicate rock mass quality, with higher values indicating higher quality and lower values indicating lower quality (Johnson and DeGraff, 1988).

Borehole data was not available to determine the RQD values, therefore the RQD values

were estimated using Palstrom's method (Palstrom, 1982), which determines the RQD by counting the number of joints within 35 ft³ (1 m³) of the rock outcrop. The following equation was used to calculate RQD using this method: $RQD = 115 - 3.3 J_v$, where J_v = total number of joints per cubic meter ($RQD = 100$ for $J_v < 4.5$) (Barton et al., 1974). Palstrom and Broch (2006) report that for $J_v = 4$ to 44 the equation, $RQD = 110 - 2.5J_v$, gives a better correlation and thus was used when applicable.

2.2.4 Sampling Procedure

Rock samples for laboratory testing were collected in the field. The samples were required to be at least 6 in x 6 in x 6 in (15.2 cm x 15.2 cm x 15.2 cm) with at least one flat side so that a minimum of four cores could be drilled from them. Granite samples with various textures and color were selected to ensure that a variety of the granite present at MORU was represented for testing. Samples fulfilling these requirements were searched for around the grounds at MORU. Two schist and four granite samples were collected from the ground (they were not broken off of the slopes themselves because of the Park's regulations). Rock block samples 1a (schist) and 3 (granite) were both collected near Location 12 (L12) slightly off of SD Highway 244 (Figure 2.1). Rock block sample 1b (schist) was collected near Location 1 (L1) along SD Highway 244 (Figure 2.1). Rock block sample 2 (granite) was collected slightly southeast of Location 11 (L11) along SD Highway 244 (Figure 2.1). Rock block sample 4 (granite) was collected near Location 20 (L20) north-northwest of the Mount Rushmore sculptures in the middle valley (Figure 2.1). Rock block sample 5 (granite) was collected from the talus near the presidential trail slightly southeast of the Mount Rushmore sculptures (as indicated on Figure 2.1). The sample designations, rock types, and collection locations are summarized in Table 2.1.

Table 2.1: Rock block sample designations, rock type, and collection locations.

Rock Block Designation #	Rock Type	Approximate Collection Location (Figure 2.1)
1a	Schist	L12
1b	Schist	L1
2	Granite	L11
3	Granite	L12
4	Granite	L20
5	Granite	Talus slope below the MORU sculptures

2.3 Laboratory Investigations

2.3.1 Coring of the Rock Samples

In the laboratory at Kent State University, each rock block sample was cored a minimum of four times. The drill in the laboratory cuts cores to a diameter of 2.2 in (5.7 cm), slightly larger than the NX-size (2.125 in/5.4 cm) cores. Four cores were cut from each rock block (excluding the two schist rock block samples 1a and 1b), and three of the cut cores were lapped according to the American Society for Testing and Materials (ASTM) standard outlined in ASTM method D7012-13 (ASTM , 2013). Schist block 1a provided one core of sufficient length and schist block 1b provided no cores of sufficient length for testing unconfined compressive strength, according to ASTM method D7012-13 (ASTM, 2013). Three disks were cut from the fourth core of each rock block sample and were lapped as specified in the tensile strength testing procedure (ASTM Method D3967-08, ASTM, 2008a). The remaining pieces of core were cut for the point load test (ASTM, 2008b), an empirical method for determining unconfined compressive strength.

2.3.2 Density Test

Density (mass/volume) was determined for the four granite and two schist rock block samples collected from MORU. Three cores from each granite block (samples 2, 3, 4 and 5), and

three disks from schist rock block sample 1a, and three disks from schist rock block sample 1b were oven dried for 24 hours at 105 °C. The specimens were cooled to room temperature and were weighed to the nearest tenth of a gram. Five measurements taken of the diameter and length of each specimen were averaged to calculate the volume. These data were used to calculate density. Table E.1 in Appendix E contains the density measurement data.

2.3.3 Absorption Test

Absorption was measured following ASTM method D6473-10 (ASTM, 2010). Three cores from each granite rock block sample (samples 2, 3, 4 and 5), three cores from schist rock block sample 1a, and three disks from schist rock block sample 1b were soaked in water for 24 hours. After 24 hours, the specimens were surface dried and weighed to the nearest tenth of a gram. The specimens were then oven dried for 24 hours at 105 °C. After 24 hours in the oven, the specimens were cooled and immediately weighed to the nearest tenth of a gram. The following equation was used to calculate absorption:

$$\text{Absorption} = (B-A/A) \times 100$$

where: A = dry weight of the specimen, and B = saturated surface dried weight.

Table E.2 in Appendix E contains the absorption measurement data.

2.3.4 Friction Angle Test

The method suggested by Stimpson (1981) was used to estimate the basic friction angle of each rock block sample except for schist 1b, as the rock block sample could not be successfully cored due to its schistose nature. Three cores of each sample were placed on the tilting table such that two cores were placed next to each other, restrained and unable to slide, and the third core was placed on top of the other two cores, free to slide. The base was slowly lifted and the angle at which the third core moved was measured with a Brunton compass and

recorded. The cores were rotated to a fresh surface, and the test was repeated a total of three times to obtain the average tilt angle, which was used in the following formula to calculate the basic friction angle: Basic angle of friction (Φ) = $\tan^{-1}(1.155 \tan \alpha)$ where α = tilt angle of the base at sliding (Stimpson, 1981). Table E.3 in Appendix E contains the measurement data for the friction angle test.

2.3.5 Unconfined Compressive Strength (UCS) Test

The unconfined compressive strength (UCS) was determined using ASTM method D7012-13 (ASTM, 2013), which will be referred to as the standard test method herein, and the point load test method D5731-08 (ASTM, 2008b).

2.3.5.1 UCS Test by the Standard Test Method

The ASTM method requires that NX size (2.125 in/5.4 cm) core samples with a length/diameter (L/D) ratio of 2.0-2.5 should be used for testing. However, as previously noted the cores used for this test were slightly larger with a diameter of 2.2 in (5.7 cm). The L/D ratio ranged between 2.1-2.5.

An axial load was applied to each of the core samples until failure occurred. The load at failure was recorded for each sample tested. The UCS was calculated by dividing the failure load by the cross sectional area of the sample. Table E.4 in Appendix E contains the measurement data for the standard test method.

2.3.5.2 Point Load Test

UCS of the MORU rock samples were also determined using the point load test. Since there was a shortage of the remaining samples; only three cores were tested for granite rock block samples 2 and 4 and for the schist rock block samples 1a and 1b. Granite rock block

samples 3 or 5 could not be tested because of insufficient sample. Axial testing was completed and is suitable for core specimens with length/diameter ratio values of 0.3-1.0 (ASTM, 2008b). The core specimens for the Point Load Test in this study each had a length/diameter ratio of 0.7-0.9, meeting the test specifications.

For the tests, each specimen was placed between two conical platens of the testing apparatus and the load was slowly applied until failure occurred. The uncorrected point load strength index (I_s) for the core specimens were calculated using the following equation (ASTM, 2008b):

$$I_s = P/D_e^2$$

where: P = failure load, and $D_e^2 = 4A/\pi$

$$A = WD$$

where: A = minimum cross-sectional area of a plane through the platen contact points,
 W = sample diameter, D = platen separation.

Wyllie and Mah (2004) state that if the point load test is conducted on specimens with a diameter different from 50 mm, the I_s value must then be standardized to the size-corrected Point Load Strength Index $I_{s(50)}$ using the following equation (ASTM, 2008b):

$$I_{s(50)} = F * I_s$$

where: $F = (D_e/50)^{0.45}$

D_e = equivalent core diameter.

The UCS was calculated by multiplying the $I_{s(50)}$ value by 24 (Hoek and Bray, 1981). Hoek and Bray (1981) state that the constant value of 24 is for a 54 mm core, and even though the core diameter for the specimens tested in this study were 57 mm, the value of 24 was used in

the estimations of the UCS values. Table E.5 in Appendix E contains the measurement data for the point load test.

2.3.6 Tensile Strength

The tensile strength was determined using the Brazilian test as suggested by ASTM method D3967-08 (ASTM, 2008a). This is an indirect test for the tensile strength of a rock sample in which compression results in tension. For each rock block sample, three lapped disks were tested for tensile strength. The same testing machine was used for this test as for the UCS test. The tensile strength was calculated using the following formula:

$$\text{Tensile strength} = 2P / \pi * l * d$$

where: l = thickness of disk (1 in/2.5 cm), d = disk diameter, P = failure load (when fracture developed).

Table E.6 in Appendix E contains the measurement data for the tensile strength test.

2.3.7 Slake Durability Test

The slake durability test was completed following ASTM method D4644-08 (ASTM, 2008c). This test is used to evaluate the durability of weak rocks after two cycles of wetting and drying. A band of schist cuts through granite rock comprising MORU sculptures (Figure 1.5). The slake durability test was used to evaluate the potential for differential weathering between these two rock types.

The second cycle slake durability index was determined for schist samples 1a and 1b, and granite sample 2. Both schist samples are mica schists, however sample 1b is coarser grained than sample 1a. Granite sample 2 was chosen for the test because it had the highest unconfined compressive strength value. The worst case scenario for differential weathering (undercutting) is

evaluated when comparing the second cycle slake durability index values for the strongest granite to the second cycle slake durability index values for the schist.

The test samples each had a total weight of roughly 1.1 lb. (500 g) and consisted of 10 representative pieces, each weighing about 0.088-0.13 lb. (40-60 g). The samples were oven dried for 24 hours and then weighed. Each sample was then placed in a 2.00 mm (No. 10) square-mesh drum, which was then mounted in the trough. The trough was filled with water at room temperature and the drum was then rotated in water for 10 minutes at 25 rotations per minute (200 total rotations). After 10 minutes, the drum was immediately removed from the trough and the material retained in the drum was oven dried for 24 hours and weighed. The procedure was repeated on the oven dried sample to determine the second cycle slake durability index (I_d2) as follows: (oven dried weight left after two cycles/original oven dried weight) x 100.

2.3.8 Freeze-Thaw Test

The freeze-thaw durability test was completed at BASF in Beachwood, Ohio, a concrete testing facility. ASTM method C666/C666M-03 was used for this test (ASTM, 2003). As listed in Table E.8 in Appendix E, six hand sized specimens from each rock block collected at MORU were tested. The specimens varied in size and shape. The specimens were oven dried for 24 hours and were weighed before the freeze thaw test was conducted. The specimens were saturated for 24 hours before the freeze-thaw test began.

The freeze-thaw machine at the BASF facility automatically freezes and thaws the samples throughout the test. Due to machine malfunctions, samples had to be changed between machines in the facility. Due to this, sample numbers 1b (schist) and 3 (granite) were subjected to 318 freeze-thaw cycles, whereas samples 1a (schist), 2 (granite), 4 (granite), and 5 (granite) were subjected to 312 cycles. After the completion of the freeze-thaw test, the specimens were

dried for 24 hours and weighed when cooled. The total mass lost and the percent change in mass was recorded for each specimen. These data were used to determine the average values of each sample type. Table E.8 in Appendix E contains the measurement data for the freeze-thaw durability test.

2.3.9 Thin Section Analysis

Polished thin sections were made for each rock block sample collected at MORU (two schist and four granite samples) by Quality Thin Sections in Tucson, Arizona. These thin sections were analyzed under a polarizing microscope in the lab at Kent State University. The minerals present were identified and their percentages were estimated.

2.3.10 SEM Analysis

The UCS values for the granite, obtained by both the standard test method as well as the point load test were unexpectedly low. To further explore the reason for this low strength, polished thin sections of the MORU granite were analyzed for micro-fractures using a Hitachi TM-3030 SEM in the lab at Kent State University.

2.4 Data Analysis

2.4.1 Extracting Discontinuity and Slope Orientations of the MORU Sculptures from LiDAR

Data using SPLIT-FX

Discontinuity orientations could not be measured on the MORU presidential sculptures manually in the field. Therefore, a LiDAR point cloud and Split-FX software (Split Engineering, 2014) were used to extract discontinuity orientation data. The LiDAR was provided by the NPS and is a combined aerial and terrestrial data set. Split Engineering, LLC was generous enough to convert the data set into a usable format with the Split-FX software (Split Engineering, 2014).

According to personal correspondence with Split Engineering, LLC, they used MATLAB software to copy every 1,000 points to get a 1/1000 resolution of the sculptures region. They then opened the data in Split-FX and got the coordinates for a box enclosing Mt. Rushmore. Next, they went back to the xyz file in the MATLAB software and read every point in that box. This was still a very large file, which made it difficult to work with, so Split Engineering, LLC then decimated the data by 100 to bring it down to a workable size. More points were still needed to see the discontinuities within the sculptures so a full resolution scan of each head was completed.

Using the LiDAR point cloud prepared by Split Engineering, LLC and images of the sculptures, the discontinuities identified by both techniques were traced. The Split-FX software calculates the best-fit plane that fits the points along the trace of the discontinuity (Split Engineering, 2014) and the orientation of this plane in terms of dip and dip direction.

The Split-FX software was also used to determine the slope orientations of the foreheads and noses of all four sculptures for use in the kinematic analyses. The slope orientations were obtained by drawing patches on the slopes of interest. Using the insert patch function of the program, three points were selected on a slope, which formed a triangle. The program would then give the dip and dip direction of the plane of the inserted patch, which is the orientation of the slope. This process was repeated three times for each slope and the values were averaged.

2.4.2 Statistical Analysis

Microsoft Excel was used to create histograms of the following quantitative data for use in the rock mass characterization systems: degree of weathering, RQD, continuity, spacing, JRC and roughness, infilling material, and aperture. The highest frequency of each parameter (unless otherwise noted) was used for the calculations in the rock mass characterization systems.

2.4.3 In-Situ Hydraulic Conductivity Determination

The in-situ hydraulic conductivity of the rock mass in Region 3 (the closest region studied near the MORU sculptures) was approximated using the empirical correlations between permeability and joint aperture and spacing. The equation for hydraulic conductivity (k) is as follows (Wyllie & Mah, 2004):

$$\text{Hydraulic conductivity (k)} \approx \frac{ge^3}{12vb}$$

where: g = gravitational acceleration (9.81 m/s²), e = joint aperture, b = joint spacing, and v = coefficient of kinematic viscosity of fluid (1.01x10⁻⁶ m²/s).

2.4.4 Stereonet Analysis

Discontinuity orientation data were plotted on a stereonet using the Dips software program (Rocscience, 2016a). The program contours the discontinuity orientation data and the high pole concentrations (warmer colors) on the stereonets indicate the mean orientation values of the discontinuity sets or, as they are called in this study, the principal joint sets. Rocscience (2015a) reports that, “a useful rule of thumb is that any cluster with a maximum concentration of greater than 6% is very significant. 4-6% represents a marginally significant cluster. Less than 4% should be regarded with suspicion unless the overall quantity of data is very high (several hundreds of poles)”. Following this rule of thumb and using the cluster analysis (unless otherwise noted), the principal joint sets were determined. The cluster analysis in Dips (Rocscience, 2016a) uses an algorithm based on the fuzzy cluster analysis to determine the principal joint sets (Rocscience, 2015b). The user manually chooses the center of the data cluster and the algorithm determines which poles belong to the principal joint set within a maximum radius (specified as 25 degrees in this case) (Rocscience, 2015b). Because the rock mass at

MORU was divided into four “regions”, with multiple locations where discontinuity data were collected, the principal joint sets were determined for each rock type separately within the four regions at MORU as well as for the three rock types as a whole with all the discontinuity data combined from each region (note: pegmatite rock data were only collected in regions 1 and 2).

2.4.5 Rock Mass Characterization

2.4.5.1 Rock Mass Characterization by Rock Mass Rating (RMR) System

The RMR system, developed by Bieniawski (1989), classifies a rock mass using the following six parameters: uniaxial compressive strength of the intact rock material, RQD, spacing of the discontinuities, condition of the discontinuities, groundwater conditions, and the orientation of the discontinuities. For the RMR system, ratings are assigned for each parameter according to the RMR system classification chart that can be found in Appendix B. The RMR is the summation of the assigned ratings (Hoek, 2007). Based on the RMR, the rock mass is classified as very poor, poor, fair, good, and very good (Bieniawski, 1989).

During the mapping process at MORU, the discontinuity parameters required for the RMR system (Bieniawski, 1989) were recorded. The RMR system classifies the condition of the discontinuities based on discontinuity persistence (continuity), infilling material, roughness, aperture, and weathering (Bieniawski, 1989). Roughness was recorded as JRC and these values were categorized based on the RMR roughness classifications. Since there was not any literature found stating the conversion between JRC values and the RMR roughness classification categories, this study classified any JRC value ranging from 0-1 as slickensided, JRC values of 1-2 as smooth, JRC values of 2-12 as slightly rough, JRC values of 12-18 as rough, and JRC values of 18-20 as very rough. This conversion was adjusted based on judgments from field observations. Aperture (separation) was based on visual inspection. Dearman’s chart (Dearman,

1976) was used to classify the degree of weathering according to the RMR system classifications: unweathered, slightly weathered, moderately weathered, highly weathered, and decomposed (Bieniawski, 1989).

2.4.5.2 Rock Mass Characterization by Quality System (Q-system)

The Q-system, developed by Barton et al. (1974), estimates the rock mass quality (Q) using the following equation: $Q = \frac{RQD}{J_n} * \frac{J_r}{J_a} * \frac{J_w}{SRF}$, where: RQD = rock quality designation, J_n = joint set number, J_r = joint roughness number, J_a = joint alteration number, J_w = joint water reduction factor, and SRF = stress reduction factor (Barton et al., 1974). The first two factors in the Q-system equation (RQD/J_n) represent the structure of the rock mass (their quotient represents a measurement of the block size) (Bieniawski, 1989). The quotient of the third and fourth factors (J_r/J_a) in the equation represents the shear strength along the discontinuities (Bieniawski, 1989). The quotient of the fifth and sixth parameters (J_w/SRF) represents the “active stress” (Bieniawski, 1989).

Parameter J_n was determined with the principal joint sets determined from stereonet plots of the discontinuity orientation data collected from MORU. Parameter J_r was estimated based on JRC values and was adjusted based on field observations. Parameter J_a was documented in the field by visual observation of the discontinuities. Parameter J_w was determined from the presence of water. The SRF parameter is more suited for underground excavations than for surface excavations because the Q-system was developed based on studies involving tunnels. Due to this, the value was estimated for the purposes of this study.

The parameters were rated using Table B.3 in Appendix B. Based on the Q-value, the rock mass is classified as exceptionally poor, extremely poor, very poor, poor, fair, good, very good, extremely good, and exceptionally good (Bieniawski, 1989).

2.4.6 Kinematic Analysis

The Dips software program (Rocscience, 2016a) was used to perform a kinematic analysis for the foreheads and noses of each MORU sculpture. The kinematic analysis indicates the potential for occurrence of planar sliding, wedge sliding, or toppling failure. The analyses were completed by considering only the principal joint set (PJS) planes and intersections, and by considering all of the planes and intersections.

The general conditions for a planar failure include: (1) the strike of the discontinuity is within ± 20 degrees of the strike of the slope face, (2) the discontinuity daylights on the slope face, and (3) the dip of the discontinuity is greater than the friction angle (Wyllie and Mah, 2004). Figure 2.2 shows an example of a planar sliding kinematic analysis.

Figure 2.2: Planar sliding kinematic analysis (pole vector mode) (Rocscience, 2016b). The outer boundary (daylight envelope) of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. Pole vectors which fall within the red shaded critical area on the stereonet indicate potential planar sliding failures (Rocscience, 2016b).

Wedge failures are evaluated using Markland's Test (Wyllie and Mah, 2004). The general conditions for a wedge failure include: (1) the line of intersection between two planes daylights on the slope face, and (2) the line of intersection plunges more steeply than the friction angle (Wyllie and Mah, 2004). Wedge failures were observed in the field in various Regions at MORU. Figures 2.3 and 2.4 show examples of the wedge failures in Region 3. Figure 2.5 shows an example of a wedge sliding kinematic analysis.

Figure 2.3: Example of a wedge failure in the granite rock from Region 3 at MORU.

Figure 2.4: An example of a wedge failure in the granite from in Region 3 at MORU. This wedge is formed by the intersection of conjugate joints.

Figure 2.5: Wedge sliding kinematic analysis using the mean set plane intersections (principal joint set plane intersections) (Rocscience, 2016c). The inner boundary of the critical zone is the slope dip and the outer boundary is the friction angle of the discontinuity plane. Intersections which fall within the red shaded critical zone on the stereonet indicate potential wedge sliding failures (Rocscience, 2016c).

Two types of toppling failures can be evaluated with the Dips program (Rocscience, 2016a), direct and flexural toppling. Hudson and Harrison (1997) state that the two kinematic feasibility criteria for direct toppling are as follows: (1) there are two discontinuity planes whose intersections dip into the slope, in order to provide the appropriate condition for the formation of the faces of rock blocks, and (2) there is a discontinuity plane to form the base of a toppling block.

Flexural toppling occurs when near vertical discontinuities dipping into the slope break in flexure as they bend forward (Wyllie and Mah, 2004). Generally, the base plane of a flexural topple is not as well defined as a direct topple (Wyllie and Mah, 2004). The kinematic feasibility

criteria for flexural toppling are as follows (Hudson and Harrison, 1997): (1) discontinuity planes dip into the slope at a sufficiently high angle to allow inter-layer slip movement, and (2) the dip direction of the discontinuities should lie within $\pm 20^\circ$ of the slope. This study however, used more conservative lateral limits of ± 30 degrees in the toppling analyses as recommended by Goodman (1980).

Figure 2.6 shows an example of a direct toppling failure kinematic analysis. The red shaded regions are the primary critical zones for direct toppling and the yellow shaded regions are the secondary critical zones for oblique toppling [oblique toppling occurs when the intersection of the discontinuity planes are near vertical, but fall outside of the lateral limits (Rocscience, 2016d)].

Figure 2.6: Direct and oblique toppling analysis using the principal joint set plane intersections and principal joint set pole vectors (base planes) (Rocscience, 2016d). The red shaded area on the stereonet is the critical area for direct toppling (intersections and base plane poles). The yellow shaded area on the stereonet is the critical area for oblique toppling (intersections and base plane poles). The outer curved limit of the critical zone for direct toppling is constructed by taking 90 minus the slope angle (Rocscience, 2016d).

Rocscience (2016d) states that there are several different criteria to simultaneously consider for the direct and oblique toppling analyses. Figure 2.7 from Rocscience (2016d) shows three different zones labeled on the stereonet that can be used to describe the different criteria to be considered for these analyses. Intersections that fall within zones 1 and 2 represent the risk of toppling blocks that may form (Rocscience, 2016d). Intersections that fall in zone 3 represent the risk of oblique toppling blocks (Rocscience, 2016d). Poles that fall in zones 2 and 3 represent base planes that have the potential to act as release surfaces for the toppling blocks (Rocscience, 2016d).

Figure 2.7: The three different zones that are used to describe the different criteria to be considered for direct and oblique toppling analyses (Rocscience, 2016d). Intersections that fall within zones 1 and 2 represent potential toppling blocks that may form. Intersections that fall within zone 3 represent oblique toppling blocks that have the potential to form. Poles that fall within zones 2 and 3 represent base planes that have the potential to act as release surfaces for the toppling blocks (Rocscience, 2016d).

Figure 2.8 shows an example of a flexural toppling failure kinematic analysis. The red shaded region is the critical zone for flexural toppling failure. Any pole vectors that fall in this region indicate potential flexural toppling failures.

For the kinematic analyses, the slope of each sculptures' forehead were divided into sections including the right side, left side, and center. The nose of each sculpture was also divided into sections including the right side, left side, and front. The average slope orientations obtained using the Split-FX software, the principal joints obtained from the stereonet analyses, and the basic friction angle of the granite rock was used to complete the kinematic analyses.

Figure 2.8: Flexural toppling failure kinematic analysis (pole vector mode) (Rocscience, 2016e). Planes cannot topple if interlayer slip movement is not possible. Rocscience (2016e) states, "...for slip to occur, the bedding normal must be inclined less steeply than a line inclined at an angle equivalent to the friction angle above the slope. This results in a slip limit plane which defines the critical zone for flexural toppling". The slip limit is constructed by taking the slope angle minus the friction angle. The dip direction of the slip limit is equal to the dip direction of the slope face. Pole vectors which fall within the red shaded critical area on the stereonet indicate potential flexural toppling failures (Rocscience, 2016e).

2.4.7 Factor of Safety Calculations of the Potential Failures

The limit equilibrium analysis was used to calculate the factor of safety (FS) values of the potential plane and wedge failures indicated by the kinematic analyses when considering the principal joint set planes and intersections (FS not calculated for kinematic analyses considering all planes and intersections in the file due to high numbers of critical poles/ intersections and study time constraints). According to the limit equilibrium theory, the FS is the ratio of the resisting forces to the driving forces (Watts et al., 2003). The FS equation is as follows (Wyllie and Mah, 2003):

$$FS = \frac{c A + W \cos \Psi_p \tan \phi}{W \sin \Psi_p}$$

where: c = cohesion, A = area of the sliding surface, W = weight of the block lying above the sliding surface, Ψ_p = dip of the sliding surface, ϕ = friction angle.

When the FS is less than one, the driving forces are greater than the resisting forces indicating that the slope is unstable. A FS greater than one indicates a stable slope, whereas a FS equal to one represents the limiting equilibrium condition (Watts et al., 2003; Wyllie and Mah, 2004; Admassu, 2010). Detailed information regarding the FS calculations for the plane and wedge failures can be found in Watts et al. (2003). The Rocscience software programs RocPlane (Rocscience, 2016f) and Swedge (Rocscience, 2016g) were used to calculate the FS values of the potential plane and wedge failures.

Quantitative analyses which measure the degree of instability of the potential toppling failures were not completed due to lack of information such as the overall base inclination and the width of the toppling blocks.

2.4.7.1 Sensitivity Analyses for the Factor of Safety (FS) against Planar Sliding and Wedge Sliding (When $FS < 1$)

Many of the FS values against planar sliding and wedge sliding for various slopes on each of the sculptures are less than one. $FS < 1$ indicates unstable slopes, however failures have not been observed on the sculptures. In the FS calculations, cohesion is assumed to be zero and the basic friction angle of 40° (assuming smooth discontinuities) is used. Direct shear tests were not completed due to limited rock samples and study time constraints; however this type of test would measure the cohesion of the granite rock. Because the cohesive strength of the granite at MORU was not determined in this study, sensitivity analyses were completed to estimate the cohesion value required for $FS > 1$. This was done using friction angle values of 40° , 45° , and 50° to not only consider the basic friction angle, but possible effective friction angle values, which consider roughness along the discontinuities, as well. Sensitivity analyses were also completed to estimate the highest value of friction required along the discontinuities for $FS > 1$ (assuming cohesion = 0). The Rocscience software programs RocPlane (Rocscience, 2016f) and Swedge (Rocscience, 2016g) were used for the analyses.

2.4.8 Rock Block Monitoring System in Light of the Kinematic Analysis Results and Factor of Safety (FS) Values

As discussed in Chapter 1, the National Park Service currently has a rock block monitoring system on several blocks on the sculptures. The monitoring data were not available to this study, but the areas on the sculptures currently being monitored were evaluated in light of the results determined by the planar sliding and wedge sliding kinematic analyses and the FS values (when considering the principal joint set planes and intersections). These results and values together were used to identify areas on the sculptures where discontinuities are not

currently being monitored and would benefit from further studies of the condition of the discontinuities to determine if additional areas should be monitored. Slopes which had kinematic analysis results of 20% probability of failure or higher and FS values less than one were identified.

2.4.9 Overall Slope Probabilistic Analyses of the MORU Sculptures Considering both Static and Seismic Conditions

The software program Slide (Rocscience, 2016h) was used to complete a Probabilistic Slope Stability Analysis (PSSA) for the entire slopes on which each of the MORU sculptures are located. A traditional slope stability analysis assumes that all of the parameters of the model [e.g. UCS, Geologic Strength Index (GSI), seismic coefficients, etc.] are exactly known, whereas a PSSA takes into account the uncertainty of the model parameters by allowing the user to assign a statistical distribution to one or more of the parameters (Rocscience, 2016i).

The input parameters are considered as random variables and are generated by assigning to each a probability distribution function (PDF) (Admassu, 2010). A PDF is defined by the type of statistical distribution (normal, uniform, triangular, beta, exponential, lognormal, gamma) and the statistical parameters of the distribution (mean, standard deviation, minimum, and maximum values) (Rocscience, 2016j). The PDF describes the range of potential values for the random variables in the analysis (Admassu, 2010; Rocscience, 2016j). These variable values, which are used in the factor of safety calculations, are assigned random numbers generated by the user defined sampling method, which is usually the Monte Carlo simulation (Admassu, 2010).

The PSSA's were performed considering the Overall Slope (OS) method. The OS method usually locates multiple Global Minimum slip surfaces on which the PSSA is completed. This is because the entire search for a Global Minimum slip surface is repeated N times (N = number of

samples). Each search is completed with a new set of random variables for the input parameters (Rocscience, 2016k). For each Global Minimum slip surface identified, the slope stability calculation is repeated N times, with samples generated for each random variable.

The FS for a given GM slip surface is calculated with the limit equilibrium analysis method selected by the user. In the limit equilibrium procedure, the slope is divided into a series of vertical slices, determining the resisting and driving forces for each slice, and then calculating the ratio of the sum of the resisting forces to the sum of the driving forces (Admassu, 2010).

The PSSA results in a distribution of factor of safety values that is used to calculate the probability of failure (PF) for the slope (Rocscience, 2016i). The PF is a measure of safety for the slope and is calculated by dividing the number of slip surfaces that have a factor of safety value less than one by the total number of samples (Rocscience, 2016l). Other measures of safety calculated from a PSSA are the mean factor of safety and the reliability index (RI) of the slope. The RI is calculated assuming the distribution of the factor of safety values from the probabilistic analysis are either normally or lognormally distributed (Rocscience, 2016l). It represents the number of standard deviations which separate the mean factor of safety from the critical factor of safety (i.e. when the factor of safety equals 1) (Rocscience, 2016l). The results of the PSSA indicate which distribution is the best fit for the factor of safety data. The RI equations and more detailed information can be found in Rocscience (2016l).

The MORU rock mass was divided into four sections for which four different slope profiles were generated and analyzed. Each slope section represents the overall slopes where the presidential sculptures are located. Slope profiles were generated using MORU LiDAR data in ArcGIS® ArcMap™ (Esri, 2014). These slope profiles were generalized and drawn in the Slide program (Rocscience, 2016h).

The Overall Slope Probabilistic analyses for each slope section were completed with and without a seismic load coefficient applied. The seismic condition was evaluated because the National Park Service is interested in the effect of vibrations, caused by July 4th fireworks, on the MORU sculptures. A fireworks display was not conducted during the course of this study; therefore earthquake data were used for the slope stability analysis. It is assumed in this study that if the MORU sculptures are safe against failure when an earthquake force is applied, the air blast resulting from fireworks will not be a concern to their structural stability. The seismic load coefficient of 0.14 (horizontal and vertical directions), used in the stability analyses, was estimated using the 2014 USGS map titled “Two-percent probability of exceedance in 50 years map of peak ground acceleration” (USGS, 2014), which can be found in Appendix B. Hynes-Griffin and Franklin (1984) suggest using a seismic coefficient corresponding to 50% of the Peak Ground Acceleration (PGA), but the full value of PGA was used in order to be more conservative.

For each analysis the Monte-Carlo sampling method with 2500 samples was used. This number of samples was sufficient for the analyses because it allowed a stable, final value for the FS to be achieved (Rocscience, 2016k). The limit equilibrium method used in this study was the Janbu simplified method (Janbu, 1968), as it is one of the recommended analysis methods for non-circular slip surfaces (Rocscience, 2016m). In weak materials like highly weathered or closely fractured rock, failure occurs along a roughly circular shape (Wyllie and Mah, 2004). Since granite is a hard rock with well-defined sets of discontinuities, it is assumed that the critical slip surface will be controlled by the discontinuities throughout the rock; therefore a non-circular slip surface was chosen for the analyses.

A non-circular, optimized path search was used for each analysis and 5000 slip surfaces were analyzed. The path search method was used for the non-circular analysis because it is appropriate for situations where the location of a slip surface is not known. The slip surfaces with a FS less than 1.5 were defined for optimization, which is a search technique that allows one to search for slip surfaces with lower FS values than would have been found otherwise (Rocscience, 2016n). The algorithm used in the optimization technique can be found in Greco (1996).

The material parameters used in the analyses were the unit weight and UCS of the granite, as determined in the laboratory, the GSI value of the granite, the strength type (which was the Generalized Hoek-Brown type), the Hoek-Brown intact rock constant (m_i) for the granite, and the disturbance factor (D). A GSI value of 62 was used as calculated by the computer software program RocData (Rocscience, 2016o), with discontinuity and RQD data from the granite rock in Region 3 at MORU as input parameters. An m_i value of 32 and was estimated using a chart in RocData (Rocscience, 2016o). The Slide 7.0 program (Rocscience, 2016h) indicates that a disturbance factor should only be applied to damaged rock around excavations or behind the slope and not to the entire rock mass. The analyses in this study considered the entire rock mass, thus the disturbance factor was estimated as zero. Groundwater effects were not considered as most of the slopes studied were dry in the field.

The GSI, m_i , and UCS values were assigned as random variables because the analysis results were sensitive to these input parameters and/or their mean values are not precisely known. The horizontal and vertical seismic coefficients were also assigned as random variables in the seismic analysis. Normal distributions were assigned to the random variables. Rocscience

(2016p) states that the standard deviation can be estimated for a normal distribution using the following equation:

$$\text{Standard Deviation } (\sigma) = (\text{HCV} - \text{LCV})/6$$

where: HCV = highest conceivable value of the random variable and LCV = lowest conceivable value of the random variable.

This equation was used to calculate the standard deviation values of the random variables. The HCV and LCV values were estimated with data collected in the field in Region 3 at MORU, data determined in the lab for the granite rock collected at MORU, the m_i values chart in RocData (Rocscience, 2016o), and the USGS (2014) map. The random variable data used in analyses are listed in Table 2.2.

Table 2.2: Random variables used in the probabilistic analyses.

Random Variable	Mean	Standard Deviation
GSI	62	7
Hoek-Brown m_i constant	32	1
UCS (kPa)	33,000	3500
Horizontal and Vertical Seismic Coefficient	0.14	0.02

2.4.10 Comparison of the Results of this Study to the Results of RESPEC Study

As discussed in Chapter 1, the study by RESPEC collected the orientation data of the discontinuities exposed on the MORU sculptures. In order to compare the principal joint sets determined by this study to RESPEC data, the discontinuity orientations reported by RESPEC were plotted and contoured in this study using the Dips program by Rocscience [Note: the discontinuity orientation data collected by RESPEC are reported in Boyle and Vogt (1992)].

RESPEC also determined the slope orientations of select areas of the MORU sculptures [Note: these data are reported in the RESPEC report by Boyle and Vogt (1992)]. The only slope surface that was comparable to the areas on the sculptures that this study analyzed in the kinematic analyses is the right side of the forehead of the Washington sculpture. In order to compare the results of this study to that by RESPEC, a kinematic analysis was conducted using the slope orientation on the right side of the forehead on the Washington sculpture as reported by RESPEC, and the principal joint sets identified from their data as well.

CHAPTER 3 - DATA PRESENTATION AND RESULTS

3.1 Field Data

3.1.1 Rock Description and Degree of Weathering Data

Table C.1 in Appendix C presents the data describing each rock type encountered at MORU. This includes the rock type, color, mineralogy, and texture. Structures present in the rock such as faults, folds, or any other distinctive features are also included. The table also lists the degree of weathering of the rocks at MORU using the chart by Dearman (1976), which grades the weathering of the rock mass on a scale ranging from I (fresh) - VI (residual soil). The granite rock at MORU is mainly composed of quartz, feldspar, mica, and hornblende. The granite is mainly medium grained and the degree of weathering ranges from III (moderately weathered) to IV (highly weathered). The schist rock is mainly composed of quartz and biotite with some muscovite present as well. It has a schistose texture and the degree of weathering ranges from III (moderately weathered) to V (completely weathered). The pegmatite is mainly composed of quartz, feldspar, mica, and hornblende. The pegmatite has grain sizes greater than 30 mm and the degree of weathering ranges from III (moderately weathered) to IV (highly weathered). The pegmatite was encountered the least in the field and there was not as much data collected for this rock as there was for the schist and granite. Table 3.1 summarizes the degree of weathering of the rock types encountered in each region at MORU.

Table 3.1: Summary of the degree of weathering (based on the charts by Dearman, 1976) of the different rock types encountered in the four regions at MORU. Listed are ranges with the highest frequency based on the histograms in Appendix G. Note: Pegmatite was not encountered or there was not sufficient data collected for this rock type in Regions 3 and 4.

Region	Rock Type	Degree of Weathering
1	Granite	III-IV (Moderately to highly weathered)
	Schist	IV-V (Highly to completely weathered)
	Pegmatite	IV-V (Highly to completely weathered)
2	Granite	III (Moderately weathered)
	Schist	IV (Highly weathered)
	Pegmatite	III-IV (Moderately to highly weathered)
3	Granite	III (Moderately weathered)
	Schist	III (Moderately weathered)
4	Granite	III (Moderately weathered)
	Schist	III (Moderately weathered)

The data in Table 3.1 shows that the granite and schist are relatively less weathered in Regions 3 (closest to the MORU sculptures) and 4.

3.1.2 Discontinuity Data

The exposed discontinuities at MORU were mapped considering different aspects including geometry (dip and dip direction), continuity, spacing, surface irregularities (JRC), infilling material, and the presence of water. Aperture data were also collected for the discontinuities. The discontinuity data are presented in Appendix D. Table 3.2 summarizes the average discontinuity data, except the geometry.

Table 3.2 shows that the discontinuities in the granite and schist in Region 3, the area closest to the sculptures, are on average more continuous than in other regions. The table also shows that the average discontinuity spacing in the granite in Region 2 is largest, while in the schist it is largest in Region 3. Furthermore, the average JRC is highest for the discontinuities in both the granite and schist in Region 4. Generally, the discontinuities in granite and schist did not have any infilling material and were dry. In regards to weathering of the discontinuities, Table

Table 3.2: Average discontinuity data for each region studied at MORU.

Region	Rock Type	Continuity	Spacing	Aperture	JRC	Infilling	Water	Weathering (Dearman, 1976)
1	Granite	20.1 ft (6.1 m)	3.3 ft (1 m)	3.5 in (8.9 cm)	11 - 12	None	Dry	III - IV (Moderate – High)
	Schist	3.8 ft (1.2 m)	1 ft (0.3 m)	0.5 in (1.3 cm)	6 - 7	None	Dry	IV – V (High – Complete)
	Pegmatite	7.4 ft (2.3 m)	No Data	0.2 in (0.5 cm)	16	None	Dry	IV – V (High – Complete)
2	Granite	13.2 ft (4 m)	5.8 ft (1.8 m)	3.6 in (9.1 cm)	10 - 11	None	Dry	III (Moderate)
	Schist	2.9 ft (0.9 m)	2.2 ft (0.7 m)	0.2 in (0.5 cm)	4	None	Dry	V (High)
	Pegmatite	8.4 ft (2.6 m)	3.8 ft (1.1 m)	0.5 in (1.3 cm)	10	None	Dry	V (High)
3	Granite	25.9 ft (7.9 m)	4.5 ft (1.4 m)	5.7 in (14.5 cm)	8	None	Dry	III (Moderate)
	Schist	11.4 ft (3.5 m)	3.7 ft (1.1 m)	0.7 in (1.8 cm)	6 - 8	None	Dry	III (Moderate)
	Pegmatite	NA	NA	NA	NA	NA	NA	NA
4	Granite	22 ft (6.7 m)	3.7 ft (1.1 m)	8.4 in (21.3 cm)	14 - 15	None	Dry	III (Moderate)
	Schist	10.9 ft (3.3 m)	1.9 ft (0.4 m)	1 in (2.5 cm)	9 - 10	None	Dry	III (Moderate)
	Pegmatite	NA	NA	NA	NA	NA	NA	NA

3.2 shows that on average: the granite rock is moderately weathered in all regions except for Region 1, whereas it moderately to highly weathered; the schist rock in Regions 3 and 4 are on average less weathered than in Regions 1 and 2; and the pegmatite rock was less weathered on average in Region 2 as compared to Region 1.

3.1.3 Rock Quality Designation (RQD) Data

Table 3.3 lists the RQD values estimated for each region studied at MORU, using Palstrom's method (Palstrom, 1982). The RQD for granite ranges from 93-97%, for schist it ranges from 70-85%, and for pegmatite, which was only studied in Region 2, the RQD is 78%. According to the RQD classification found in West (1995), the high values of RQD ($> 90\%$) for granite, the rock in which the sculptures are carved, indicate excellent quality rock. Table 3.3 shows that the RQD for granite was very similar for each Region studied. The RQD for schist is lowest in Region 1 and highest in Region 4.

Table 3.3: RQD values for each region at MORU. RQD values for the pegmatite rock type were not estimated for Regions 1, 3, and 4.

	Region 1 RQD (%)		Region 2 RQD (%)			Region 3 RQD (%)		Region 4 RQD (%)	
	Granite	Schist	Granite	Schist	Pegma- tite	Granite	Schist	Granite	Schist
	100	100	98	58	78	88	83	98	90
	90	40	100	68		100	73	100	93
	100		78	100		90		88	73
			90			98		90	80
			100			100		93	88
						100		78	
								100	
								100	
								100	
								85	
								100	
Avg. RQD (%)	97	70	93	75	78	96	78	94	85

3.1.4 Description of the Samples Collected from MORU

Rock block samples 1a and 1b (refer to Table 2.1 for sample designations) are both mica schists containing minerals such as biotite, muscovite, and quartz; however, sample 1b is coarser grained than sample 1a (the average grain size of sample 1a is 0.5 mm and for sample 1b the average grain size is 1 mm). All of the granite rock block samples contain feldspar, quartz, mica, and amphibole minerals. Sample 2 is a white to grey, medium-grained granite (average grain size is 3-4 mm). Sample 3 is a medium-grained (average grain size is 3 mm) pink to grey granite with some iron staining. Sample 4 is also pink to grey in color with iron staining present. Sample 4 is medium-grained (average grain size 3-4 mm), with a portion of the sample being pegmatitic. Sample 5 is a fine to medium-grained granite (average grain size is 2-3 mm), is pink to grey in color, and is iron stained.

3.2 Laboratory Test Results

3.2.1 Density, Absorption, and Basic Friction Angle Test Results

The density, absorption, and basic friction angle results for each MORU sample are listed in Table 3.4. The average values of these properties for the schist and granite rock types are listed in Table 3.5.

The relatively high density ($> 162 \text{ pcf}/2.6 \text{ Mg/m}^3$) and low absorption (1.5% or less) values suggest that these rocks, in their solid form, are not subject to freeze-thaw damage. The basic friction angle can be modified using parameters such as surface irregularities to determine the internal angle of friction along the discontinuities. The average basic friction angle of the MORU granite is 41° . However Wylie and Mah (2004) report that the friction angle for granite typically ranges from 34° - 40° . In light of this and in order to be more conservative, a basic

friction angle of 40° was used for the kinematic analyses and was not modified for surface irregularities.

Table 3.4: Laboratory results determined for each of the samples collected at MORU.

Rock Block Sample #	Sample Type	Density (lb/ft³)	Absorption (%)	Basic Angle of Friction (°)
1a	Schist	172	0.8	40
1b	Schist	174	1.5	NA
2	Granite	163	0.7	41
3	Granite	162	1.1	43
4	Granite	164	0.7	41
5	Granite	163	1.0	40

Table 3.5: Average laboratory results for the schist and granite rock types studied at MORU.

Sample Type	Average Density (lb/ft³)	Average Absorption (%)	Average Basic Angle of Friction (°)
Schist	173	1.1	40
Granite	163	0.9	41

3.2.2 Unconfined Compressive Strength (UCS) and Tensile Strength Results

Table 3.6 presents the results of UCS tests, using both the standard test method and the point load test method. The table also lists the results for the tensile strength test. Table 3.7 lists the averages of these data for the schist and granite rock types. The UCS of pegmatite was not determined in the laboratory due to lack of sample, therefore pegmatite was assigned an UCS value of 4,355 psi (30 MPa) which is 90% of the average UCS for granite [strength decreases with increasing grain size (West, 1995)]. Images of the failed samples can be found in Appendix F.

The UCS values for the granite samples, obtained by both methods, are unexpectedly low ranging from 4,046 psi to 7,118 psi (27.9 MPa to 49.1 MPa). UCS for granites typically ranges

from 7,076 psi to 46,980 psi (48.8 MPa to 323.9 MPa) (Johnson and DeGraff, 1988). To further explore the reason for this low strength, thin sections of the rock samples were analyzed for micro-fractures using the SEM to determine if this could be a factor in their low strength. These results are discussed later in section 3.2.6.

Table 3.6: The strength values for each rock block sample collected from MORU. The values obtained by the standard test method represent the average of three specimens tested for each rock block sample (note: one specimen was tested for sample 1a because only one core was successfully obtained from the rock block). The fields listed with NA represent missing data due to insufficient samples meeting ASTM standards for testing. Note: 145 psi = 1 MPa.

Rock Block Sample #	Sample Type	Unconfined Compressive Strength (psi) – Standard Test Method	Unconfined Compressive Strength (psi) – Point Load Test Method	Tensile Strength (psi) – ASTM Method
1a	Schist	8,403	9,076	737
1b	Schist	NA	NA	743
2	Granite	7,118	6,777	471
3	Granite	4,046	NA	275
4	Granite	4,136	5,195	353
5	Granite	4,056	NA	276

Table 3.7: Average values of the unconfined compressive strength and tensile strength for the schist and granite rocks. Note: 145 psi = 1 MPa.

Sample Type	Average Unconfined Compressive Strength (psi) – Standard Test Method	Average Unconfined Compressive Strength (psi) - Point Load Test Method	Average Tensile Strength (psi) - ASTM Method
Schist	8,403	9,076	740
Granite	4,839	5,986	344

3.2.3 Slake Durability Test Results

Table 3.8 lists the laboratory results for the slake durability test. According to the ISRM classification (ISRM, 1979), the schist sample 1a has high durability, the schist sample 1b has medium durability, and the granite sample 2 has high durability. The results show that there is no

difference in the slake durability index values between the schist sample 1a and the granite sample 2, indicating no potential for undercutting. There is a slight difference between the slake durability index values of the schist sample 1b and the granite 2, indicating a slight potential for undercutting.

Table 3.8: Slake Durability test results for the rock studied at MORU.

Rock Block Sample #	Rock Type	1st Cycle Slake Durability Index (I_d1) (%)	2nd Cycle Slake Durability Index (I_d2) (%)	ISRM Durability Classification Based on I_d2 (ISRM, 1979)
1a	Schist	97	96	High
1b	Schist	72	61	Medium
2	Granite	97	96	High

3.2.4 Freeze-Thaw Test Results

Table 3.9 lists the average results for the freeze-thaw durability test (ASTM, 2003). The average percent change in mass for each of the granite specimens, after 300 freeze-thaw cycles, is relatively low ($< 2\%$). This low percent change in mass of the granite is corroborated by the average absorption of granite being $< 1\%$, which indicates low susceptibility to freeze-thaw damage.

The schist samples exhibit higher average change in mass after 300 freeze-thaw cycles ($> 5\%$), indicating that schist has lower freeze-thaw durability than granite. Schist sample 1b is coarser grained, is most schistose, and has higher absorption values than schist sample 1a, indicating that the schist sample 1b is more susceptible to freeze-thaw action. The granite samples have very similar freeze-thaw durability. Granite rock block sample 5 has the highest average percent change in its mass, which is likely due to fractures in the hand sized samples. Water in the fractures expands and contracts during the freeze-thaw cycles, causing the specimen to break apart. A limitation of this test was that the specimens tested for each rock type were not all uniform in size. This was due to the

fact that there was limited supply left of the rock blocks from MORU. This may account for the variability in the values of the mass lost for each of the rock type specimens.

Table 3.9: Average freeze-thaw durability test results.

Rock Block Sample #	Rock Type	Average Total Mass Lost (g)	Average % Change in Mass
1a	Schist	14.3	5.9
1b	Schist	20.8	5.5
2	Granite	3.6	1.0
3	Granite	1.4	0.7
4	Granite	2.1	0.8
5	Granite	3.1	1.1

3.2.5 Thin Section Analysis Results

Table 3.10 lists the mineral percentage estimates for each thin section of the MORU rock blocks.

3.2.6 SEM Analysis Results

The SEM images of the granite thin sections (Figures 3.1 - 3.4) show that all of the samples have micro-fractures. The presence of the micro-fractures in the samples may be the main reason for the low strength of the granite that was tested in this study. Weathering of the rock specimens may be another factor contributing to the reduced strength of the granite. This is because the granite rock block samples that were collected from MORU were not fresh pieces broken off outcrops, rather they were samples lying around the grounds of the memorial and it is unknown when they were broken off the rock mass (it is prohibited to collect outcrop samples in a national park). It is likely that a piece of fresh granite with minimal weathering from MORU would have higher UCS than the granite rock blocks tested in this study.

Table 3.10: Approximate mineral percentages for the thin sections of the MORU rock blocks.

Rock Block Sample #	Rock Type	Mineral	Percentage
1a	Schist	Biotite	35
		Quartz	25
		Muscovite	15
		K-feldspar (~ 10% Microcline)	15
		Plagioclase	10
1b	Schist	Quartz	45
		Biotite	35
		Plagioclase	15
		Muscovite	2
		Opaque minerals	<1
2	Granite	K-feldspar (Microcline ~ 30%; Orthoclase ~ 15%; Some perthitic)	45
		Plagioclase	25
		Muscovite	17
		Quartz	10
		Biotite	3
3	Granite	K-feldspar (Orthoclase ~25%; Microcline ~ 20%; Some perthitic)	45
		Plagioclase	25
		Muscovite	15
		Quartz	10
		Biotite	5
		Opaque minerals	<1
4	Granite	K-feldspar (Microcline ~ 40%; Orthoclase ~10%)	50
		Plagioclase	25
		Muscovite	20
		Quartz	5
		Biotite	<1
5	Granite	K-feldspar (Microcline ~ 30%; Orthoclase ~ 10%; Some perthitic)	40
		Plagioclase	30
		Muscovite	20
		Quartz	10
		Biotite	<1
		Amphibole	<1

Figure 3.1: Granite 2 sample. Red arrow indicates a micro-fracture present in the sample. Note: not all micro-fractures are shown with arrows.

Figure 3.2: Granite 3 sample. Red arrow indicates an area where micro-fractures are present in the sample. Note: not all micro-fractures are shown with arrows.

Figure 3.3: Granite 4 sample. Red arrow indicates a micro-fracture present in the sample. Note: not all micro-fractures are shown with arrows.

Figure 3.4: Granite 5 sample. Red arrows indicate areas where micro-fractures are present in the sample. Note: not all micro-fractures are shown with arrows.

3.3 Data Analysis and Results

3.3.1 Discontinuity and Slope Orientation Data for the MORU Sculptures

The orientation data for the discontinuities traversing the MORU sculptures, obtained using LiDAR data and the Split-FX software (Split Engineering, 2014), are listed in Table 3.11. A total of 53 discontinuities were measured for the four MORU sculptures. The average slope orientations of the sculptures foreheads and noses, obtained using the same software, are listed in Table 3.12. Table 3.11 shows that 57% of the joints are steeper than 70 degrees, 24% are between 70 and 45 degrees, and 19% are gentler than 45 degrees.

3.3.2 Statistical Analysis

The frequency histograms for the discontinuity data used in the rock mass characterization (degree of weathering, RQD, continuity, spacing, JRC, infilling material, aperture) can be found in Appendix G. A summary of the highest frequency data, as determined from the histograms, is presented in Table 3.13.

3.3.3 In-Situ Hydraulic Conductivity Data and Results

The in situ hydraulic conductivity (k) values assuming clean, smooth discontinuities in the granite and schist rock in Region 3 at MORU are listed in Table 3.14. There was a wide range in the aperture and spacing values collected for the granite and schist rock studied in Region 3 at MORU; therefore the low, high, median, and average values of the in situ hydraulic conductivity (k) are listed. A few of the values of k are extremely high due to the high values of aperture and spacing. The high permeability values of the granite and schist suggest that the MORU rock mass in Region 3 (area studied closest to the sculptures) is well drained and the potential for water freezing in the discontinuities is minimal.

Table 3.11: Discontinuity orientation data for the sculptures obtained using LiDAR and Split-FX.

Number	Dip (degrees)	Dip Direction (degrees)
1	71	181
2	75	335
3	62	296
4	78	325
5	89	355
6	77	349
7	81	158
8	76	338
9	23	230
10	29	258
11	82	151
12	42	285
13	14	56
14	84	334
15	77	120
16	63	348
17	69	333
18	55	341
19	82	172
20	69	349
21	90	284
22	40	324
23	74	320
24	37	92
25	88	213
26	33	108
27	51	249
28	31	209
29	73	103
30	72	114
31	68	118
32	83	320
33	89	304
34	59	38
35	64	28
36	29	251
37	78	59
38	48	110
39	85	49
40	67	293
41	86	190

Table 3.11 – Continued.

Number	Dip (degrees)	Dip Direction (degrees)
42	84	324
43	74	309
44	80	40
45	84	134
46	87	77
47	4	128
48	71	205
49	82	165
50	68	243
51	89	88
52	57	290
53	86	94

Table 3.12: Average slope orientations for the MORU sculptures obtained using LiDAR and Split-FX software (Split Engineering, 2014).

Sculpture	Nose (Average)			Forehead (Average)		
	Right	Left	Front	Right	Left	Center
Washington	80°/211°	78°/066°	72°/139°	76°/195°	79°/070°	72°/136°
Jefferson	75°/182°	72°/023°	43°/098°	69°/145°	68°/042°	59°/099°
Roosevelt	78°/156°	68°/013°	66°/094°	80°/140°	84°/062°	79°/083°
Lincoln	82°/232°	80°/081°	71°/145°	84°/222°	78°/099°	78°/146°

Table 3.13: Highest frequency data obtained from histograms of various discontinuity data.

Region at MORU	Rock Type	Degree of Weathering*	RQD**	Continuity**	Spacing**	JRC***	Infill**	Average Aperture**
1	Granite	Moderate–High	90-100%	3-10 m	0.6-2 m	2-12 (Slightly Rough)	None	>5 mm
	Schist	High-Complete	25-50%; 90-100%	<1 m	200-600 mm	2-12 (Slightly Rough)	None	0 mm
	Pegmatite	High-Complete	NA	1-3 m	NA	12-18 (Rough)	None	0 mm
2	Granite	Moderate	90-100%	3-10	0.6-2 m	2-12 (Slightly Rough)	None	>5 mm
	Schist	High	50-75%	<1 m	0.6-2 m	1-2 (Smooth)	None	0 mm
	Pegmatite	High	75-90%	<1 m; 1-3 m; 3-10 m	0.6-2 m	2-12 (Slightly Rough)	None	0 mm - >5 mm
3	Granite	Moderate	90-100%	3-10 m	0.6-2 m	1-2 (Smooth); 2-12 (Slightly Rough)****	None	>5 mm
	Schist	Moderate	50-75%; 75-90%	1-3 m	0.6-2 m	1-2 (Smooth)	None	0 mm
4	Granite	Moderate	90-100%	3-10 m	0.6-2 m	18-20 (Very Rough)	None	>5 mm
	Schist	Moderate	75-90%	1-3 m	200-600 mm	2-12 (Slightly Rough)	None	>5 mm

*Dearman (1976) classification.

**Bieniawski (1989) classification.

***The JRC values were categorized based on the RMR roughness classifications. This study classified the JRC values based on judgement and field observations. The roughness categories by Bieniawski (1989) are in parentheses next to the JRC values. JRC values of 2 fell in the slightly rough category based on field observations.

**** The Slightly Rough category was included for Region 3 because even though it was not the highest frequency for the data, its frequency was very close to that of the smooth category.

Table 3.14: Hydraulic conductivity (k) and the average discontinuity values collected from Region 3 at MORU.

Rock Type	Aperture in Region 3 at MORU (cm)		Spacing in Region 3 at MORU (cm)		k (cm/s)
Granite	Low	0	Low	10	0
	High	121.9	High	400	592323372
	Median	1.3	Median	98	176
	Average	14.5	Average	140	348915
Schist	Low	0	Low	20	0
	High	20.3	High	210	1436135
	Median	0	Median	110	0
	Average	1.8	Average	110	524

3.3.4 Stereonet Analysis

The program Dips (Rocscience, 2016a) was used to plot and contour discontinuity data on stereonet plots. These stereonet plots were used to determine the principal joint sets (PJS). The PJS for each rock type within the four regions at MORU as well as for the three rock types as a whole, with all the discontinuity data combined from each region (note: pegmatite data were only collected in regions 1 and 2), are listed in Tables 3.15-3.17. The Dips (Rocscience, 2016a) stereonet plots of the data listed in the tables are in Appendix H. Tables 3.15-3.17 indicate joint sets A and B to be the most dominant discontinuities.

Region 3 is the closest area to the sculptures among the four areas where discontinuity data were collected in the field. A total of 59 discontinuity orientations were measured in the field in Region 3, and 53 discontinuity orientations were traced on the MORU sculptures using the LiDAR point cloud and Split-FX software (Split Engineering, 2014). Discontinuity data clusters for the two individual data sets were similar; therefore the two data sets were combined to determine the principal joints, which were used in the kinematic analyses of the MORU sculptures.

Table 3.15: Principal joint set data for the granite rock in each region studied at MORU.

Granite		
	Principal Joint Set	Dip/Dip Direction
All Regions	A	83°/320°
	B	78°/254°
Region 1	A	85°/323°
	B	74°/241°
Region2	A	82°/318°
	B	76°/258°
	C	86°/181°
	D	31°/061°
Region 3	A	82°/329°
	B	80°/254°
	E	75°/299°
	F	88°/028°
Region 4	A	84°/315°
	B	78°/245°
	G	81°/354°
Sculptures (using Split-FX)	A	82°/337°
	E	60°/295°
	H	27°/237°
	I	80°/114°
Sculptures (Split-FX and Region 3 data combined)	A	83°/337°
	B	82°/256°
	E	71°/302°
	F	89°/029°
	I	74°/116°

Table 3.16: Principal joint set data for the schist rock in each region studied at MORU.

Schist		
	Principal Joint Set	Dip/Dip Direction
All Regions	A	83°/324°
	B	68°/262°
	D	39°/071°
	E	77°/292°
Region 1	A	86°/330°
	B	68°/261°
	D	41°/078°
	J	85°/239°
	K	32°/358°
Region2	A	83°/320°
	D	30°/048°
	E	82°/292°
	J	88°/066°
Region 3	A	83°/317°
	B	63°/268°
	D	40°/077°
Region 4	A	77°/321°
	E	78°/287°
	J	75°/229°

Table 3.17: Principal joint set data for the pegmatite rock in each region studied at MORU.

Pegmatite		
	Principal Joint Set	Dip/Dip Direction
Region 1 & 2	A	69°/321°
	E	84°/297°
	J	72°/225°
	L	69°/166°
	M	87°/095°
Region 1	B	81°/265°
	J	72°/225°
Region 2	A	68°/320°
	B	49°/257°
	E	84°/297°
	L	74°/167°
	M	87°/095°

CHAPTER 4 – ROCK MASS CHARACTERIZATION OF MOUNT RUSHMORE NATIONAL MEMORIAL

4.1 Rock Mass Characterization Using the Rock Mass Rating (RMR) System Results

The RMR system, developed by Bieniawski (1989), was used to classify the MORU rock in each region. The ratings for each parameter were assigned based on the data summarized in Table 3.13 and the unconfined compressive strength values determined in the laboratory. The presence of water was negligible in the field; therefore the rock was rated as dry. If there was a range in the data, an average value was used to assign the rating value. Table 4.1 presents the individual scores for the RMR parameters, summation of scores, and the final ratings for all four regions. All of the rocks studied in each of the four regions at MORU were classified as good rock. The engineering properties such as the cohesion of the rock mass and the angle of internal friction of the rock mass can be estimated using the RMR classification. For a rock classified as “good”, the estimated rock mass cohesion ranges from 43.5 psi – 58.0 psi (0.3 MPa - 0.4 MPa), and the rock mass angle of internal friction ranges from 35° - 40° (Bieniawski, 1989).

4.2 Rock Mass Characterization Using the Rock Mass Quality System (Q-system) Results

The Q-System, developed by Barton et al. (1974), was also used to classify the MORU rock. The parameters for the system were estimated using the data in Table 3.13, the principal joint sets determined in the study, and visual estimates made in the field. If there was a parameter value that had a range, the average value was used to assign a rating value. Table 4.2 summarizes the Q-system ratings and results.

Table 4.1: Rock Mass Rating (RMR) System parameter ratings and results.

			RMR Parameter Ratings and Results									
			Region 1			Region 2			Region 3		Region 4	
RMR Parameter			Granite	Schist	Pegmatite	Granite	Schist	Pegmatite	Granite	Schist	Granite	Schist
1	Strength of Intact Rock Material		7	7	7	7	7	7	7	7	7	7
2	RQD		20	12.5	17*	20	13	17	20	15	20	17
3	Spacing of discontinuities		15	10	15*	15	15	15	15	15	15	10
4	Condition of Discontinuities	Continuity	2	6	4	2	6	4	2	4	2	4
		Aperture	0	6	6	0	6	4	0	6	0	0
		Roughness	3	3	5	3	1	3	2	1	6	3
		Infilling	6	6	6	6	6	6	6	6	6	6
		Weathering	2	0.5	0.5	3	1	1	3	3	3	3
5	Water		15	15	15	15	15	15	15	15	15	15
RMR Rating			70	66	76	71	70	72	70	72	74	65
Class Number			II	II	II	II	II	II	II	II	II	II
Rock Description			Good	Good	Good	Good	Good	Good	Good	Good	Good	Good

*Ratings assigned based on Region 2. These parameters were not measured in the field for pegmatite in Region 1.

Table 4.2: Rock Mass Quality (Q) System parameter ratings and results.

		Q-system Ratings and Results									
		Region 1			Region 2			Region 3		Region 4	
	Q-System Parameter	Granite	Schist	Pegmatite	Granite	Schist	Pegmatite	Granite	Schist	Granite	Schist
1	RQD	100	70	80*	90	75	80	100	80	90	85
2	Joint Set Number (Jn)	4	15	4	15	15	15	15	9	9	9
3	Joint Roughness Number (Jr)	2.75	2.75	3	2.75	2	2.75	2.5	2	3.5	2.75
4	Joint Alteration Number (Ja)	1	1	1	1	1	1	1	1	1	1
5	Joint Water Reduction	1	1	1	1	1	1	1	1	1	1
6	Stress Reduction Factor	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Q-Value		28	5	24	7	4	6	7	7	14	10
Rock Classification		Good	Fair	Good	Fair	Fair	Fair	Fair	Fair	Good	Good

The results of RMR system rock mass characterization, shown in Table 4.1, indicate that the three types of rock present at MORU classify as good to fair quality rock. This explains the longevity of this important monument since its construction and suggests its continued stability in the future, with proper maintenance and monitoring.

The results of the Q-system rock mass characterization, shown in Table 4.2, indicate that the granite and pegmatite rock in Region 1 classify as good rock, the granite and schist in Region 4 also classify as good rock, but the rock studied in the other regions at MORU all classify as fair rock. The fair classifications are not the same as the RMR system classifications for these regions. The difference in the classifications between the two systems may be due to the fact that the SRF value in the Q-system calculations were based on the “low stress, near surface” value (see Table B.3 in Appendix B) as there is not a value for surface excavations because the Q-system was developed for tunneling.

CHAPTER 5 – STABILITY EVALUATION OF MOUNT RUSHMORE NATIONAL MEMORIAL

5.1 Kinematic Analysis Considering the Principal Joint Set (PJS) Planes and Intersections

The Dips software program (Rocscience, 2016a) was used to conduct a kinematic analysis to determine the potential modes of slope failure along the slopes of the foreheads and noses of the MORU presidential sculptures. Input parameters for the analyses included the principal joint sets (PJS) orientation data determined from the stereonet analyses, the slope orientations determined from the LiDAR, and the modified basic angle of friction.

The kinematic analysis results for the foreheads and noses of the MORU sculptures are listed in Tables 5.1-5.16. The results for the planar sliding and flexural toppling kinematic analyses are presented as a percentage of poles within the individual PJS. The results for the wedge sliding and direct/oblique toppling kinematic analyses are presented as a percentage of the total intersections between the PJS planes. The result percentages are an estimate of the probability of failure with respect to all of the planes of the individual PJS (in the case of planar sliding or flexural toppling), or with respect to the total number of intersections between the PJS planes (in the case of wedge sliding or direct/oblique toppling) (Rocscience, 2016c). The stereonet plots for the Washington sculpture are presented in Figures 5.1-5.24. The stereonet plots for the other three sculptures can be found in Appendix I. It should be noted the designation of right or left refers to the sculptures right or left. The results of the kinematic analysis indicate that the potential for planar sliding, wedge sliding, and toppling failure exists

for each of the MORU sculptures, but the potential varies for each of the slopes analyzed on the individual sculptures.

5.1.1 Washington Sculpture

Figures 5.1-5.6 show the stereonet plots evaluating the potential for planar sliding. Table 5.1 provides a summary of the results. The results indicate that there is a potential for planar sliding along all of the slopes except for the left side of Washington's nose and forehead. The probability of planar sliding is low, ranging from 6%-11% along the slopes on the right side of the nose and forehead, and along the slope on the front of the nose. The probability of planar sliding along the central slope of Washington's forehead is highest (20%).

The stereonet plots of the kinematic analyses for evaluating the potential for wedge sliding are shown in Figures 5.7-5.12. Table 5.2 summarizes the results of the analyses. The results show that there is a risk of wedge sliding along all of the slopes analyzed. The probability of wedge sliding is highest (20%) along the slopes on the right side of the nose and on the left side of the forehead. The other slopes analyzed only have a probability of 10%.

The stereonet plots of the kinematic analyses for evaluating the potential for direct and oblique toppling are provided in Figures 5.13 -5.18. The results are summarized in Table 5.3. The slopes along the forehead and nose of the Washington sculpture all have the potential for direct and oblique toppling except for the right side of the forehead, which does not show any potential for direct toppling. The probability of direct toppling failure is low (10%) along the slopes on the right and left side of the nose, and the left side of the forehead. The probability of direct toppling is highest (50%) along the slopes on the front and central areas of the nose and forehead. The probability of oblique toppling was opposite the direct toppling results with the highest potential (50%-60%) being along the right and left sides of the nose and forehead. All of

the analyses for each of the slopes indicated that there are joints that may act as sliding or release planes (base planes) for the blocks.

The stereonet plots of the kinematic analyses evaluating the potential for flexural toppling are provided in Figures 5.19-5.24. Table 5.4 summarizes the results. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Washington sculpture. All of the slopes have a high probability of flexural toppling with respect to the total number of principal joint set planes; however the left side of the nose and forehead, and the front and central slopes of the nose and forehead have the highest probabilities.

Figure 5.1: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Washington’s nose. The probability of planar sliding is low along this slope.

Figure 5.2: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Washington's nose. There is no potential for planar sliding along this slope as none of the pole vectors fall within the critical zone for planar sliding.

Figure 5.3 Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the front slope of Washington's nose. The probability of planar sliding is low along this slope.

Figure 5.4: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Washington's forehead. The probability of planar sliding is low along this slope.

Figure 5.5: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Washington's forehead. The probability of planar sliding is very low along this slope.

Figure 5.6: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the center of Washington's forehead. There is a risk for planar sliding on the center of Washington's forehead. Set I has a planar sliding probability of 20% with respect to the principal joint set planes.

Table 5.1: Kinematic analysis results (considering the principal joint set (PJS) planes) for planar sliding on the slopes of the Washington sculpture at MORU. "Set" refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Washington Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Planar Sliding	Nose (Right)	Set: F	2	18	11
	Nose (Left)	NA	0	NA	0
	Nose (Front)	Set: I	1	10	10
	Forehead (Right)	Set: F	1	18	6
	Forehead (Left)	NA	0	NA	0
	Forehead (Center)	Set: I	2	10	20

Figure 5.7: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and E, and sets B and I) fall within the critical zone for wedge sliding.

Figure 5.8: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.

Figure 5.9: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the front of Washington's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Figure 5.10: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Figure 5.11: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure 5.12: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the center of Washington's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Table 5.2: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Washington sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Washington Sculpture Slope	Critical Intersections (PJS Planes)		Total Number Intersections (PJS Planes)	%
Wedge Sliding	Nose (Right)	Sets: I & B; E & A	2	10	20
	Nose (Left)	Sets: I & A	1	10	10
	Nose (Front)	Sets: I & B	1	10	10
	Forehead (Right)	Sets: I & B	1	10	10
	Forehead (Left)	Sets: I & A; I & F	2	10	20
	Forehead (Center)	Sets: I & B	1	10	10

Figure 5.13: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.14: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.15: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the front of Washington's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.16: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's forehead. There is a risk for oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There is no risk for direct toppling. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.17: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.18: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Washington's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Table 5.3: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Washington sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Washington Sculpture Slope	Total Critical Intersections (PJS Planes) & Base Plane Pole Vectors		Total Intersections (PJS Planes) & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling	1	10	10
		Oblique Toppling	5	10	50
		Base Plane (All Pole Vectors)	15	112	13
		Base Plane (Set: F)	2	18	11
	Nose (Left)	Direct Toppling	1	10	10
		Oblique Toppling	6	10	60
		Base Plane (All Pole Vectors)	7	112	6
	Nose (Front)	Direct Toppling	5	10	50
		Oblique Toppling	1	10	10
		Base Plane (All Pole Vectors)	11	112	10
		Base Plane (Set: I)	4	10	40
	Forehead (Right)	Direct Toppling	0	10	0
		Oblique Toppling	6	10	60
		Base Plane (All Pole Vectors)	16	112	14
		Base Plane (Set: F)	2	18	11
	Forehead (Left)	Direct Toppling	1	10	10
		Oblique Toppling	6	10	60
		Base Plane (All Pole Vectors)	6	112	5
	Forehead (Center)	Direct Toppling	5	10	50
		Oblique Toppling	1	10	10
		Base Plane (All Pole Vectors)	11	112	10
		Base Plane (Set: I)	4	10	40

Figure 5.19: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Washington's nose. Principal joint set I has a 44% probability of failure with respect to the PJS planes in the set.

Figure 5.20: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Washington's nose. There are 17 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure 5.21: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the front slope of Washington's nose. There are 27 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure 5.22: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Washington's forehead. There are 14 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure 5.23: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Washington's forehead. There are 16 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure 5.24: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the central slope of Washington's forehead. There are 24 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Table 5.4: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Washington sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Washington Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Flexural Toppling	Nose (Right)	Set: F	8	18	44
	Nose (Left)	Set: B	15	18	83
		Set: F	2	18	11
	Nose (Front)	Set: A	16	25	64
		Set: E	10	11	91
		Set: I	1	10	10
	Forehead (Right)	Set: A	7	25	28
		Set: F	7	18	39
	Forehead (Left)	Set: B	15	18	83
		Set: F	1	18	6
	Forehead (Center)	Set: A	13	25	52
		Set: E	10	11	91
		Set: I	1	10	10

5.1.2 Jefferson Sculpture

Table 5.5 presents the results of planar sliding for the Jefferson sculpture. The results indicate that the only slope analyzed which has a potential of planar sliding is the central slope of Jefferson’s forehead. The other slopes analyzed do not show any potential for this type of failure. The probability of planar sliding along the central slope of Jefferson’s forehead is low (10%).

Table 5.6 presents the results for the wedge sliding analyses. There is no potential of wedge sliding along the slopes on the front and center of the nose and forehead. The other slopes analyzed have a low probability (10%) of wedge sliding.

Table 5.7 presents the kinematic analysis results for direct and oblique toppling. There is no potential for direct toppling along the slopes on the right side of the nose and the left side of the forehead and the probability of failure is low (10%) along the slope on the left side of the

nose. The probability, however, is high for the slopes along the front of the nose and the right side of the forehead (50% and 40% respectively).

The oblique toppling results show that the probability of failure with respect to the total number of intersections for the PJS is lowest (10%) for the slopes along the front of the nose and the center of the forehead. The rest of the slopes have a probability of 20% or higher, with the slopes along the right side of the nose and the left side of the forehead showing the highest probability of flexural toppling (60%). All of the analyses for each of the slopes indicate that there are joints that may act as sliding or release planes (base planes) for the blocks.

Table 5.5: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Jefferson Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Planar Sliding	Nose (Right)	NA	0	NA	0
	Nose (Left)	NA	0	NA	0
	Nose (Front)	NA	0	NA	0
	Forehead (Right)	NA	0	NA	0
	Forehead (Left)	NA	0	NA	0
	Forehead (Center)	Set: I	1	10	10

Table 5.6: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Jefferson Sculpture Slope	Total Critical Intersections (PJS Planes)		Total Number of Intersections (PJS Planes)	%
Wedge Sliding	Nose (Right)	Sets: I & B	1	10	10
	Nose (Left)	Sets: I & A	1	10	10
	Nose (Front)	NA	0	10	0
	Forehead (Right)	Sets: I & B	1	10	10
	Forehead (Left)	Sets: I & A	1	10	10
	Forehead (Center)	NA	0	10	0

Table 5.7: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Jefferson Sculpture Slope	Total Critical Intersections (PJS Planes) & Base Plane Pole Vectors		Total Intersections (PJS Planes) & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: PJS Planes (Intersections)	0	10	0
		Oblique Toppling: PJS Planes (Intersections)	6	10	60
		Base Plane (All Pole Vectors)	16	112	14
		Base Plane (Set: F)	1	18	6
	Nose (Left)	Direct Toppling: PJS Planes (Intersections)	1	10	10
		Oblique Toppling: PJS Planes (Intersections)	3	10	30
		Base Plane (All Pole Vectors)	12	112	11
		Base Plane (Set: F)	1	18	6
	Nose (Front)	Direct Toppling: PJS Planes (Intersections)	5	10	50
		Oblique Toppling: PJS Planes (Intersections)	1	10	10
		Base Plane (All Pole Vectors)	5	112	4
	Forehead (Right)	Direct Toppling: PJS Planes (Intersections)	4	10	40
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	10	112	9
		Base Plane (Set: I)	2	10	20
	Forehead (Left)	Direct Toppling: PJS Planes (Intersections)	0	10	0
		Oblique Toppling: PJS Planes (Intersections)	6	10	60
		Base Plane (All Pole Vectors)	10	112	9
	Forehead (Center)	Direct Toppling: PJS Planes (Intersections)	5	10	50
		Oblique Toppling: PJS Planes (Intersections)	1	10	10
		Base Plane (All Pole Vectors)	6	112	5
		Base Plane (Set: I)	1	10	10

Table 5.8 presents the kinematic analysis results flexural toppling. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Jefferson sculpture. All of the slopes have a significant probability of flexural toppling with respect to the total number of principal joint set planes; however the slope along the right side of the forehead has the highest probability.

Table 5.8: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Jefferson sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Jefferson Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Flexural Toppling	Nose (Right)	Set: A	13	25	52
		Set: F	4	18	22
	Nose (Left)	Set: F	10	18	56
	Nose (Front)	Set: B	1	18	6
		Set: E	1	11	9
		Set: I	2	10	20
	Forehead (Right)	Set: A	20	25	80
		Set: E	7	11	64
	Forehead (Left)	Set: B	6	18	33
		Set: F	9	18	50
	Forehead (Center)	Set: B	9	18	50
		Set: E	4	11	36
		Set: I	2	10	20

5.1.3 Roosevelt Sculpture

The planar sliding results for Roosevelt sculpture are listed in Table 5.9. The results indicate that there is little to no risk of planar sliding along any of the slopes analyzed except for the slope along the right side of the forehead.

Table 5.10 presents the results for the wedge sliding analyses. The risk of wedge sliding exists for all of slopes analyzed on the Roosevelt sculpture. The probability of failure is lowest (10%) along the slopes on the left and front of the nose. The other slopes analyzed have higher probabilities, each at 20%.

Table 5.9: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Roosevelt Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Planar Sliding	Nose (Right)	NA	0	NA	0
	Nose (Left)	NA	0	NA	0
	Nose (Front)	Set I:	1	10	10
	Forehead (Right)	Set: A	1	25	4
		Set : I	3	10	30
	Forehead (Left)	NA	0	NA	0
	Forehead (Center)	Set: I	1	10	10

Table 5.10: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Roosevelt Sculpture Slope	Total Critical Intersections (PJS Planes)		Total Number of Intersections (PJS Planes)	%
Wedge Sliding	Nose (Right)	Sets: I & B; I & F	2	10	20
	Nose (Left)	Sets: I & A	1	10	10
	Nose (Front)	Sets: I & A	1	10	10
	Forehead (Right)	Sets: I & B; I & F	2	10	20
	Forehead (Left)	Sets: I & A; I & F	2	10	20
	Forehead (Center)	Sets: I & A; I & F	2	10	20

Table 5.11 lists the kinematic analysis results for direct and oblique toppling. All of the slopes analyzed for the Roosevelt sculpture have a potential for direct and oblique toppling. In regards to the direct toppling results, the probability of failure is lowest (10%) for the slopes along the right and left sides of the nose, and the left side of the forehead. The potential is higher for the slope along the center of the forehead, which has a probability of failure of 20%. The slopes along the front of the sculpture’s nose and right side of the forehead have the highest probabilities of direct toppling failure with respect to the total number of intersections for the PJS (40% and 50% respectively).

The oblique toppling results show that the probability of failure is lowest (10%) for the

Table 5.11: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Roosevelt Sculpture Slope	Total Critical Intersections (PJS Planes) & Base Plane Pole Vectors		Total Intersections (PJS Planes) & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: PJS Planes (Intersections)	1	10	10
		Oblique Toppling: PJS Planes (Intersections)	6	10	60
		Base Plane (All Pole Vectors)	11	112	10
		Base Plane (Set: A)	1	25	4
	Nose (Left)	Direct Toppling: PJS Planes (Intersections)	1	10	10
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	11	112	10
		Base Plane (Set: A)	1	25	4
	Nose (Front)	Direct Toppling: PJS Planes (Intersections)	4	10	40
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	6	112	5
		Base Plane (Set: I)	1	10	10
	Forehead (Right)	Direct Toppling: PJS Planes (Intersections)	5	10	50
		Oblique Toppling: PJS Planes (Intersections)	1	10	10
		Base Plane (All Pole Vectors)	15	112	13
		Base Plane (Set: A)	1	25	4
		Base Plane (Set: I)	6	10	60
	Forehead (Left)	Direct Toppling: PJS Planes (Intersections)	1	10	10
		Oblique Toppling: PJS Planes (Intersections)	6	10	60
		Base Plane (All Pole Vectors)	10	112	9
		Base Plane (Set: F)	2	18	11
	Forehead (Center)	Direct Toppling: PJS Planes (Intersections)	2	10	20
		Oblique Toppling: PJS Planes (Intersections)	5	10	50
		Base Plane (All Pole Vectors)	8	112	7
		Base Plane (Set: I)	2	10	20

slope along the right side of the forehead. The other slopes show higher probabilities, with the slopes along left side and the front of the nose having probabilities of 20%, and the slopes along the right side of the nose, the left side of the forehead, and the central slope of the forehead having probabilities of 60%, 60%, and 50%, respectively. All of the analyses for each of the slopes indicate that there are joints that may act as sliding or release planes (base planes) for the blocks.

Table 5.12 presents the kinematic analysis results flexural toppling. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Roosevelt sculpture. All of the slopes have a significant probability of flexural toppling with respect to the total number of principal joint set planes; however the slope along the right side of the nose, and all of the slopes on the forehead have the highest probabilities.

Table 5.12: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Roosevelt sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Roosevelt Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Flexural Toppling	Nose (Right)	Set: A	13	25	52
		Set: E	10	11	91
		Set: I	1	10	10
	Nose (Left)	Set: A	2	25	8
		Set: F	10	18	56
	Nose (Front)	Set: B	11	18	61
		Set: E	6	11	55
		Set: I	2	10	20
	Forehead (Right)	Set: A	17	25	68
		Set: E	11	11	100
		Set: I	1	10	10
	Forehead (Left)	Set: B	15	18	83
		Set: E	3	11	27
		Set: I	2	10	20
	Forehead (Center)	Set: B	15	18	83
		Set: E	3	11	27
		Set: I	2	10	20

5.1.4 Lincoln Sculpture

Table 5.13 presents the planar sliding results for Lincoln sculpture. The results indicate that there is no potential for planar sliding along the slopes on the left or front of the nose, or on the center of the forehead. The other slopes have a potential for planar sliding, with the left side of the forehead having the highest probability (40%) of planar sliding.

Table 5.14 presents the results for the wedge sliding analyses. The potential for wedge sliding exists for all of slopes analyzed on the Lincoln sculpture. The slope along the front of the nose has the lowest probability (10%) of wedge sliding, while the rest of the slopes have a probability of 20%.

Table 5.15 shows the kinematic analysis results for direct and oblique toppling. All of the slopes analyzed for the Lincoln sculpture have a potential for direct and oblique toppling. The slope along the left side of the nose has the lowest probability (10%) of direct toppling failure. The slopes along the right side of the nose and forehead have higher probability (20%), and the slopes along the front of the sculpture's nose, the left side of the forehead, and the central slope of the forehead have the highest probabilities of direct toppling failure (40%, 50%, and 40% respectively) with respect to the total number of intersections for the PJS.

The oblique toppling results show that the probability of failure with respect to the total number of intersections for the PJS is lowest (10%) along the slope on the left side of the forehead. The slopes along the right side and front of the nose, as well as the right side of the forehead have higher probabilities (20%). The probability of failure for oblique toppling along the slopes on the left side of the nose and the central slope on the forehead have the highest probabilities of failure (60% and 30% respectively) with respect to the total number of intersections for the PJS.

Table 5.13: Kinematic analysis results (considering principal joint set (PJS) planes) for planar sliding on the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Lincoln Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Planar Sliding	Nose (Right)	Set: F	1	18	6
		Set: B	3	18	17
	Nose (Left)	NA	0	NA	0
	Nose (Front)	NA	0	NA	0
	Forehead (Right)	Set: F	3	18	17
	Forehead (Left)	Set: I	4	10	40
	Forehead (Center)	NA	0	NA	0

Table 5.14: Kinematic analysis results for wedge sliding (considering the principal joint set (PJS) plane intersections) on the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Lincoln Sculpture Slope	Total Critical Intersections (PJS Planes)		Total Number of Intersections (PJS Planes)	%
Wedge Sliding	Nose (Right)	Sets: E & A; I & B	2	10	20
	Nose (Left)	Sets: I & A; I & F	2	10	20
	Nose (Front)	Sets: I & B	1	10	10
	Forehead (Right)	Sets: E & A; I & B	2	10	20
	Forehead (Left)	Sets: I & A; I & F	2	10	20
	Forehead (Center)	Sets: I & B; I & F	2	10	20

Table 5.15: Kinematic analysis results for direct and oblique toppling (considering the principal joint set (PJS) plane intersections) along the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS.

Kinematic Analysis	Lincoln Sculpture Slope	Total Critical Intersections (PJS Planes) & Base Plane Pole Vectors		Total Intersections (PJS Planes) & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: PJS Planes (Intersections)	2	10	20
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	18	112	16
		Base Plane (Set: B)	2	18	11
		Base Plane (Set: F)	5	18	28
	Nose (Left)	Direct Toppling: PJS Planes (Intersections)	1	10	10
		Oblique Toppling: PJS Planes (Intersections)	6	10	60
		Base Plane (All Pole Vectors)	8	112	7
		Base Plane (Set: I)	2	10	20
	Nose (Front)	Direct Toppling: PJS Planes (Intersections)	4	10	40
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	10	112	9
		Base Plane (Set: I)	2	10	20
	Forehead (Right)	Direct Toppling: PJS Planes (Intersections)	2	10	20
		Oblique Toppling: PJS Planes (Intersections)	2	10	20
		Base Plane (All Pole Vectors)	18	112	16
		Base Plane (Set: F)	3	18	17
		Base Plane (Set: B)	3	18	17
	Forehead (Left)	Direct Toppling: PJS Planes (Intersections)	5	10	50
		Oblique Toppling: PJS Planes (Intersections)	1	10	10
		Base Plane (All Pole Vectors)	12	112	11
		Base Plane (Set: I)	7	10	70
	Forehead (Center)	Direct Toppling: PJS Planes (Intersections)	4	10	40
		Oblique Toppling: PJS Planes (Intersections)	3	10	30
		Base Plane (All Pole Vectors)	13	112	12
		Base Plane (Set: A)	1	25	4
		Base Plane (Set: I)	4	10	40

All of the analyses for each of the slopes indicate that there are joints that may act as sliding or release planes (base planes) for the blocks.

Table 5.16 presents the kinematic analysis results flexural toppling. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Lincoln sculpture. All of the slopes have a significant probability of flexural toppling with respect to the total number of principal joint set planes; however the slopes along the left side and front of the nose, as well as the left side and central slope on the forehead have the highest probabilities.

Table 5.16: Kinematic analysis results for flexural toppling (considering the principal joint set (PJS) planes) along the slopes of the Lincoln sculpture at MORU. “Set” refers to the PJS (the planes are plotted as pole vectors on the stereonet).

Kinematic Analysis	Lincoln Sculpture Slope	Critical PJS Pole Vectors		Total Number of Pole Vectors in the Set	%
Flexural Toppling	Nose (Right)	Set: B	1	18	6
		Set: F	6	18	33
	Nose (Left)	Set: B	15	18	83
		Set: E	2	11	18
		Set: I	1	10	10
	Nose (Front)	Set: A	20	25	80
		Set: E	7	11	64
	Forehead (Right)	Set: F	8	18	44
	Forehead (Left)	Set: B	11	18	61
		Set: E	9	11	82
		Set: I	2	10	20
	Forehead (Center)	Set: A	20	25	80
		Set: E	7	11	64

5.2 Kinematic Analysis Considering All Discontinuity Planes and Intersections

The kinematic analyses were also completed considering all of the discontinuity orientation data, as opposed to considering only the principal joint sets (PJS). Input parameters

for the analyses included all of the discontinuity orientation data (plotted as pole vectors), the slope orientations determined from the LiDAR, and the modified basic angle of friction.

The kinematic analysis results for foreheads and noses of the MORU sculptures are listed in Tables 5.17-5.32. The results for the planar sliding and flexural toppling kinematic analyses are presented as a percentage of all poles in the file. The results for the wedge sliding and direct/oblique toppling kinematic analyses are presented as a percentage of all intersections. The resulting percentages are an estimate of the probability of failure with respect to all of the planes in the file (in the case of planar sliding or flexural toppling), or the total number of intersections between the planes (in the case of wedge sliding or direct/oblique toppling) (Rocscience, 2016c). The stereonet plots for planar sliding and flexural toppling are the same as presented in Figures 5.1-5.6 and 5.19-5.24 (for the Washington sculpture) and in Appendix I (for the Jefferson, Roosevelt, and Lincoln sculptures). The stereonet plots for the wedge sliding and direct toppling analyses for the Washington sculpture are presented in Figures 5.25-5.36, while the stereonet plots for the other three sculptures can be found in Appendix J. The results of the kinematic analysis indicate that the potential for planar sliding, wedge sliding, and toppling failure exists for each of the MORU sculptures, but the potential varies for each of the slopes analyzed on the individual sculptures.

5.2.1 Washington Sculpture

Table 5.17 presents the results of planar sliding for the Washington sculpture. The results indicate that there is a potential for planar sliding along all of the slopes except along the left side of the nose. The probability of planar sliding is low, ranging from 0% - 7%.

Table 5.17: Kinematic analysis results for planar sliding on the slopes of the Washington sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Washington Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Planar Sliding	Nose (Right)	All Poles	6	112	5
	Nose (Left)	All Poles	0	112	0
	Nose (Front)	All Poles	1	112	1
	Forehead (Right)	All Poles	8	112	7
	Forehead (Left)	All Poles	1	112	1
	Forehead (Center)	All Poles	2	112	2

The stereonet plots of the kinematic analyses for evaluating the potential for wedge sliding are shown in Figures 5.25-5.30. Table 5.18 presents the results of wedge sliding for the Washington sculpture. The results indicate that all of the slopes analyzed have the potential for wedge sliding. The right sides of the nose and forehead have the highest (22% and 17%, respectively) probability of wedge sliding.

The stereonet plots of the kinematic analyses for evaluating the potential for direct and oblique toppling are provided in Figures 5.31-5.36. The results are summarized in Table 5.19. The results indicate that all of the slopes analyzed have the potential for both types of toppling failures. The slopes along the left side of the nose, the front of the nose, the left side of the forehead, and the center of the forehead have the highest (21%) probability of direct toppling. All of the slopes on the sculpture have similar oblique toppling probabilities ranging from 18%-22%; however the slopes along the left side of the nose and forehead have the highest (22%) probability.

The flexural toppling results are summarized in Table 5.20. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Washington sculpture. The slopes on the left side of the nose, front of the nose, left side of the forehead, and the central slope on the forehead have the highest probabilities (15%, 24%, 16%, and 21%, respectively) of failure with respect to all of the planes in the file.

Figure 5.25: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 22% with respect to the total number of intersections.

Figure 5.26: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 12% with respect to the total number of intersections.

Figure 5.27: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope on Washington's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 7% with respect to the total number of intersections.

Figure 5.28: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 17% with respect to the total number of intersections.

Figure 5.29: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Washington's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections.

Figure 5.30: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Washington's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 8% with respect to the total number of intersections.

Table 5.18: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Washington sculpture at MORU. "All Planes" indicates all planes in the file.

Kinematic Analysis	Washington Sculpture Slope	Total Critical Intersections		Total Number of Intersections	%
Wedge Sliding	Nose (Right)	All Planes	1375	6216	22
	Nose (Left)	All Planes	756	6216	12
	Nose (Front)	All Planes	462	6216	7
	Forehead (Right)	All Planes	1068	6216	17
	Forehead (Left)	All Planes	804	6216	13
	Forehead (Center)	All Planes	474	6216	8

Figure 5.31: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's nose. There is a 14% probability of direct toppling and an 18% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.32: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's nose. There is a 21% probability of direct toppling and 22% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.33: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Washington's nose. There is a 21% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.34: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's forehead. There is an 11% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.35: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Washington's forehead. There is a 21% probability of direct toppling and 22% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure 5.36: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Washington's forehead. There is a 21% probability of direct toppling and 19% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Table 5.19: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Washington sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.3.

Kinematic Analysis	Washington Sculpture Slope	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: All Planes (Intersections)	893	6216	14
		Oblique Toppling: All Planes (Intersections)	1091	6216	18
	Nose (Left)	Direct Toppling: All Planes (Intersections)	1279	6216	21
		Oblique Toppling: All Planes (Intersections)	1357	6216	22
	Nose (Front)	Direct Toppling: All Planes (Intersections)	1304	6216	21
		Oblique Toppling: All Planes (Intersections)	1237	6216	20
	Forehead (Right)	Direct Toppling: All Planes (Intersections)	712	6216	11
		Oblique Toppling: All Planes (Intersections)	1251	6216	20
	Forehead (Left)	Direct Toppling: All Planes (Intersections)	1321	6216	21
		Oblique Toppling: All Planes (Intersections)	1401	6216	22
	Forehead (Center)	Direct Toppling: All Planes (Intersections)	1327	6216	21
		Oblique Toppling: All Planes (Intersections)	1205	6216	19

Table 5.20: Kinematic analysis results for flexural toppling along the slopes of the Washington sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Washington Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Flexural Toppling	Nose (Right)	All Poles	13	112	12
	Nose (Left)	All Poles	17	112	15
	Nose (Front)	All Poles	27	112	24
	Forehead (Right)	All Poles	18	112	16
	Forehead (Left)	All Poles	16	112	14
	Forehead (Center)	All Poles	24	112	21

5.2.2 Jefferson Sculpture

Table 5.21 presents the results of planar sliding for the Jefferson sculpture. The results indicate that there is a potential for planar sliding along all of the slopes except along the front of the nose and the right side of the forehead. The probability of planar sliding is very low, ranging from 0% - 4%.

Table 5.22 presents the results of wedge sliding for the Jefferson sculpture. The results indicate that all of the slopes analyzed have the potential for wedge sliding, however the potential is low. The slopes along the right side of the nose and the left side of the nose have the highest (14% and 13%, respectively) probability of wedge sliding.

The direct and oblique toppling results are listed in Table 5.23. The results indicate that all of the slopes analyzed have the potential for both types of toppling failures. The slopes along the right side of the forehead and the center of the forehead have the highest (19% and 17%, respectively) probability of direct toppling. All of the slopes have probabilities of oblique toppling between 18% - 21%, with the right side of the forehead having the highest probability.

The flexural toppling results are summarized in Table 5.24. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Jefferson sculpture. The slope

along the front of the nose has the lowest probability of failure (4%), whereas the slopes on the right sides of the nose and forehead have the highest probabilities (18 and 24%, respectively).

Table 5.21: Kinematic analysis results for planar sliding on the slopes of the Jefferson sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Jefferson Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Planar Sliding	Nose (Right)	All Poles	3	112	3
	Nose (Left)	All Poles	4	112	4
	Nose (Front)	All Poles	0	112	0
	Forehead (Right)	All Poles	0	112	0
	Forehead (Left)	All Poles	3	112	3
	Forehead (Center)	All Poles	1	112	1

Table 5.22: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Jefferson sculpture at MORU. “All Planes” indicates all planes in the file.

Kinematic Analysis	Jefferson Sculpture Slope	Total Critical Intersections		Total Number of Intersections	%
Wedge Sliding	Nose (Right)	All Planes	895	6216	14
	Nose (Left)	All Planes	823	6216	13
	Nose (Front)	All Planes	2	6216	0.03
	Forehead (Right)	All Planes	376	6216	6
	Forehead (Left)	All Planes	575	6216	9
	Forehead (Center)	All Planes	202	6216	3

Table 5.23: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Jefferson sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.7.

Kinematic Analysis	Jefferson Sculpture Slope	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: All Planes (Intersections)	805	6216	13
		Oblique Toppling: All Planes (Intersections)	1263	6216	20
	Nose (Left)	Direct Toppling: All Planes (Intersections)	757	6216	12
		Oblique Toppling: All Planes (Intersections)	1128	6216	18
	Nose (Front)	Direct Toppling: All Planes (Intersections)	860	6216	14
		Oblique Toppling: All Planes (Intersections)	1237	6216	20
	Forehead (Right)	Direct Toppling: All Planes (Intersections)	1165	6216	19
		Oblique Toppling: All Planes (Intersections)	1281	6216	21
	Forehead (Left)	Direct Toppling: All Planes (Intersections)	873	6216	14
		Oblique Toppling: All Planes (Intersections)	1179	6216	19
	Forehead (Center)	Direct Toppling: All Planes (Intersections)	1073	6216	17
		Oblique Toppling: All Planes (Intersections)	1246	6216	20

Table 5.24: Kinematic analysis results for flexural toppling along the slopes of the Jefferson sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Jefferson Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Flexural Toppling	Nose (Right)	All Poles	20	112	18
	Nose (Left)	All Poles	15	112	13
	Nose (Front)	All Poles	4	112	4
	Forehead (Right)	All Poles	27	112	24
	Forehead (Left)	All Poles	16	112	14
	Forehead (Center)	All Poles	15	112	13

5.2.3 Roosevelt Sculpture

The planar sliding results for Roosevelt sculpture are listed in Table 5.25. The results indicate the probability of planar sliding is very low, ranging from 0% - 4%.

Table 5.26 presents the results of wedge sliding for the Roosevelt sculpture. The results indicate that all of the slopes analyzed have the potential for wedge sliding. The probability of wedge sliding ranges from 6% - 19%, with the slope on the left side of the forehead having the highest probability.

The direct and oblique toppling results are listed in Table 5.27. The results indicate that all of the slopes analyzed have the potential for both types of toppling failures. The slope along the left side of the nose has the lowest probability (11%) of direct toppling, while all of the other slopes have similar probabilities for this type of failure ranging from 17%-23%. The slope along the center of the forehead has the highest (23%) probability of direct toppling. All of the slopes have similar probabilities of oblique toppling ranging from 16%-22%. The slope along the left side of the forehead has the highest (22%) probability of oblique toppling.

The flexural toppling results are summarized in Table 5.28. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Roosevelt sculpture. The slope along the left side of the nose has the lowest probability (14%) of flexural toppling with respect to all of the planes in the file. The slope on the right side of the nose, and the right, left and central slopes on the forehead have the highest probabilities (21%, 27%, 20%, and 18%, respectively).

Table 5.25: Kinematic analysis results for planar sliding on the slopes of the Roosevelt sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Roosevelt Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Planar Sliding	Nose (Right)	All Poles	0	112	0
	Nose (Left)	All Poles	3	112	3
	Nose (Front)	All Poles	1	112	1
	Forehead (Right)	All Poles	4	112	4
	Forehead (Left)	All Poles	1	112	1
	Forehead (Center)	All Poles	1	112	1

Table 5.26: Kinematic analysis results for wedge sliding (considering all intersections) on the slopes of the Roosevelt sculpture at MORU. “All Planes” indicates all planes in the file.

Kinematic Analysis	Roosevelt Sculpture Slope	Total Critical Intersections		Total Number of Intersections	%
Wedge Sliding	Nose (Right)	All Planes	711	6216	11
	Nose (Left)	All Planes	677	6216	11
	Nose (Front)	All Planes	364	6216	6
	Forehead (Right)	All Planes	854	6216	14
	Forehead (Left)	All Planes	1157	6216	19
	Forehead (Center)	All Planes	778	6216	13

Table 5.27: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Roosevelt sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.11.

Kinematic Analysis	Roosevelt Sculpture Slope	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: All Planes (Intersections)	1074	6216	17
		Oblique Toppling: All Planes (Intersections)	1300	6216	21
	Nose (Left)	Direct Toppling: All Planes (Intersections)	689	6216	11
		Oblique Toppling: All Planes (Intersections)	1022	6216	16
	Nose (Front)	Direct Toppling: All Planes (Intersections)	1260	6216	20
		Oblique Toppling: All Planes (Intersections)	1210	6216	19
	Forehead (Right)	Direct Toppling: All Planes (Intersections)	1351	6216	22
		Oblique Toppling: All Planes (Intersections)	1248	6216	20
	Forehead (Left)	Direct Toppling: All Planes (Intersections)	1286	6216	21
		Oblique Toppling: All Planes (Intersections)	1337	6216	22
	Forehead (Center)	Direct Toppling: All Planes (Intersections)	1413	6216	23
		Oblique Toppling: All Planes (Intersections)	1317	6216	21

Table 5.28: Kinematic analysis results for flexural toppling along the slopes of the Roosevelt sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Roosevelt Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Flexural Toppling	Nose (Right)	All Poles	24	112	21
	Nose (Left)	All Poles	16	112	14
	Nose (Front)	All Poles	19	112	17
	Forehead (Right)	All Poles	30	112	27
	Forehead (Left)	All Poles	22	112	20
	Forehead (Center)	All Poles	20	112	18

5.2.4 Lincoln Sculpture

Table 5.29 presents the planar sliding results for Lincoln sculpture. The results indicate the probability of planar sliding is low, ranging from 0% - 6%. The slopes which have a potential of planar sliding are the right side of the nose, the right side of the forehead, and the left side of the forehead.

Table 5.30 presents the results of wedge sliding for the Lincoln sculpture. The results indicate that all of the slopes analyzed have the potential for wedge sliding. The probability of wedge sliding ranges from 7% - 28%, with the slopes on the right side of the nose and the right side of the forehead having the highest probability (27% and 28%, respectively).

The direct and oblique toppling results are listed in Table 5.31. The results indicate that all of the slopes analyzed have the potential for both types of toppling failures. The slopes along the left side of the nose, front of the nose, left side of the forehead, and center of the forehead have the highest probabilities (23%, 19%, 23%, and 20%, respectively) of direct toppling. All of the slopes have similar probabilities of oblique toppling ranging from 17%-21%. The slopes along the left side of the nose, front of the nose, and the center of the forehead have the highest (21%) probabilities of oblique toppling.

The flexural toppling results are summarized in Table 5.32. The results indicate there is a potential for flexural toppling on all of the slopes analyzed for the Lincoln sculpture. The slope along the right side of the nose has the lowest probability of failure (9%) with respect to all of the planes in the file. The left and right sides of the nose, and the left and central slopes on the forehead have the highest probabilities (17%, 24%, 20%, and 25%, respectively).

In general, the kinematic analyses based on the PJS planes and based on all of the discontinuity planes show similar results where certain types of failures are more likely to occur on the sculptures. The differences between the kinematic analyses are likely due to the scatter between the discontinuity data on the stereonet.

Table 5.29: Kinematic analyses results for planar sliding on the slopes of the Lincoln sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Lincoln Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Planar Sliding	Nose (Right)	All Poles	7	112	6
	Nose (Left)	All Poles	0	112	0
	Nose (Front)	All Poles	0	112	0
	Forehead (Right)	All Poles	7	112	6
	Forehead (Left)	All Poles	4	112	4
	Forehead (Center)	All Poles	0	112	0

Table 5.30: Kinematic analyses results for wedge sliding (considering all intersections) on the slopes of the Lincoln sculpture at MORU. “All Planes” indicates all planes in the file.

Kinematic Analysis	Lincoln Sculpture Slope	Total Critical Intersections		Total Number of Intersections	%
Wedge Sliding	Nose (Right)	All Planes	1679	6216	27
	Nose (Left)	All Planes	829	6216	13
	Nose (Front)	All Planes	427	6216	7
	Forehead (Right)	All Planes	1725	6216	28
	Forehead (Left)	All Planes	830	6216	13
	Forehead (Center)	All Planes	707	6216	11

Table 5.31: Kinematic analysis results for direct and oblique toppling (considering all intersections) along the slopes of the Lincoln sculpture at MORU. “All Planes” indicates all planes in the file. The base planes are not listed, but are the same as in Table 5.15.

Kinematic Analysis	Lincoln Sculpture Slope	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Nose (Right)	Direct Toppling: All Planes (Intersections)	842	6216	14
		Oblique Toppling: All Planes (Intersections)	1079	6216	17
	Nose (Left)	Direct Toppling: All Planes (Intersections)	1415	6216	23
		Oblique Toppling: All Planes (Intersections)	1333	6216	21
	Nose (Front)	Direct Toppling: All Planes (Intersections)	1192	6216	19
		Oblique Toppling: All Planes (Intersections)	1281	6216	21
	Forehead (Right)	Direct Toppling: All Planes (Intersections)	933	6216	15
		Oblique Toppling: All Planes (Intersections)	1096	6216	18
	Forehead (Left)	Direct Toppling: All Planes (Intersections)	1456	6216	23
		Oblique Toppling: All Planes (Intersections)	1246	6216	20
	Forehead (Center)	Direct Toppling: All Planes (Intersections)	1223	6216	20
		Oblique Toppling: All Planes (Intersections)	1285	6216	21

Table 5.32: Kinematic analysis results for flexural toppling along the slopes of the Lincoln sculpture at MORU. “All Poles” indicates all planes (plotted as pole vectors on the stereonet) in the file.

Kinematic Analysis	Lincoln Sculpture Slope	Critical Pole Vectors		Total Number of Pole Vectors	%
Flexural Toppling	Nose (Right)	All Poles	10	112	9
	Nose (Left)	All Poles	19	112	17
	Nose (Front)	All Poles	27	112	24
	Forehead (Right)	All Poles	12	112	11
	Forehead (Left)	All Poles	22	112	20
	Forehead (Center)	All Poles	28	112	25

5.3 Factor of Safety Calculations of the Potential Failures Considering the Principal Joint Set Planes and Intersections

The factor of safety (FS) against planar sliding for the slopes on each of the sculptures with the potential for this type of failure were calculated using the Rocscience program RocPlane (Rocscience, 2016f). The factor of safety (FS) against wedge sliding for the slopes on each of the sculptures with the potential for this type of failure were calculated using the Rocscience program Swedge (Rocscience, 2016g).

5.3.1 Washington Sculpture

Factor of safety (FS) values against planar sliding for the poles of the principal joint sets falling in the critical region range from 0.3-0.4 (Table 5.33). FS values against wedge sliding for the critical intersections of the principal joint sets range from 0.2-1.3 (Table 5.34). There is only one potential wedge failure that has a $FS < 1$ and it is on the slope on the left side of Washington's forehead.

Table 5.33: Factor of safety (FS) against planar sliding along the slopes of the Washington sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Set	Critical Plane Dip (degrees)	Slope Face Dip (degrees)	Upper Slope Dip (degrees)	FS
Planar Sliding (Considering only Principal Joint Sets)	Nose (Right)	Yes	F	71	80	57	0.3
	Nose (Right)	Yes	F	73	80	57	0.3
	Nose (Left)	No	NA	NA	78	57	NA
	Nose (Front)	Yes	I	67	72	57	0.4
	Forehead (Right)	Yes	F	71	76	5	0.3
	Forehead (Left)	No	NA	NA	79	5	NA
	Forehead (Center)	Yes	I	67	72	5	0.4
	Forehead (Center)	Yes	I	68	72	5	0.3

Table 5.34: Factor of safety (FS) against wedge sliding along the slopes of the Washington sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Sets (Critical Planes 1 & 2)	Critical Plane 1 Dip/Dip Direction (degrees)	Critical Plane 2 Dip/Dip Direction (degrees)	Upper Slope Dip/Dip Direction (degrees)	FS
Washington Wedge Sliding	Nose (Right)	Yes	I & B	74/116	82/256	57/139	1.3
	Nose (Right)	Yes	E & A	71/302	83/337	57/139	1.0
	Nose (Left)	Yes	I & A	74/116	83/337	57/139	1.2
	Nose (Front)	Yes	I & B	74/116	82/256	57/139	1.3
	Forehead (Right)	Yes	I & B	74/116	82/256	5/136	1.3
	Forehead (Left)	Yes	I & A	74/116	83/337	5/136	1.2
	Forehead (Left)	Yes	I & F	74/116	89/029	5/136	0.2
	Forehead (Center)	Yes	I & B	74/116	82/256	5/136	1.3

5.3.2 Jefferson Sculpture

The FS against planar sliding for the Jefferson sculpture is 0.8, as listed in Table 5.35. FS values against wedge sliding for the critical intersections of the principal joint set planes range from 1.2-1.3 (Table 5.36).

5.3.3 Roosevelt Sculpture

The FS values against planar sliding for the critical poles of the principal joint sets range from 0.2-0.8 (Table 5.37). FS values against wedge sliding for the critical intersections of the principal joint sets range from 0.2-1.3 (Table 5.38). The values less than one are along the slopes on the right side of the nose and forehead, and on the left and center of the forehead.

Table 5.35: Factor of safety (FS) against planar sliding along the slopes of the Jefferson sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Set	Critical Plane Dip (degrees)	Slope Face Dip (degrees)	Upper Slope Dip (degrees)	FS
Jefferson Planar Sliding (Considering only Principal Joint Sets)	Nose (Right)	No	NA	NA	75	36	NA
	Nose (Left)	No	NA	NA	72	36	NA
	Nose (Front)	No	NA	NA	43	36	NA
	Forehead (Right)	No	NA	NA	69	5	NA
	Forehead (Left)	No	NA	NA	68	5	NA
	Forehead (Center)	Yes	I	48	59	5	0.8

Table 5.36: Factor of safety (FS) against wedge sliding along the slopes of the Jefferson sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Sets (Critical Planes 1 & 2)	Critical Plane 1 Dip/Dip Direction (degrees)	Critical Plane 2 Dip/Dip Direction (degrees)	Upper Slope Dip/Dip Direction (degrees)	FS
Jefferson Wedge Sliding	Nose (Right)	Yes	I & B	74/116	82/256	36/098	1.3
	Nose (Left)	Yes	I & A	74/116	83/337	36/098	1.2
	Nose (Front)	No	NA	NA	NA	36/098	NA
	Forehead (Right)	Yes	I & B	74/116	82/256	5/099	1.3
	Forehead (Left)	Yes	I & A	74/116	83/337	5/099	1.2
	Forehead (Center)	No	NA	NA	NA	5/099	NA

Table 5.37: Factor of safety (FS) against planar sliding along the slopes of the Roosevelt sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Set	Critical Plane Dip (degrees)	Slope Face Dip (degrees)	Upper Slope Dip (degrees)	FS
Roosevelt Planar Sliding (Considering only Principal Joint Sets)	Nose (Right)	No	NA	NA	78	45	NA
	Nose (Left)	No	NA	NA	68	45	NA
	Nose (Front)	Yes	I	48	66	45	0.8
	Forehead (Right)	Yes	A	67	80	11	0.4
	Forehead (Right)	Yes	I	74	80	11	0.2
	Forehead (Right)	Yes	I	77	80	11	0.2
	Forehead (Right)	Yes	I	78	80	11	0.2
	Forehead (Left)	No	NA	NA	84	11	NA
	Forehead (Center)	Yes	I	73	79	11	0.3

Table 5.38: Factor of safety (FS) against wedge sliding along the slopes of the Roosevelt sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Sets (Critical Planes 1 & 2)	Critical Plane 1 Dip/Dip Direction (degrees)	Critical Plane 2 Dip/Dip Direction (degrees)	Upper Slope Dip/Dip Direction (degrees)	FS
Roosevelt Wedge Sliding	Nose (Right)	Yes	I & B	74/116	82/256	45/094	1.3
	Nose (Right)	Yes	I & F	74/116	89/029	45/094	0.2
	Nose (Left)	Yes	I & A	74/116	83/337	45/094	1.2
	Nose (Front)	Yes	I & A	74/116	83/337	45/094	1.2
	Forehead (Right)	Yes	I & B	74/116	82/256	11/083	1.3
	Forehead (Right)	Yes	I & F	74/116	89/029	11/083	0.2
	Forehead (Left)	Yes	I & A	74/116	83/337	11/083	1.2
	Forehead (Left)	Yes	I & F	74/116	89/029	11/083	0.2
	Forehead (Center)	Yes	I & A	74/116	83/337	11/083	1.2
	Forehead (Center)	Yes	I & F	74/116	89/029	11/083	0.2

5.3.4 Lincoln Sculpture

The FS values against planar sliding for the critical poles of the principal joint sets range from 0.1-0.8 (Table 5.39). FS values against wedge sliding for the critical intersections of the principal joint sets range from 0.2-1.3 (Table 5.40). The values less than one were along the slopes on the left side of the nose and forehead, and on the center of the forehead.

Table 5.39: Factor of safety (FS) against planar sliding along the slopes of the Lincoln sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Set	Critical Plane Dip (degrees)	Slope Face Dip (degrees)	Upper Slope Dip (degrees)	FS
Lincoln Planar Sliding (Considering only Principal Joint Sets)	Nose (Right)	Yes	B	68	82	61	0.3
	Nose (Right)	Yes	B	73	82	61	0.3
	Nose (Right)	Yes	B	76	82	61	0.2
	Nose (Right)	Yes	F	78	82	61	0.2
	Nose (Left)	No	NA	NA	80	61	NA
	Nose (Front)	No	NA	NA	71	61	NA
	Forehead (Right)	Yes	F	71	84	13	0.3
	Forehead (Right)	Yes	F	73	84	13	0.3
	Forehead (Right)	Yes	F	83	84	13	0.1
	Forehead (Left)	Yes	I	48	78	13	0.8
	Forehead (Left)	Yes	I	68	78	13	0.3
	Forehead (Left)	Yes	I	72	78	13	0.3
	Forehead (Left)	Yes	I	73	78	13	0.3
	Forehead (Center)	No	NA	NA	78	13	NA

Table 5.40: Factor of safety (FS) against wedge sliding along the slopes of the Lincoln sculpture.

	Slope Analyzed	Sliding Potential	Principal Joint Sets (Critical Planes 1 & 2)	Critical Plane 1 Dip/Dip Direction (degrees)	Critical Plane 2 Dip/Dip Direction (degrees)	Upper Slope Dip/Dip Direction (degrees)	FS
Lincoln Wedge Sliding	Nose (Right)	Yes	E & A	71/302	83/337	61/145	1.0
	Nose (Right)	Yes	I & B	74/116	82/256	61/145	1.3
	Nose (Left)	Yes	I & A	74/116	83/337	61/145	1.2
	Nose (Left)	Yes	I & F	74/116	89/029	61/145	0.2
	Nose (Front)	Yes	I & B	74/116	82/256	61/145	1.3
	Forehead (Right)	Yes	E & A	71/302	83/337	13/146	1.0
	Forehead (Right)	Yes	I & B	74/116	82/256	13/146	1.3
	Forehead (Left)	Yes	I & A	74/116	83/337	13/146	1.2
	Forehead (Left)	Yes	I & F	74/116	89/029	13/146	0.2
	Forehead (Center)	Yes	I & B	74/116	82/256	13/146	1.3
	Forehead (Center)	Yes	I & F	74/116	89/029	13/146	0.2

5.3.5 Sensitivity Analyses for the Factor of Safety (FS) against Planar Sliding (When $FS < 1$)

The sensitivity analyses for the slopes with a $FS < 1$ were completed using the Rocscience (2016f) program RocPlane. The FS values were calculated considering the principal joint set planes. The input data for the calculations are listed in Table 5.41.

Table 5.41: Input data for the factor of safety calculations against planar sliding (considering the PJS planes). The numbers in the slope column are for reference and use in Table 5.42.

Sculpture	Slope	Principal Joint Set	Critical Plane Dip (degrees)	Slope Face Dip (degrees)	Upper Slope Dip (degrees)	Slope Height (ft)
Washington	Nose (Right)-1	F	73	80	57	13
	Nose (Right)-2	F	71	80	57	13
	Nose (Front)-1	I	67	72	57	13
	Forehead (Right)-1	F	71	76	5	23
	Forehead (Center)-1	I	67	72	5	23
	Forehead (Center)-2	I	68	72	5	23
Jefferson	Forehead (Center)-1	I	48	59	5	22
Roosevelt	Nose (Front)-1	I	48	66	45	7
	Forehead (Right)-1	A	67	80	11	18
	Forehead (Right)-2	I	74	80	11	18
	Forehead (Right)-3	I	77	80	11	18
	Forehead (Right)-4	I	78	80	11	18
	Forehead (Center)-1	I	73	79	11	18
Lincoln	Nose (Right)-1	B	68	82	61	14
	Nose (Right)-2	B	73	82	61	14
	Nose (Right)-3	B	76	82	61	14
	Nose (Right)-4	F	78	82	61	14
	Forehead (Right)-1	F	71	84	13	35
	Forehead (Right)-2	F	73	84	13	35
	Forehead (Right)-3	F	83	84	13	35
	Forehead (Left)-1	I	48	78	13	35
	Forehead (Left)-2	I	68	78	13	35
	Forehead (Left)-3	I	72	78	13	35
	Forehead (Left)-4	I	73	78	13	35

Table 5.42 lists the sensitivity analysis results for all of the sculptures. When assuming friction values of 40°, 45°, and 50° along the discontinuities, the highest cohesion values required to increase the $FS > 1$ are 440 lb/ft² (21 kPa), 405 lb/ft² (19 kPa), 365 lb/ft² (17 kPa), respectively. A figure in Hoek and Bray (1981) provides cohesive strength (c) values obtained by back analysis of slopes. From this chart, the c values mobilized at failure for weathered granite slopes were 500 lb/ft² (24 kPa). This value is an indication that the highest c value from the sensitivity analysis is a reasonable assumption of c for the granite rock at MORU. When considering cohesion = 0, the friction values required for $FS > 1$ ranged from 49° - 84°. The majority of the friction values were very high and improbable, indicating that both cohesion and friction along the discontinuities are required for $FS > 1$.

5.3.6 Sensitivity Analyses for the Factor of Safety (FS) against Wedge Sliding (When $FS < 1$)

The sensitivity analyses for the slopes with a $FS < 1$ were completed using the Rocscience (2016g) program Swedge. The FS values were calculated considering the intersections between the principal joint set planes. Table 5.43 lists the input data for the calculations. The results for the sensitivity analyses are listed in Table 5.44. When assuming friction values of 40°, 45°, and 50° along the discontinuity planes, the highest cohesion values required to increase the $FS > 1$ are 67 lb/ft² (3.2 kPa), 63 lb/ft² (3.0 kPa), 58 lb/ft² (2.8 kPa), respectively. These are reasonable assumptions of cohesion values as they are less than 500 lb/ft² (24 kPa) referenced previously for weathered granites in Hoek and Bray (1981). When considering cohesion = 0, the friction values required for $FS > 1$ ranged from 41° - 75°. The majority of the friction values were very high and improbable, indicating that both cohesion and friction along the discontinuities are required for $FS > 1$.

Table 5.42: Factor of safety (FS) against planar sliding and sensitivity analysis results (considering the PJS planes). c = cohesion, Φ = friction. The numbers in the slope column are for reference and use in Table 5.41.

Sculpture	Slope	FS when $c = 0$ lb/ft²; $\Phi = 40^\circ$	c required for FS > 1 when $\Phi = 40^\circ$ (lb/ft²)	c required for FS > 1 when $\Phi = 45^\circ$ (lb/ft²)	c required for FS > 1 when $\Phi = 50^\circ$ (lb/ft²)	Φ requi- red for FS > 1 when $c = 0$ (degr- ees)
Washington	Nose (Right)-1	0.3	95	89	81	74
	Nose (Right)-2	0.3	115	106	96	72
	Nose (Front)-1	0.4	59	53	45	68
	Forehead (Right)-1	0.3	115	106	96	72
	Forehead (Center)-1	0.4	104	93	80	68
	Forehead (Center)-2	0.3	85	78	68	69
Jefferson	Forehead (Center)-1	0.8	76	33	0	49
Roosevelt	Nose (Front)-1	0.8	37	16	0	49
	Forehead (Right)-1	0.4	203	181	156	68
	Forehead (Right)-2	0.2	115	109	100	75
	Forehead (Right)-3	0.2	62	59	56	78
	Forehead (Right)-4	0.2	43	41	39	79
	Forehead (Center)-1	0.3	113	105	96	74
Lincoln	Nose (Right)-1	0.3	174	157	137	69
	Nose (Right)-2	0.3	130	121	112	74
	Nose (Right)-3	0.2	94	89	84	77
	Nose (Right)-4	0.2	66	63	60	79
	Forehead (Right)-1	0.3	440	405	365	72
	Forehead (Right)-2	0.3	392	367	340	74
	Forehead (Right)-3	0.1	45	44	43	84
	Forehead (Left)-1	0.8	280	124	0	49
	Forehead (Left)-2	0.3	317	285	246	69
	Forehead (Left)-3	0.3	214	199	180	73
	Forehead (Left)-4	0.3	184	171	158	74

Table 5.43: Input data (excluding slope orientation) for the factor of safety calculations against wedge sliding (considering the PJS intersections).

Sculpture	Slope Analyzed	Principal Joint Sets (Critical Planes 1 & 2)	Critical Plane 1 Dip/Dip Direction (degrees)	Critical Plane 2 Dip/Dip Direction (degrees)	Upper Slope Dip/Dip Direction (degrees)	Slope Height (ft)
Washington	Nose (Right)	E & A	71/302	83/337	57/139	13
	Forehead (Left)	I & F	74/116	89/029	5/136	23
Roosevelt	Nose (Right)	I & F	74/116	89/029	45/094	7
	Forehead (Right)	I & F	74/116	89/029	11/083	18
	Forehead (Left)	I & F	74/116	89/029	11/083	18
	Forehead (Center)	I & F	74/116	89/029	11/083	18
Lincoln	Nose (Right)	E & A	71/302	83/337	61/145	14
	Nose (Left)	I & F	74/116	89/029	61/145	14
	Forehead (Right)	E & A	71/302	83/337	13/146	35
	Forehead (Left)	I & F	74/116	89/029	13/146	35
	Forehead (Center)	I & F	74/116	89/029	13/146	35

Table 5.44: Factor of safety (FS) against wedge sliding and sensitivity analysis results (considering the PJS intersections). c = cohesion, Φ = friction.

Sculpture	Slope	Wedge Contact	FS when $c = 0$ lb/ft²; $\Phi = 40^\circ$	c required for FS > 1 when $\Phi = 40^\circ$ (lb/ft²)	c required for FS > 1 when $\Phi = 45^\circ$ (lb/ft²)	c required for FS > 1 when $\Phi = 50^\circ$ (lb/ft²)	Φ required for FS > 1 when $c = 0$ (degrees)
Washington	Nose (Right)	Both Planes	1	1	0	0	41
	Forehead (Left)	Both Planes	0.2	5	5	4	74
Roosevelt	Nose (Right)	Plane 1 only	0.2	2	2	2	75
	Forehead (Right)	Plane 1 only	0.2	61	57	53	75
	Forehead (Left)	Both Planes	0.2	34	32	30	74
	Forehead (Center)	Both Planes	0.2	25	24	22	74
Lincoln	Nose (Right)	Both Planes	1	2	0	0	41
	Nose (Left)	Both Planes	0.2	19	18	17	74
	Forehead (Right)	Both Planes	1	4	0	0	41
	Forehead (Left)	Both Planes	0.2	67	63	58	74
	Forehead (Center)	Plane 1 only	0.2	53	49	46	75

5.4 Rock Block Monitoring System in Light of the Kinematic Analysis Results and Factor of Safety Values (Considering the Principal Joint Set Planes and Intersections)

Areas on the sculptures currently being monitored by the rock block monitoring system at MORU were evaluated in light of the results determined by the planar sliding and wedge sliding kinematic analyses and the factor of safety values (when considering the principal joint set planes and intersections). These results and values together have identified areas on the sculptures, where discontinuities are not currently being monitored and would benefit from further studies of the condition of the discontinuities to determine if additional areas should be monitored. The slopes of interest are listed in Table 5.45 and include the left side and center of the forehead on the Washington sculpture, as well as the right side of the nose and all slopes on the forehead of the Roosevelt sculpture.

Table 5.45: Slopes along the sculptures which had kinematic analysis results of 20% probability of failure or higher, factor of safety values less than one, and do not have any discontinuities monitored by the rock block monitoring system.

Kinematic Analysis	Sculpture	Slope
Planar	Washington	Forehead (Center)
Planar	Roosevelt	Forehead (Right)
Wedge	Washington	Forehead (Left)
Wedge	Roosevelt	Nose (Right)
Wedge	Roosevelt	Forehead (Right)
Wedge	Roosevelt	Forehead (Left)
Wedge	Roosevelt	Forehead (Center)

5.5 Overall Slope Probabilistic Analysis of the MORU Sculptures Considering both Static and Seismic Conditions

The Overall Slope Probabilistic Analyses for each of the MORU sculptures were completed using the program Slide (Rocscience, 2016h). The results of the static and seismic analyses for the entire Washington slope are included in Figures 5.37 and 5.38. The figures for the remaining three MORU sculptures can be found in Appendix K. The results of these analyses are summarized in Table 5.46.

The results in Table 5.46 include the mean factor of safety, the reliability index (RI), and the probability of failure (PF) for the overall slopes of the MORU sculptures. A rule of thumb regarding the RI is that a value greater than 3 indicates a safe slope (Rocscience, 2016l). The results show that most of the RI values were over 3; however one falls slightly below this value for the seismic condition evaluated for the Lincoln sculpture. Due to the fact that the value is so close to 3, it is considered acceptable. The other two measures of safety for the overall slopes of the MORU sculptures indicate that the slopes are safe, as all of the factor of safety values are greater than one and the PF values were all 0%.

Figure 5.37: Overall Slope Probabilistic Analysis considering the static condition for the entire slope on which the Washington sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters.

Figure 5.38: Overall Slope Probabilistic Analysis considering the seismic condition (0.14 horizontal and vertical seismic load coefficients) for the entire slope on which the Washington sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters.

Table 5.46: Results of the Overall Slope Probabilistic Analysis for the MORU sculptures. The Slide program (Rocscience, 2016h) indicates which statistical distribution best fits the factor of safety distribution for the reliability index calculations, therefore only the results for the best fit statistical distribution are listed and the other is marked as NA.

Sculpture	Mean Factor of Safety		Reliability Index				Probability of Failure (%)	
			Normal		Lognormal			
	Static	Seismic	Static	Seismic	Static	Seismic	Static	Seismic
Washington	3.3	2.6	NA	NA	6.0	4.6	0	0
Jefferson	4.5	3.6	NA	3.7	7.8	NA	0	0
Roosevelt	5.2	4.1	NA	NA	5.7	4.7	0	0
Lincoln	4.4	3.4	3.3	2.9	NA	NA	0	0

5.6 Comparison of the Results of this Study to the Results of RESPEC Study

Table 5.47 lists the principal joint sets determined using RESPEC data as compared to the principal joint sets determined by this study. The contoured stereonet of the RESPEC data can be found in Appendix L.

As Table 5.47 shows, the stereonet plots of both data sets identify principal joint sets A, B, and F. The discontinuity data from RESPEC identifies principal joint set N, which was not indicated by the data collected in this study. This joint set is nearly horizontal and, as reported by Fisher (2011), the resolution capability of LiDAR does not fully account for a surface of this orientation. Manual collection of discontinuity orientations with a Brunton compass will account for these surfaces. However, the nearly horizontal discontinuities at the sculptures site are not of concern with respect to slope instability.

Table 5.47: Principal joint sets determined using the RESPEC data [reported in the RESPEC report by Boyle and Vogt (1992)] as compared to the sets determined by the data in this study.

Granite			
Principal Joint Sets Determined for the Sculptures using RESPEC Data		Principal Joint Sets Determined for the Sculptures by This Study	
Principal Joint Set	Dip/Dip Direction	Principal Joint Set	Dip/Dip Direction
A	84°/334°	A	83°/337°
B	89°/078°	B	82°/256°
-	-	E	71°/302°
F	89°/216°	F	89°/029°
-	-	I	74°/116°
N	2°/325°	-	-

Two principal joint sets, E and I, were identified by this study, but were not identified with the RESPEC data. Principal joint set E was identified from the discontinuity orientation data collected in the field in Region 3, and set I was identified from the orientation data collected with the LiDAR. The identification of the additional principal joint sets in this study may increase the number of potential failures identified by the kinematic analyses.

In order to compare the results of this study to that by RESPEC, a kinematic analysis was conducted using the slope orientation on the right side of the forehead on the Washington sculpture as reported by RESPEC, and the principal joint sets identified from their data as well. The RESPEC slope orientation used in the analysis is listed in Table 5.48. The stereonet of the kinematic analyses are shown in Figures 5.39, 5.40, and 5.41. The results from the kinematic analysis are summarized in Tables 5.49 and 5.50. The results show that, when using RESPEC data, there is no risk for planar sliding or wedge sliding along the slope on the right side of Washington's forehead, however there is a slight risk for direct and oblique toppling. This is similar to the findings of this study which indicates that the slope on the right side of Washington's forehead has a low risk of planar sliding and wedge sliding, no risk of direct

toppling, and a significant risk of oblique toppling. Factor of safety values could not be calculated using the RESPEC data as there was not enough information available in their document to perform the required analysis. Their study did state that the block on the right side of Washington's forehead is not critical.

Sculpture	Location on Sculpture	Slope Dip/Dip Direction as Determined by RESPEC (degrees)	Slope Dip/Dip Direction as Determined by This study (degrees)
Washington	Right side of the forehead	63°/200°	76°/195°

Figure 5.39: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope of Washington's right side of the forehead. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is no probability of planar sliding along the slope on the right side of Washington's forehead.

Figure 5.40: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Washington's forehead using the intersections of the principal joint set planes. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is no risk for wedge sliding along this slope.

Figure 5.41: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Washington's forehead. This analysis was completed using the discontinuity and slopes orientation data collected by RESPEC. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Table 5.49: Kinematic analyses results for planar and wedge sliding on the right side of the forehead on the Washington sculpture using the RESPEC data and the data from this study.

Analysis	Results using RESPEC Data				Results from this Study			
	Total Critical Pole Vectors/ Intersections		Total Number of Pole Vectors/ Intersections	%	Total Critical Pole Vectors/ Intersections		Total Number of Pole Vectors/ Intersections	%
Planar Sliding	NA	0	NA	0	Set: F	1	18	6
Wedge Sliding	NA	0	6	0	Sets: I & B	1	10	10

Table 5.50: Kinematic analysis results for toppling on the right side of the forehead on the Washington sculpture using the RESPEC data and the data in this study.

Analysis	Results using RESPEC Data				Results from this Study			
	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%	Total Critical Intersections & Base Plane Pole Vectors		Total Intersections & Base Plane Pole Vectors	%
Direct & Oblique Toppling	Direct Toppling: PJS Planes (Intersections)	1	6	17	Direct Toppling: PJS Planes (Intersections)	0	10	0
	Oblique Toppling: PJS Planes (Intersections)	1	6	17	Oblique Toppling: PJS Planes (Intersections)	6	10	60
	Base Plane (All Pole Vectors)	3	122	2	Base Plane (All Pole Vectors)	16	112	14
	Base Plane (Set: N)	2	16	13	Base Plane (Set: F)	2	18	11

It is possible that the difference in the results is due to the fact that the slope dip of the right side of Washington's forehead, as identified in this study, is slightly higher than that reported by RESPEC, allowing the discontinuities to daylight on the slope surface. Also, this study identified two steeply dipping principal joint sets, which were not identified when using the RESPEC data.

CHAPTER 6 – DISCUSSION

6.1 Slake Durability Results and Undercutting Potential on the Sculptures

The second cycle slake durability index values between schist sample 1a and granite sample 2 indicated no potential for undercutting, whereas the values between schist sample 1a and granite sample 2 indicated a slight potential for undercutting. Undercutting was not prominent in the field at MORU, but considering the importance of the sculptures, it is recommended that differential weathering between schist and granite rock from which the sculptures are carved be monitored on long term basis.

6.2 Freeze-Thaw Durability of the MORU Rock

The relatively high density ($> 162 \text{ pcf}/2.6 \text{ Mg/m}^3$) and low absorption (1.5% or less) values suggest that the intact granite and schist rock are not subject to freeze-thaw damage. The freeze-thaw test results confirmed this for the granite rock as the specimens had relatively low average percent change in mass ($<2\%$) after 300 freeze-thaw cycles. The schist rock however, had higher average percent change in mass ($>5\%$), with the specimens of schist 1b exhibiting lower freeze-thaw durability than the specimens of schist 1a. The results confirm that the granite, in its intact form, is not subject for freeze thaw, whereas the schist is (especially schist sample 1b).

6.3 Kinematic Analysis and Factor of Safety Calculations Indicating Unstable Slopes on the Sculptures

The kinematic analysis results indicate that the potential for planar sliding, wedge sliding, and toppling failure exists for various slopes on each of the MORU sculptures. Several factor of safety (FS) values against planar and wedge sliding are less than one, indicating unstable conditions. However, failures have not been observed on the sculptures. This may be due to several reasons including the fact that the FS calculations only consider the orientations of the slope and the critical plane, and the friction along the discontinuities. The FS calculations did not consider cohesion (cohesion is assumed as zero) or discontinuity conditions such as roughness, waviness, etc., which may result in higher friction angle and, hence, higher FS values. The analysis also assumes that friction is consistent along the entirety of the discontinuity, which may not be the case. There may be areas along the discontinuity that have higher friction, which would increase the FS value. There may also be areas along the discontinuity where there are still intact rock segments causing the slopes to remain stable.

6.4 Effect of Vibrations due to Fourth of July Fireworks Celebrations on the Stability of the Mount Rushmore National Memorial Sculptures

The Overall Slope Probabilistic Analyses, evaluating the effects of seismic loading on the stability of the entire slopes on which each the MORU sculptures are located, indicate that all of the slopes are safe against failure. This study assumes that if the slopes are stable against the earthquake force modeled, the vibrations produced by fireworks air blasts will not cause failures along the slopes. In light of the results considering the seismic condition, vibrations caused by the Fourth of July fireworks celebrations at MORU do not pose a threat to the stability of the sculptures.

CHAPTER 7 – CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS

7.1 Conclusions

The main conclusions of this research can be summarized as follows:

1. The second cycle slake durability results indicate a slight potential for undercutting between the schist and granite rock at MORU. Due to the importance of the sculptures, it is recommended that the schist band which cuts through the granite sculptures be monitored.
2. The intact granite rock, due to its relatively high average density (163 pcf/2.6 Mg/m³), low average absorption (0.9%), and low average percent mass change after ~300 freeze-thaw cycles (<2%) is not subject to freeze thaw damage. The intact schist rock has relatively high average density (173 pcf/2.8 Mg/m³) and low average absorption (1.1%), however the freeze-thaw durability tests indicate the rock is subject to freeze-thaw damage due to its relatively high average percent mass change after ~300 freeze-thaw cycles (>5%).
3. The granite, schist, and pegmatite rock masses studied in the four regions at MORU classify as good rock according to the Rock Mass Rating (RMR) system and fair to good rock according to the Q-system.
4. The kinematic analysis results indicate that the potential for planar sliding, wedge sliding, direct/oblique toppling, and flexural toppling failure exists for various slopes on each of the MORU sculptures. Wedge sliding and toppling failures have the highest potentials.

The factor of safety (FS) values against planar and wedge sliding range from 0.1-0.8 and 0.2-1.3, respectively. The FS values < 1 indicate unstable conditions, however failures have not been observed on the sculptures. It is possible that factors such as cohesion, the condition of the discontinuities (waviness, roughness, etc.) or the presence of intact rock segments increase the stability of the slopes. Sensitivity analyses completed for the slopes with $FS < 1$ indicated that a cohesion value of $\leq 440 \text{ lb/ft}^2$ ($\leq 21 \text{ kPa}$) is required to increase the $FS > 1$ (for both planar and wedge sliding). A figure in Hoek and Bray (1981) provides cohesive strength (c) values obtained by back analysis of slopes. From this chart, the c values mobilized at failure for weathered granite slopes were 500 lb/ft^2 (24 kPa). This value is an indication that the highest c value from the sensitivity analysis is a reasonable assumption of c for the granite rock at MORU. Sensitivity analyses also indicate that when cohesion = 0, the friction values required for $FS > 1$ range from 41° - 84° (for both planar and wedge sliding). The majority of the friction values were very high and improbable, indicating that both cohesion and friction along the discontinuities are required for $FS > 1$.

5. The areas on the MORU sculptures that have the potential for planar sliding (probability of failure with respect to the principal joint set planes of 20% or higher and factor of safety values < 1) and do not have any discontinuities currently being monitored by the rock block monitoring system include the slope on the central area of the forehead of the Washington sculpture and the slope on the right side of the forehead of the Roosevelt sculpture. Similarly, the areas with a potential for wedge sliding (probability of failure with respect to the total number of intersections between the principal joint set planes of 20% or higher and factor of safety values < 1) and do not have any discontinuities

currently being monitored by the rock block monitoring system include the slope on the left side of the forehead of the Washington sculpture, the right side of the nose on the Roosevelt sculpture, and the right, left, and central slopes on the forehead of the Roosevelt sculpture. These slopes may benefit from further studies of the condition of the discontinuities to determine if additional areas should be monitored.

6. The Overall Slope Probabilistic Analyses results for the entire slope areas of each of the MORU sculptures included the Mean Factor of Safety (FSM), Reliability Index (RI), and Probability of Failure (PF) for the overall slopes. The analyses were completed considering both the static condition and the seismic condition with a seismic load coefficient of 0.14 (horizontal and vertical directions) applied to the slopes. For the Washington sculpture considering the static condition, the FSM, RI, and PF values are 3.3, 6.0, and 0%, respectively. For the seismic condition, the corresponding values are: 2.6, 4.6, and 0%. For the Jefferson sculpture considering the static condition, the FSM, RI, and PF values are 4.5, 7.8, and 0%, respectively. For the seismic condition the values corresponding are: 3.6, 3.7, and 0%. For the Roosevelt sculpture considering the static condition, the FSM, RI, and PF values are: 5.2, 5.7, and 0%, respectively. For the seismic condition the corresponding values are: 4.1, 4.7, and 0%. For the Lincoln sculpture considering the static condition, the FSM, RI, and PF values are: 4.4, 3.3, and 0%, respectively. For the seismic condition the corresponding values are: 3.4, 2.9, and 0%. These results show that when applying a seismic load to the slopes, the factor of safety and RI values decreased. For both the static and seismic conditions, however, the values indicate that the overall slopes of the sculptures are safe.

7.2 Recommendations for Future Research

Continual research and monitoring of the discontinuities on the MORU sculptures is imperative to ensure the long term stability of the sculptures. This study found two additional principal joint sets not found in the data by RESPEC. This may be due to the fact that the LiDAR point cloud data used in this study had lower resolution in some areas of the sculptures. This means that some discontinuities on the sculptures may not be best represented by the data. The LiDAR was a combined aerial and terrestrial data set and merging the scans resulted in some areas on the sculptures to have few or no points. The point cloud files that were merged are from many scans taken from different directions causing the resolution issue. It is recommended that higher resolution LiDAR data of the sculptures be used with the Split-FX program (Split-Engineering, 2014) to verify the principal joint sets determined in this study. With higher resolution data, the slope orientations of the sculptures obtained by this study can also be verified. Kinematic analyses can be conducted with the new data to further verify the results of this study. All potential plane, wedge, and toppling failures indicated by this study should be observed and additional on-site data be collected to confirm the results.

Additionally, it is recommended that future studies carry out quantitative analyses which measure the degree of instability of the potential toppling failures. Information such as the overall base inclination of the blocks, and the width of the toppling blocks will need to be determined for these analyses. Lastly, future studies may include calculating the factor of safety for planar sliding, wedge sliding, and toppling failures with an applied seismic force to the slopes.

REFERENCES

- Admassu, Y., 2010, Developing Design Methodology for Cut Slopes in Ohio: Ph.D. Dissertation, Department of Geology, Kent State University, Kent, Ohio, 618p.
- American Society for Testing and Materials (ASTM), 2003, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing C666/C 666M-03: ASTM International, West Conshohocken, PA, 2003, www.astm.org
- American Society for Testing and Materials (ASTM), 2008a, Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens D3967-08: ASTM International, West Conshohocken, PA, 2008, doi: 10.1520/D3967-08, www.astm.org
- American Society for Testing and Materials (ASTM), 2008b, Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classification D5731-08: ASTM International, West Conshohocken, PA, 2008, doi: 10.1520/D5731-08, www.astm.org
- American Society for Testing and Materials (ASTM), 2008c, Standard Test Method for Slake Durability of Shales and Similar Weak Rocks D4644-08: ASTM International, West Conshohocken, PA, 2008, doi: 10.1520/D4644-08, www.astm.org
- American Society for Testing and Materials (ASTM), 2010, Standard Test Method for Specific Gravity and Absorption of Rock for Erosion Control D6473-10: ASTM International, West Conshohocken, PA, 2010, doi: 10.1520/D6473-10, www.astm.org

- American Society for Testing and Materials (ASTM), 2013, Standard Test Method for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens Under Varying States of Stress and Temperatures D7012-13: ASTM International, West Conshohocken, PA, 2013, doi: 10.1520/D7012, www.astm.org
- Barton, N.R., 1982, Shear strength investigations for surface mining, Ch. 7, 3rd Int. Conf. on Surface Mining, Vancouver, SME 1982, p. 171-196.
- Barton, N.R., Lien, R., and Lunde, J., 1974, Engineering classification of rock masses for the design of tunnel support: *Rock Mechanics and Rock Engineering*, v. 6, p. 189-239.
- Bieniawski, Z.T., 1989, *Engineering Rock Mass Classifications*: Wiley, New York, 251 p.
- Boyle, W.J. and Vogt, T.J., 1992, Structural Stability Analysis of Mount Rushmore National Memorial; Phase III- Stability Analysis: Topical Report RSI-0430, prepared by RESPEC Inc., Rapid City, South Dakota, four Mount Rushmore National Memorial Society, Rapid City, South Dakota, 114 p.
- Dahl, P.S., Wehn, D.C., and Feldmann, S.G., 1993, The systematics of trace-element partitioning between coexisting muscovite and biotite in metamorphic rocks from the Black Hills, South Dakota, USA: *Geochimica et Cosmochimica Acta*, v. 57, no. 11, p. 2487-2505. doi: 10.1016/0016-7037(93)90412-P Retrieved from <http://digitalcommons.kent.edu/geolpubs/16>
- Dearman, W.R., 1976, Weathering classification in the characterisation of rock: A revision: *Bulletin of the International Association of Engineering Geology*, no. 13, p. 123-127.
- Deere, D.U., Hendron, A.J., Jr., Patton, F.D., and Cording, E.J., 1967, Design of surface and near-surface construction in rock: *Proc. 8th Symp. Rock Mech., Am. Inst. Min. Metall. & Pet. Eng., Minneapolis, Minn.* p 237-302.

- Esri, 2014, ArcGIS® desktop release 10.2.2: Computer Software, available at www.esri.com
- Fisher, J., 2011, Use of Remote Sensing in the Collection of Discontinuity Data for the Analysis and Design of Cut Slopes: M.S. Thesis, Department of Geology, Kent State University, Kent, Ohio, 239 p.
- Goodman, R. E., 1980, Introduction to Rock Mechanics: Wiley, Toronto, 492 p.
- Goodman, R. E. and Shi, G., 1985, Block Theory and Its Application to Rock Engineering: Prentice-Hall, Englewood Cliffs, 338 p.
- Google Earth Pro, 2013, version 7.1.2.2041, available at www.google.com/earth/
- Graham, J., 2008, Mount Rushmore National Memorial Geologic Resource Evaluation Report: Natural Resource Report NPS/NRPC/GRD/NRR—2008/038. National Park Service, Denver, Colorado. NPS D-95, June 2008, 36 p.
- Greco, V.R., 1996, Efficient Monte Carlo technique for locating critical slip surface: Journal of Geotechnical Engineering: v. 122, no. 7, p. 517-525.
- Hoek, E., 2007, Rock Mass Classification. Practical Rock Engineering: <https://www.rockscience.com/> (accessed January 2014).
- Hoek, E. and Bray, J.W., 1981, Rock Slope Engineering: The Institute of Mining and Metallurgy, London, 358 p.
- Hudson J. A. and Harrison, J. P., 1997, Engineering Rock Mechanics: An Introduction to the Principles: Elsevier Science, Oxford, 456 p.
- Hynes-Griffin, M. E. and Franklin, A.G., 1984, Rationalizing the Seismic Coefficient Method: U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Misc. Paper GL-84-13, 37 p.

- International Society for Rock Mechanics (ISRM), 1979, Suggested methods for determining swelling and slake-durability index properties: International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, v. 16 no. 2, p. 151-156.
- Janbu, N., 1968, Slope Stability Computations: Soil Mechanics and Foundation Engineering Report: Technical University of Norway, Trondheim, p. 47-86.
- Johnson, R.B. and DeGraff, J.V., 1988, Principles of Engineering Geology: Wiley, New York, 512 p.
- Jones, J., 2011, A symbol of democracy: The Mount Rushmore National Memorial: Civil Engineering, v. 81, no. 2, p. 48-51.
- Micron Optics, Inc., 2010, Case study – Mount Rushmore Rock Block Monitoring System: Keystone, South Dakota 2010:
<http://www.micronoptics.ru/uploads/library/documents/MicronOptics-Mt%20Rushmore%202010.pdf> (accessed July 2016).
- National Park Service, 2005, Geology Fieldnotes, Mount Rushmore National Memorial South Dakota: <http://www.nature.nps.gov/geology/parks/moru/> (accessed July 2016).
- National Park Service, 2014a, Mount Rushmore Student Guide. U.S. Department of the Interior, National Park Service: <http://www.nps.gov/moru/forkids/mount-rushmore-student-guide.htm> (accessed January 2014).
- National Park Service, 2014b, Park statistics: Mount Rushmore National Memorial, South Dakota: <http://www.nps.gov/moru/parkmgmt/statistics.htm> (accessed January 2014).
- National Park Service, 2016, Geologic Activity:
<https://www.nps.gov/moru/learn/nature/geologicactivity.htm> (accessed July 2016).

- Palstrom, A., 1982, The volumetric joint count – a useful and simple measure of the degree of rock jointing, in Proceedings: Fourth International Congress of the International Association of Engineering Geology, Delhi, p. 221-228.
- Palstrom, A. and Broch, E., 2006, Use and misuse of rock mass classification systems with particular reference to the Q-system: Tunnels and Underground Space Technology, v. 21, p. 575-593.
- Park, H. J. and West, T. R., 2002, Sampling bias of discontinuity orientation caused by linear sampling technique: Engineering Geology, v. 66, p. 99-110.
- Piteau, D. R. and Martin, D. C., 1977, Description of the Detailed Line Engineering Mapping Method: Rock Slope Engineering, Part G, Federal Highway Administration, Reference Manual FHWA-13-97-208: Portland, Oregon, 29 p.
- Powell, J.E., Norton, J.J., and Adolphson, D.G., 1973, Water Resources and Geology of Mount Rushmore National Memorial, South Dakota: U.S. Geological Survey Water- Supply Paper 1865, 57 p.
- Priest, S. D., 1993, Discontinuity Analysis for Rock Engineering: Chapman and Hall, London, 473 p.
- RESPEC Inc., 1989, Structural Analysis of Mount Rushmore, Mount Rushmore National Memorial, Keystone, South Dakota: Report RSI/P-358, Prepared by RESPEC Inc., Rapid City, South Dakota, p. 1-24.
- RESPEC Inc., 2000, Design and Installation of a Rock Block Monitoring System for the Sculpture on Mount Rushmore: Prepared by RESPEC Inc., Rapid City, South Dakota, 24 p.

Rocscience, 2015a, Toppling, planar sliding, wedge sliding. Dips tutorial manual:

<https://www.rocscience.com> (accessed August 2015).

Rocscience, 2015b, Sets from cluster analysis. Dips help topics:

https://www.rocscience.com/help/dips/webhelp/dips/Sets_from_Cluster_Analysis.htm
(accessed August 2015).

Rocscience, 2016a, Dips (version 7.0): Rocscience Inc., Toronto, Ontario,

<https://www.rocscience.com>

Rocscience, 2016b, Planar sliding. Dips help topics:

<https://www.rocscience.com/help/dips/webhelp7/Dips.htm> (accessed September 2016).

Rocscience, 2016c, Wedge sliding. Dips help topics:

https://www.rocscience.com/help/dips/webhelp/dips/Wedge_Sliding.htm (accessed
September 2016).

Rocscience, 2016d, Direct toppling. Dips help topics:

https://www.rocscience.com/help/dips/webhelp/dips/Direct_Toppling.htm (accessed
September 2016).

Rocscience, 2016e, Flexural Toppling. Dips help topics:

<https://www.rocscience.com/help/dips/webhelp7/Dips.htm> (accessed May 20, 2017).

Rocscience, 2016f, RocPlane (version 3.0): Rocscience Inc., Toronto, Ontario,

<https://www.rocscience.com>

Rocscience, 2016g, Swedge (version 6.0): Rocscience Inc., Toronto, Ontario,

<https://www.rocscience.com>

Rocscience, 2016h, Slide (version 7.0): Rocscience Inc., Toronto, Ontario,

<https://www.rocscience.com>

Rocscience, 2016i, Probabilistic analysis overview:

https://www.rocscience.com/help/slide/webhelp/slide_model/probability/Probabilistic_Analysis_Overview.htm (accessed March 2016).

Rocscience, 2016j, Statistical distributions overview:

https://rocscience.com/help/slide/webhelp/slide_model/probability/Statistical_Distributions_Overview.htm (March 2016).

Rocscience, 2016k, Probabilistic analysis:

<https://www.rocscience.com/help/slide/webhelp7/Slide.htm> (March 2016).

Rocscience, 2016l, Probabilistic results overview:

https://www.rocscience.com/help/slide/webhelp/slide_interpret/probability/Probabilistic_Analysis_Overview.htm (March 2016).

Rocscience, 2016m, Critical slip surface search methods in Slide 7.0:

<https://www.rocscience.com/documents/pdfs/rocnews/2016spring/Slide%20Search%20Methods.pdf> (accessed November 2016).

Rocscience, 2016n, Optimize surfaces:

https://www.rocscience.com/help/slide/webhelp/slide_model/surfaces/Optimize_Surfaces.htm (accessed September 2016).

Rocscience, 2016o, RocData (version 5.0): Rocscience Inc., Toronto, Ontario,

<https://www.rocscience.com>

Rocscience, 2016p, Normal distribution:

https://www.rocscience.com/help/slide/webhelp/slide_model/probability/Normal_Distribution.htm (accessed September 2016).

Singh, B. and Goel, R. K., 1999, Rock Mass Classification: A Practical Approach in Civil Engineering: Elsevier, Oxford, 267 p.

Split Engineering, 2014, Split-FX (version 2.3.0.21): Split Engineering LLC, Tucson, Arizona, <http://www.spliteng.com>.

Stimpson, B., 1981, A suggested technique for determining the basic friction angle of rock surfaces using core: International Journal of Rock Mechanics and Mining Sciences and Geomechanics, v. 18, p. 63-65.

USGS, 2014, Two-percent probability of exceedance in 50 years map of peak ground acceleration: <http://earthquake.usgs.gov/hazards/products/conterminous/> (accessed March 2016).

Watts, C.F., Gilliam, D.R., Hrovatic, M.D., and Hong, H., 2003, User's Manual. Rockpack III for Windows Rock Slope Stability Computerized Analysis Package. Part Two – Safety Factor Calculations: C.F Watts & Associates; Consulting Engineering Geologists, 48 p.

West, T.R., 1995, Geology Applied to Engineering: Prentice Hall, Englewood Cliffs, 560 p.

Wyllie, D.C. and Mah, C.W., 2004, Rock Slope Engineering: Civil and Mining: Spon, London, 431 p.

APPENDICIES

APPENDIX A: PHOTOGRAPHS OF THE DISCONTINUITY DATA COLLECTION
LOCATIONS WITHIN THE FOUR STUDY REGIONS AT MORU

Figure A.1: Schist rock in Region 1, Location 1.

Figure A.2: Granite and schist rock in Region 1, Location 2.

Figure A.3: Schist and granite rock in Region 1, Location 10.

Figure A.4: Granite rock in Region 1, Location 11.

Figure A.5: Granite rock in Region 1, Location 11.

Figure A.6: Granite and schist rock in Region 1, Location 12.

Figure A.7: Pegmatite and granite rock in Region 1 Location 13.

Figure A.8: Pegmatite and granite rock in Region 1 Location 13.

Figure A.9: Granite and schist rock in Region 2, Location 8.

Figure A.10: Granite and schist rock in Region 2, Location 8.

Figure A.11: Granite, schist, and pegmatite rock in Region 2, Location 9.

Figure A.12: Granite, schist, and pegmatite rock in Region 2, Location 9.

Figure A.13: Mainly granitic rock in Region 2, Location 14.

Figure A.14: Mainly granite rock and some schist rock in Region 2, Location 14.

Figure A.15: Schist and granite rock in Region 2, Location 14.

Figure A.16: Schist rock in Region 2, Location 14.

Figure A.17: Granite rock in Region 2, Location 15.

Figure A.18: Granite rock in Region 2, Location 15.

Figure A.19: Granite rock in Region 2, Location 16.

Figure A.20: Granite in Region 2, Location 16.

Figure A.21: Granite rock in Region 2, Location 16.

Figure A.22: Schist and granite rock in Region 2, Location 24.

Figure A.23: Schist and granite rock in Region 2, Location 24.

Figure A.24: Schist and granite rock in Region 2, Location 24.

Figure A.25: Granite rock in Region 2, Location 27.

Figure A.26: Granite rock in Region 3, Location 22.

Figure A.27: Granite rock in Region 3, Location 23.

Figure A.28: Granite rock in Region 3, Location 23.

Figure A.29: Granite rock in Region 3, Location 23.

Figure A.30: Granite rock in Region 3, Location 23.

Figure A.31: Granite rock in Region 3, Location 23.

Figure A.32: Schist rock in Region 3, Location 23.

Figure A.33: Schist rock in Region 3, Location 23.

Figure A.34: Schist rock in Region 3, Location 25.

Figure A.35: Schist rock in Region 3, Location 25.

Figure A.36: Schist rock in Region 3, Location 26.

Figure A.37: Schist rock in Region 3, Location 26.

Figure A.38: Schist rock in Region 3, Location 26.

Figure A.39: Schist rock in Region 3, Location 26.

Figure A.40: Schist rock in Region 3, Location 26.

Figure A.41: Granite rock in Region 4, Location 3-1.

Figure A.42: Granite rock in Region 4, Location 3-1.

Figure A.43: Granite rock in Region 4, Location 3-2.

Figure A.44: Schist rock in Region 4, Location 3-3.

Figure A.45: Schist rock in Region 4, Location 3-3.

Figure A.46: Granite, pegmatite and schist rock in Region 4, Location 4.

Figure A.47: Granite rock in Region 4, Location 5.

Figure A.48: Granite rock in Region 4, Location 5.

Figure A.49: Granite rock in Region 4, Location 5.

Figure A.50: Granite rock in Region 4, Location 6.

Figure A.51: Granite rock in Region 4, Location 6.

Figure A.52: Granite rock in Region 4, Location 7.

Figure A.53: Granite rock in Region 4, Location 17.

Figure A.54: Granite rock in Region 4, Location 17.

Figure A.55: Schist and granite rock in Region 4, Location 17.

Figure A.56: Granite rock in Region 4, Location 17.

Figure A.57: Granite rock in Region 4, Location 17.

Figure A.58: Granite rock in Region 4, Location 17.

Figure A.59: Schist and granite rock in Region 4, Location 17.

Figure A.60: Granite rock with some pegmatitic areas in Region 4, Location 18.

Figure A.61: Schist and granite rock with some pegmatitic areas in Region 4, Location 18.

Figure A.62: Granite rock in Region 4, Location 19.

Figure A.63: Granite rock in Region 4, Location 20.

Figure A.64: Granite rock in Region 4, Location 29.

Figure A.65: Schist rock in Region 4, Location 30.

Figure A.66: Schist rock in Region 4, Location 31.

APPENDIX B: CHARTS, TABLES, AND MAPS (WEATHERING CLASSIFICATION,
JOINT ROUGHNESS COEFFICIENT, ROCK MASS RATING AND Q-SYSTEM
CLASSIFICATIONS, USGS MAP OF PEAK GROUND ACCELERATION)

Table B.1: Weathering classification by Dearman (1976) used to describe the degree of weathering of the rock mass and the discontinuities present within the rock mass at MORU.

Fresh	I	No visible sign of rock material weathering; perhaps slight discoloration on major discontinuity surfaces.
Slightly weathered	II	Discoloration indicates weathering of rock material and discontinuity surfaces. All the rock material may be discoloured by weathering.
Moderately weathered	III	Less than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a continuous framework or as corestones.
Highly weathered	IV	More than half of the rock material is decomposed and/or disintegrated to a soil. Fresh or discoloured rock is present either as a discontinuous framework or as corestones.
Completely weathered	V	All rock material is decomposed and/or disintegrated to soil. The original mass structure and material fabric are still largely intact.
Residual soil	VI	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.

Figure B.1: Surface irregularities were documented as Joint Roughness Coefficient (JRC) using this chart by Barton (1982) (Singh and Goel, 1999).

Table B.2: The Rock Mass Rating System parameters and their ratings (table from Hoek, 2007).

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS									
Parameter			Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4 - 10 MPa	2 - 4 MPa	1 - 2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100 - 250 MPa	50 - 100 MPa	25 - 50 MPa	5 - 25 MPa	1 - 5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality <i>RQD</i>		90% - 100%	75% - 90%	50% - 75%	25% - 50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6 - 2 . m	200 - 600 mm	60 - 200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow per 10 m tunnel length (l/m)	None	< 10	10 - 25	25 - 125	> 125		
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1, - 0.2	0.2 - 0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		
B. RATING ADJUSTMENT FOR DISCONTINUITY ORIENTATIONS (See F)									
Strike and dip orientations			Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable		
Ratings	Tunnels & mines		0	-2	-5	-10	-12		
	Foundations		0	-2	-7	-15	-25		
	Slopes		0	-5	-25	-50			
C. ROCK MASS CLASSES DETERMINED FROM TOTAL RATINGS									
Rating			100 ← 81	80 ← 61	60 ← 41	40 ← 21	< 21		
Class number			I	II	III	IV	V		
Description			Very good rock	Good rock	Fair rock	Poor rock	Very poor rock		
D. MEANING OF ROCK CLASSES									
Class number			I	II	III	IV	V		
Average stand-up time			20 yrs for 15 m span	1 year for 10 m span	1 week for 5 m span	10 hrs for 2.5 m span	30 min for 1 m span		
Cohesion of rock mass (kPa)			> 400	300 - 400	200 - 300	100 - 200	< 100		
Friction angle of rock mass (deg)			> 45	35 - 45	25 - 35	15 - 25	< 15		
E. GUIDELINES FOR CLASSIFICATION OF DISCONTINUITY conditions									
Discontinuity length (persistence)			< 1 m	1 - 3 m	3 - 10 m	10 - 20 m	> 20 m		
Rating			6	4	2	1	0		
Separation (aperture)			None	< 0.1 mm	0.1 - 1.0 mm	1 - 5 mm	> 5 mm		
Rating			6	5	4	1	0		
Roughness			Very rough	Rough	Slightly rough	Smooth	Slickensided		
Rating			6	5	3	1	0		
Infilling (gouge)			None	Hard filling < 5 mm	Hard filling > 5 mm	Soft filling < 5 mm	Soft filling > 5 mm		
Rating			6	4	2	2	0		
Weathering			Unweathered	Slightly weathered	Moderately weathered	Highly weathered	Decomposed		
Ratings			6	5	3	1	0		
F. EFFECT OF DISCONTINUITY STRIKE AND DIP ORIENTATION IN TUNNELLING**									
Strike perpendicular to tunnel axis				Strike parallel to tunnel axis					
Drive with dip - Dip 45 - 90°		Drive with dip - Dip 20 - 45°		Dip 45 - 90°			Dip 20 - 45°		
Very favourable		Favourable		Very unfavourable			Fair		
Drive against dip - Dip 45-90°		Drive against dip - Dip 20-45°		Dip 0-20 - Irrespective of strike°					
Fair		Unfavourable		Fair					

Table B.3: The Q-system parameters and their ratings (table from Hoek, 2007).

DESCRIPTION	VALUE	NOTES
1. ROCK QUALITY DESIGNATION	<i>RQD</i>	
A. Very poor	0 - 25	1. Where <i>RQD</i> is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate <i>Q</i> .
B. Poor	25 - 50	
C. Fair	50 - 75	2. <i>RQD</i> intervals of 5, i.e. 100, 95, 90 etc. are sufficiently accurate.
D. Good	75 - 90	
E. Excellent	90 - 100	
2. JOINT SET NUMBER	<i>J_n</i>	
A. Massive, no or few joints	0.5 - 1.0	
B. One joint set	2	
C. One joint set plus random	3	
D. Two joint sets	4	
E. Two joint sets plus random	6	
F. Three joint sets	9	1. For intersections use $(3.0 \times J_n)$
G. Three joint sets plus random	12	
H. Four or more joint sets, random, heavily jointed, 'sugar cube', etc.	15	2. For portals use $(2.0 \times J_n)$
J. Crushed rock, earthlike	20	
3. JOINT ROUGHNESS NUMBER	<i>J_r</i>	
a. Rock wall contact		
b. Rock wall contact before 10 cm shear		
A. Discontinuous joints	4	
B. Rough and irregular, undulating	3	
C. Smooth undulating	2	
D. Slickensided undulating	1.5	1. Add 1.0 if the mean spacing of the relevant joint set is greater than 3 m.
E. Rough or irregular, planar	1.5	
F. Smooth, planar	1.0	
G. Slickensided, planar	0.5	2. <i>J_r</i> = 0.5 can be used for planar, slickensided joints having lineations, provided that the lineations are oriented for minimum strength.
c. No rock wall contact when sheared		
H. Zones containing clay minerals thick enough to prevent rock wall contact	1.0 (nominal)	
J. Sandy, gravely or crushed zone thick enough to prevent rock wall contact	1.0 (nominal)	
4. JOINT ALTERATION NUMBER	<i>J_a</i>	<i>φ_r</i> degrees (approx.)
a. Rock wall contact		
A. Tightly healed, hard, non-softening, impermeable filling	0.75	1. Values of <i>φ_r</i> , the residual friction angle, are intended as an approximate guide to the mineralogical properties of the alteration products, if present.
B. Unaltered joint walls, surface staining only	1.0	
C. Slightly altered joint walls, non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	2.0	
D. Silty-, or sandy-clay coatings, small clay-fraction (non-softening)	3.0	
E. Softening or low-friction clay mineral coatings, i.e. kaolinite, mica. Also chlorite, talc, gypsum and graphite etc., and small quantities of swelling clays. (Discontinuous coatings, 1 - 2 mm or less)	4.0	

Table B.3: (cont'd.) The Q-system parameters and their ratings (table from Hoek, 2007).

4. JOINT ALTERATION NUMBER	J_a	ϕ degrees (approx.)
b. Rock wall contact before 10 cm shear		
F. Sandy particles, clay-free, disintegrating rock etc.	4.0	25 - 30
G. Strongly over-consolidated, non-softening clay mineral fillings (continuous < 5 mm thick)	6.0	16 - 24
H. Medium or low over-consolidation, softening clay mineral fillings (continuous < 5 mm thick)	8.0	12 - 16
J. Swelling clay fillings, i.e. montmorillonite, (continuous < 5 mm thick). Values of J_a depend on percent of swelling clay-size particles, and access to water.	8.0 - 12.0	6 - 12
c. No rock wall contact when sheared		
K. Zones or bands of disintegrated or crushed	6.0	
L. rock and clay (see G, H and J for clay	8.0	
M. conditions)	8.0 - 12.0	6 - 24
N. Zones or bands of silty- or sandy-clay, small clay fraction, non-softening	5.0	
O. Thick continuous zones or bands of clay	10.0 - 13.0	
P. & R. (see G.H and J for clay conditions)	6.0 - 24.0	
5. JOINT WATER REDUCTION	J_w	approx. water pressure (kgf/cm²)
A. Dry excavation or minor inflow i.e. < 5 l/m locally	1.0	< 1.0
B. Medium inflow or pressure, occasional outwash of joint fillings	0.66	1.0 - 2.5
C. Large inflow or high pressure in competent rock with unfilled joints	0.5	2.5 - 10.0
D. Large inflow or high pressure	0.33	2.5 - 10.0
E. Exceptionally high inflow or pressure at blasting, decaying with time	0.2 - 0.1	> 10
F. Exceptionally high inflow or pressure	0.1 - 0.05	> 10
6. STRESS REDUCTION FACTOR		SRF
a. Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated		
A. Multiple occurrences of weakness zones containing clay or chemically disintegrated rock, very loose surrounding rock any depth)	10.0	1. Reduce these values of SRF by 25 - 50% but only if the relevant shear zones influence do not intersect the excavation
B. Single weakness zones containing clay, or chemically disintegrated rock (excavation depth < 50 m)	5.0	
C. Single weakness zones containing clay, or chemically disintegrated rock (excavation depth > 50 m)	2.5	
D. Multiple shear zones in competent rock (clay free), loose surrounding rock (any depth)	7.5	
E. Single shear zone in competent rock (clay free). (depth of excavation < 50 m)	5.0	
F. Single shear zone in competent rock (clay free). (depth of excavation > 50 m)	2.5	
G. Loose open joints, heavily jointed or 'sugar cube', (any depth)	5.0	

Table B.3: (cont'd.) The Q-system parameters and their ratings (table from Hoek, 2007).

DESCRIPTION	VALUE		NOTES
6. STRESS REDUCTION FACTOR	SRF		
b. Competent rock, rock stress problems			
	σ_c/σ_1	σ_t/σ_1	2. For strongly anisotropic virgin stress field
H. Low stress, near surface	> 200	> 13	2.5 (if measured): when $5 \leq \sigma_1/\sigma_3 \leq 10$, reduce σ_c
J. Medium stress	200 - 10	13 - 0.66	1.0 to $0.8\sigma_c$ and σ_t to $0.8\sigma_t$. When $\sigma_1/\sigma_3 > 10$,
K. High stress, very tight structure (usually favourable to stability, may be unfavourable to wall stability)	10 - 5	0.66 - 0.33	0.5 - 2 reduce σ_c and σ_t to $0.6\sigma_c$ and $0.6\sigma_t$, where σ_c = unconfined compressive strength, and σ_t = tensile strength (point load) and σ_1 and σ_3 are the major and minor principal stresses.
L. Mild rockburst (massive rock)	5 - 2.5	0.33 - 0.16	5 - 10
M. Heavy rockburst (massive rock)	< 2.5	< 0.16	10 - 20
c. Squeezing rock, plastic flow of incompetent rock under influence of high rock pressure			
N. Mild squeezing rock pressure			5 - 10
O. Heavy squeezing rock pressure			10 - 20
d. Swelling rock, chemical swelling activity depending on presence of water			
P. Mild swelling rock pressure			5 - 10
R. Heavy swelling rock pressure			10 - 15
ADDITIONAL NOTES ON THE USE OF THESE TABLES			
When making estimates of the rock mass Quality (Q), the following guidelines should be followed in addition to the notes listed in the tables:			
1. When borehole core is unavailable, RQD can be estimated from the number of joints per unit volume, in which the number of joints per metre for each joint set are added. A simple relationship can be used to convert this number to RQD for the case of clay free rock masses: $RQD = 115 - 3.3 J_v$ (approx.), where J_v = total number of joints per m^3 ($0 < RQD < 100$ for $35 > J_v > 4.5$).			
2. The parameter J_n representing the number of joint sets will often be affected by foliation, schistosity, slaty cleavage or bedding etc. If strongly developed, these parallel 'joints' should obviously be counted as a complete joint set. However, if there are few 'joints' visible, or if only occasional breaks in the core are due to these features, then it will be more appropriate to count them as 'random' joints when evaluating J_n .			
3. The parameters J_r and J_a (representing shear strength) should be relevant to the weakest significant joint set or clay filled discontinuity in the given zone. However, if the joint set or discontinuity with the minimum value of J_r/J_a is favourably oriented for stability, then a second, less favourably oriented joint set or discontinuity may sometimes be more significant, and its higher value of J_r/J_a should be used when evaluating Q. The value of J_r/J_a should in fact relate to the surface most likely to allow failure to initiate.			
4. When a rock mass contains clay, the factor SRF appropriate to loosening loads should be evaluated. In such cases the strength of the intact rock is of little interest. However, when jointing is minimal and clay is completely absent, the strength of the intact rock may become the weakest link, and the stability will then depend on the ratio rock-stress/rock-strength. A strongly anisotropic stress field is unfavourable for stability and is roughly accounted for as in note 2 in the table for stress reduction factor evaluation.			
5. The compressive and tensile strengths (σ_c and σ_t) of the intact rock should be evaluated in the saturated condition if this is appropriate to the present and future in situ conditions. A very conservative estimate of the strength should be made for those rocks that deteriorate when exposed to moist or saturated conditions.

Figure B.2: The seismic load coefficient for the global stability analysis of MORU was estimated using this 2014 USGS map of peak ground acceleration (USGS, 2014).

APPENDIX C: ROCK DESCRIPTIONS AND WEATHERING DATA

Table C.1: The rock and weathering description for the three rock types present at the four regions at MORU. The degree of weathering of the rocks at MORU was documented using the classification chart by Dearman (1976). The range listed is from the histograms in Appendix G.

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
1	1	Quartz Mica Schist	Greyish tan	Quartz, biotite, muscovite.	Schistose	There are pockets and veins of granite within the schist. The rock is highly jointed and is weathered. Slightly north from Location 1 pygmatic folding is present (see Figure C.1). Also present is kinked foliation in the schist (Figure C.2).	IV-V (Highly to completely weathered)
1	2	Granite	Grey with orange buff/yellow areas on weathered surfaces.	Quartz, biotite, muscovite, plagioclase	Medium grained	-	III-IV (Moderately to highly weathered)
1	2	Schist	Greyish tan	Quartz, biotite, muscovite.	Schistose	-	IV-V (Highly to completely weathered)
1	10	Schist	Grey	Biotite, quartz, muscovite	Schistose	Quartz and feldspar pockets and coarse grained granitic to pegmatitic intrusions (some folded) are present in the schist (Figures C.3 - C.10)	IV-V (Highly to completely weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
1	10	Granite	White	Quartz, mica, feldspar	Medium to coarse grained	-	III-IV (Moderately to highly weathered)
1	11	Granite	Grey to white	Quartz, plagioclase, muscovite, biotite, hornblende	Medium grained	-	III-IV (Moderately to highly weathered)
1	11	Schist	Grey	Mica, quartz	Schistose	-	IV-V (Highly to completely weathered)
1	12	Granite	Grey to pink	Quartz, feldspar, mica, hornblende	Medium to coarse grained	-	III-IV (Moderately to highly weathered)
1	12	Schist	Grey	Quartz, biotite, muscovite	Schistose	-	IV-V (Highly to completely weathered)
1	13	Pegmatite	White to pink	Quartz, plagioclase, potassium feldspar, muscovite, biotite, hornblende	Average grain size >30 mm	-	IV-V (Highly to completely weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
1	13	Granite	White to pink	Quartz, plagioclase, potassium feldspar, muscovite, biotite, hornblende	Mainly coarse grained	-	III-IV (Moderately to highly weathered)
1	13	Schist	Grey	Mica, quartz	Schistose	-	IV-V (Highly to completely weathered)
2	8	Granite	White to pink	Quartz, plagioclase, potassium feldspar, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
2	8	Schist	Grey	Mica, quartz	Schistose	-	IV (Highly weathered)
2	9	Granite	White	Feldspar, quartz, muscovite, hornblende	Medium to coarse grained (Average grain size 5 mm)	-	III (Moderately weathered)
2	9	Schist	Grey	Mica, quartz	Schistose	-	IV (Highly weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
2	9	Pegmatite	White	Feldspar, quartz, mica, hornblende	Average grain size >30 mm	-	IV (Highly weathered) Note: III (moderately weathered) was also prevalent.
2	14	Granite	White to pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium grained (Average grain size 5 mm) some pegmatitic areas	-	III (Moderately weathered)
2	14	Schist	Grey	Mica, quartz	Schistose	-	IV (Highly weathered)
2	15	Granite	Grey with orangeish buff/yellow areas on weathered surfaces.	Feldspar, quartz, mica, hornblende	Medium grained	-	III (Moderately weathered)
2	16	Granite	Grey weathered surfaces	Feldspar, quartz, mica, hornblende	Medium grained	-	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
3	21	Granite	White to pink	Feldspar, quartz, mica, hornblende	Medium to coarse grained	Some spalling is present (see Figure C.11). Some fractures are filled with pegmatitic veins. Pegmatitic pockets with quartz and feldspar (see Figure C.12 - C.13). A hornblendite dike can be seen in Figure C.14. Conjugate joint can be seen in Figure C.15. Schist xenoliths present in the granite (Figure C.16)	III (Moderately weathered)
3	21	Pegmatite	White to pink	Plagioclase, potassium feldspar, quartz, biotite, muscovite, hornblende	Average grain size >30 mm	-	-
3	22	Granite	White/grey/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	Conjugate joints can be seen in Figure C.17.	III (Moderately weathered)
3	23	Granite	White/grey/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	Stress release joints visible due to unroofing of the granite (Figure C.18)	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
3	23	Schist	Grey	Mica, Quartz	Schistose	-	III (Moderately weathered)
3	24	Quartz Mica Schist	Grey to buff	Quartz, biotite, muscovite.	Schistose	Folding can be seen in the schist (Figures C.19 - C.21).	III (Moderately weathered)
3	24	Granite	Grey to pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
3	25	Schist	Grey	Mica, quartz	Schistose	A fold in schist with a granite vein can be seen in Figure C.22 (exact location was not recorded, but it was between L25 - L28).	III (Moderately weathered)
3	26	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
3	27	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
3	28	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
4	3-1	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	Tension crack which resulted from cooling of the magma (see Figure C.23). Freeze-thaw is evident in the granite because spalling has occurred (see Figure C.24).	III (Moderately weathered)
4	3-2	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	3-3	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	4	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	4	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	4	Pegmatite	White	Feldspar, quartz	Average grain size >30 mm	-	-
4	5	Granite	Grey/white/pink	Feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
4	5	Pegmatite	White	Feldspar,quartz	Average grain size >30 mm	-	-
4	6	Granite	Grey/pink	Plagioclase, potassium feldspar,quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	6	Pegmatite	Grey/pink	Feldspar,quartz	Average grain size >30 mm	-	-
4	7	Granite	Grey/pink	Plagioclase, potassium feldspar,quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	7	Pegmatite	Grey/white/pink	Feldspar,quartz	Average grain size >30 mm	-	-
4	8	Granite	Grey/white/pink	Plagioclase, potassium feldspar,quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	8	Schist	Grey	Mica, quartz	Schistose	Folded schist with pockets of pegmatitic quartz (Figure C.25)	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
4	17	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	17	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	18	Granite	Grey/white/pink	Feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	18	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	19	Granite	Grey/white/pink	Feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	19	Pegmatite	White	Feldspar, quartz, mica	Average grain size >30 mm	-	-
4	20	Granite	Grey/white/pink	Feldspar, quartz, mica, hornblende	Medium to coarse grained with some areas pegmatitic	-	III (Moderately weathered)
4	20	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)

Region	Location	Rock Type	Color	Mineralogy	Texture	Additional Info	Degree of Weathering
4	29	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	29	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	30	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	31	Schist	Grey	Mica, quartz	Schistose	-	III (Moderately weathered)
4	31	Granite	Grey/white/pink	Plagioclase, potassium feldspar, quartz, mica, hornblende	Medium to coarse grained	-	III (Moderately weathered)
4	31	Pegmatite	White	-	Average grain size >30 mm	Dikes	-

Figure C.1: Ptygmatic folding in schist with veins of granite visible in the field slightly north of Region 1, Location 1.

Figure C.2: Kinked foliation in schist (slightly north of Region 1, Location 1).

Figure C.3: Quartz and plagioclase pockets within the schist in Region 1, Location 10.

Figure C.4: Quartz and plagioclase pocket. Folding can be seen in the granitic veins in the schist in Region 1, Location 10.

Figure C.5: Quartzite pocket in schist at Region 1, Location 10.

Figure C.6: Quartzite pocket in schist at Region 1, Location 10.

Figure C.7: Folded granitic sill in schist at Region 1, Location 10.

Figure C.8: Granitic sills and quartzite pockets present in the schist at Region 1, Location 10.

Figure C.9: En echelon granitic veins within schist in Region1, Location 10.

Figure C.10: Coarse-grained granitic to pegmatitic intrusions in the schist slope within Region 1, Location 10.

Figure C.11: Spalling of granite due to freeze-thaw damage (Region 3, Location 21).

Figure C.12: Pegmatitic pocket composed mainly of feldspar and quartz (Region 3, Location 21).

Figure C.13: Pegmatitic pocket composed mainly of feldspar and quartz (Region 3, Location 21).

Figure C.14: Hornblende dike in Region 3, Location 21.

Figure C.15: Conjugate joint in granite with a rock hammer for scale (Region 3, Location 21).

Figure C.16: Schist xenolith within granite (Region 3, Location 21).

Figure C.17: Conjugate joint in the granite (Region 3, Location 22).

Figure C.18: Granite rock within Region 3, Location 23.

Figure C.19: Folded schist indicated by the red box (Region 3, Location 24).

Figure C.20: Folding in schist (Region 3, Location 24).

Figure C.21: Folding in schist (Region 3, Location 24).

Figure C.22: Folded schist with a pink granite sill outlined in red. Rock hammer for scale (Regions 3, Between Locations 25 and 28).

Figure C.23: Tension crack in granite in Region 4, location 3-1 at MORU. Rock hammer for scale.

Figure C.24: Spalling of the granite due to freeze thaw in Region 4 at location 3-1. The red box indicates where the spalling has occurred.

Figure C.25: Folded schist with pockets of pegmatitic quartz (Region 4, Location 8).

APPENDIX D: DISCONTINUITY DATA

Table D.1 Discontinuity data for each region studied at MORU. Note: No. = joint number and L = location.

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling Material	Water	Weathering (Dearman, 1976)	Rock Type/Notes
1	10	44	240	0.6	NA	10	NA	Dry	III	Granite
2	10	86	145	0.1	0	5	None	Dry	III	Granite
3	10	74	320	0.5	0-20	6	None	Dry	III	Granite
4	10	82	260	0.5	0	12	None	Dry	II-III	Granite/Wedge
5	10	83	134	0.5	0	12	None	Dry	II-III	Granite/Wedge
6	10	82	024	1.4	NA	12-14	NA	Dry	III	Granite
7	10	60	292	-	-	-	-	Dry	-	Granite
8	10	89	139	-	-	-	-	Dry	-	Granite
9	10	88	143	-	-	-	-	Dry	-	Granite
10	10	59	225	-	-	-	-	Dry	-	Granite
11	10	69	239	1.7	NA	12-14	NA	Dry	III	Granite
12	10	86	146	1.7	0	12-14	None	Dry	III-IV	Granite
13	2	59	204	7.6	0	18-20	None	Dry	-	Granite
14	2	77	356	7.6	NA	16-18	NA	Dry	III	Granite
15	2	88	143	7.6	76-152	18-20	Weathered granite (clayey)	Dry	III	Granite
16	2	78	243	9.1	6-457	18-20	None	Dry	I	Granite
17	2	72	107	1.8	NA	18-20	NA	Dry	III	Granite
18	11	78	243	7.6	-	14	-	Dry	III-IV	Granite
19	11	86	271	7.6	-	5	NA	Dry	IV	Granite
20	11	78	212	5.2	3-102	4-5	None	Dry	IV	Granite
21	11	85	208	0.6	5-20	6	None	Dry	IV	Granite
22	11	74	088	1.9	0-1	8	None	Dry	III	Granite

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
23	11	50	322	2.1	0-10	5-6	None	Dry	III-IV	Granite
24	11	86	321	5.8	0-25	5-6	None	Dry	III-IV	Granite
25	11	72	238	1.2	0-6	3-4	None	Dry	IV	Granite
26	11	55	095	1.2	6-13	8-10	None	Dry	V	Granite
27	11	80	196	7.0	102-305	10	None	Dry	V	Granite
28	11	67	106	2.1	NA	8	NA	Dry	IV	Granite
29	11	75	096	5.5	NA	8	NA	Dry	IV	Granite
30	11	78	327	9.1	0-102	4-5	None	Dry	IV	Granite
31	11	84	082	2.4	0-38	8-10	Some Soil	Dry	IV	Granite
32	11	79	330	1.8	0-25	10	None	Dry	IV	Granite
33	11	84	326	76.2	32-1372	16-18	Some Broken rocks	Dry	IV	Granite
34	11	85	181	10.7	6-914	16	None	Dry	IV	Granite
35	11	53	231	3.7	NA	8	NA	Dry	IV	Granite
36	11	71	328	-	-	-	-	Dry	-	Granite
37	11	82	178	-	-	-	-	Dry	-	Granite
38	11	84	268	-	-	-	-	Dry	-	Granite
39	11	54	304	-	-	-	-	Dry	-	Granite
40	12	50	249	3.7	15-119	18-20	Some Broken rocks	Dry	III-IV	Granite/Undulating
41	12	78	351	7.6	-	18-20	NA	Dry	III-IV	Granite
42	12	41	269	1.2	0-10	18	None	Dry	III-IV	Granite
43	12	54	279	8.2	10-38	20	None	Dry	III-IV	Granite
44	12	86	342	7.6	13-457	18-20	None	Dry	IV	Granite
45	12	57	318	-	-	16-18	None	Dry	IV	Granite

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
46	12	79	318	-	-	-	-	Dry	-	Granite
47	12	87	328	-	-	-	-	Dry	-	Granite
48	12	47	283	-	NA	-	NA	Dry	IV	Granite
49	12	82	301	-	-	-	-	Dry	-	Granite
50	12	82	320	-	-	-	-	Dry	-	Granite
51	12	75	314	-	-	-	-	Dry	-	Granite
52	12	89	327	-	-	-	-	Dry	-	Granite
53	1	76	256	1.5	0	5	NA	Dry	IV	Schist
54	1	41	81	0.9	0	3	NA	Dry	III	Schist
55	1	66	347	1.8	-	5	NA	Dry	III-IV	Schist
56	1	76	254	3.0	76	2	Weathered schist	Dry	II-III	Schist
57	1	77	248	0.6	102	5	Weathered schist	Dry	IV	Schist
58	1	74	261	3.7	10-76	2	Weathered schist	Dry	III	Schist
59	1	69	261	3.7	0-25	2	Weathered schist	Dry	II-III	Schist
60	1	74	328	0.3	NA	12-14	NA	Dry	I-II	Schist
61	1	71	352	3.7	NA	18-20	NA	Dry	III-IV	Schist
62	1	17	114	1.5	-	16-18	NA	Dry	III-IV	Schist
63	1	86	358	3.0	0-13	2	None	Dry	II-III	Schist
64	2	55	71	1.5	0-152	2	None	Dry	II	Schist
65	2	52	353	0.9	0	16-18	NA	Dry	III	Schist
66	2	75	320	1.2	0-152	18-20	Negligible to none	Dry	III	Schist

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
67	10	85	233	1.4	0	4	NA	Dry	IV-V	Schist - Joint
68	10	20	063	-	-	-	-	Dry	V	Schist - Foliation
69	10	69	321	0.4	0	3-4	None	Dry	V	Schist - Joint
70	10	85	165	0.7	0	2-3	None	Dry	V	Schist - Joint
71	10	84	238	0.5	NA	6	NA	Dry	V	Schist - Joint
72	10	87	243	-	NA	5	NA	Dry	V	Schist - Joint
73	10	28	065	0.5	0	2	None	Dry	V	Schist - Foliation
74	10	68	273	0.2	0	2	None	Dry	IV-V	Schist - Joint
75	10	80	092	0.2	0	2	None	Dry	V	Schist - Joint
76	10	81	236	1.7	10	4-5	Weathered rock material	Dry	IV-V	Schist - Joint
77	10	64	265	0.4	0	17	None	Dry	IV-V	Schist - Joint/ Wedge
78	10	82	343	0.3	0	7	None	Dry	IV-V	Schist - Joint/ Wedge
79	10	82	225	0.6	NA	8	NA	Dry	IV-V	Schist - Joint
80	10	86	230	1.1	NA	6-8	NA	Dry	IV-V	Schist - Joint
81	10	89	154	0.2	0	2	None	Dry	IV-V	Schist - Joint
82	10	89	155	0.5	NA	6	NA	Dry	IV-V	Schist - Joint
83	10	32	084	0.8	0	2	None	Dry	IV-V	Schist - Foliation
84	10	69	259	0.4	0	2	None	Dry	IV	Schist - Joint
85	10	10	025	-	-	-	NA	Dry	IV	Schist - Foliation
86	10	44	053	-	-	-	-	Dry	III	Schist - Foliation
87	10	43	086	-	-	-	-	Dry	-	Schist - Foliation
88	10	41	113	-	-	-	-	Dry	-	Schist - Foliation
89	10	60	254	-	-	-	-	Dry	-	Schist - Joint

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
90	10	83	161	-	-	-	-	Dry	-	Schist - Joint
91	10	32	081	-	-	-	-	Dry	-	Schist - Foliation
92	10	79	323	-	-	-	-	Dry	-	Schist - Joint
93	10	85	060	-	-	-	-	Dry	-	Schist - Joint
94	10	35	065	0.8	0	5	None	Dry	III	Schist - Foliation
95	10	81	221	1.2	NA	2-3	NA	Dry	IV	Schist - Joint
96	10	49	086	-	-	-	-	Dry	-	Schist - Joint
97	10	88	134	-	-	-	-	Dry	-	Schist - Joint
98	10	53	258	-	-	-	-	Dry	-	Schist - Joint
99	10	39	108	-	-	-	-	Dry	-	Schist - Foliation
100	10	80	335	-	-	-	-	Dry	-	Schist - Joint
101	10	73	265	-	-	-	-	Dry	-	Schist - Joint
102	10	52	262	-	-	-	-	Dry	-	Schist - Joint
103	10	83	236	-	-	-	-	Dry	-	Schist - Joint
104	10	88	151	2.3	-	2	None	Dry	III-IV	Schist - Joint
105	10	70	259	-	-	-	-	Dry	-	Schist - Joint
106	11	87	101	1.1	0	2	None	Dry	IV	Schist - Joint
107	11	80	065	-	-	-	-	Dry	-	Schist - Foliation
108	11	75	256	0.5	0-2	3	None	Dry	IV	Schist - Joint
109	11	89	315	0.3	-	10-12	None	Dry	IV	Schist - Joint
110	11	87	148	-	-	-	-	Dry	-	Schist - Joint
111	11	48	059	-	-	-	-	Dry	-	Schist - Foliation
112	11	50	264	0.22	0	10	None	Dry	IV	Schist
113	11	87	332	0.11	0	10	None	Dry	IV	Schist
114	11	60	081	0.4	2	10-12	None	Dry	IV	Schist - Joint

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
115	11	43	075	-	-	-	-	Dry	-	Schist - Foliation
116	11	32	010	-	-	-	-	Dry	-	Schist - Foliation
117	11	58	079	-	-	-	-	Dry	-	Schist - Foliation
118	11	64	260	0.5	0-6	10-12	None	Dry	IV	Schist - Joint
119	12	34	351	-	-	-	-	Dry	IV-V	Schist - Foliation
120	12	34	348	-	-	-	-	Dry	IV-V	Schist - Foliation
121	12	82	251	-	-	-	-	Dry	IV-V	Schist - Joint
122	12	89	253	1.7	0-5	10-12	None	Dry	IV-V	Schist - Joint
123	12	89	266	3.7	-	8-10	None	Dry	IV	Schist - Joint
124	12	87	330	0.6	0-20	2-3	None	Dry	IV-V	Schist - Foliation/ Wedge
125	12	82	258	0.8	0-20	2-3	None	Dry	IV-V	Schist - Foliation/ Wedge
126	12	85	250	1.1	0-10	2-3	None	Dry	IV	Schist - Joint
127	13	35	003	-	-	-	-	Dry	-	Schist
128	13	80	215	4.6	NA	18	NA	Dry	IV	Pegmatite
129	13	84	259	3.0	0	16	None	Dry	IV-V	Pegmatite
130	13	42	172	3.0	NA	-	NA	Dry	IV-V	Pegmatite
131	13	79	271	2.6	0-13	18	None	Dry	IV-V	Pegmatite
132	13	57	198	-	-	-	-	Dry	IV-V	Pegmatite
133	13	67	224	1.8	0	16-18	None	Dry	IV-V	Pegmatite
134	13	75	239	0.9	0-2	16	None	Dry	IV-V	Pegmatite
135	13	79	041	0.3	5-10	18	Some weathered rocks	Dry	IV-V	Pegmatite
136	13	67	224	-	-	-	-	Dry	-	Pegmatite

Region 1										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
137	13	79	070	-	-	-	-	Dry	-	Pegmatite
138	13	72	323	1.8	0-20	8	None	Dry	-	Pegmatite
139	11	-	-	2.1	-	-	-	Dry	-	Pegmatite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling Material	Water	Weathering (Dearman, 1976)	Rock Type/Notes
140	24	74	253	6.1	76-127	15	Some Broken granite	Dry	III	Granite
141	24	83	136	6.1	-	15	Some Broken granite	Dry	III	Granite
142	24	74	253	6.1	51-127	18-20	Broken granite	Dry	III-IV	Granite
143	24	76	316	4.6	51-127	18-20	None	Dry	III	Granite
144	24	77	320	4.6	51-127	18-20	None	Dry	III	Granite
145	24	88	306	4.6	38-102	18-20	None	Dry	III	Granite
146	24	88	209	2.1	102	15	Broken rocks	Dry	III-IV	Granite
147	24	60	256	2.1	76-152	18-20	None	Dry	III	Granite
148	24	66	262	2.1	76-152	18-20	None	Dry	III	Granite
149	24	88	130	2.4	25-76	18-20	None	Dry	III-IV	Granite
150	24	75	262	1.5	76	18-20	None	Dry	III	Granite
151	24	75	253	1.5	76-152	18-20	None	Dry	III	Granite
152	24	74	265	1.5	0	NA	None	Dry	-	Granite
153	24	74	260	3.0	0	NA	None	Dry	-	Granite
154	24	83	215	2.4	0	18-20	Broken rocks	Dry	III	Granite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
155	24	78	214	2.4	152	18-20	None	Dry	III	Granite
156	24	67	257	2.4	64-203	8-10	Broken rocks and Soil	Dry	IV	Granite
157	24	64	124	-	-	-	-	Dry	-	Granite
158	24	85	86	-	-	-	-	Dry	-	Granite
159	27	89	005	7.6	305	2	Some Broken rocks and Soil	Dry	II	Granite
160	27	80	332	7.6	305-610	15	Broken rocks	Dry	III	Granite
161	27	85	181	-	-	-	-	-	-	Granite
162	27	78	340	-	-	-	-	-	-	Granite
163	27	69	306	-	-	-	-	-	-	Granite
164	8	39	050	4.6	6-25	16-18	None	Dry	III-IV	Granite
165	8	41	065	2.4	10-229	16-18	None	Dry	III-IV	Granite
166	8	89	144	3.0	0-25	15	Soil	Dry	III-IV	Granite
167	8	82	100	7.0	38-610	8	Soil	Dry	III-IV	Granite
168	8	76	304	-	-	-	-	Dry	-	Granite
169	8	89	099	-	-	-	-	Dry	-	Granite
170	8	62	323	2.2	0-13	NA	None	Dry	II	Granite
171	8	78	172	1.0	0	5	None	Dry	-	Granite
172	8	32	142	4.0	0-13	8	None	Dry	III	Granite
173	8	24	097	-	-	-	-	Dry	-	Granite
174	8	24	065	-	-	-	-	Dry	-	Granite
175	8	41	057	-	-	-	-	Dry	-	Granite
176	8	80	138	3.0	NA	14	NA	Dry	III-IV	Granite
177	8	28	078	-	-	-	-	Dry	-	Granite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
178	8	20	064	4.4	6-102	8-10	None	Dry	III-IV	Granite
179	8	70	004	-	-	-	-	Dry	-	Granite
180	8	82	096	4.9	NA	10-12	NA	Dry	III	Granite
181	8	87	093	-	-	-	-	Dry	-	Granite
185	9	64	275	3.4	5	2-3	None	Dry	III	Granite
186	9	52	284	1.5	6	2-3	None	Dry	III	Granite
187	9	60	023	2.3	13-19	2-3	None	Dry	III-IV	Granite/Wedge
188	9	89	109	2.4	13-19	2-3	None	Dry	III-IV	Granite/Wedge
189	9	50	135	2.6	NA	6-8	NA	Dry	III	Granite
190	9	48	132	3.0	NA	8-10	NA	Dry	III	Granite
191	9	53	286	7.0	0-6	2	None	Dry	III	Granite
192	9	43	121	3.5	5-10	6-8	None	Dry	II	Granite
193	9	78	292	0.6	5	6	Soil	Dry	III-IV	Granite
194	9	83	300	0.8	64	6	None	Dry	IV-V	Granite
195	14	85	321	4.9	5-51	6-8	None	Dry	III	Granite
196	14	85	001	4.9	10-51	6-8	None	Dry	III	Granite/Wedge
197	14	83	312	4.9	10-51	6-8	None	Dry	III	Granite/Wedge
198	14	77	162	-	-	-	-	Dry	-	Granite
199	14	20	232	-	-	-	-	Dry	-	Granite
200	14	53	069	-	-	-	-	Dry	-	Granite
201	14	87	149	-	-	-	-	Dry	-	Granite
202	14	82	323	-	-	-	-	Dry	-	Granite
203	14	81	322	-	-	-	-	Dry	-	Granite
204	14	85	186	-	-	-	-	Dry	-	Granite
205	14	83	324	-	-	-	-	Dry	-	Granite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
206	14	78	326	-	-	-	-	Dry	-	Granite
207	14	65	260	-	-	-	-	Dry	-	Granite
208	14	89	124	-	-	-	-	Dry	-	Granite
209	14	74	313	-	-	-	-	Dry	-	Granite
210	14	85	129	-	-	-	-	Dry	-	Granite
211	14	77	315	-	-	-	-	Dry	-	Granite
212	14	73	244	-	-	-	-	Dry	-	Granite
213	14	81	202	-	-	-	-	Dry	-	Granite
214	14	80	324	-	-	-	-	Dry	-	Granite
215	14	80	253	-	-	-	-	Dry	-	Granite
216	14	83	313	-	-	-	-	Dry	-	Granite
217	14	72	256	-	-	-	-	Dry	-	Granite
218	14	80	302	-	-	-	-	Dry	-	Granite
219	14	85	036	-	-	-	-	Dry	-	Granite
220	14	70	259	-	-	-	-	Dry	-	Granite
221	14	25	133	-	-	-	-	Dry	-	Granite
222	14	70	172	-	-	-	-	Dry	-	Granite
223	14	17	235	-	-	-	-	Dry	-	Granite
224	15	81	193	-	-	-	-	Dry	-	Granite
225	15	82	158	-	-	-	-	Dry	-	Granite
226	15	25	049	-	-	-	-	Dry	-	Granite
227	15	69	233	-	-	-	-	Dry	-	Granite
228	15	73	192	-	-	-	-	Dry	-	Granite
229	15	62	225	-	-	-	-	Dry	-	Granite
230	15	32	054	-	-	-	-	Dry	-	Granite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
231	15	68	289	-	-	-	-	Dry	-	Granite
232	15	65	218	-	-	-	-	Dry	-	Granite
233	15	72	316	-	-	-	-	Dry	-	Granite
234	15	84	319	-	-	-	-	Dry	-	Granite
235	15	45	089	2.4	1-25	8-10	None	Dry	-	Granite
236	15	89	347	7.0	152-305	14-16	Some Soil and broken rocks	Dry	III	Granite
237	15	87	345	16.8	NA	8	NA	Dry	III	Granite
238	15	19	086	-	-	-	-	Dry	-	Granite
239	15	79	012	7.9	NA	8	NA	Dry	III	Granite
240	15	80	316	8.2	0-305	8-10	None	Dry	III	Granite
241	15	69	053	1.2	0-13	6-8	None	Dry	III	Granite
242	15	75	254	0.5	5-20	4-5	None	Dry	III-IV	Granite
243	15	83	255	1.5	0-13	2	Soil	Dry	III	Granite
244	15	22	083	-	-	-	-	Dry	-	Granite
245	15	87	183	4.0	635	-	None	Dry	III-IV	Granite
246	15	85	189	4.0	635	8-10	None	Dry	III-IV	Granite
247	15	69	090	-	-	-	-	Dry	-	Granite
248	15	84	091	-	-	-	-	Dry	-	Granite
249	15	31	047	-	-	-	-	Dry	IV	Granite
250	15	85	279	3.4	89	8-10	Soil	Damp	IV	Granite
251	15	38	080	-	-	-	-	Dry	-	Granite
252	15	41	034	-	-	-	-	Dry	-	Granite
253	15	26	018	-	-	-	-	Dry	-	Granite
254	15	18	082	-	-	-	-	Dry	-	Granite

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
255	15	70	310	-	-	-	-	Dry	-	Granite
256	15	84	243	-	-	-	-	Dry	-	Granite
257	15	33	045	2.8	38-127	18-20	None	Dry	IV	Granite
258	15	41	038	2.3	51-254	5-6	None	Dry	IV	Granite
259	15	84	330	-	-	-	-	Dry	-	Granite
260	16	89	332	13.7	NA	5	NA	Dry	IV	Granite
261	16	84	322	-	-	-	-	Dry	-	Granite
262	16	37	053	5.8	0-41	8-10	Some broken rocks	Dry	IV	Granite
263	16	23	281	3.8	0-20	10	None	Dry	III-IV	Granite
264	16	29	213	1.5	0-20	16-18	None	Dry	IV	Granite
265	16	52	094	6.1	0-5	5	None	Dry	III-IV	Granite
266	16	89	335	-	-	-	-	Dry	-	Granite
267	16	80	251	-	-	-	-	Dry	-	Granite
268	16	89	195	-	-	-	-	Dry	-	Granite
269	16	78	259	-	-	-	-	Dry	-	Granite
270	16	87	171	3.7	0-13	3	Soil	Dry	III	Granite
271	16	48	316	-	-	-	-	-	-	Granite
272	16	41	312	-	-	-	-	-	-	Granite
273	16	54	286	-	-	-	-	-	-	Granite
274	16	51	234	-	-	-	-	-	-	Granite
182	8	37	024	-	-	-	-	Dry	-	Schist
183	8	73	324	-	-	-	-	Dry	-	Schist - Joint
184	8	77	060	-	-	-	-	Dry	-	Schist - Foliation
275	24	75	162	1.8	0	2-4	None	Dry	III	Schist

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
276	24	71	228	1.8	0	2-4	None	Dry	III	Schist
277	24	20	050	-	-	-	-	Dry	-	Schist - Foliation
278	24	45	053	-	-	-	-	Dry	-	Schist - Foliation
279	24	53	260	-	-	-	-	Dry	-	Schist - Joint
280	24	79	308	-	-	4-8	-	Dry	-	Schist
281	24	78	312	-	-	-	-	Dry	-	Schist
282	24	76	244	-	-	-	-	Dry	-	Schist
283	24	80	152	-	-	-	-	Dry	-	Schist
284	24	56	017	-	-	-	-	Dry	-	Schist
285	9	25	031	-	-	-	-	Dry	IV	Schist - Foliation
286	9	81	141	0.6	-	2	NA	Dry	IV	Schist - Joint
287	9	26	059	0.3	-	-	-	Dry	III-IV	Schist - Foliation
288	9	36	045	-	-	-	-	Dry	-	Schist - Foliation
289	9	26	054	-	-	-	-	Dry	-	Schist - Foliation
290	9	85	070	0.5	0	2	None	Dry	III	Schist - Joint
291	9	88	116	0.6	0	2	None	Dry	III	Schist - Joint/ Wedge
292	9	88	066	0.5	0	2	None	Dry	III	Schist - Joint/ Wedge
293	9	77	289	0.4	4	2	None	Dry	IV	Schist - Joint
294	9	28	046	0.8	0	2	None	Dry	III-IV	Schist - Foliation
295	9	88	340	-	-	-	-	Dry	-	Schist - Joint
296	9	79	328	0.1	-	2	-	Dry	III-IV	Schist
297	9	30	061	0.6	0	2	None	Dry	III-IV	Schist - Foliation
298	9	75	292	0.4	0	2	None	Dry	III-IV	Schist - Joint

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
299	9	86	035	0.2	0	2	None	Dry	IV	Schist - Joint
300	9	82	315	-	-	-	-	Dry	-	Schist - Joint
301	9	75	316	0.6	25	2	None	Dry	IV	Schist - Joint
302	9	85	288	1.5	20-36	8	Broken rocks	Dry	III-IV	Schist - Joint
303	9	69	178	1.2	20-36	8-10	Broken rocks	Dry	III-IV	Schist - Joint
304	9	82	295	-	-	-	-	Dry	-	Schist - Joint
305	9	40	009	-	-	-	-	Dry	-	Schist - Foliation
306	9	70	179	3.0	NA	8	NA	Dry	IV	Schist - Joint
307	9	82	291	-	-	-	-	Dry	-	Schist - Joint
308	9	71	194	-	-	-	-	Dry	-	Schist - Joint
309	9	86	068	-	-	-	-	Dry	-	Schist - Joint
310	9	81	328	-	-	-	-	Dry	-	Schist - Joint
311	9	18	045	-	-	-	-	Dry	IV-V	Schist - Foliation
312	9	50	065	-	-	-	-	Dry	IV-V	Schist - Foliation
313	9	08	045	-	-	-	-	Dry	-	Schist - Foliation
314	9	87	068	-	-	-	-	Dry	-	Schist - Joint
315	9	53	086	-	-	-	-	Dry	-	Schist - Joint
316	9	35	038	-	-	-	-	Dry	-	Schist - Foliation
317	9	80	353	-	-	-	-	Dry	IV-V	Schist - Joint
318	9	79	288	-	-	-	None	Dry	IV-V	Schist - Joint
319	9	55	162	-	-	-	None	Dry	IV-V	Schist - Joint
320	9	73	014	-	-	-	-	Dry	IV-V	Schist - Joint
321	9	36	066	-	-	-	-	Dry	IV-V	Schist - Foliation
322	9	43	131	-	-	-	-	Dry	-	Schist - Joint
323	9	43	067	-	-	-	-	Dry	-	Schist - Foliation

Region 2										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
324	9	84	275	-	-	-	-	Dry	-	Schist - Joint
325	9	86	298	0.8	0	10	None	Dry	V	Schist - Joint
326	9	69	323	3.0	0	10	None	Dry	III-IV	Pegmatite
327	9	67	316	2.4	0	8	None	Dry	III-IV	Pegmatite
328	9	85	095	7.6	0	8-10	None	Dry	IV	Pegmatite
329	9	88	095	-	-	-	-	Dry	-	Pegmatite
330	9	39	265	1.8	5-10	8-10	Weathered pegmatite	Dry	IV	Pegmatite
331	9	85	187	0.6	NA	10-12	NA	Dry	IV	Pegmatite
332	9	70	168	-	-	-	-	Dry	-	Pegmatite
333	9	89	167	-	-	-	-	Dry	-	Pegmatite
334	9	85	292	0.4	0	6	None	Dry	IV	Pegmatite/Wedge
335	9	72	169	0.6	0	6	None	Dry	IV	Pegmatite/Wedge
336	9	51	258	3.7	0-10	10	None to Some Soil	Dry	IV	Pegmatite
337	9	64	162	1.5	NA	8-10	NA	Dry	III-IV	Pegmatite
338	9	13	256	0.8	10	16	None	Dry	III	Pegmatite
339	9	64	068	-	-	-	-	Dry	-	Pegmatite
340	9	81	291	7.6	6-76	10	Soil/Broken rocks	Dry	III-IV	Pegmatite
341	9	89	128	2.4	0-25	10	None	Dry	III	Pegmatite
342	9	58	250	0.8	0	18	None	Dry	IV	Pegmatite
343	9	78	355	4.0	3-25	15	None	Dry	III-IV	Pegmatite
344	9	80	298	1.2	38-89	10	Broken rocks	Dry	IV	Pegmatite

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling Material	Water	Weathering (Dearman, 1976)	Rock Type/Notes
345	21	65	291	4.6	0-5	2	None	Dry	II	Granite
346	21	83	263	5.0	0-25	2	None	Dry	II	Granite
347	21	35	328	2.1	25-38	NA	None	Dry	III	Granite
348	21	38	208	4.9	0-6	4-6	None	Dry	III	Granite/Undulating
349	21	90	212	4.6	0-13	2	None	Dry	II	Granite
350	21	47	235	3.7	6-102	20	None to some weathered granite	Dry	III-IV	Granite/Undulating
351	21	-	-	3.7	6-13	2	None	Dry	II	Granite
352	21	90	234	9.1	25-38	4	None to slight to some granite	Dry	III	Granite/Undulating
353	21	-	-	9.1	NA	NA	NA	Dry	III	Granite
354	21	85	254	3.0	0-6	2	None	Dry	II	Granite
355	21	53	199	2.4	0	18-20	None	Dry	III	Granite/Undulating
356	21	73	180	4.6	0-25	4	Weathered rock pieces	Dry	III	Granite
357	21	73	221	2.4	0-25	NA	Quartz	Dry	III	Granite
358	21	87	318	2.4	6	2	None	Dry	II-III	Granite
359	21	87	261	5.2	0-25	2	Granite infill	Dry	II	Granite
360	21	87	255	5.2	0-25	2	Granite infill	Dry	II	Granite
361	21	75	266	-	0	2	None	Dry	II	Granite

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
362	21	78	260	3.7	0	2	None	Dry	-	Granite
363	21	67	122	3.5	6-51	2	Broken rocks	Dry	I	Granite
364	21	69	264	3.7	6-51	2	Broken rocks	Dry	I	Granite
365	21	32	095	9.1	0	NA	None	Dry	II	Granite
366	21	83	329	4.6	13-76	2	Broken rocks and Soil	Damp	III	Granite/Undulating
367	21	89	350	8.5	610-1219	2-3	Broken rocks and Soil	Dry	III	Granite
368	21	82	033	8.5	610-1219	2-3	Broken rocks and Soil	Dry	III	Granite
369	21	89	319	8.5	610-1219	2-3	None	Dry	III	Granite
370	21	87	045	22	1219	18-20	None	Damp	III	Granite
371	21	80	355	-	-	-	-	-	-	Granite
372	21	77	336	8.5	610-1219	4-5	Soil and Broken rocks	Dry	III	Granite
373	21	80	329	5	-	18-20	NA	Dry	III	Granite
374	21	85	206	1.5	0	2	None	Dry	II	Granite
375	21	46	210	20	610	NA	Dike pegmatite	Dry	II	Granite
376	21	89	236	2.4	0	2	None	Dry	II	Granite
377	22	86	201	4.6	13-51	8-10	Broken rocks	Dry	IV	Granite
378	22	74	352	4.6	76-102	18-20	Weathered material	Dry	III-IV	Granite
379	22	89	252	2.4	0	3	None	Dry	-	Granite
380	22	76	005	3.7	0	3	None	Dry	-	Granite
381	22	24	295	0.5	0	6	None	Dry	III	Granite

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
382	22	89	292	2.4	0	3	None	Dry	III	Granite
383	22	77	012	3.7	0	3	None	Dry	III	Granite
384	22	72	027	18	76-305	18-20	None	Dry	III-IV	Granite
385	22	64	213	-	-	-	-	Dry	-	Granite
386	22	62	203	-	-	-	-	Dry	-	Granite
387	22	78	245	2.4	0-6	2-4	None	Dry	III	Granite
388	22	61	264	1.2	19-38	2-4	None	Dry	III	Granite
389	22	86	216	3.0	0	2	None	Dry	III	Granite
390	23	47	032	4.6	38-152	2	Weathered rocks	Dry	III-IV	Granite
391	23	76	249	1.8	6-13	8-10	None	Dry	III-IV	Granite
392	23	75	179	0.9	76	15-16	None	Dry	III-IV	Granite
393	23	81	015	32.8	610-1067	18-20	Dike of quartz	Dry	IV	Granite
394	23	83	030	24.4	NA	20	NA	Dry	II-III	Granite
395	23	76	295	24.4	6-25	15-16	None	Dry	II	Granite
396	23	89	206	24.4	229-305	15-16	Rocks	Dry	III	Granite
397	23	76	304	24.4	229-305	15-16	Rocks	Dry	III	Granite
398	23	78	143	24.4	6-25	15-16	None	Dry	II-III	Granite
399	23	72	313	24.4	76-229	20	Broken rocks	Dry	III-IV	Granite
400	23	74	121	0.9	6	4-6	None	Dry	-	Granite
401	23	83	205	0.9	0	4-6	None	Dry	-	Granite/Wedge
402	23	79	343	0.9	0	2	None	Dry	III	Granite/Wedge
403	23	72	301	30.5	25-457	18-20	None	Dry	III-IV	Granite
404	23	81	256	4.6	0	20	None	Dry	III-IV	Granite

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
405	23	60	009	3.0	0	20	None	Dry	III-IV	Granite
406	23	-	-	1.8	0	6-8	None	Dry	III-IV	Granite
407	23	37	065	-	NA	NA	NA	Dry	-	Schist - Foliation
408	23	25	091	-	-	-	-	Dry	-	Schist
409	23	74	281	1.2	NA	2	None	Dry	III-IV	Schist
410	23	40	091	-	-	-	-	Dry	-	Schist - Foliation
411	23	85	176	-	-	-	-	Dry	-	Schist
412	23	60	060	-	-	-	-	Dry	-	Schist - Foliation
413	23	76	292	-	-	-	-	Dry	-	Schist
414	23	38	082	-	-	-	-	Dry	-	Schist - Foliation
415	23	67	306	-	-	-	-	Dry	-	Schist - Joint
416	23	36	100	-	-	-	-	Dry	-	Schist - Foliation
417	23	66	270	-	-	-	-	Dry	-	Schist - Joint
418	23	73	085	-	-	-	-	Dry	-	Schist - Joint
419	23	44	094	-	-	-	-	Dry	-	Schist - Foliation
420	25	41	072	-	-	-	-	-	-	Schist - Foliation
421	25	73	197	1.5	3	2-4	None	Dry	III	Schist - Joint
422	25	40	100	-	-	-	-	-	-	Schist - Foliation
423	25	65	294	-	-	-	-	-	-	Schist
424	25	87	190	-	-	-	-	-	-	Schist - Joint
425	25	61	126	3.0	NA	2-4	NA	Dry	III	Schist - Joint
426	25	65	282	-	0	2-4	None	Dry	II	Schist - Joint
427	25	74	172	-	-	-	-	-	-	Schist
428	25	76	264	-	-	-	-	-	-	Schist - Joint
429	25	68	275	1.2	0	10	None	Dry	III-IV	Schist - Joint

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
430	25	84	267	-	-	-	-	-	-	Schist - Joint
431	25	60	280	-	-	-	-	-	-	Schist - Joint
432	25	60	275	1.8	0	2-4	None	Dry	III	Schist - Joint
433	25	61	255	-	-	-	-	-	-	Schist - Joint
434	25	41	074	-	-	-	-	-	-	Schist - Foliation
435	25	81	315	1.5	0	2-4	None	Dry	II	Schist - Joint
436	25	67	220	2.4	152-254	2-4	None	Dry	III	Schist - Joint
437	25	32	081	-	-	-	-	-	-	Schist - Foliation
438	25	62	270	-	-	-	-	-	-	Schist - Joint
439	25	72	272	0.6	6-25	2	Soil	Dry	III	Schist - Joint
440	25	41	257	0.5	0	8	None	Dry	III	Schist - Joint
441	25	71	086	-	-	-	-	-	-	Schist - Foliation
442	25	86	323	-	-	-	-	-	-	Schist - Joint
443	25	80	291	-	-	-	-	-	-	Schist - Joint
444	25	38	054	-	-	-	-	-	-	Schist - Foliation
445	25	71	281	-	-	-	-	-	-	Schist - Joint
446	25	24	062	-	-	-	-	-	-	Schist - Foliation
447	25	67	289	1.5	25-76	2-4	None	Dry	III	Schist - Joint
448	25	64	273	2.1	0-25	2	None	Dry	II	Schist - Joint
449	26	70	252	0.6	0	2	None	Dry	II	Schist - Joint
450	26	89	81	-	-	-	-	Dry	-	Schist - Joint
451	26	88	163	3.7	NA	18-20	NA	Dry	II-III	Schist - Joint
452	26	66	261	18.3	51-102	2-4	Soil and rock material	Dry	III	Schist - Joint
453	26	68	266	-	-	-	-	Dry	-	Schist - Joint

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
454	26	62	255	-	-	2	-	Dry	-	Schist - Joint
455	26	72	225	-	-	2	-	Dry	-	Schist - Joint
456	26	60	256	9.1	NA	18-20	NA	Dry	III	Schist - Joint
457	26	88	223	2.4	0	16-20	None	Dry	II	Schist - Joint
458	26	60	257	1.8	0	8-10	None	Dry	III	Schist - Joint
459	26	22	64	-	-	-	-	Dry	-	Schist - Foliation
460	26	81	159	-	-	-	-	Dry	-	Schist - Joint
461	26	61	260	1.2	NA	8-10	NA	Dry	III	Schist - Joint
462	26	89	343	1.5	0	18-20	None	Dry	III	Schist - Joint
463	26	71	223	1.5	0	18-20	None	Dry	III	Schist - Joint
464	26	65	264	1.2	0	8-10	None	Dry	III	Schist - Joint
465	26	61	261	-	-	-	-	Dry	-	Schist - Joint
466	26	48	250	-	-	-	-	Dry	-	Schist - Joint
467	26	80	161	-	-	-	-	Dry	-	Schist - Joint
468	26	89	144	-	-	-	-	Dry	-	Schist - Joint
469	26	50	246	-	-	-	-	Dry	-	Schist - Joint
470	26	68	150	-	-	-	-	Dry	-	Schist - Joint
471	26	70	154	0.6	0	4-6	None	Dry	III	Schist - Joint
472	26	55	266	-	-	-	-	Dry	-	Schist - Joint
473	26	80	148	9.1	0-13	4-6	None	Dry	III	Schist - Joint
474	26	71	260	9.1	0-13	4-6	None	Dry	III	Schist - Joint
475	26	74	336	-	-	-	-	Dry	-	Schist - Joint
476	26	61	264	9.1	0-13	16-18	Weathered rocks	Dry	III	Schist - Joint
477	26	52	84	-	-	-	-	Dry	-	Schist - Joint

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
478	26	55	256	-	-	-	-	Dry	-	Schist - Joint
479	26	68	3	-	-	-	-	Dry	-	Schist - Joint
480	26	51	81	-	-	-	-	Dry	-	Schist - Joint
481	26	58	303	-	-	-	-	Dry	-	Schist - Joint
482	26	57	291	-	-	-	-	Dry	-	Schist - Joint
483	26	85	150	-	-	-	-	Dry	-	Schist - Joint
484	26	71	263	-	-	-	-	-	-	Schist - Joint
485	28	57	70	-	-	-	-	-	-	Schist - Foliation
486	28	83	314	-	-	-	-	-	-	Schist - Joint
487	28	80	124	-	-	-	-	-	-	Schist - Joint
488	28	81	312	-	-	-	-	-	-	Schist - Joint
489	28	86	315	-	-	-	-	-	-	Schist - Joint
490	28	54	67	-	-	-	-	-	-	Schist - Foliation
491	28	53	284	-	-	-	-	-	-	Schist - Joint
492	28	64	310	-	-	-	-	-	-	Schist - Joint
493	28	40	75	-	-	-	-	-	-	Schist - Foliation
494	28	55	320	-	-	-	-	-	-	Schist - Joint
495	28	85	270	-	-	-	-	-	-	Schist - Joint
496	28	70	260	-	-	-	-	-	-	Schist - Joint
497	28	85	190	-	-	-	-	-	-	Schist - Joint
498	28	59	260	-	-	-	-	-	-	Schist - Joint
499	28	56	273	-	-	-	-	-	-	Schist - Joint
500	28	37	25	-	-	-	-	-	-	Schist - Foliation
501	28	37	65	-	-	-	-	-	-	Schist - Foliation

Region 3										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
502	28	76	305	-	-	-	-	-	-	Schist - Joint
503	28	74	200	-	-	-	-	-	-	Schist - Joint

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling Material	Water	Weathering (Dearman, 1976)	Rock Type/Notes
504	3-1	80	329	2.1	13-38	2	Some weathered granite	Dry	III	Granite
505	3-1	84	228	2.1	NA	18-20	NA	Dry	III	Granite
506	3-1	82	326	2.4	NA	2	NA	Dry	III	Granite
507	3-1	80	296	2.4	NA	2	NA	Dry	III	Granite
508	3-1	82	328	3.0	0	2	None	Dry	III	Granite
509	3-1	90	143	3.0	25-51	2	Negligible to some weathered granite	Dry	III	Granite
510	3-1	90	203	3.7	NA	2	NA	Dry	III	Granite
511	3-1	88	256	3.0	NA	2	NA	Dry	III	Granite
512	3-2	18	329	1.5	0	2	None	Dry	I-II	Granite
513	3-2	75	323	2.4	NA	2	NA	Dry	III	Granite
514	3-2	68	117	2.4	25-51	18-20	Negligible	Dry	III-IV	Granite/Undulating
515	3-2	82	351	15.2	NA	2	NA	Dry	III	Granite
516	3-2	90	338	12.2	25-76	2	None	Dry	III	Granite

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
517	3-2	69	272	15.2	0	2	None	Dry	-	Granite
518	17	50	94	0.7	10-152	20	None	Dry	III-IV	Granite
519	17	77	245	0.9	0-5	4-5	None	Dry	IV	Granite
520	17	77	269	2.4	10-41	12-14	Some Broken rocks	Dry	IV	Granite
521	17	79	241	2.4	2.5-15	12-14	Soil	Dry	IV	Granite
522	17	78	342	7.6	NA	20	NA	Dry	III	Granite
523	17	71	338	7.6	NA	18-20	NA	Dry	III	Granite
524	17	53	257	3.4	2.5-305	14-15	Soil	Dry	III-IV	Granite
525	17	61	113	2.4	2-10	NA	Soil	Dry	IV	Granite
526	17	60	085	0.9	0-5	10-12	None	Dry	IV	Granite
527	17	52	092	0.9	0-5	10-12	None	Dry	IV	Granite
528	17	66	102	0.6	0-20	16-18	Soil	Dry	III-IV	Granite
529	17	72	303	1.2	51-152	18-20	Soil	Dry	IV	Granite
530	17	86	266	1.8	0-71	14-16	None	Dry	III	Granite
531	17	77	134	7.6	-	18-20	Soil	Dry	III-IV	Granite
532	17	75	111	7.6	51-610	20	-	Dry	-	Granite
533	17	79	344	-	-	-	-	Dry	-	Granite
534	17	49	040	-	-	-	-	Dry	-	Granite
535	17	83	124	7.6	762-1372	20	Soil	Dry	-	Granite
536	17	86	126	7.6	762-1372	20	Soil	Dry	-	Granite
537	17	84	136	-	-	-	-	Dry	-	Granite
538	17	49	155	1.2	0-2	16-18	None	Dry	IV	Granite
539	17	85	137	6.1	1219-1829	20	None	Dry	III-IV	Granite

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
540	17	33	218	0.9	0	18-20	None	Dry	III-IV	Granite
541	17	84	336	-	-	-	-	Dry	-	Granite
542	17	84	336	1.2	5-10	10	None	Dry	III	Granite
543	17	26	221	-	-	-	-	Dry	-	Granite
544	17	81	127	-	-	-	-	Dry	-	Granite
545	17	88	002	9.1	0-6	6-8	None	Dry	-	Granite
546	17	77	246	-	-	-	-	Dry	-	Granite
547	17	60	327	-	-	-	-	Dry	-	Granite
548	17	72	247	-	-	-	-	Dry	-	Granite
549	17	76	032	-	-	-	-	Dry	-	Granite
550	17	72	250	-	-	-	-	Dry	-	Granite
551	17	78	238	-	-	-	-	Dry	-	Granite
552	17	81	125	27.4	10-89	18-20	None	Dry	III-IV	Granite/Wedge
553	17	84	017	27.4	10-89	18-20	None	Dry	III-IV	Granite/Wedge
554	17	75	127	-	-	-	-	Dry	-	Granite
555	17	25	295	-	-	-	-	Dry	-	Granite
556	17	89	353	-	-	-	-	Dry	-	Granite
557	17	77	357	-	-	-	-	Dry	-	Granite
558	17	80	355	27.4	-	-	-	Dry	-	Granite
559	17	86	137	-	NA	20	NA	Dry	III-IV	Granite
560	18	82	228	5.5	305-1524	20	Broken rocks	Dry	IV	Granite
561	18	80	228	1.2	25	20	Broken rocks	Dry	IV	Granite
562	18	72	356	-	-	20	-	Dry	-	Granite/Undulating
563	18	87	320	-	-	-	-	Dry	-	Granite
564	18	83	357	-	-	-	-	Dry	-	Granite

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
565	18	85	357	-	-	-	-	Dry	-	Granite
566	18	89	260	-	-	-	-	Dry	-	Granite
567	18	89	197	-	-	-	-	Dry	-	Granite
568	18	81	098	-	-	-	-	Dry	-	Granite
569	18	76	195	-	-	-	-	Dry	-	Granite
570	18	78	184	-	-	-	-	Dry	-	Granite
571	29	77	325	1.1	0-10	10	None	Dry	III	Granite
572	29	-	-	-	-	-	-	Dry	III	Granite
573	29	-	-	2.0	-	10	NA	Dry	III	Granite
574	29	71	327	1.1	0	NA	None	Dry	III	Granite
575	29	-	-	0.8	-	12	NA	Dry	III	Granite
576	29	-	-	-	-	-	-	Dry	III	Granite
577	29	71	315	0.9	0-100	12	None	Dry	III	Granite
578	29	42	041	1.2	0	6	None	Dry	III-IV	Granite
579	29	79	320	2.4	0-20	8	None	Dry	III	Granite
580	29	77	288	1.2	0	18	None	Dry	III	Granite
581	29	68	062	2.4	-	12-14	NA	Dry	III	Granite
582	29	37	035	2.7	0	20	None	Dry	III-IV	Granite
583	29	74	311	0.5	30	6-8	None	Dry	III	Granite
584	29	20	031	1.5	0-457	10-12	None	Dry	III	Granite
585	4	-	-	7.6	25-305	20	Broken rocks	Dry	III	Granite
586	4	73	226	0.9	0-13	18-20	None	Dry	III-IV	Granite
587	4	80	209	3.4	0-13	18-20	None	Dry	III-IV	Granite
588	4	78	316	10.3	NA	20	NA	Dry	III-IV	Granite
589	4	33	107	1.5	0	20	None	Dry	III	Granite/Undulating

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
590	4	79	302	1.8	25-51	20	None	Dry	III	Granite
591	4	88	319	2.7	13-51	18	Soil and Broken rocks	Dry	III	Granite
592	4	14	255	4.3	0-6	18	None	Dry	III	Granite
593	4	80	303	1.5	NA	18	NA	Dry	III	Granite
594	4	02	221	22.9	0-25	20	None	Dry	III	Granite
595	4	74	305	4.3	0-13	18	None	Dry	III	Granite
596	4	80	311	3.4	0-25	18-20	Soil	Dry	III	Granite
597	4	88	015	21.3	-	16-18	None	Dry	III	Granite
598	4	86	313	21.3	-	16-18	None	Dry	III	Granite
599	5	21	000	6.4	-	20	-	Dry	III	Granite
600	5	72	316	6.4	NA	8-10	NA	Dry	III	Granite
601	5	73	010	26	0-127	18-20	None	Dry	III	Granite
602	5	26	347	1.2	5-10	10	None	Dry	III	Granite
603	5	83	298	4.6	NA	18-20	NA	Dry	III	Granite
604	5	88	328	4.3	0-51	18-20	None	Dry	II-III	Granite
605	5	74	347	10.1	6-305	20	None	Dry	III	Granite
606	5	84	272	2.7	10-305	10	None	Dry	III	Granite
607	5	87	282	2.7	NA	10-12	NA	Dry	III	Granite
608	5	70	296	4.0	6-38	-	None	Dry	III	Granite
609	6	87	337	18.6	305-1727	18-20	None	Dry	III-IV	Granite
610	6	84	317	18.6	305-1727	18-20	None	Dry	III-IV	Granite
611	6	80	316	18.6	305-1727	18-20	None	Dry	III-IV	Granite
612	6	87	329	18.6	305-610	18-20	None	Dry	III	Granite
613	6	80	316	18.6	305-610	18-20	None	Dry	III	Granite

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
614	6	72	235	6.1	6-203	10	None	Dry	III	Granite
615	6	43	240	5.2	6-25	18-20	None	Dry	II-III	Granite
616	6	88	326	21.1	305-1829	18-20	Some Broken rocks	Dry	III	Granite
617	6	84	310	21.1	305-1829	18-20	Rocks	Dry	III	Granite
618	6	59	213	4.6	6-610	5	None	Dry	III	Granite
619	6	54	206	-	-	-	-	Dry	-	Granite
620	6	71	231	4.6	152-610	18-20	None	Dry	III	Granite
621	6	75	239	4.6	152-610	18-20	None	Dry	III	Granite
622	6	58	236	-	-	-	-	Dry	-	Granite
623	7	86	332	7.6	203-610	16	Broken rocks	Dry	III	Granite
624	7	78	319	7.6	203-610	16	Broken rocks	Dry	III	Granite
625	7	86	340	-	-	-	-	Dry	-	Granite
626	7	72	315	-	-	-	-	Dry	-	Granite
627	7	83	324	-	-	-	-	Dry	-	Granite
628	7	78	006	-	-	16-18	None	Dry	III	Granite
629	7	51	272	3.4	0-25	18	None	Dry	III-IV	Granite
630	7	70	344	7.3	-	-	Some Broken rocks	Dry	-	Granite
631	7	81	001	7.3	-	-	Some Broken rocks	Dry	-	Granite
632	7	64	001	7.3	305-762	16	Some Broken rocks	Dry	-	Granite
633	7	89	141	-	-	-	-	Dry	-	Granite
634	7	82	258	9.8	6	10-12	None	Dry	III	Granite
635	7	28	274	-	-	-	-	Dry	-	Granite

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
636	7	80	271	-	-	-	-	-	-	Granite
637	7	23	196	-	-	-	-	-	-	Granite
638	7	81	311	-	-	-	-	-	-	Granite
639	7	80	246	-	-	-	-	-	-	Granite
640	7	80	310	-	-	-	-	Dry	-	Granite
641	19	79	306	5.2	-	20	-	Dry	IV	Granite
642	19	90	108	6.7	-	20	-	Dry	IV	Granite
643	19	76	259	15.2	-	-	-	Dry	-	Granite
644	19	86	138	-	-	-	-	Dry	-	Granite
645	20	86	249	9.1	-	-	-	Dry	-	Granite
646	20	61	140	-	-	-	-	Dry	IV	Granite
647	20	77	135	2.4	-	-	-	Dry	-	Granite/Wedge
648	20	88	243	3.4	-	-	-	Dry	-	Granite/Wedge
649	20	80	248	3.0	-	-	-	Dry	-	Granite
650	20	85	254	-	-	-	-	Dry	-	Granite
651	20	84	024	-	-	-	-	Dry	-	Granite
652	3-3	81	216	0.8	0	2	None	Dry	III	Schist
653	3-3	68	012	1.8	NA	2	NA	Dry	III	Schist
654	3-3	66	328	0.6	NA	2	NA	Dry	III	Schist
655	3-3	90	177	3.0	6-76	2	None	Dry	III	Schist
656	3-3	88	261	3.7	0-13	3-4	None	Dry	III	Schist
657	3-3	56	341	1.0	NA	20	None	Dry	III-IV	Schist
658	3-3	79	288	3.0	0	2-4	None	Dry	III	Schist
659	3-3	68	015	3.0	NA	4-6	NA	Dry	III	Schist
660	3-3	78	240	3.0	6-13	6-8	None	Dry	III	Schist

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
661	3-3	81	315	3.0	6-13	6-8	None	Dry	III	Schist
662	3-3	59	337	0.6	NA	2	NA	Dry	III	Schist
663	3-3	66	276	6.1	0-6	2-4	None	Dry	-	Schist
664	3-3	76	274	6.1	0-6	2-4	None	Dry	-	Schist
665	3-3	83	353	24.4	76-305	4-6	Broken rocks	Damp	III	Schist
666	3-3	89	331	24.4	NA	20	NA	Dry	III	Schist
667	17	86	117	-	-	-	-	Dry	-	Schist - Foliation
668	17	68	115	-	-	-	-	Dry	-	Schist - Foliation
669	17	78	239	-	-	-	-	Dry	-	Schist - Joint
670	17	64	169	-	-	-	-	Dry	-	Schist - Joint
671	17	84	009	-	-	-	-	Dry	-	Schist - Joint
672	17	58	042	-	-	-	-	Dry	-	Schist - Foliation
673	17	44	043	-	-	-	-	Dry	-	Schist - Foliation
674	29	67	048	1.2	0	NA	None	Dry	III-IV	Schist - Foliation
675	30	82	289	2.0	10-25	12	None	Dry	III	Schist
676	30	85	320	2.1	51-61	8-10	None	Dry	III-IV	Schist
677	30	59	064	0.8	0	6	None	Dry	III	Schist - Foliation
678	30	71	242	1.5	0	12	None	Dry	III-IV	Schist
679	30	80	317	1.5	-	6	NA	Dry	III-IV	Schist
680	30	76	292	2.1	0-38	8-10	None	Dry	III-IV	Schist
681	30	89	355	4.6	25-457	16-18	None	Dry	III-IV	Schist
682	30	74	314	0.9	0	4-6	None	Dry	III	Schist - Joint
683	30	60	083	0.6	0-13	NA	None	Dry	-	Schist - Foliation
684	30	75	050	-	-	-	-	Dry	-	Schist - Foliation
685	30	70	083	1.5	0-25	5	Rocks & Soil	Dry	III	Schist

Region 4										
No.	L	Dip	Dip Direction	Continuity (m)	Aperture (mm)	JRC	Infilling	Water	Weathering (Dearman, 1976)	Rock Type/Notes
686	31	74	221	1.1	NA	18	NA	Dry	III-IV	Schist - Joint
687	31	80	319	1.5	0	8-10	None	Dry	III	Schist - Joint
688	31	85	224	1.5	0	8-10	None	Dry	III	Schist - Joint
689	31	79	316	1.1	0-10	6-8	None	Dry	III	Schist - Joint
690	31	31	116	0.3	0	4-6	None	Dry	III-IV	Schist - Joint
691	31	74	326	0.8	0-13	18	None	Dry	III	Schist - Joint
692	31	84	208	0.8	0-13	18	None	Dry	III	Schist - Joint
693	31	79	319	0.3	0	4-6	None	Dry	III	Schist - Joint
694	31	83	309	-	-	-	-	Dry	-	Schist
695	31	79	318	8.2	NA	18-20	NA	Dry	III	Schist - Joint
696	31	77	317	2.1	0	18	None	Dry	III	Schist - Joint
697	31	74	357	2.1	0-10	18-20	None	Dry	III	Schist - Joint
698	31	75	290	2.1	0-10	18-20	None	Dry	III	Schist - Joint
699	31	64	243	1.2	0-10	16-18	None	Dry	III	Schist - Foliation
700	31	67	225	3.7	6-305	20	Broken rocks	Dry	III-IV	Schist - Foliation
701	31	75	336	6.1	NA	18-20	NA	Dry	III	Schist - Joint
702	4	59	072	2.1	0	2-3	None	Dry	III	Schist - Foliation
703	4	75	323	3.7	0-38	18	Soil	Dry	III	Schist - Joint
704	4	74	232	3.7	NA	20	NA	Dry	III	Schist - Joint

APPENDIX E: LABORATORY DATA (DENSITY, ABSORPTION, BASIC ANGLE OF
FRICTION, UNCONFINED COMPRESSIVE STRENGTH, TENSILE STRENGTH, SLAKE
DURABILITY, FREEZE-THAW DURABILITY)

Table E.1: Density measurement data and results as determined in the laboratory. Note: L=length; D=diameter.

Rock Block Sample #	Core /Disk	Sample Type	Mass (g)	Measure-ment 1 (cm)		Measure-ment 2 (cm)		Measure-ment 3 (cm)		Measure-ment 4 (cm)		Measure-ment 5 (cm)		Density (g/cm ³)	Density (lb/ft ³)
				L	D	L	D	L	D	L	D	L	D		
1a	A	Schist	177.0	2.5	5.7	2.5	5.7	2.6	5.7	2.6	5.7	2.6	5.7	2.7	170.5
1a	B	Schist	177.8	2.6	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.6	5.7	2.7	171.3
1a	C	Schist	179.7	2.6	5.7	2.6	5.7	2.6	5.7	2.6	5.7	2.6	5.7	2.8	173.1
1b	A	Schist	176.3	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.7	169.8
1b	B	Schist	183.1	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.8	176.4
1b	C	Schist	181.6	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.5	5.7	2.8	174.9
2	A	Granite	948.5	14.2	5.7	14.2	5.7	14.2	5.7	14.2	5.7	14.2	5.7	2.6	163.4
2	B	Granite	885.9	13.3	5.7	13.3	5.7	13.3	5.7	13.3	5.7	13.3	5.7	2.6	163.0
2	C	Granite	891.1	13.3	5.7	13.3	5.7	13.3	5.7	13.3	5.7	13.3	5.7	2.6	163.9
3	A	Granite	803.4	12.2	5.7	12.2	5.7	12.2	5.7	12.2	5.7	12.2	5.7	2.6	161.4
3	B	Granite	927.7	14.0	5.7	14.0	5.7	14.0	5.7	14.0	5.7	14.0	5.7	2.6	162.4
3	C	Granite	874.5	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	2.6	162.3
4	A	Granite	879.2	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	2.6	163.8
4	B	Granite	932.5	13.9	5.7	13.9	5.7	13.9	5.7	13.9	5.7	13.9	5.7	2.6	164.1
4	C	Granite	902.5	13.5	5.7	13.5	5.7	13.5	5.7	13.5	5.7	13.5	5.7	2.6	163.6
5	A	Granite	880.2	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	2.6	163.4
5	B	Granite	877.2	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	13.2	5.7	2.6	162.8
5	C	Granite	855.7	13.0	5.7	13.0	5.7	13.0	5.7	13.0	5.7	13.0	5.7	2.6	161.3

Table E.2: Absorption measurement data and results as determined in the laboratory.

Rock Block Sample #	Core	Sample Type	Mass (g)	Absorption (%)
1a	A	Schist	918.1	0.8
1a	B	Schist	877.1	0.8
1a	C	Schist	814.0	0.8
1b	A	Schist	192.4	1.4
1b	B	Schist	130.2	1.6
1b	C	Schist	222.3	1.4
2	A	Granite	949.4	0.7
2	B	Granite	887.0	0.7
2	C	Granite	893.9	0.7
3	A	Granite	808.9	1.1
3	B	Granite	931.7	1.1
3	C	Granite	885.2	1.1
4	A	Granite	890.6	0.8
4	B	Granite	939.2	0.7
4	C	Granite	914.5	0.7
5	A	Granite	890.3	1.0
5	B	Granite	879.9	1.0
5	C	Granite	868.0	1.0

Table E.3: Basic friction angle measurement data and results as determined in the laboratory for the rock block samples.

Rock Block Sample #	Sample Type	Tilt Angle Trial 1 (degrees)	Tilt Angle Trial 2 (degrees)	Tilt Angle Trial 3 (degrees)	Average Tilt Angle (degrees)	Basic Angle of Friction (degrees)
1a	Schist	37	36	36	36	40
1b	Schist	NA	NA	NA	NA	NA
2	Granite	36	37	37	37	41
3	Granite	38	37	41	39	43
4	Granite	37	37	37	37	41
5	Granite	36	36	37	36	40

Table E.4: Unconfined compressive strength (UCS) test measurement data and results as determined by the standard test method (ASTM, 2013).

Rock Block Sample #	Core	Sample Type	Average Core length (in)	Average Core Diameter (in)	Length to Diameter Ratio	Cross Sectional Area of Core (in²)	Failure Load (lb)	Time to Failure (min)	Rate of Loading (lb/min)	UCS (lb/in²)
1a	A	Schist	4.6	2.2	2.1	3.9	32985	20.7	1591	8403
1a	B	Schist	NA	NA	NA	NA	NA	NA	NA	NA
1a	C	Schist	NA	NA	NA	NA	NA	NA	NA	NA
1b	A	Schist	NA	NA	NA	NA	NA	NA	NA	NA
1b	B	Schist	NA	NA	NA	NA	NA	NA	NA	NA
1b	C	Schist	NA	NA	NA	NA	NA	NA	NA	NA
2	A	Granite	5.6	2.2	2.5	4.0	32451	20.8	1562	8209
2	B	Granite	5.2	2.2	2.3	4.0	27903	12.5	2232	7058
2	C	Granite	5.2	2.2	2.3	4.0	24066	12.2	1968	6088
3	A	Granite	4.8	2.2	2.1	3.9	15800	6.0	2633	4002
3	B	Granite	5.5	2.2	2.5	3.9	16532	11.5	1434	4188
3	C	Granite	5.2	2.2	2.3	3.9	15583	11.2	1391	3947
4	A	Granite	5.2	2.2	2.3	3.9	17026	16.9	1009	4313
4	B	Granite	5.5	2.2	2.4	4.0	17481	16.9	1034	4422
4	C	Granite	5.3	2.2	2.4	4.0	14515	10.6	1372	3672
5	A	Granite	5.2	2.2	2.3	3.9	17679	11.6	1520	4478
5	B	Granite	5.2	2.2	2.3	3.9	16710	15.9	1050	4233
5	C	Granite	5.1	2.2	2.3	3.9	13645	12.0	1142	3456

Table E.5: Unconfined compressive strength (UCS) measurement data and test results as determined with the point load test method (ASTM, 2008b). The ram area used in the calculations for each test was 14.426 cm². Note: PLI = point load index; Val = valid; Inval = invalid.

Rock Block Sample #	Co-re	Rock Type	Avg. length (cm)	Avg. Diameter W (cm)	Platen Separation, D (cm)	Pressure Gage Reading at Failure (kg/cm ²)	Failure Load, P (kg)	De ² (cm ²)	PLI, Is (MN/m ²)	Size Corrected PLI, Is(50) (MN/m ²)	Results	UCS (MN/m ²)	UCS (lb/in ²)
1a	A	Schist	4.9	5.7	5.0	61	880	36	2.4	2.6	Val	63	9076
1a	B	Schist	5.2	5.7	5.4	54.9	NA	39	NA	NA	Inval	NA	NA
1a	C	Schist	5.3	5.7	5.4	62	NA	39	NA	NA	Inval	NA	NA
1b	A	Schist	4.0	5.7	4.0	27	NA	29	NA	NA	Inval	NA	NA
1b	B	Schist	4.2	5.7	4.3	41.3	NA	31	NA	NA	Inval	NA	NA
1b	C	Schist	4.1	5.7	4.2	38.8	NA	30	NA	NA	Inval	NA	NA
2	A	Granite	5.3	5.7	5.5	49	707	40	1.8	2.0	Val	47	6820
2	B	Granite	5.2	5.7	5.3	53.5	772	38	2.0	2.2	Val	52	7609
2	C	Granite	5.2	5.7	5.3	41.5	599	38	1.5	1.7	Val	41	5902
4	A	Granite	5.2	5.7	5.3	35.4	511	38	1.3	1.4	Val	35	5035
4	B	Granite	5.2	5.7	5.4	38	548	39	1.4	1.5	Val	37	5365
4	C	Granite	5.2	5.7	5.4	37	534	39	1.3	1.5	Val	36	5187

Table E.6: Tensile strength measurement data and test results as determined in the laboratory for the rock block samples.

Rock Block Sample #	Core	Sample Type	Average Disk Thickness (in)	Average Disk Diameter (in)	Failure Load (lb)	Time to Failure (min)	Rate of Loading (lb/min)	Tensile Strength (lb/in²)
1a	A	Schist	1.0	2.2	2670	7.0	384	754
1a	B	Schist	1.0	2.2	2511	5.0	507	698
1a	C	Schist	1.0	2.2	2729	6.3	433	758
1b	A	Schist	1.0	2.2	2511	8.0	316	714
1b	B	Schist	1.0	2.2	3362	6.5	521	954
1b	C	Schist	1.0	2.2	1978	4.2	474	561
2	A	Granite	1.0	2.2	1483	2.6	570	421
2	B	Granite	1.0	2.2	1701	6.7	253	474
2	C	Granite	1.0	2.2	1839	4.9	375	520
3	A	Granite	1.0	2.2	989	1.0	989	277
3	B	Granite	1.0	2.2	1028	1.3	779	288
3	C	Granite	1.0	2.2	929	2.2	428	260
4	A	Granite	1.0	2.2	1365	9.2	148	384
4	B	Granite	1.0	2.2	1167	2.0	598	335
4	C	Granite	1.0	2.2	1226	5.0	244	340
5	A	Granite	1.0	2.2	949	1.8	536	265
5	B	Granite	1.0	2.2	1048	4.3	247	297
5	C	Granite	1.0	2.2	949	5.2	181	265

Table E.7: Slake durability measurement data and results as determined in the laboratory.

Rock Block Sample #	Sample Type	Weight of Pan (g)	Dry weight of pan + sample (g)	Dry weight of pan + sample after 1 cycle (g)	Dry weight of pan + sample after 2 cycles (g)	1st Cycle Slake Durability Index, I_{d1} (%)	2nd Cycle Slake Durability Index, I_{d2} (%)
1a	Schist	13.7	526.2	511.8	503.2	97.2	95.5
1b	Schist	13.7	526.5	383.8	328.7	72.2	61.4
2	Granite	13.7	525.4	512.1	505.2	97.4	96.1

Table E.8: Freeze-thaw measurement data and durability test results.

Rock Block Sample #	Rock Type	Sub ID	Initial Mass (g)	Final Mass (g) (after ~300 cycles)	Total Mass Lost (g)	% Change
1a	Schist	A	362.1	349.4	12.7	3.5
		B	248.9	188.7	60.2	24.2
		C	252.7	251.3	1.4	0.6
		D	170.7	169.7	1	0.6
		E	193.6	192.9	0.7	0.4
		F	155.2	145.2	10	6.4
1b	Schist	A	538.5	465.3	73.2	13.6
		B	527.4	517.7	9.7	1.8
		C	517.2	511.4	5.8	1.1
		D	376.2	371.1	5.1	1.4
		E	229.8	221.1	8.7	3.8
		F	192.7	170.5	22.2	11.5
2	Granite	A	388.9	386.9	2	0.5
		B	380.8	379	1.8	0.5
		C	391.1	379.5	11.6	3.0
		D	300.6	299.5	1.1	0.4
		E	371.4	367.4	4	1.1
		F	343.7	342.6	1.1	0.3
3	Granite	A	375.1	372.9	2.2	0.6
		B	232	229.7	2.3	1.0
		C	175.5	174.1	1.4	0.8
		D	167.1	165.9	1.2	0.7
		E	175.8	175.1	0.7	0.4
		F	81.3	80.6	0.7	0.9

Table E.8 continued						
4	Granite	A	151	150.3	0.7	0.5
		B	420.6	411.9	8.7	2.1
		C	156.5	155.8	0.7	0.4
		D	87.9	87.2	0.7	0.8
		E	201.7	200.8	0.9	0.4
		F	231.4	230.6	0.8	0.3
5	Granite	A	296.8	293.3	3.5	1.2
		B	322	312.1	9.9	3.1
		C	476.8	473.5	3.3	0.7
		D	108	107	1	0.9
		E	107.6	107.1	0.5	0.5
		F	126.9	126.3	0.6	0.5

APPENDIX F: FAILED-SAMPLE PICTURES

Figure F.1: The core of schist sample 1a failed using ASTM method D7012-13. This was the only core of sufficient dimensions obtained from the rock blocks, and therefore was the only core failed for schist 1a.

Figure F.2: The three schist 1a samples failed using method ASTM method D3967-08. The disks are listed as 1a-A, 1a-B, and 1a-C in Table E.6 in Appendix E.

Figure F.3: The three schist 1a samples failed using the point load test following ASTM, 2008b. Only the first sample labeled 1-A in the image on the far left provided valid test results as the other two samples did not fail with a clean break through the sample.

Figure F.4: The three schist 1b samples failed using ASTM method D3967-08. Note: Due to its schistose nature, schist 1b did not provide cores of sufficient size to fail samples using ASTM method D7012-13.

Figure F.5: The three schist 1b samples failed using the point load test following ASTM, 2008b. None of the samples failed with a clean break; therefore all of the data collected from the test was invalid.

Figure F.6: The three granite 2 cores failed using ASTM method D7012-13.

Figure F.7: The three granite 2 samples failed using ASTM method D3967-08. The disks are listed as 1a-A, 1a-B, and 1a-C in Table E.6 in Appendix E.

Figure F.8: The three granite 2 samples failed using the point load test following ASTM, 2008b.

Figure F.9: The three granite 3 cores failed using ASTM method D7012-13.

Figure F.10: The three granite 3 samples failed using ASTM method D3967-08. The disks are listed as 1a-A, 1a-B, and 1a-C in Table E.6 in Appendix E.

Figure F.11: The three granite 4 cores failed using ASTM method D7012-13.

Figure F.12: The three granite 4 samples failed using ASTM method D3967-08. The disks are listed as 1a-A, 1a-B, and 1a-C in Table E.6 in Appendix E.

Figure F.13: The three granite 4 samples failed using the point load test following ASTM, 2008b.

Figure F.14: The three granite 5 cores failed using ASTM method D7012-13.

Figure F.15: The three granite 5 samples failed using ASTM method D3967-08. The disks are listed as 1a-A, 1a-B, and 1a-C in Table E.6 in Appendix E.

APPENDIX G. HISTOGRAMS OF THE DISCONTINUITY DATA

Figure G.1: Region 1, granite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.2: Region 1, schist frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.3: Region 1, pegmatite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.4: Region 2, granite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.5: Region 2, schist frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.6: Region 2, pegmatite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.7: Region 3, granite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.8: Region 3, schist frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.9: Region 4, granite frequency histogram for the degree of weathering of the rock mass and the discontinuities using the chart by Dearman, 1976.

Figure G.10: Region 4, schist frequency histogram for the degree of weathering of the rock mass and the discontinuity using the chart by Dearman, 1976.

Figure G.11: Granite frequency histogram for the RQD at each region studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.12: Schist frequency histogram for the RQD at each region studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.13: Pegmatite frequency histogram for the RQD at each region studied at MORU. Note: Pegmatite rock was not encountered or there was not sufficient data on this rock type in regions 2-4. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.14: Region 1 frequency histogram for the continuity of the discontinuities within each rock type studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.15: Region 2 frequency histogram for the continuity of the discontinuities within each rock type studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.16: Region 3 frequency histogram for the continuity of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.17: Region 4 frequency histogram for the continuity of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.18: Region 1 frequency histogram for the spacing of the discontinuities for each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.19: Region 2 frequency histogram for the spacing of the discontinuities within each rock type studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.20: Region 3 frequency histogram for the spacing of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.21: Region 4 frequency histogram for the spacing of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.22: Region 1 frequency histogram for the JRC and roughness of the discontinuities within each rock type studied at MORU. Roughness was recorded as JRC in the field. The JRC values were categorized based on the RMR roughness classifications. Since there was not any literature found stating the conversion between JRC values and the RMR roughness classification categories, this study classified the JRC values based on judgement and field observations. The roughness classifications by Bieniawski (1989) are in parentheses next to the JRC values. JRC values of 2 fell in the slightly rough category based on field observations.

Figure G.23: Region 2 frequency histogram for the JRC and roughness of the discontinuities within each rock type studied at MORU. Roughness was recorded as JRC in the field. The JRC values were categorized based on the RMR roughness classifications. Since there was not any literature found stating the conversion between JRC values and the RMR roughness classification categories, this study classified the JRC values based on judgement and field observations. The roughness classifications by Bieniawski (1989) are in parentheses next to the JRC values. JRC values of 2 fell in the slightly rough category based on field observations.

Figure G.24: Region 3 frequency histogram for the JRC and roughness of the discontinuities for each rock type studied at MORU. Roughness was recorded as JRC in the field. The JRC values were categorized based on the RMR roughness classifications. Since there was not any literature found stating the conversion between JRC values and the RMR roughness classification categories, this study classified the JRC values based on judgement and field observations. The roughness classifications by Bieniawski (1989) are in parentheses next to the JRC values. JRC values of 2 fell in the slightly rough category based on field observations. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region.

Figure G.25: Region 4 frequency histogram for the JRC and roughness of the discontinuities for each rock type studied at MORU. Roughness was recorded as JRC in the field. The JRC values were categorized based on the RMR roughness classifications. Since there was not any literature found stating the conversion between JRC values and the RMR roughness classification categories, this study classified the JRC values based on judgement and field observations. The roughness classifications by Bieniawski (1989) are in parentheses next to the JRC values. JRC values of 2 fell in the slightly rough category based on field observations. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region.

Figure G.26: Region 1 frequency histogram for the infilling material of the discontinuities within each rock type studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.27: Region 2 frequency histogram for the infilling material of the discontinuities within each rock type studied at MORU. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.28: Region 3 frequency histogram for the infilling material of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.29: Region 4 frequency histogram for the infilling material of the discontinuities within each rock type studied at MORU. Note: Pegmatite was not encountered and/or there was not sufficient data collected of this rock type in this region. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.30: Frequency histogram for the aperture of the discontinuities within the granite studied in Region 1. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.31: Frequency histogram for the aperture of the discontinuities within the schist studied in Region 1. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.32: Frequency histogram for the aperture of the discontinuities within the pegmatite studied in Region 1. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.33: Frequency histogram for the aperture of the discontinuities within the granite studied in Region 2. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.34: Frequency histogram for the aperture of the discontinuities within the schist studied in Region 2. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.35: Frequency histogram for the aperture of the discontinuities within the pegmatite studied in Region 2. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.36: Frequency histogram for the aperture of the discontinuities within the granite studied in Region 3. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.37: Frequency histogram for the aperture of the discontinuities within the schist studied in Region 3. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.38: Frequency histogram for the aperture of the discontinuities within the granite studied in Region 4. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

Figure G.39: Frequency histogram for the aperture of the discontinuities within the schist studied in Region 4. Aperture was recorded in the field as a range from low to high. The average aperture was calculated from this range. The class sizes in the histogram are based on the range of values of the classification parameters in the RMR system (Bieniawski, 1989).

APPENDIX H: STEREONET ANALYSIS

Figure H.1: Stereonet plot of the contoured discontinuity pole data for all of granite rock studied at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 4% and above (as suggested in Rocscience, 2015a).

Figure H.2: Stereonet plot of the contoured discontinuity pole data for all of granite rock studied in Region 1 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joint set B was manually chosen and the cluster analysis function was not used for set B due to user judgement that the central point of the set should fall in the highest concentration area. The dip direction of set B is slightly greater than +/- 10 degree of the dip direction of set B in the data set with all of the granite discontinuity poles plotted, but it is believed that this is the same principal joint set. Principal joints were assigned based on clusters with maximum density concentrations of 5.4% and above since there were only 52 poles plotted for this region and the areas with 3.6%-5.4% have too much scatter to accurately estimate a principal joint set. (as suggested in Rocscience, 2015a).

Figure H.3: Stereonet plot of the contoured discontinuity pole data for all of granite rock studied in Region 2 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 4% and above since there were a decent quantity of poles plotted (132 poles).

Figure H.4: Stereonet plot of the contoured discontinuity pole data for all of granite rock studied in Region 3 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Sets A and E were manually chosen, and the cluster analysis was not used for these two sets since there is a lot of variability in the pole data in the southeast corner of the stereonet. Principal joints were assigned based on clusters with maximum density concentrations of 4.4% and above.

Figure H.5: Stereonet plot of the contoured discontinuity pole data for all of granite rock studied in Region 4 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 4% and above.

Figure H.6: Stereonet plot of the contoured discontinuity pole data for all of the granite sculptures at MORU. The poles in the data set were determined using the Split-FX software (Split Engineering, 2014). The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Set E was manually chosen by the user. The principal joints were assigned based on clusters with maximum density concentrations of 4.2% and above.

Figure H.7: Stereonet plot of the contoured discontinuity pole data for the combined areas of the granite sculptures and Region 3 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. The principal joints were assigned based on clusters with maximum density concentrations of 3.0% and above to include set E, which was a set seen in both data sets for Region 3 and the Split-FX data for the sculptures.

Figure H.8: Stereonet plot of the contoured discontinuity pole data for all of schist rock studied at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Set E was manually chosen by the user so that the central point of the set fell within the highest density concentration. Principal joints were assigned based on clusters with maximum density concentrations of 3.5% and above since there were several hundred poles plotted (as suggested in Rocscience, 2015a).

Figure H.9: Stereonet plot of the contoured discontinuity pole data for all of schist rock studied in Region 1 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 4.4% and above.

Figure H.10: Stereonet plot of the contoured discontinuity pole data for all of schist rock studied in Region 2 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Sets A and E were manually chosen by the user and scatter was taken into account. The user did not agree with the cluster analysis for these two sets. The dip direction of set D is less than +/- 10 degree of the dip direction of set D in the data set with all of the schist discontinuity poles plotted, but it is believed that this is the same principal joint set. Principal joints were assigned based on clusters with maximum density concentrations of 4.8% and above.

Figure H.11: Stereonet plot of the contoured discontinuity pole data for all of schist rock studied in Region 3 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 4.2% and above.

Figure H.12: Stereonet plot of the contoured discontinuity pole data for all of schist rock studied in Region 4 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 5.7% and above.

Figure H.13: Stereonet plot of the contoured discontinuity pole data for all of pegmatite rock studied at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 6.0% and above.

Figure H.14: Stereonet plot of the contoured discontinuity pole data for all of pegmatite rock studied in Region 1 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Principal joints were assigned based on clusters with maximum density concentrations of 13.3% and above since there were only 11 poles plotted.

Figure H.15: Stereonet plot of the contoured discontinuity pole data for all of pegmatite rock studied in Region 2 at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. Sets L was manually chosen by the user and scatter was taken into account. The user did not agree with the cluster analysis for this set. The dip of set B is less than +/- 10 degrees of the dip of set B in the other discontinuity data sets plotted, but it is believed that this is the same principal joint set. Principal joints were assigned based on clusters with maximum density concentrations of 9.0% and above.

APPENDIX I: KINEMATIC ANALYSIS CONSIDERING PRINCIPAL JOINT SET PLANES
AND INTERSECTIONS

Figure I.1: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Jefferson's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is very low along the slope on the right side of Jefferson's nose.

Figure I.2: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Jefferson's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is very low along the slope on the left side of Jefferson's nose.

Figure I.3: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the front slope of Jefferson's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the slope on the front of Jefferson's nose.

Figure I.4: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Jefferson's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the slope on the right side of Jefferson's forehead.

Figure I.5: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Jefferson's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is very low along the slope on the left side of Jefferson's forehead.

Figure I.6: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the central slope of Jefferson's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is low along the central slope of Jefferson's forehead.

Figure I.7: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Jefferson's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Figure I.8: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Jefferson's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.

Figure I.9: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the front side of Jefferson's nose using the intersections of the principal joint set planes. There is no risk for wedge sliding on this slope as there are no intersections between the principal joint set planes which fall within the critical zone for wedge sliding.

Figure I.10: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Jefferson's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Figure I.11: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Jefferson's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.

Figure I.12: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope of Jefferson's forehead using the intersections of the principal joint set planes. There is no risk for wedge sliding on this slope as there are no intersections between the principal joint set planes which fall within the critical zone for wedge sliding.

Figure I.13: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the right slope on Jefferson's nose. There is a risk for oblique toppling, but no risk for direct toppling as there are intersections between the principal joint set planes which fall in the critical areas for oblique toppling, but not in the direct toppling area. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.14: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Jefferson's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.15: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope of Jefferson's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are only non-sliding release planes as there are critical pole vectors that fall within the friction cone (non-sliding release planes), but none that fall outside of the friction cone limits (sliding release planes).

Figure I.16: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Jefferson's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.17: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Jefferson's forehead. There is a risk for oblique toppling, but no risk for direct toppling as there are intersections between the principal joint set planes which fall in the critical areas for oblique toppling, but not in the direct toppling area. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.18: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Jefferson's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.19: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Jefferson's nose. There are 17 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.20: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Jefferson's nose. Principal joint set F has a 56% probability of failure with respect to the PJS planes in the set.

Figure I.21: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the front slope of Jefferson's nose. There are 4 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.22: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Jefferson's forehead. There are 27 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.23: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Jefferson's forehead. There are 15 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.24: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the central slope of Jefferson's forehead. There are 15 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.25: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Roosevelt's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the slope on the right side of Roosevelt's nose.

Figure I.26: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Roosevelt's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is very low along the slope on the left side of Roosevelt's nose.

Figure I.27: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the front slope of Roosevelt's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is low along the front slope of Roosevelt's nose.

Figure I.28: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Roosevelt's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is significant along the slope on the right side of Roosevelt's forehead as principal joint set I has a probability of 30%.

Figure I.29: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Roosevelt's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is very low along the slope on the left side of Roosevelt's forehead.

Figure I.30: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the central slope of Roosevelt's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. The probability of planar sliding is low along the central slope of Roosevelt's forehead.

Figure I.31: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Roosevelt's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets B and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.32: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Roosevelt's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.

Figure I.33: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope of Roosevelt's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets A and I) falls within the critical zone for wedge sliding.

Figure I.34: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Roosevelt's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets B and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.35: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Roosevelt's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.36: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Roosevelt's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.37: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Roosevelt's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.38: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Roosevelt's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.39: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Roosevelt's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.40: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Roosevelt's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.41: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Roosevelt's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.42: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Roosevelt's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.43: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Roosevelt's nose. There are 24 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.44: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Roosevelt's nose. There are 12 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.45: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the front slope of Roosevelt's nose. There are 19 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.46: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Roosevelt's forehead. There are 29 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.47: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Roosevelt's forehead. There are 19 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.48: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the central slope of Roosevelt's forehead. There are 20 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.49: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Lincoln's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is a risk for planar sliding on the right side of Lincoln's nose. Set B has a planar sliding probability of nearly 20%.

Figure I.50: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Lincoln's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the slope on the left side of Lincoln's nose.

Figure I.51: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the front of Lincoln's nose. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the slope on the front of Lincoln's nose.

Figure I.52: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the right side of Lincoln's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is a risk for planar sliding on the right side of Lincoln's forehead. Set F has a planar sliding probability of nearly 20%.

Figure I.53: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the slope on the left side of Lincoln's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is a risk for planar sliding on the right side of Lincoln's forehead. Set I has a planar sliding probability of 40%.

Figure I.54: Stereonet plot of the kinematic analysis evaluating the potential for planar sliding along the central slope of Lincoln's forehead. The outer boundary of the critical zone for planar sliding is constructed by taking 90 minus the slope dip. There is no risk of planar sliding along the central slope of Lincoln's forehead.

Figure I.55: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Lincoln's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and E, and sets B and I) fall within the critical zone for wedge sliding.

Figure I.56: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Lincoln's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.57: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope of Lincoln's nose using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as one intersection (Sets B and I) falls within the critical zone for wedge sliding.

Figure I.58: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Lincoln's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and E, and sets B and I) fall within the critical zone for wedge sliding.

Figure I.59: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Lincoln's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets A and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.60: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Lincoln's forehead using the intersections of the principal joint set planes. There is a risk for wedge sliding on this slope as two intersections (Sets B and I, and sets F and I) fall within the critical zone for wedge sliding.

Figure I.61: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Lincoln's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.62: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Lincoln's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.63: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Lincoln's nose. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.64: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Lincoln's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.65: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Lincoln's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.66: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope of Lincoln's forehead. There is a risk for direct and oblique toppling as there are intersections between the principal joint set planes which fall in the critical areas. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure I.67: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Lincoln's nose. There are 7 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.68: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Lincoln's nose. There are 18 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.69: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the front slope of Lincoln's nose. There are 27 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.70: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the right side of Lincoln's forehead. Principal joint set F has a 44% probability of failure with respect to the PJS planes in the set.

Figure I.71: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the slope on the left side of Lincoln's forehead. There are 22 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

Figure I.72: Stereonet plot of the kinematic analysis evaluating the potential for flexural toppling along the central slope on Lincoln's forehead. There are 27 total critical principal joint set planes (plotted as pole vectors on the stereonet) that may act as potential flexural topples.

APPENDIX J: KINEMATIC ANALYSIS CONSIDERING ALL DISCONTINUITY PLANES
AND INTERSECTIONS

Figure J.1: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Jefferson's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 14% with respect to the total number of intersections.

Figure J.2: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Jefferson's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections.

Figure J.3: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope on Jefferson's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 0.03% with respect to the total number of intersections.

Figure J.4: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Jefferson's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 6% with respect to the total number of intersections.

Figure J.5: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Jefferson's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 9% with respect to the total number of intersections.

Figure J.6: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Jefferson's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 3% with respect to the total number of intersections.

Figure J.7: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Jefferson's nose. There is a 13% probability of direct toppling and a 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.8: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Jefferson's nose. There is a 12% probability of direct toppling and 18% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.9: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Jefferson's nose. There is a 14% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.10: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Jefferson's forehead. There is a 19% probability of direct toppling and 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.11: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Jefferson's forehead. There is a 14% probability of direct toppling and 19% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.12: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Jefferson's forehead. There is a 17% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.13: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Roosevelt's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 11% with respect to the total number of intersections.

Figure J.14: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Roosevelt's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 11% with respect to the total number of intersections.

Figure J.15: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope on Roosevelt's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 6% with respect to the total number of intersections.

Figure J.16: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Roosevelt's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 14% with respect to the total number of intersections.

Figure J.17: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Roosevelt's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 19% with respect to the total number of intersections.

Figure J.18: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Roosevelt's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections.

Figure J.19: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Roosevelt's nose. There is a 17% probability of direct toppling and a 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.20: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Roosevelt's nose. There is an 11% probability of direct toppling and 16% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.23: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Roosevelt's forehead. There is a 21% probability of direct toppling and 22% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.24: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Roosevelt's forehead. There is a 23% probability of direct toppling and 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.25: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Lincoln's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 27% with respect to the total number of intersections.

Figure J.26: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Lincoln's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections.

Figure J.27: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the front slope on Lincoln's nose using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 7% with respect to the total number of intersections.

Figure J.28: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the right side of Lincoln's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 28% with respect to the total number of intersections.

Figure J.29: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the slope on the left side of Lincoln's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 13% with respect to the total number of intersections.

Figure J.30: Stereonet plot of the kinematic analysis evaluating the potential for wedge sliding along the central slope on Lincoln's forehead using the intersections of all of the discontinuity planes in the file. In the primary (red) critical zone for wedge sliding, wedges can slide on either two planes or one plane. In the secondary (yellow) critical zones for wedge sliding, wedges only slide on one plane. The potential for wedge sliding is 11% with respect to the total number of intersections.

Figure J.31: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Lincoln's nose. There is a 14% probability of direct toppling and a 17% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.32: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Lincoln's nose. There is a 23% probability of direct toppling and 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.33: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the front slope on Lincoln's nose. There is a 19% probability of direct toppling and 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.34: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the right side of Lincoln's forehead. There is a 15% probability of direct toppling and 18% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.35: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the slope on the left side of Lincoln's forehead. There is a 23% probability of direct toppling and 20% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

Figure J.36: Stereonet plot of the kinematic analysis evaluating the potential for direct and oblique toppling along the central slope on Lincoln's forehead. There is a 20% probability of direct toppling and 21% probability of oblique toppling with respect to the total number of intersections. There are both sliding and non-sliding release planes as there are critical pole vectors that fall both within the friction cone (non-sliding release planes) and outside of the friction cone limits (sliding release planes).

APPENDIX K: OVERALL SLOPE PROBABILISTIC ANALYSIS RESULTS

Figure K.1: Overall Slope Probabilistic Analysis considering the static condition for the entire slope on which the Jefferson sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters.

Figure K.2: Overall Slope Probabilistic Analysis considering the seismic condition (0.14 horizontal and vertical seismic load coefficients) for the entire slope on which the Jefferson sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a beta distribution (Slide indicates the RI was calculated using the normal distribution). Scale is in meters.

Figure K.3: Overall Slope Probabilistic Analysis considering the static condition for the entire slope on which the Roosevelt sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters.

Figure K.4: Overall Slope Probabilistic Analysis considering the seismic condition (0.14 horizontal and vertical seismic load coefficients) for the entire slope on which the Roosevelt sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a lognormal distribution. Scale is in meters.

Figure K.5: Overall Slope Probabilistic Analysis considering the static condition for the entire slope on which the Lincoln sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a gamma distribution (Slide indicates the RI was calculated using the normal distribution). Scale is in meters.

Figure K.6: Overall Slope Probabilistic Analysis considering the seismic condition (0.14 horizontal and vertical seismic load coefficients) for the entire slope on which the Lincoln sculpture is located. The Overall Slope Method results are indicated and the various colored slip surfaces are the Global Minimum slip surfaces generated by this method. The best fit for the F.S. values is a gamma distribution (Slide indicates the RI was calculated using the normal distribution). Scale is in meters.

APPENDIX L: STERENET USING RESPEC DISCONTINIUTY DATA REPORTED IN
BOYLE AND VOGT (1992)

Figure L.1: Stereonet plot of the contoured discontinuity pole data collected by RESPEC Inc. and reported in Boyle and Vogt (1992) for the granite sculptures at MORU. The principal joint sets are labeled. The cluster analysis function was used in the Dips program (Rocscience, 2016a) to determine the joint sets in order to account for scatter in the data, therefore the central point of the joint set may not fall in the area of the highest density contour. The principal joints were assigned based on clusters with maximum density concentrations of 6.0% and above.