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**ROCK SLOPE KINEMATICS OF
THE MISSION PEAK LANDSLIDE, FREMONT, CA**

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

By

Michael Jurasius

May 2002

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ABSTRACT

ROCK SLOPE KINEMATICS OF THE MISSION PEAK LANDSLIDE, FREMONT, CA

By Michael Jurasius

The stability of the Mission Peak Landslide head scarp is controlled by at least four pervasive discontinuities. Kinematic analyses of these discontinuities supported field evidence for: 1) flexural toppling along (J2: 76/110), 2) single plane sliding on (J4: 42/260), and 3) wedge failures incorporating sets sub parallel to (J1: 60/196). Block Theory was applied to the retrogressive block failures along the head scarp boundaries to identify the most unstable block geometry (key blocks) intersecting the scarp face. Predicted key block geometry was inconsistent with corresponding block molds in the scarp face. This was attributed to statistical orientation error, and inconsistencies in joint spacing.

Head block deformation and total rock debris runout distance were numerically modeled using Discontinuous Deformation Analysis (DDA). Pseudostatic analyses showed complex modes of failure correlative to field observations. Total rock debris runout distances were comparable to results computed from the energy-line method, though unreliable due to numerical creep and inconsistent kinematics under dynamic conditions.

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TABLE OF CONTENTS

	Page
STATEMENT OF PURPOSE	1
INTRODUCTION	2
Background	2
Project Overview	6
1998 Partial Reactivation of the Mission Peak Landslide	7
Regional Geologic Setting	8
Regional Hydrology	12
Mission Ridge Geomorphology	12
Other Studies	14
FIELD DATA	18
Introduction	18
Methods	20
Results and Discussion	22
STEREOGRAPHIC ANALYSIS	35
Introduction	35
Methods	38
Results and Discussion	40
BLOCK THEORY	50
Introduction	50
Principles of Block Theory	52
Assumptions	53
Conditions for Block Removability	55
Mode of Failure	57

Critical Key Block Method	58
Joint Combination Probability Parameter.....	59
Joint Pyramid Shape Parameter.....	60
Block Instability Parameter.....	60
Methods.....	62
Application to retrogressive Scarp Failure	62
Application of Block Theory on a Regional Scale.....	66
Results and Discussion	66
Retrogressive Scarp Failure Results	66
Regional Scale Block Theory Results	76
DISCONTINUOUS DEFORMATION ANALYSIS	87
Introduction	87
DDA Theory	89
Input Parameters	91
Model Output.....	94
Kinematics of Head-block Deformation.....	95
Head-block Deformation Results	97
Run-out Analysis Methods.....	112
Run-out Analysis Results.....	115
Discussion and Conclusions.....	116
CONCLUSIONS.....	124
REFERENCES CITED	129
APPENDIX A: FIELD DATA	132
APPENDIX B: STEREOGRAPHIC ANALYSIS.....	143
APPENDIX C: BLOCK THEORY DATA.....	145
APPENDIX D: DDA MODELS.....	162

LIST OF ILLUSTRATIONS

Figure	Page
1. Location Map of Mission Peak Landslide	3
2. Oblique Aerial Photo of the Head-scarp and Central Portion of the Mission Peak Landslide	4
3. Photo of Active Block Failure Sequence, July 22, 1998	5
4. Structural Cross Section and Photo of Briones/Orinda Fm. Contact.....	10
5. Photo of Briones Sandstone (Tbr) Outcrop Showing Heterogeneity in Fracture Spacing	11
6. Histograms of 1871-1999 Precipitation Records for Mission Ridge.....	13
7. Sackungen Diagram Modified from Kieffer 1998.....	15
8. Aerial Photo taken by U.S.G.S. July 1998 of Head Scarp Region with Annotated Structural Data Locations	19
9. Lower Hemisphere, Equal Area Projection of Discontinuity Poles	21
10. Fisher Distribution Contour Plot of Discontinuity Poles	21
11. Photo of Northern Flank Outcrop Showing Bedding and Joint Spacing	23
12. Aerial Photo of Head-scarp with Annotated Regional Structure	24
13. Photo of Right Flank Approximating J1 Orientation.....	25
14. Photo of Secondary Carbonate Seams Sub-parallel to Tbr.....	27
15. Photo of March 22, 1998 Right Flank of Head Scarp.....	28
16. Photo of J1 Cutting Across Steep Western Escarpment	29
17. Photo of Prominent Tension Crack Approximating J2.....	31

18. Photo of Western Scarp Face of Head-block Approximating J3.....	32
19. Photo Looking South Along Strike of Mission Ridge Approximating J4	34
20. Photo of Small Wedge Failure on Southern Flank of Head Scarp	36
21. Photo of Two Regional Scale Wedges.....	37
22. Regional Stereographic Toppling Analysis.....	41
23. Regional Stereographic Planar Failure Analysis.....	42
24. Wedge Stability Sensitivity Analysis for Location 34.....	44
25. Wedge Stability Sensitivity Analysis for Location 33.....	45
26. Wedge Stability Sensitivity Analysis for Location 31.....	46
27. Wedge Stability Sensitivity Analysis for Scar Block	47
28. Stereographic Projection of Joint Intersections From Active Raveling Region with Superposition of Pre-Post 1998 Head Scarp.....	48
29. Scale Diagram of Hypothetical Scar Block Failure Sequence	49
30. Photo of Upper Right Flank Showing Key Block Molds	51
31. Diagram of Block Types Modified after Goodman and Shi, 1985.....	54
32. Diagram of Block Removability Theorem for Two Dimensions Modified after Goodman and Shi, 1985.....	56
33. Aerial Photo Annotated with Six Excavation Surfaces Used in Analysis	65
34. Photo of Excavation Surface A	69
35. Photo of Excavation Surface B.....	70
36. Photo of Excavation Surface C.....	71

37. Photo of Excavation Surface D	72
38. Photo of Excavation Surface E.....	73
39. Photo of Excavation Surface F	74
40. Histogram Plot Summaries for Block Failure Likelihood Function.....	77
41. Histogram Plot Summaries for Joint Combination Probability	78
42. Histogram Plot Summaries for Shape Parameter	79
43. Histogram Plot Summaries for Block Instability Parameter.....	80
44. Enlarged Structural Location Map of Head-scarp Modified after Geolith Consultants, inc. 1998	83
45. Polar Projection of 56 Discontinuity Poles Modified after Geolith Consultants, Inc. 1998	83
46. Block Pyramids 0011-1 and 0111-1 Predicted to Fail in Key Block Analysis Modified after Geolith Consultants, Inc	83
47. Stereographic Projection of JPs 0101, 0111, and 0001 Generated from Four Dominant Joint Planes.....	85
48. Block Pyramids 0101-1 and 0111-1 Predicted to Fail in Key Block Analysis using Four Dominant Joint Planes	86
49. Oblique Aerial Photo of Head-Block Region.....	88
50. Diagram of Applied Block Boundary Conditions	94
51. Original Geometry for Joint Friction Sensitivity Analysis	99
52. Results of Joint Friction Sensitivity Analysis	100
53. Original Geometry for Joint Spacing $J_1 = 3$ m, $J_2 = 4.6$ m	102

54. Results of Head-block Deformation for J1 = 3 m, J2 = 4.6 m	103
55. Original Geometry for Joint Spacing J1 = 1.5 m, J2 = 4.6 m	105
56. Results of Head-block Deformation for J1 = 1.5 m, J2 = 4.6 m	106
57. Original Geometry for Joint Spacing J1 = 4.6m, J2 = 1.5 m	107
58. Results of Head-block Deformation for J1 = 4.6m, J2 = 1.5 m	108
59. The effect of $E = 1.0 \times 10^8$ psf on Head-block Deformation	109
60. The effect of $E = 1.0 \times 10^{10}$ psf on Head-block Deformation	110
61. The effect of $\nu = 0.25$ on Head-block Deformation	111
62. Rock Debris Run-out Paths used in DDA Analysis	113
63. Original Head-block Geometry and Run-out Path Profiles	114
64. Run-out Analysis Results for Path A-A	117
65. Run-out Analysis Results for Path B-B	118
66. Maximum Run-out Distance Determined from Energy-Line Method	
Modified after Geolith Consultants, Inc. 1998.....	122

Table

1. Physical Properties of the Briones Sandstone	40
2. Block Instability Parameter	62
3. Summary of Structural Data used in Key Block Analysis.....	63
4. Summary of Critical Key Block Analysis Results	68

STATEMENT OF PURPOSE

The purpose of this study was to test the applicability of two relatively new and alternative analytical methods to evaluate discontinuous rock masses: Block Theory and Discontinuous Deformation Analysis (DDA). These methods have recently been developed to aid interpretation of block kinematics and rock slope-stability. Neither technique has enjoyed widespread application to complex slope-stability problems. The intent of this work is to determine their validity using statistically averaged discontinuity orientations, utilizing assumed ranges of physical properties, such as friction, joint spacing, and deformation parameters. The stereographic methods of Hoek and Bray (1981) serve as a reconnaissance study to evaluate possible modes of failure and a means to estimate joint friction, cohesion, and the impact of pore water pressure on stability under limit equilibrium conditions.

The applicability of a given analysis depends both on how well the simplifying assumptions fit the observed structural and kinematic conditions in the field, and on the degree of accuracy with which model input data can be obtained. Both Block Theory and DDA reasonably approximate block geometry, kinematics, and slope stability using linear mathematical operators base on the planarity of observed structure and failure surfaces. The uncertainty of orientation, frequency, continuity, and strength parameters of pervasive structure permeating the headscarp at depth or in inaccessible regions justified the use of statistical averaging and extrapolation. The main purpose of this study was to assess each model's accuracy in predicting kinematic modes and stability characteristics observed in the field.

INTRODUCTION

Background

The Mission Peak Landslide Complex is located in the southeast corner of the Niles 7.5 minute quadrangle, southeast of the town of Fremont, and about 30 miles southeast of the city of Oakland, California. It extends just over 1.5 kilometers, from the crest of Mission Ridge west-southwest to Mission Boulevard (Figure 1). Mission Ridge is one of several longitudinal topographic highs belonging to the Diablo Range of the California Coast Ranges, which bounds the southeastern edge of San Francisco Bay. The head scarp of the 1998 Mission Peak Landslide, which is the focus of this study, resides entirely within the steep to moderate west-facing slope of Mission Ridge (Figure 2). It covers about one-tenth of the total landslide length and accounts for about 140 meters, or one-third, of the total relief. This abrupt contrast in topography is attributed to the contrasting rock strength and uplift of Mission Ridge along the Mission Fault.

The impetus for conducting a block kinematics and slope stability study stemmed from ongoing displacements and rock fall (Figure 3) observed in the head scarp region in the months following the partial reactivation of the Mission Peak Landslide on March 22, 1998. Although these events and the instability of Mission Ridge posed no immediate threat to human lives, understanding the mechanisms that govern instability could provide valuable insight for predicting 1) conditions when slope failure is most imminent, and 2) the expected magnitude of failure. This study will ultimately address the likelihood of a catastrophic failure of the head block versus smaller, more gradual

Figure1. Location of the Mission Peak landslide and head scarp. The head scarp lies within Mission Ridge to the immediate southeast of the town of Fremont, California.

Figure 2. Central and upper section (head scarp) of the Mission Peak Land Slide shortly after its partial reactivation. Note the well developed graben immediately below the head scarp.

Figure 3. Observed rock fall on July 22, 1998 approximately four months after the partial reactivation of the Mission Peak Landslide. These photos were taken a few seconds apart.

block failures, based on field observation and analytical findings.

Kinematic and rock slope stability analyses rely chiefly on the structural fabric of the rock defined by various discontinuities such as bedding, joints, and shear planes.

Practitioners in the field of rock mechanics characterize discontinuities by their orientation, continuity or aerial extent, spacing, surface shape and roughness, and infillings (Norrish and Wyllie, 1996). The greatest task in this study was characterizing the dominant discontinuities and their associated properties because of limited accessibility, outcrop size, obfuscation by erosion and smaller fractures, and danger of rock fall. These properties, which ultimately define block geometry, size, and stability in many cases, had to be generalized or assumed in order to conduct the analyses in this study.

Project Overview

The delineation of dominant discontinuity orientations from a large population of structural data was achieved jointly by field observation and statistical processing.

Three types of kinematic analyses are applied with these data: 1) stereographic (Hoek and Bray, 1981), 2) Block Theory (Goodman and Shi, 1985), and 3) Discontinuous Deformation Analysis (DDA, Shi, 1988). The conventional stereographic methods of Hoek and Bray (1981) serve as a simple means for testing the kinematic freedom of failed or failing blocks such as the head block. Block Theory is an alternative stereographic method used specifically to identify critically unstable blocks intersecting

the precipitous scarp face. This type of analysis required the use of structural data intersecting the scarp face opposed to structure measured on a regional scale. Finally, DDA is used to perform a two dimensional, numerical analysis of the kinematics, modes of failure, and stability of many blocks simultaneously under varying strength and deformation parameters. As with stereographic methods, regional discontinuities are used to construct an idealized structural model of the head block. The results provide insight to more complex modes of failures and consequential head block deformation, and maximum run-out distances that might be expected in a catastrophic failure.

The 1998 Partial Reactivation of the Mission Peak Landslide

That portion of Mission Ridge immediately upslope of the 1998 slide underwent a rapid transformation. Ravelling, coupled with larger block failures, occurred at random intervals throughout the summer of 1998. The influence of ground water on this activity is unknown; however, large block failures appeared to occur independently of hydrological influences, with the worst rockfalls occurring in August. By the end of summer, an estimated $45,873 \text{ m}^3$ ($60,000 \text{ yds}^3$) of coarse sandstone talus had been shed onto the head scarp graben of the 1998 slide below (Figure 3). By December 1998, the talus had regained its original angle of repose (about 35°), covering the central portion of the 1998 head scarp.

Regional Geologic Setting

The geology of Mission Ridge and the surrounding region has been mapped by Hall (1956,1958), Helley, Lajoie and Burke (1972), Radbruch (1974), Nilsen (1975), Herd (1978), Dibblee (1980), Crane (1988), Graymer and others (1994), and Rogers and Drumm (1999). All studies concur that a large Pleistocene coalescing landslide covers much of the region below Mission Ridge. This large Pleistocene landslide complex largely covers the late Miocene terrestrial red and green conglomerates, siltstones, and claystones of the Orinda Formation, which form the lower foothills of Mission Ridge. The head scarp lies entirely in the contrasting steep slope of Mission Ridge, which is composed of gray to buff Miocene marine sandstone of the Briones Formation. These rocks are interpreted by most geologists to be tightly folded and overturned in the Tularcitos Syncline, with the overturned eastern limb forming Mission Ridge (Figure 4). Hall (1956, 1958), Dibblee (1980), and Crane (1988) show outcrops of the western limb of Briones Sandstone downslope and south of the landslide below 244 m (800 ft) elevation. Two faults are projected beneath the Mission Peak Landslide: the dormant Warm Springs fault near the toe of the 1998 failure, and the active Mission fault subparallel to the base of Mission Ridge.

Near the head scarp, the Briones Formation consists of resistant, well-cemented wacke interbedded with highly jointed, poorly cemented wacke (Figure 5). These contrasting strength properties may be attributed to a transition in lithofacies. Hall (1956, 1958) describes three members of the Briones Formation that cumulatively attain

a maximum thickness of 1,524 meters (5,000 ft) in the southern half of the Pleasanton area. The three members are summarized as follows: 1) an upper fine- to medium-grained wacke, 2) a middle lithic wacke and bioclastic member, and 3) a lower fine-grained sandstone and interbedded silty claystone member. The middle member is associated with sharp ridges, hogbacks, and peaks such as Mission Peak, and appears to comprise the greater portion of Mission Ridge based on observations of fresh exposures in the main scarp region.

The Mission fault is interpreted to play an important role in the slope instability of Mission Ridge. Its exact location is controversial because it appears to be covered entirely by colluvium in the vicinity of the Mission Peak Landslide. Numerous seismic studies have been conducted in this region (Oppenheimer and MacGregor-Scott, 1992; Oppenheimer and others, 1992; Andrews and others, 1992). These studies revealed right-lateral dip-slip motion along a near-vertical surface roughly coinciding with the strike of Mission Ridge. The micro-seismicity ($M \leq 3.0$) recorded over approximately 25 years likely has had little effect on the stability of Mission Ridge. In the region of Mission Peak, Hall (1956, 1958) noted outcrops of Orinda beds in the Tularcitos Syncline striking into the older Briones Formation and a salient fault-line scarp along the west side of Mission Peak. Field evidence also supported vertical to high angle reverse motion with approximately 300 meters of displacement along the Mission fault (Hall, 1956).

Figure 4. Structural geology section showing Tularcitos Syncline and Mission Ridge modified from Geolith Consultants, Inc. (1998). The photo below is a southern view of a newly exposed contact between the Briones and Orinda Fm. interpreted as the eastern limb of the Tularcitos Syncline.

Figure 5. Photo of Briones Sandstone outcrop on the right flank of the head scarp showing adjacent zones of more competent rock (top) to highly fractured, friable rock (bottom).

Regional Hydrology

The direct impact of water on the stability of the head scarp region appears to contribute only to local erosion and small block failures, based on observation after periods of heavy precipitation during the course of this study. Historically, the mean annual precipitation from 1906-1956 varied between 18 and 22 inches from the bay margins to the top of the ridge. Although precipitation was 20-25% greater at the ridge crest, it appeared to have an insignificant effect on rock slope stability in the head scarp region, based on relatively unchanged scarp geometry observed in air photos during this period. Increasing levels of precipitation from 1993 to 1997 following a dry period from 1986-1993 (Figure 6) appear to be linked to the reactivation of the Mission Peak Landslide in 1998 and the subsequent removal of lateral support at the base of Mission Ridge (Geolith Consultants, Inc., 1998).

Mission Ridge Geomorphology

The geomorphology of Mission Ridge and the abutting slopes below offers insight into the geologic processes controlling slope stability in the region. For example, the remarkably steep planarity of the southwest face of Mission Ridge probably is structurally controlled by a pervasive joint set dipping 40° southwest. This feature appears to have served as the dominant slide plane for a large block that once occupied the prominent erosion scar on Mission Ridge. A similar mechanism is proposed for the northern right flank of the evacuation scar, which exhibits a suspicious linear character

Figure 6. Precipitation records for 120 months and 12 month running sums. Note the general long term pattern of wet periods and the increase of precipitation between 1993 to the present.

in air photos and topographic maps. When viewed topographically, this flank approximates a second pervasive joint (60/196), which was confirmed by direct measurement of joint surfaces cutting across the large head block just south of the 1998 head scarp. Uniform weathering of the Briones Sandstone along this entire flank and of large talus blocks below suggests that this event was probably catastrophic (D. Rogers, personal communication, 1998).

Sackungen are uphill-facing tensile scarps and grabens. Erosion often reduces these features to anomalous steps or benches in a steep, continuous slope. Sackungen have been recognized in the upper elevations of the headblock and along the slope, south of the 1998 slide. These features are attributed to continuous deformations. Figure 7 presents two possible mechanisms, toppling and slumping, by which sackungen features may form. The toppling model assumes that deformations near the slope toe are associated with deep-seated rock creep (Kieffer, 1998).

Obsequent or back-facing scarps are typically associated with toppling sackungen, and recognized as evidence for interlayer slip between cantilevered rock columns (Hoek and Bray, 1981). The orientation of pervasive fractures sub-parallel to the headblock separation crack and associated obsequent scarps directly below the apex extensometer suggests that head block deformation may be attributed to flexural toppling.

Other Studies

No known studies of the underlying structure and rock slope stability of Mission

Figure 7. Sackungen resulting from both toppling and slumping modes of failure modified from Kieffer (1998).

Ridge were conducted prior to the reconnaissance study by Geolith Consultants, Inc. (GCI, 1998). GCI conducted a preliminary kinematics study using Key Block Analysis (Goodman and Shi, 1985), delineating four statistical joint sets interpreted from 56 attitudes measured around the perimeter of the active head scarp. Their analysis suggested that at least two key blocks of markedly different geometry with approximate factors of safety ($F.S. = 0.3$) controlled the stability of the newly exposed 3-20 meter high head scarp. No field correlations of these findings were presented.

Observed extensional features along the boundaries of the head block spurred real-time monitoring by the U.S.G.S., which used an array of eight extensometer pins across the prominent tension crack at the top. Displacements were measured manually with Invar extensometer tape until April 25, 1998, when a permanent recording extensometer (EXT 1) was installed across the lower portion of the tension crack. The system was upgraded with the installation of a second extensometer (EXT 2) at the apex of the head block on June 5, 1998. This new array is monitored via a solar-powered cellular phone, left on site, which began to operate on June 17, 1998. Approximately 1 meter (3 ft.) of cumulative displacement was recorded between EXT 1 and EXT 2 during the time of this study (Appendix A-2).

A Global Positioning System (GPS) benchmark was later installed for acquiring higher spatial resolution of the headblock displacement (Appendix A). Extensometer data was augmented by the GPS, horizontal equivalent of northings and easting, where the supplementary south and west directions are represented by negative values

respectively. Additionally, GPS provided data for computing the vertical displacement of the headblock over time. The combined horizontal and vertical components produces a three dimensional displacement vector denoted slope. The general displacement trend of the headblock during the time of this project has been downward and nearly due west (R. LaHusen, personal communication, 2001). Graphical GPS records for the year 2000 are shown in Appendix A-3.

FIELD DATA

Introduction

Field data were collected intermittently between June 1998 and December 2000. The main objective was to characterize the dominant structure that appeared to be controlling instability and kinematics of the bedrock slope above the March 1998 landslide (Figure 8). The highly fractured nature of the Briones Sandstone required careful selection of the most representative joint surfaces, which were commonly masked by interlayer fracture sets. Over 600 attitude measurements were extracted to determine dominant patterns. Four dominant discontinuity sets were concluded from the collected data.

Several additional structural parameters were required for conducting limit equilibrium analyses of unstable blocks: 1) the continuity or aerial extent of a systematic discontinuity, 2) joint spacing, 3) and strength parameters (cohesive strength and joint friction). The continuity and spacing were extremely challenging to assess because of limited outcrop exposure. The resulting extraction of this data was less systematic and required that small outcrop measurements be extrapolated through the unstable head block region where active rock fall prohibited exploration. Joint strength parameters were estimated by back-calculating conditions necessary for the failure of prominent block-pull-outs along the scarp face. This method did not require representative sampling for direct shear tests or *in-situ* tilt tests that might have otherwise lead to erroneous conclusions.

Figure 8. U.S.G.S. aerial photo taken July 1998, of the Mission Peak Landslide head scarp region. Numbered locations indicate outcrops where structural data was collected. Uphill facing scarps at locations 19, 18, and 15 pre-existed the March 1998 Landslide.

Methods

The regional structure of Mission Ridge is shown in the lower-hemisphere equal-area projection of poles (Figure 9). This pole plot and all others were generated on DIPS 4.0 (Diederichs and Hoek, 1989). The structural fabric of the Briones Sandstone is comprised of bedding interfaces, joints, and shear surfaces. Attitudes of these features were measured in most cases directly from surface exposures left by block pull-outs and wedge-type failures. Initially, measurements were recorded along the more stable right flank of the prominent evacuation scar, where structure was less obscured by slope wash and less disturbed by creep. The most dominant structures were then correlated to the structural fabric of the head block. This was achieved using aerial photographs and direct measurements of salient discontinuities, once active rock fall ceased.

Dominant orientations were extracted from the highly dispersed global data set by correlation of dominant structure observed in the field with sets distributed about a great circle. Data were contoured using the Fisher Distribution method. Except for J1 and bedding (Tbr), which were represented by the statistical mean of the contoured data cluster, the dominant structures were localized on the basis of field observations, and are shown as great circles in Figure 10.

Joint spacing was difficult to extract using such methods as scan-line surveying (Priest and Hudson, 1981) where intersecting systematic joint traces are tallied within a unit length over a prescribed distance to assure that no larger spacings are omitted. The steep slopes, erosion, and poor accessibility prevented utilization of this method. Joint spacing was instead measured directly from individual outcrops with a tape measure,

Figure 9. Lower hemisphere, equal area projection of discontinuity poles

Figure 10. Fisher distribution contour plot delineating the major discontinuities of the head scarp: J1, J2 (tension crack), J3 (steep western face of headblock), J4 (western ridge slope), and Briones bedding (Tbr) dipping back into Mission Ridge.

where joint surfaces were sufficiently exposed to assure a reasonably accurate orthogonal distance between any two adjacent surfaces. These measurements later were averaged to obtain representative values. Some measurements were extracted photogrammetrically (Figure 11) where joint spacing was obscured by erosion or small-scale fracturing, using an enlarged color copy of a scaled outcrop photo and partly adopting the method of Priest and Hudson (1981) and Rives, Razack, Petit, and Rawnsley, (1992).

Results and Discussion

Four global structures (denoted J1, J2, J3, and J4) were interpreted to be controlling the block kinematics and rock slope stability of the head scarp region (Figure 12) based on statistical analysis (Figure 10) and field observation. Bedding (Tbr) and J1 form well defined pole clusters, but the poles describing J2, J3, and J4, are dispersed along periphery great circles representing planes dipping steeply to the east and west. Each of these structures are discussed briefly in the following paragraphs.

Bedding is remarkably consistent with respect to elevation on Mission Ridge (Appendix A) and has a mean orientation of 42/11. The majority of measurements were recorded from the ridge base to near the ridge crest along the more stable right flank of the evacuation scar (Figure 13). Although this orientation reinforces the stability of Mission Ridge, it appears to indirectly control slope instability and the size of block failure through thickness, variable lithology, and differential weathering. Furthermore, since the Briones Formation has been subjected to tight folding with ongoing compression within the step-over between the Hayward and Calaveras faults, bedding

Figure 11. One of numerous outcrop photos used to facilitate measurement of joint spacing. This photo of an asperity at location 9 shows traces of two systematic subsets of discontinuities associated with the global J1 and J3.

Head scarp Global Structure		
Joint Set	Mean orientation (dip/dip direction)	Associated Global Feature
J1	60/196	Right flank of evacuation scar
J2	76/110	Tension crack bounding SE side of headblock
J3	80/260	Steep western face of head block
J4	42/260	Western slope of Mission Ridge
Tbr	42/11	Briones Sandstone bedding

Figure 12. Regional structure of the Mission Peak Landslide head scarp. The lines approximate features in the photo and not actual orientations.

Figure 13. Northern view of the right flank approximating J1. The orientation of bedding with respect to the slope is shown by the white line.

interfaces likely become the foci for interlayer slip. These zones are characterized by shears, usually spaced more widely than joints, and contain roughly parallel seams of sheared and crushed rock (Goodman, 1980). Similar features appear sub-parallel to bedding and have been preserved along the right flank of the evacuation scar (Figure 14).

Joints are interpreted to be the most ubiquitous structure through out the region. They are differentiated from bedding and shear surfaces by their displacement normal to the parting surface. They are often filled by soil, colluvium, and precipitation of secondary carbonate (Figure 14). Joint hierarchy was established based on structural pervasiveness and continuity. It does not, however, imply that one set is more important than another in terms of their kinematic influence on block failure. For example, J4, though poorly represented, may be crucial in the displacement of the large head block.

The most pervasive joint set, denoted J1, exhibits the best-defined cluster. It is represented by a mean orientation of 60/196 (dip/dip direction) and appears in the majority of local pole plots for each of the 36 outcrops. On a regional scale, this orientation roughly approximates the linear right flank escarpment of the prominent evacuation scar (Figure 13) and the 1998 head scarp near the base of Mission Ridge (Figure 15). Traces of this joint set were also vividly discerned in photos of the steep western escarpment of the head block (Figure 16). J1 is ubiquitous along the steep south-western faces of the head block where it appears to be a shear surface as shown by striations plunging sub-parallel to dip direction.

The second joint set (J2) includes a subset of poles representing the large tension

Figure 14. A zone of closely spaced secondary carbonate seams sub-parallel to bedding. The seams dip about 40 degrees to the northeast. Note the high frequency of interlayer fracture contributing to the low competency.

Figure 15. Northern right flank of 1998 head scarp approximating pervasive J1 dipping 60 degrees to the south. Note the buff colored colluvium plastered on scarp wall. This infill consists of coarse talus blocks and fines and is roughly 0.5 to 1 meter thick.

Figure 16. Traces of pervasive J1 shown cutting steeply across the western escarpment of the head block region.

crack with a mean orientation of 76/110 (Figure 17). Head block displacement during the summer of 1998 caused this fracture to propagate in both directions, and to widen about 1 meter. Measurement of a deep planar fracture exposed along a newly formed crown scarp just below the apex extensometer (EXT 1) confirmed that the above orientation permeates the headblock. The depth of this crack was projected to approximately 30 meters (100 feet) based on opposing wall measurements projected at depth. Several shallow excavations made within the head block along the edge of a prominent asperity (Figure 8, location 23) showed systematic fracturing sub-parallel to the tension crack occurring at intervals of 0.05 to 0.3 meters (0.2 to 1.0 ft).

The steep west facing asperity of the head block (Figure 8, location 35) represents a third set (J3) distributed again along a great circle. This face is relatively planar with a height of more than 30 meters and an estimated mean orientation of 80/260. While it is assumed that this joint extends to great depth based on the extent of the face, the extent of its development is less certain since any trace of it has been covered by soil or colluvium. The spacing is estimated to be 2 meters or more based on the parallel fracture directly behind the face (Figure 18). This orientation approximates the western face of a prominent tower of more competent sandstone near the bottom of the right flank and a large joint on its eastern side (Figure 8, location 3).

The final joint set (J4) is the least-represented though assumed to be a critical element in the kinematics of large-scale block failures. Sparse outcrops along the ridge line of the right flank exhibit planar, though weathered, faces sub-parallel to the ridge

Figure 17. Large tension crack bounding the SE side of the head block. This crack is interpreted to be a subset of J2 dipping steeply between 75 to 80 degrees SE into Mission Ridge. The crack is approximately 3 m wide and 7 m deep near the top.

Figure 18. West face of large head block faceted by the steeply dipping J3 (80/260) occurring nearly orthogonal to bedding. Note the parallel fracture (arrow) used as partial evidence for estimating the spacing of this set.

slope. A mean orientation of 42/260 was determined from several exhumed locations on the ridge slope in the vicinity of the head scarp (Figure 19). Mission Ridge serves as testimony to the ubiquitous and consistent nature of this joint set, which likely contributes to larger-scale block failures.

Shear surfaces were identified by the presence of slickensided surfaces. The majority of preserved measurable surfaces appeared to be high on the scarp walls where recent block failures had not yet been covered by rock detritus. Shears were most apparent along the lower western face of the head block (Figure 8, location 34) where vast amounts of blocks had recently failed. These surfaces, which were measured shortly after the cessation of active rock fall about a year after the landslide occurred, coincided with the pervasive joint set J1.

Joint friction was the most difficult parameter to estimate for any given discontinuity because of the variable nature of joint orientation, surface roughness, fill materials, and rock strength. Joint infill likely exerts an adverse affect on joint strength through its intrinsically low shear strength and its ability to impede seepage and enhance pore pressure (Hoek and Bray, 1981). Joint infill in the head scarp region includes carbonate (Figure 14) and coarse colluvium, as seen on the 1998 head scarp (Figure 15), and clay rich soils (Figure 20). The effect that each fill material has on overall block stability, and the spatial distribution of these materials, were not evaluated as part of this study.

Figure 19. South view looking towards San Jose showing exposed J4 surfaces in foreground and overall planarity of the western slopes of Mission Ridge. The head scarp is to the south of this location.

STEREOGRAPHIC ANALYSIS

Introduction

The intensely fractured nature of the Briones Sandstone forming Mission Ridge promotes the development of discrete blocks of rock that are susceptible to failure when specific kinematic conditions are met. Block kinematics, or the motion of individual blocks disregarding all forces initiating movement, is governed by the orientation of discontinuities with respect to each other and the slope face. The conventional stereographic methods of Hoek and Bray (1981) provide an efficient means of testing the expected kinematics and modes of failure in the unfailed bedrock ridge above the active head scarp of the 1998 Mission Peak Landslide. This study focused on the kinematic potential for sliding and toppling based on observed rock fall and geomorphic evidence along the head scarp boundaries.

Block failure along the head scarp appeared to occur on two scales: 1) a local scale (Figure 20) with block diameter ranging from 1-10 meters (3-30 ft.), and a regional scale (Figure 21) with block size ranging from 10-30+ meters (30-100+ ft.). On a local scale, wedge pull-outs preserved along the scarp face present evidence for sliding on one or two planes. The directly measured orientations of these local wedge sliding surfaces are applied to the wedge stability equations (Appendix B-2) of Hoek and Bray (1981). Sensitivity analyses on joint friction, cohesive strength, unit weight of rock, wedge height, and influence of effective stress by addition of water, were conducted

Figure 20. An example of a “local scale” wedge failure along the southern flanks of the head scarp.

Figure 21. Two "regional scale" wedges considered in the stereographic analysis of the bedrock ridge above the March 1998 landslide head scarp. The bounding discontinuities of both blocks were estimated topographically.

within an accepted range of values to specifically confine joint strength parameters under limiting equilibrium conditions.

On a regional scale, two blocks were examined: 1) the scar block that once occupied the prominent scar extending from the talus cone at the base of Mission Ridge to proximity of the ridge crest, and 2) the adjacent head block bounding the southern side of the scar. Both of these rock masses are interpreted as wedges and analyzed accordingly. One focus of this study was to assess the likelihood of catastrophic detachment of the head block, which experienced accelerated movement during the summer of 1998, several months after the Mission Peak Landslide.

Methods

The kinematic analyses employed the dominant discontinuities obtained from statistical analysis (described in Field Data) as well as direct field measurements taken at specific locations for local block analyses. Additionally, cohesive strengths (c), joint friction (ϕ_j), and the unit weight of the rock (γ) were needed to conduct limit equilibrium analyses. These parameters are presented as a range of values (table 1) rather than a single number because of the contrasting properties associated with weathering in the Briones Sandstone (D. Rogers, personal communication, 1998).

The stereographic methods of Hoek and Bray (1981) were conducted both by hand, using an equal-area stereonet, and with the aid of several stereographic analysis programs. A DOS-based stereographic program called DIPS (Diederichs and Hoek, 1989) was used to generate all stereoplots. Manual stereographic construction facilitated

angular measurements between planes, intersection vectors, and poles used in the wedge stability calculations (Appendix B-1).

A kinematic analysis for toppling was conducted using the entire data set presented stereographically in the Field Data section, and subsets of these data local to the scarp face. On both regional and local scales, two kinematic limits were used to establish the toppling zone: 1) a stereographically projected small cone defining the suggested 30 degree limit of toppling discontinuity strike to the trend of the slope face, and 2) a great circle projected with the estimated joint friction value ($\varphi_j = 30$) inclined above the plane of the slope, as prescribed by Goodman (1980). The limit equilibrium analysis for toppling presented in Hoek and Bray (1981) requires block dimensions and forces that were unknown and could be evaluated more efficiently with Discontinuous Deformation Analysis (DDA), a numerical method explored in this study.

The wedge stability equations (Appendix B) of Hoek and Bray (1981) were entered on a Microsoft Excel spreadsheet to allow for rapid computation of the factor of safety (F.S.). Sensitivity analyses were conducted by evaluating a range of estimated values for joint friction (φ_j), joint cohesion (c), unit weight of the rock (γ), wedge height (H), and seepage conditions (γ_w).

Regional data were used to analyze the kinematics of the scar block and head block. Additionally, planes were estimated from topographic lineaments. These planes are again summarized as follows: 1) the right flank of the scarp (J1; 60/196), 2) the tension crack (J2; 76/110), 3) the precipitous western face of the head block (J3; 80/260), and 4) the average ridge slope (J4; 42/260).

Physical Properties of the Briones Sandstone	
Dry unit weight	130-135 pcf
Weathered	117-125 pcf
Silty/silt stone	110-122 pcf
Porosity	.08-.20
Friction	
Phi (rock)	45°
Phi (joint)	20-30°
Cohesion	
Extremely weathered	50 psf
Less weathered	1,500 psf

Table 1. Physical properties of the Briones Sandstone obtained from J. D. Rogers (personal communication, 1998).

Results and Discussion

Toppling on a regional scale along the pervasive J2 is kinematically possible, with the mean orientation of the representative tension crack lying entirely in the topple zone (Figure 22). The extent and frequency to which this major discontinuity pervades the head scarp region needs to be verified before conclusions can be made. On a local scale, toppling appears to be insignificant except at locations 8, 11, and 12 (Figure 8), which encompass the remaining discontinuities within the topple zone dipping east-northeast. Toppling is not obvious from field observation because of extensive coverage of slope wash and talus. Tension cracks and obsequent slopes generated by normal

Figure 22. Regional stereographic analysis for toppling. The pervasive J2 represented by the tension crack falls within the slip limit boundary 30 degrees on either side of the scarp face dip vector. Flexural toppling may be occurring on J2 internal to the head block.

displacements are strong evidence for toppling (Goodman, 1980) and appear within the head block directly below the apex extensometer (EXT 2).

A regional planar kinematic analysis (Figure 23) suggests that J4, represented by the small group of poles within the daylight envelope is the only major discontinuity of concern. The absence of J4 on an outcrop scale suggests that it occurs over significantly larger spacing intervals, behaving as a shear surface for the head block or the pre-existing scar block. On average, this discontinuity dips about 10 ° steeper than the slope face, generating kinematic stability for the head block. Whether the basal detachment surface

Figure 23. Regional stereographic analysis for planar failure. Poles representing J4 sub-parallel to the western slope of Mission Ridge are the only kinematically viable discontinuities for planar failure with respect to average ridge slope (42/253).

is planar or bi-planar, stability is jeopardized when the abutting head scarp graben block moves away from the base of Mission Ridge, generating scarps that daylight J4.

Wedge failures are ubiquitous along the northern and southern flanks of the head scarp (Figure 20). At a local scale, the conjugate joint sets forming these wedges dip variably between the southwest and northwest with a line of intersection plunging generally 50°-70° southward, roughly 40°-50° oblique to the average slope face orientation approximated by J4. The kinematic analyses of three wedge pull-outs labeled in accordance to Figure 8 and the hypothetical scar block (Figure 21) are shown

in Figures 24-27. The joint plane intersections of these particular failures plunged 35°-50° southwestward.

Sensitivity analyses on the factor of safety (F.S) to changes in rock strength parameters, produced mid-range joint frictions ($\phi_j = 25^\circ$) and relatively low joint cohesions ($c < 500$ psf). Plane B, which closely approximates the mean of J1 at location 34 (Figure 24), location 33 (Figure 25), and the Scar Block (Figure 27), contributes the lowest values to the overall F.S. Stability under saturated conditions required cohesion values of about 50-300 psf more than cohesion under dry conditions. This small increase in cohesion on the sliding planes may be attributed to the intrinsically steep discontinuities and planar intersections that allow pore water to drain rapidly.

Wedge stability along the head scarp appears to be largely controlled by displacement of the buttressing head scarp graben block. The juxtaposition of a topographically reconstructed pre-1998 landslide slope to the post-1998 scarp (Figure 28) at the base of Mission Ridge reveals the potential for many new joint intersections, developed from discontinuities collected in the actively raveling portion of the head scarp, to daylight. The failure of the scar block likely resulted from a much earlier, but similar, back-rotation of the head scarp graben block, allowing the critical joint plane or intersection to be exposed (Figure 29). This same process appears to govern the westward displacement of the prominent head block, which experienced a brief period of acceleration following the 1998 landslide.

Location 34: Wedge Limit equilibrium Analysis				
INPUT DATA		FUNCTION VALUE		CALCULATED ANSWER
$\Psi_a =$	48	$\cos(\Psi_a) =$	0.6691	A = 1.5921
$\Psi_b =$	56	$\cos(\Psi_b) =$	0.5592	
$\Psi_s =$	46	$\sin(\Psi_s) =$	0.7193	B = -0.7089
$\theta_{na,nb} =$	21	$\cos(\theta_{na,nb}) =$	0.9336	
		$\sin(\theta_{na,nb}) =$	0.3584	
$\theta_{2,4} =$	45	$\sin(\theta_{2,4}) =$	0.7071	X = 13.8839
$\theta_{4,5} =$	19	$\sin(\theta_{4,5}) =$	0.3256	
$\theta_{2,na} =$	81	$\cos(\theta_{2,na}) =$	0.1564	
$\theta_{1,3} =$	58.5	$\sin(\theta_{1,3}) =$	0.8526	Y = -10.3796
$\theta_{3,5} =$	25.5	$\sin(\theta_{3,5}) =$	0.4305	
$\theta_{1,nb} =$	101	$\cos(\theta_{1,nb}) =$	-0.1908	
$\phi_A =$	25	$\tan(\phi_A) =$	0.4663	F.S. = 1.0
$\phi_B =$	25	$\tan(\phi_B) =$	0.4663	
$\gamma =$	135	$\gamma_w / 2\gamma =$	0.0000	plane A: 54/210 plane B: 63/175 slope face: 86/230 upper slope: 35/235
$\gamma_w =$	0	$3c_A / \gamma H =$	0.0833	
$c_A =$	300	$3c_B / \gamma H =$	0.0556	
$c_B =$	200			
$H =$	80			

Figure 24. Wedge stability sensitivity analysis for failed wedge at location 34.

Location 33: Wedge Limit Equilibrium Analysis				
INPUT DATA		FUNCTION VALUE		CALCULATED ANSWER
$\Psi_a =$	58	$\cos(\Psi_a) =$	0.5299	A = 0.6879
$\Psi_b =$	62	$\cos(\Psi_b) =$	0.4695	
$\Psi_5 =$	47	$\sin(\Psi_5) =$	0.7314	B = 0.5999
$\theta_{na,nb} =$	86.5	$\cos(\theta_{na,nb}) =$	0.0610	
		$\sin(\theta_{na,nb}) =$	0.9981	
$\theta_{2,4} =$	56	$\sin(\theta_{2,4}) =$	0.8290	X = 4.4579
$\theta_{4,5} =$	17	$\sin(\theta_{4,5}) =$	-0.2924	
$\theta_{2,na} =$	50.5	$\cos(\theta_{2,na}) =$	0.6361	
$\theta_{1,3} =$	90	$\sin(\theta_{1,3}) =$	1.0000	Y = 2.8388
$\theta_{3,5} =$	22.5	$\sin(\theta_{3,5}) =$	0.3827	
$\theta_{1,nb} =$	23	$\cos(\theta_{1,nb}) =$	0.9205	
$\phi_A =$	25	$\tan(\phi_A) =$	0.4663	F.S. = 1.0 plane A: 58/298 plane B: 62/196 slope face: 34/260 upper slope: 86/267
$\phi_B =$	25	$\tan(\phi_B) =$	0.4663	
$\gamma =$	135	$\gamma_w / 2\gamma =$	0.0000	
$\gamma_w =$	0	$3c_A / \gamma H =$	0.0417	
$c_A =$	75	$3c_B / \gamma H =$	0.0694	
$c_B =$	125			
$H =$	40			

Figure 25. Wedge stability analysis for failed wedge at location 33.

Location 31 Wedge Limit Equilibrium Analysis				
INPUT DATA		FUNCTION VALUE		CALCULATED ANSWER
$\Psi_a =$	56	$\cos(\Psi_a) =$	0.5592	A = 1.1246
$\Psi_b =$	67	$\cos(\Psi_b) =$	0.3907	
$\Psi_s =$	39	$\sin(\Psi_s) =$	0.6293	B = 0.9119
$\theta_{na,nb} =$	105	$\cos(\theta_{na,nb}) =$	-0.2588	
		$\sin(\theta_{na,nb}) =$	0.9659	
$\theta_{2,4} =$	51.5	$\sin(\theta_{2,4}) =$	0.7826	X = 7.6255
$\theta_{4,5} =$	9	$\sin(\theta_{4,5}) =$	0.1564	
$\theta_{2,na} =$	49	$\cos(\theta_{2,na}) =$	0.6561	
$\theta_{1,3} =$	50	$\sin(\theta_{1,3}) =$	0.7660	Y = 8.7464
$\theta_{3,5} =$	8	$\sin(\theta_{3,5}) =$	0.1392	
$\theta_{1,nb} =$	51	$\cos(\theta_{1,nb}) =$	0.6293	
$\phi_A =$	25	$\tan(\phi_A) =$	0.4663	F.S. = 1.0
$\phi_B =$	27	$\tan(\phi_B) =$	0.5095	
$\gamma =$	135	$\gamma_w / 2\gamma =$	0.0000	
$\gamma_w =$	0	$3c_A / \gamma H =$	0.0000	
$c_A =$	0	$3c_B / \gamma H =$	0.0000	
$c_B =$	0			
$H =$	40			
				plane A: 56/186
				plane B: 67/311
				slope face: 75/251
				upper slope: 34/260

Figure 26. Wedge stability analysis for failed wedge at location 31.

Scar Block Wedge Limit Equilibrium Analysis				
INPUT DATA		FUNCTION VALUE		CALCULATED ANSWER
$\Psi_a =$	48	$\cos(\Psi_a) =$	0.6691	A = 1.5921
$\Psi_b =$	56	$\cos(\Psi_b) =$	0.5592	
$\Psi_s =$	46	$\sin(\Psi_s) =$	0.7193	B = -0.7089
$\theta_{na,nb} =$	21	$\cos(\theta_{na,nb}) =$	0.9336	
		$\sin(\theta_{na,nb}) =$	0.3584	
$\theta_{2,4} =$	45	$\sin(\theta_{2,4}) =$	0.7071	X = 13.8839
$\theta_{4,5} =$	19	$\sin(\theta_{4,5}) =$	0.3256	
$\theta_{2,na} =$	81	$\cos(\theta_{2,na}) =$	0.1564	
$\theta_{1,3} =$	58.5	$\sin(\theta_{1,3}) =$	0.8526	Y = -10.3796
$\theta_{3,5} =$	25.5	$\sin(\theta_{3,5}) =$	0.4305	
$\theta_{1,nb} =$	101	$\cos(\theta_{1,nb}) =$	-0.1908	
$\phi_A =$	26	$\tan(\phi_A) =$	0.4877	F.S. = 1.0
$\phi_B =$	26	$\tan(\phi_B) =$	0.4877	
$\gamma =$	135	$\gamma_w / 2\gamma =$	0.2311	plane A: 48/202 plane B: 56/178 slope face: 75/251 upper slope: 34/260
$\gamma_w =$	62.4	$3c_A / \gamma H =$	0.1111	
$c_A =$	400	$3c_B / \gamma H =$	0.0556	
$c_B =$	200			
$H =$	80			

Figure 27. Wedge stability analysis for failed scar block .

Figure 28. Superposition of joint intersections on the projected pre-post landslide slope. The discontinuities were measured along the actively raveling region of the head scarp

Figure 29. Scaled diagram of the possible mechanism for failure of the scar block . A similar process may be responsible for displacement of the prominent head block.

BLOCK THEORY

Introduction

Block Theory (Goodman and Shi, 1985) applies both stereographic and vectoral methods to identifying the removability, kinematics, and stability of joint-bounded blocks intersecting an excavation surface or free face. The purpose of this analysis is to identify and analyze critically unstable blocks, called key blocks, along the precipitous head scarp. By definition, these blocks must be removable and unstable without support. The removability of any given block is determined both by its geometry relative to the free face and limit equilibrium conditions. Once a block is removed, the space is augmented by successive block removal behind the failed key block until a massive failure occurs (Goodman, 1995). Direct evidence for key blocks is typically preserved in the form of block molds exposed along any given excavation surface in the parent rock (Figure 30).

Block theory was applied to analyzing the slope stability and block kinematics along the main head scarp region of the Mission Peak slide, where a multitude of small to moderate-sized rock falls were witnessed during field work in the summer of 1998. These events appeared to be governed by local, steeply dipping discontinuities intersecting the scarp face. In this study, the head scarp is treated as a natural excavation composed of multiple faces controlled by local systematic jointing, and all faces are assumed to be initially planar, developing from pervasive joint sets. The focus of these analyses was to compare the validity of predictions made by block theory with field observation.

Figure 30. Right flank of head scarp showing several 1-2 meter tetrahedral key blocks preserved in the form of block molds in the "excavation surface."

The unstable and, thus, unsafe nature of the raveling scarp face prohibited the extraction of orientation data directly from preserved block molds. The direct measurement of block molds is the optimal method to obtain actual block geometry and eliminate error from statistical misrepresentation on a local scale (Goodman, personal communication, 2000). The dispersion of structural data require statistical analysis of a greater number of discontinuities near the excavation surface analyzed. Similarly, Block Theory was applied on a regional scale using the four nominal orientations (J1-J4) introduced in Field Data.

Analysis of the stability of the main scarp is divided into two steps: 1) identification and analysis of the most critically unstable key blocks along the head scarp boundary by applying Block Theory and Critical Key Block Analysis (Hatzor, 1992), and 2) validation of the results by correlating predicted key blocks with observed block geometry, block molds, and modes of failure. A comprehensive discussion and mathematical validation of Block Theory is found in Goodman and Shi (1985).

Principles of Block Theory

Block Theory evaluates three fundamental properties of any given block intersecting an excavation surface: 1) block removability, 2) mode of block failure, and 3) block stability. Block removability is detected simply by evaluating block geometry in relationship to excavation surface geometry. The mode of failure and block stability analyses, conducted independently of removability analysis, evaluate incipient block motion and freedom of movement. These evaluations require additional knowledge

about the physical influences of joint strength, joint spacing, and all external forces that may affect block failure. These properties are briefly reviewed below.

Five types of blocks are considered in Block Theory, as illustrated in Figure 31. Infinite blocks (V) pose the least threat to failure along any given excavation provided that no internal fracturing occurs. Tapered blocks (IV), although finite in dimension, are nonremovable by virtue of their geometry unless liberated by the removal of surrounding blocks. The remaining three block types are categorized as removable, and differ in their degree of stability. Block type (III) is stable without friction because of its position in the excavation relative to the resultant force acting on it. Alternatively, the resultant forces acting on this block type force the block to move into the rock mass rather than outwards, into free space. Block type (II) is stable with sufficient friction and is considered as a potential key block. The key block (I), which this study attempts to identify, is theoretically unstable without support.

Assumptions

Block theory is constrained by three simplifying conditions. 1) All joint surfaces are perfectly planar. 2) The blocks being analyzed have a predetermined geometry defined entirely by the local continuity of joint sets. Alternatively, no new fractures may develop during the analysis of block movements. 3) The blocks defined by the local joint system are rigid, eliminating the possibility of block deformation.

Figure 31. Block types modified after Goodman and Shi, 1985. The excavation surface (ES) is shown on the left. (a) infinite (V); (b) tapered (IV); (c) stable (III); (d) potential key block (II); (e) key block (I).

Conditions for Block Removability

Block Theory defines each block by a combination of joint-plane and excavation-surface half-spaces, denoted as a block pyramid (BP), where half-space refers to the space above or below a given plane. The joint pyramid (JP), a subset of the BP, contains only the joint-plane half-spaces. Since removability is kinematically restricted by joint-plane orientation but not excavation surface orientation, only JPs are considered in the removability analysis. The removability of any given block is determined both by its dimensions and by its geometry with respect to the excavation surface. As shown in Figure 31, a removable block must be both finite and non-tapered in geometry. Both of these conditions are formally stated in Shi's theorem on the removability of a finite, convex block (Goodman and Shi, 1985):

A convex block is removable if its block pyramid is empty and its joint pyramid is not empty. A convex block is not removable (tapered) if its block pyramid is empty and its joint pyramid is also empty.

Figure 32 illustrates this theorem two-dimensionally. The top view is a cross-section diagram of two key blocks (A and B), formed by upper (U) and lower (L) half-space combinations highlighted by the hatchures. These half-spaces are shifted through a common origin while preserving the inter-planar angles of blocks A and B, illustrated in cross-section diagrams (b) and (c) respectively. When the half-spaces of Figure 32a are shifted through a common origin, such that inter-planar angles are preserved, pyramids are formed within the upper and lower half-space of the excavation surface (plane 5), with their apices at the origin. The shifted half-spaces that lie below the

Figure 32. Two dimensional application of the removability theorem, modified after Goodman and Shi (1985). All hatchures (a, b, and c) highlight the half-spaces which form blocks A and B. U and L denote upper and lower half-spaces of joint planes respectively. (a) Cross-section diagram showing key blocks A and B in relationship to the excavation surface. (b) Shifted half-spaces of block A through origin 0, resulting in a non-empty JP, rendering the block removable. (c) Shifted half-spaces of block B through origin 0, resulting in an empty JP, or non-removable block.

excavation surface are denoted excavation pyramids (EP), representing the jointed rock mass. The complementary shifted half-spaces above the excavation surface are denoted space pyramids (SP), representing the free space for blocks to move into. Block A (Figure 32b) is removable since its JP ($JP_A = U_1U_2U_4$) is a non-empty set and its corresponding block pyramid BP ($BP_A = U_1U_2U_4L_5$) is empty (i.e., the hatchures of plane 5 do not coincide with the JP_A half-spaces). Following similar reasoning, block B (Figure 32c) is not removable since both its JP ($JP_B = L_1U_2L_3$), and its BP ($BP_B = L_1U_2L_3L_5$) are empty sets.

The removability of a three-dimensional block is determined somewhat similarly, using visual inspection of stereographically projected joints and excavation surfaces. The removability of any JP is determined by its complete containment within the region designated as the space pyramid, or the region inside the dashed circle representing the excavation surface. All finite tapered blocks are eliminated in the three-dimensional stereographic projection because the origin, which is the only point common to all half-spaces of this non-removable block type, cannot be projected. Figure C-2 (Appendix C) shows JP 000 (formed by the upper half-spaces of all three joint-planes) to be the only removable JP since it resides entirely within the SP.

Mode of Failure

The mode of failure determines the direction of incipient motion of the removable block in question. The initial development of Block Theory limited block motion to three principle modes: 1) lifting or falling, 2) sliding on a single plane, and 3) sliding on two

planes. Later developments, however, introduced the kinematics and analysis for forward rotation or toppling, edge rotation, torsional shearing, and block slumping of prismatic blocks (Mauldon, 1992; Mauldon and Goodman, 1995). This analysis considers only the first three modes since they can be most directly supported by field observations and structural data. They are described briefly as follows.

Block lifting (mode 0) occurs when the block is simultaneously detached from all joint faces and is restricted to moving in a direction parallel to the external resultant force acting on the block. Sliding on a single plane (mode i) occurs when a block slides on plane i parallel to the the resultant force orthographically projected on plane i. In the special case where the resultant force is gravity, the block is simply limited to sliding along the dip direction of plane i. This is found stereographically using the procedure for dip direction. Sliding along two planes (mode ij) occurs along the direction of intersection of plane ij . This is determined stereographically by extending a line between the two points of intersection of the great circles representing plane i and plane j, then selecting the point that lies in the lower hemisphere or outside of the reference circle.

Critical Key Block Method

The Critical Key Block Method (Hatzor, 1992) integrates three independent parameters in order to assess which key blocks are most likely to fail: 1) joint combination probability $P(JC)$, 2) removable block shape (K), and 3) block instability (F). The Block Failure Likelihood function $P(B)$ is the product of all three parameters:

$$P(B) = P(JC) \cdot K \cdot F.$$

The method is founded upon extensive empirical testing in the field of highly discontinuous rock masses, where it was found that failed key blocks were dominantly formed by subsets of three joints intersecting over a relatively small region. This observation has been found to be generally true along the failing boundaries of the main scarp, where preserved molds are dominantly tetrahedral. The steps to obtaining the three parameters and conducting the analysis are briefly summarized below.

The Joint-Combination Probability Parameter

The Joint-Combination Probability function $P(JC)$, initially developed by Goodman and Hatzor (1991) and later modified to its present form by Mauldon (1992), uses the Poisson probability analogue to estimate the probability of a subset of discontinuities or joint combinations (JC) intersecting over a small region in space. A combination of joint sets that are closely spaced, for example, have a greater likelihood of intersecting within a relatively small volume of rock. The $P(JC)$ function requires that joint spacing and orientation first be converted to frequency ($1/\text{spacing}$) and unit normals for each joint set respectively. Each joint normal has coordinates:

$$\begin{aligned} A &= \sin\alpha\sin\beta \\ B &= \sin\alpha\cos\beta \\ C &= \cos\alpha \end{aligned}$$

where α and β represent dip and dip direction measured in degrees. A single value is then computed for $P(JC)$ for each combination of joint sets using:

$$P(JC) = (\lambda_i \lambda_j \lambda_k) |n_i \cdot n_j \times n_k|,$$

where λ represents joint frequency, n_i is the unit normal for joint-plane i , and $\cdot$ and $\times$ specify taking the dot product and cross product respectively. The sum of all $P(JC)$ is not expected to equal unity in the classical sense of probability (Hatzor, personal communication, 2000) and is to be treated only as a weighted value with respect to all other $P(JC)$.

The JP Shape Parameter

The JP shape parameter K quantifies the degree of kinematic constraint on the sliding vector of any removable JP. Stereographically, a JP with large interplanar angles produces an opened JP or small maximum-block-size. The corresponding physical key block possesses an apex (point common to all joint planes) that is near the free surface. In contrast, a JP with small interplanar angles produces physical blocks with apices remote to the free surface, and consequently constrained by a higher normal component of lateral stresses within the rock mass. The JP shape parameter is quantified by:

$$K = \frac{(A + B + C - \pi) R^2}{4\pi R^2},$$

where A , B , and C are the interplanar angles of the JP. These angles were determined vectorally using BLOCK program B05 for a more accurate and efficient computation of a large number of angles. Each angle was then visually inspected with the stereographic projection of the corresponding JP and corrected when necessary with the complementary angle ($180-\theta$).

The Block Instability Parameter

The block instability parameter (F) measures any removable JP's relative freedom to move against resisting normal forces, tangential frictional forces, and the resultant force of any other external forces acting on the block. A fictitious sliding force F^* , with components acting in opposition and equilibrium to the resultant of the above forces along the sliding direction of the block, is expressed in the limit equilibrium equation:

$$T = N \tan \varphi + F^*.$$

Block sliding occurs for $F^* > 0$, limit equilibrium is established for $F^* = 0$, and stable conditions are met for $F^* < 0$. Goodman and Shi (1985) have adapted the above equation to the three main sliding conditions discussed earlier using vector analysis. The block instability parameter is normalized such that all instability values map between 0 and 1 by:

$$F = 2^{(F^*/R)-1}.$$

The failure conditions corresponding to these values are summarized in Table 2.

The sliding force was computed for all removable JPs using the limit equilibrium BLOCK program B30 and the assumed friction value of $\varphi = 30^\circ$ for all joint sets. These values were then normalized using Microsoft Excel.

Methods

Local and regional analyses both use the stereographic projection (Appendix C-2) prescribed by Block Theory. Additionally, the steps required for determining the critical

Block Instability Parameter	Corresponding failure condition
$F = 1$	Falling
$1/2 < F < 1$	Sliding
$F = 1/2$	At limit equilibrium
$0 < F < 1/2$	Safe
$F = 0$	No mode

Table 2. The Block Instability Parameter and corresponding state of equilibrium modified after Hatzor (1992).

key blocks along each excavation surface on a local scale are reviewed.

Application of Block Theory to Retrogressive Scarp Failure

Block Theory requires four main input parameters: 1) joint orientations, 2) average joint spacing, 3) estimated joint friction values, and 4) excavation surface orientations. Systematic evaluation of local block stability along the scarp face required statistical analysis of subsets of the regional structural data near each excavation face being analyzed. Statistical pole plots were generated for each locality along the scarp face and are summarized in Appendix C-1.

Joint spacing was extracted directly from outcrops where possible or photogrammetrically, partly adopting the methods of scan-line surveying outlined by Priest and Hudson (1981) as discussed in Field Data. Spacing values associated with each local joint set were averaged to obtain a single representative value. The values were then converted to joint frequencies ($1/\text{spacing}$) for computation of the joint combination probability function $P(JC)$. These results are summarized in Table 3 (A-F).

A range of friction values ($\varphi_j = 20\text{-}30^\circ$) for weathered to more competent Briones Sandstone determined from direct shear testing (D. Rogers, personal

Critical Key Block: Structural Data			
Excavation Surface A			
Joint Set	Average Dip/Dip Direction	Average Spacing (Ft.)	True Frequency $\lambda(1/\text{Ft.})$
A: J1	75/196	1.5	0.67
B: J2	49/165	0.33	3.0
C: J3	44/250	2.0	0.50
D: J4	84/52	0.58	1.7
E: J5	69/130	1.5	0.67
Excavation Surface B			
A: J1	73/201	0.50	2.0
B: J2	61/214	0.50	2.0
C: J3	71/256	0.50	2.0
D: J4	69/299	0.42	2.4
E: J5	81/88	0.33	3.0
F: J6	54/168	0.25	4.0
Excavation Surface C			
A: J1	39/186	2.0	0.50
B: J2	69/103	0.17	5.9
C: J3	61/298	0.42	2.4
D: J4	54/329	1.0	1.0
E: J5	84/234	3.0	0.33
Excavation Surface D			
A: J1	67/180	0.25	4.0
B: J2	67/220	0.50	2.0
C: J3	80/261	0.08	12.5
D: J4	68/36	0.50	2.0
E: J5	70/137	1.5	0.67
Excavation Surface E			
A: J1	52/185	0.25	4.0
B: J2	61/236	1.5	0.67
C: J3	78/243	0.08	12.5
D: J4	86/252	3.0	0.33
E: J5	83/282	2.0	0.50
F: J6	70/83	0.33	3.0
G: J7	73/105	0.17	5.9
Excavation Surface F			
A: J1	55/187	0.25	4.0
B: J2	77/199	0.50	2.0
C: J3	69/271	0.33	3.0
D: J4	66/314	0.50	2.0

Table 3. Statistically analyzed joint orientations, joint spacing, and estimated strength parameter ϕ_j used in Critical Key Block Analysis. All corresponding stereoplots are shown in Appendix C-1.

communication, 1998) served as a basis for testing the parameter s effect on block stability. The influence of joint spacing and orientation outweighed the effect of friction on the overall block stability in the Critical Key Block Method. A conservative and uniform value of $\phi_j = 30^\circ$ was therefore used in all limit equilibrium analyses.

The excavation surface was approximated both locally and regionally to accommodate the two types of data applied. On a local scale, the active portion of the head scarp is approximated by six unique surfaces assumed to be perfectly planar. These steeply dipping asperities were visually estimated in the field with the aid of a map board while standing at an upslope vantage point. A Brunton compass was used to approximate the attitude of the map board while held parallel to the face. This process was repeated five or more times to obtain an average orientation for each face. These data are shown in Figure 33. The strike of the regional excavation surface was visually approximated from a 1:1200 topographic base map, and the dip angle trigonometrically estimated from several profile lines along the scarp face.

All possible JCs were considered for each portion of the main scarp and plotted with program B02, which allowed for rapid visual inspection of removable JPs and computation of the mode of failure for each removable JP (Appendix C-2). In cases where the block edge appeared to be on the excavation boundary (dashed line), the removable JP was confirmed vectorally using program B03, which was also used to draw the tetrahedral block of the corresponding JP. All blocks generated with this program did not represent the real physical dimensions of the block because joint spacing is not considered and statistically averaged planes are used.

Excavation Surface	Mean Dip/Dip direction	Associated raw Structural Data Loc.
A	86/267	Loc. 35
B	76/303	Loc. 34
C	85/230	Loc. 23,24
D	67/305	Loc. 25,27,33
E	80/267	Loc. 28,29,30
F	75/197	Loc. 31,32

Figure 33. Six joint controlled excavation surfaces used in the Critical Key Block analysis. The mean orientations of each surface is summarized in Table 4.2 .

Individual components of the three parameters $P(JC)$, K , and F were computed with several subroutines in the program BLOCK as described under the Critical Key Block Method. A brief description of the main programs used in BLOCK are given in Appendix C-5. Simple algorithms were then constructed on a Microsoft Excel spreadsheet for efficient computation of each of the three parameters and their product, $P(B)$. The most critically unstable block(s) were then determined from the histogram plots of $P(B)$ vs the JC number.

Application of Block Theory on a Regional Scale

Block Theory was applied on a regional scale using the four dominant discontinuities extracted from the entire population (623 orientations) of structural data. The assumption that regional discontinuities have significantly greater persistence and spacing than discontinuities near the scarp disqualifies the use of the Critical Key Block Method. Block removability and mode of failure was determined using program B02. A limit equilibrium analysis then was conducted on the removable block using a uniform friction value of $\phi_j = 30^\circ$

Results and Discussion

Retrogressive Scarp Failure

A summary of all structural data near the scarp faces is presented in Table 3. These data are derived from the mean vector of contoured joint poles from one or more data locations (Figure 8) associated with each of the six excavation surfaces, using the

Fisher Distribution method on an equal-area stereographic projection (Appendix C-1).

Most of the statistical orientations along the active head scarp boundary dip moderately to steeply southeast to southwest, generating planar intersections of similar orientation.

The degree of error between statistically averaged data and actual surfaces bounding the key blocks could not be accurately verified.

The results of Block Theory's removability and mode of failure analyses for all possible JCs are given in Appendix C-2, and C-3, Tables 1-6. For clarity, the large number of stereoplots generated for each JC have been reduced to six plots representing the predicted critical key block of escarpments A-F. A visual representation of the block pyramid BP (JP + bounding excavation surface) for each critical key block is shown in Figures 34-39.

All critical key blocks were selected based on the highest value of $P(B)$ (Figure 4.11). The dominant failure condition of most blocks, determined from their corresponding instability parameter F , was single plane sliding (Table 4). At locations C and D, critical key blocks were predicted to be at limit equilibrium (factor of safety = 1.0) or stable due to excessive frictional forces.

Three of the predicted planes of sliding (locations A, C, and F) correlate with the pervasive joint sets J4 (42/260), and J1 (60/196). The predicted orientation of sliding plane joint set 4 of location B (69/299) roughly matches the orientation of the escarpment (76/303). The orientation of this escarpment appears to be associated with a toppling mode of failure rather than sliding. This escarpment may have resulted from single or multiple wedge failures sliding southwest along J1 (Figure 35). Failure of the predicted

Critical Key Block Analysis					
Excavation Surface	JC {i;j;k}	JP Code	MODE of failure	F	Failure Condition
A	{2;3;4}	101	3	0.57	SLIDING
B	{4;5;6}	011	4	0.80	SLIDING
C	{1;2;4}	011	1	0.53	LIMIT EQUILIBRIUM
D	{3;4;5}	001	34	0.46	SAFE
E	{2;3;5}	000	2	0.73	SLIDING
F	{1;2;4}	001	1	0.67	SLIDING

Table 4. Results of Critical Key Block Analysis. The critical JC corresponds to the critical key block determined from Figure 4.11. All modes of failure are predicted to be sliding on a single plane because conditions along excavation surface D are predicted as safe. Mode 3, for example, refers to sliding on joint plane 3 of the corresponding JC.

Figure 34. Excavation surface A, showing a tetrahedral block mold near the top. Block Theory predicts single-plane sliding along 44/250 which is coincidental with the ridge slope and sub-parallel to J4. The single mold shown in the picture does not correspond to the predicted critical key block.

Figure 35. Excavation surface B, showing a salient tetrahedral block mold near the top. The predicted mode of failure is sliding a single plane along the statistical orientation 69/299. The apparent mode of failure, however, appears to be bi-planar with the pervasive J1.

Figure 36. Excavation surface C, showing several molds of block pyramid 0111 near the top. The predicted mode of failure is sliding along 39/186. The inclination of the sliding surface in the photo is reasonable, similar to the pervasive J1.

Figure 38. Excavation surface E, showing block pyramid 0111 near the top. The predicted mode of failure is sliding along J2: 61/236, which strikes 40° more westerly than the mean orientation of J1 observed in the field.

Figure 39. Excavation surface F, showing two large wedge pull outs. The statistical joint orientations used at this site produce three critical key blocks, of which JC 1 and JC2 have the slab-like form of block A and JC3 has the shape of block B. Block A slides on a single plane sub-parallel to the pervasive J1 (60/196), and block B slides along the intersection of planes 1 and 2, which both plot in the realm of pervasive J1.

critical key block at location E, is kinematically more feasible than that of location B, because the steeper escarpment allows exposure of steeply plunging joint intersections and planes along the face (Figure 38). In all cases, the sliding direction is estimated to coincide with the dip vector of the sliding plane (south-southwest), based on the assumed resultant force of gravity alone.

Discrepancies in predicted critical key-block geometry and kinematics are apparent from the observed geometry of block molds preserved along escarpments A-F (Figures 34-39). These discrepancies are attributed to several sources of error propagated through the independent parameters P(JC) and K (Figures 41 and 42): 1) inaccurate representation of discontinuities from statistical averaging, 2) the assumption that joint surfaces measured near the scarp edge intersect the excavation face below, and 3) error in representative joint spacing.

Block Theory's accuracy and validity ultimately rely on the use of structural data extracted directly from the field (Goodman, personal communication, 1999). However, the application of Block Theory to structures such as the Cumberland Gap Tunnel and Seminole Dam (Hatzor, 1992), and to rock abutment failure at Pacoima Dam (Hatzor, 1995), used statistically averaged structural data that correlated well with block molds and joint traces along the analyzed excavation surface. The main difference in comparison to this study is the extent of rock exposures from which the structural data were collected. The inability to follow the trace or aerial extent of any given joint trace along an outcrop may have led to measurement bias of highly localized fracture sets that never intersected the analyzed excavation.

The average joint spacing assigned to each statistical joint set ranged from 2.5 cm (0.08 ft) to about 1 meter (3.0 ft.). The majority of spacing values were well below 0.3 meters (1.0 ft). This extremely close spacing is likely biased due to limited outcrop size and extensive burial of bedrock by colluvial deposits. This bias probably generated unrealistically high values for $P(JC)$ and consequentially $P(B)$ used to determine the most critically unstable key blocks along the scarp face. Verification of joint spacing was limited to outcrop exposures with typically short lateral dimensions. This bias may have overlooked larger-scale joint patterns, such as joint sets possessing characteristically broader spacing (2-10 m) with anomalous zones of tight spacing (several cm).

The instability parameter (Figure 43) had an insignificant affect on the overall prediction of the most critical key block. This parameter should not be trivialized, however, because blocks held solely by friction under limit equilibrium conditions, as was predicted for several blocks not distinguished to be critical key blocks, are more sensitive to slight changes in this parameter. Efforts to conduct *in situ* tilt tests, measure joint roughness, and test infill material would facilitate more accurate results but may prove to be futile without good representative sampling.

Regional Scale Block Theory Results

Geolith Consultants conducted a reconnaissance study of rock slope stability in the active head scarp region during an on-going investigation of the geologic hazards of the 1998 Mission Peak Landslide. They measured 56 joint, bedding, and shear attitudes along the periphery of the head scarp (Figure 44 and 45). Four principal sets of

Figure 40. Summary of the Block Failure Likelihood $P(B)$ function. The highest values represent the joint pyramids most likely to fail along the six respective scarp faces. Scarp faces C and D may have several potential block failure candidates.

Figure 41. Summary of the Joint Combination Probability parameter, $P(JC)$, which is dependent on the spacing and orientation of joint sets. The highest spikes represent JCs that are most likely to intersect with in a relatively small volume of rock. Most peak values correspond with the most critical JC (Figure 4.11).

Figure 42. Summary of the JP shape parameter K, which is dependent on the size of the JP's interplanar angles. The highest spikes represent open JP's with large interplanar angles ($> 90^\circ$) corresponding to a physical block with a relatively small maximum block size and apex distance from the scarp face. These highest values also correspond to the predicted most critical key blocks.

Figure 43. Summary of the block instability parameter F, which is dependent on joint friction. A value of 35 degrees is used on all discontinuities. For JCs where $F = 0$, no failure mode exists. Note that F falls between 0.5 and 1.0 in nearly all locations, indicating that the dominant mode of failure is sliding.

discontinuities were extracted from the statistical analysis of these data: set 1: N 48 W/ 28NE (28/42); set 2: E-W/ 57 S (57/180); set 3: N-S/ 86 E (86/90); and set 4: N 12 W/ 73 NE (73/78). They topographically estimated the average free plane (jagged scarp face) orientation to be N 78 W/ 68 SW (68/192). Both set 2 and the average excavation surface orientation closely approximate J1 as determined in my study.

The stereographic projection of these dominant planes with respect to the scarp face predicts two wedge-shaped key blocks: 1) BP 0011-1 and 2) BP 0111-1 (Figure 46 a, b). The mode of failure was predicted to be bi-planar sliding along the intersection of J1 and J2 with a plunge and trend of 57/174, and single-plane sliding along the dip vector (57/180) of J1, respectively. Although no direct evidence was provided for the existence of either of these block geometries in the field, their sliding vectors are consistent with field observation and nearly coincidental with the pervasive J1 (59/191) found in this study. Geolith (1998) concluded that BP 0111-1 has the classic form of a bedrock slump described by Kieffer (1998), and that both blocks have extremely low factors of safety (F.S. = 0.3).

For comparison, I conducted a similar analysis using the four principal statistical discontinuities presented earlier. Stereographic projection of these four planes and the scarp face, which approximates the boundaries of the head block, show three removable JP s (Figure 47). Block pyramids 0101-1 and 0111-1 (Figure 48) were predicted to slide along one and two planes respectively, with both sliding directions coincidental with J1 (59/191). BP 0101-1 approximates the broad wedge shape of the head block. The joint pyramid of this block is considered open, allowing it greater kinematic freedom and

diminished confining lateral stresses. Although the block geometries do not correspond to those determined by Geolith, the kinematics are remarkably similar.

In both this regional analysis and that conducted by Geolith (1998), the main discrepancy appears to be block geometry. This discrepancy may stem from the fact that neither study used actual block mold measurements, but alternatively, statistically averaged discontinuities near the scarp face. Both studies appear to agree that the regional kinematic mode of block failure is single or bi-planar sliding on a moderately steep incline to the south-southwest (59/191). The validation of these predicted critical key blocks was conducted dominantly by visual inspection rather than direct measurement of block molds in the field.

In both regional applications, the key block geometry has no clear correlation to the boundaries of the head scarp or other significantly larger blocks expected from regional data. Regardless of the contrasting data population size, both data sets presented a high degree of dispersion. The reliance on statistical averaging of orientations alone likely produces non-existent block geometries.

Figure 44. Enlarged structure location map compiled by Geolith Consultants, 1998.

Figure 45. Polar projection of the 56 discontinuity poles shown on the map above.

Figure 46. Block pyramids predicted in the key block analysis conducted by Geolith Consultants in 1998. A: BP 0011-1 is predicted to slide along the intersection of J1 and J2 with a plunge and trend of 57/174. B: BP 0111-1 slides on J1 (57/180), which is nearly coincidental with J1 determined in this study. A static equilibrium analysis using a friction of 26° predicted the factor of safety to be about 0.3 for both blocks.

Figure 47. Stereographic projection of the four principal discontinuities and average scarp face determined from the regional data set (623 poles). Three JPs are predicted to be removable, although JP 0001 has a closed geometry and is considered safe. JP 0101 slides along the dip vector of J1 (59/191) and JP 0111 slides along the intersection of J1 and J3 with a plunge and trend of 59/191.

Figure 48. Two of the three removable blocks generated from the four principal discontinuities determined from the regional data set. A: BP 0101-1 slides along the dip vector of J1 (59/191). B: BP 0111-1 slides along the intersection of J1 and J3 in the same direction as the upper block.

DISCONTINUOUS DEFORMATION ANALYSIS

Introduction

Discontinuous Deformation Analysis (DDA) is a numerical method for analyzing the kinematics and deformation of discontinuous media such as fractured rock masses (Shi, 1988, 1993). The intensely fractured quality of the Briones Sandstone (Figure 49) made this method ideal for examining the kinematics and deformation of the failing head block above the Mission Peak Landslide. DDA is useful for approximating displacements of individual blocks, the interaction of blocks through time, and ultimately the resulting mode of failure and total displacement. The goal of this study is two-fold: 1) to determine the model's sensitivity to various structural geometries, joint strength, and rock deformation parameters; and 2) to predict and compare the total runout distance of the failed block to those results predicted by the energy-line method prescribed by Hsu (1975).

The energy-line method used for comparison predicts maximum runout distance by conservation of energy evaluated during two phases of rock transport: 1) the rock fall phase (greatest gain of kinetic energy due to minimal inter-block contact), and 2) the runout phase (greatest loss of kinetic energy due to inter-block and basal friction). Three main criteria determine the maximum runout distance: 1) the initial volume of the rock mass, 2) the total height of rock fall, and 3) slope surface roughness.

Figure 49. Oblique aerial view of the head scarp and prominent head block bounded by the evacuation scar to the north, tension crack to the south and precipitous slope face to the west. The photo was taken on 6/22/98, three months after the Mission Peak Landslide reactivated and during the period of active raveling of the head block above the landslide headscarp.

DDA Theory

The displacement and deformation of individual blocks through time are estimated by solving a system of linear equations that approximate the centroid translation (u_0, v_0), rotation (θ), normal (ϵ_x, ϵ_y), and shear (γ_{xy}) strain components of individual blocks over small time steps. The linear nature of these equations assumes each block to have uniform stresses and strains, such that parallel block edges compress or expand while maintaining parallelism. The current formulation for block displacement is a two-dimensional, first-order, linear function:

$$u = u_0 - (y - y_0)\theta + (x - x_0)\epsilon_x + ((y - y_0)/2)\gamma_{xy}$$

$$v = v_0 - (x - x_0)\theta + (y - y_0)\epsilon_y + ((x - x_0)/2)\gamma_{xy}$$

where (u, v) are the displacements of a point located at (x, y) within a block whose centroid is located at (x_0, y_0) (MacLaughlin, 1997).

DDA solves the displacement equation $[K][D] = [F]$ by minimizing the potential energy of the block system, where K , D , and F represent the coefficient, unknown, and free-term matrices respectively. The unknown, or displacement parameter set $[D]$, represents the unknown displacement variables in the equations above. The potential energy function incorporates eight variables, five of which are applicable to the kinematics of rigid block systems: 1) point loading, 2) volume loading, 3) inertia, 4) displacement constraints and 5) penetration penalties (MacLaughlin, 1997). In this study, all loads in the modeled head block are inferred to be gravity-induced and thus depend

solely on block size and rock density. The energy associated with the deformation and displacement of individual blocks is quantified at the end of each time step and added into the matrix equation above in order to minimize the total potential energy of the block system. The energy associated with movement of the block system is modeled as an analogue to the strain energy associated with the displacement of stiff springs along block boundaries. The spring stiffness is determined by the spring constant, which typically ranges from 10 to 10^3 times Young's modulus of elasticity (E), to assure that the displacement of the spring is 10^{-3} to 10^{-4} times the total block displacement (Shi, 1988).

Stiff springs are used to establish boundary conditions 4 (block displacement constraints implemented by fixed points), and 5 (penetration penalties). The block displacement constraint applies stiff springs in the x and y directions at the fixed points. The high energy contributed from these pre-tensioned springs impedes displacement because the minimum potential energy solution is obtained only when the displacement of the fixed points is negligible. This process is achieved by computing the derivatives of the spring strain energy equations with respect to block displacement.

Similarly, stiff springs are used along the block boundaries to impose no-inter-penetration and no-tension force constraints when a contact between two blocks is detected. Block inter-penetration is detected in several steps: 1) determination of block contact condition (open or closed contact) by computing the distance between a block vertex and an adjacent block edge (side) or reference line, 2) evaluation of block contact type (angle to angle, angle to edge, and edge to edge) and conversion of all contacts to vertex edge format for easier numerical evaluation, and 3) application of

penetration penalties in cases where the vertex has passed the reference line of another block. When penetration occurs, the normal force is equivalent to the product of the penetration distance d and the spring stiffness p , and the resulting strain energy of the stiff spring is used to model three block-contact conditions following Coloumb s Law.

Three conditions are established using an inequality statement between normal (R_n) and shear (R_s) spring force components. 1) When the normal component of the contact force at the block boundary is tensile, no lock or stiff spring is applied and the contact is open:

$$R_n = -pd \leq 0,$$

where p is the spring constant or stiffness factor, and d is the spring displacement.

In this case, the contact between any two blocks remains open. 2) When the shear component is greater than the compressive normal component of the spring force ($-pd$), then sliding is promoted:

$$R_s \geq R_n \tan\phi + C,$$

where ϕ and C represent the friction and cohesion along block boundaries respectively.

3) When the shear component is less than the normal component, no sliding is permitted:

$$R_s \leq R_n \tan\phi + C.$$

DDA Input Parameters

Each analysis requires two separate input files: 1) geometry, and 2) analytical parameters (Appendix D). The geometry file, which also includes specification of fixed points (block boundary conditions), point loads, and measured points, may be either

created through a graphics interface window (Figure 50), or formatted as a series of line segments listed as (x, y) coordinates. The graphics interface automatically generates a formatted coordinates file for all line segments drawn on the screen, which later may be conveniently modified in the geometry dialogue box or in an editor such as Notepad. The coordinates are manually determined in this study so that actual elevation and scale could be preserved and structure be corrected for apparent dip. Furthermore, model sensitivity to topographic variation using actual slope profiles could be observed by linear approximation of slope topography.

DDA's geometry subroutine uses a tree-cutting algorithm that eliminates all line segments containing only one intersection point. The subroutine then conducts a search for all regions bounded by three or more intersections, which define individual blocks in the system (MacLaughlin, 1997). Block boundary conditions are set by establishing fixed points inside base blocks of the model to provide a stable surface for free blocks to move on. Additional load points, measured points, and hole points may be added depending on the type of initial conditions modeled.

The analysis dialogue box (Appendix D) allows the user to specify several analytical constraints for analysis of a saved geometry file: 1) dynamic and pseudo-static modes of analysis, 2) number of time steps and maximum displacement per time step, 3) mass density and unit weight, 4) discontinuity strength parameters (friction angle, cohesion, and tensile strength), and 5) block deformation parameters (Young's Modulus and Poisson's Ratio). The maximum displacement per time step is the value entered divided by half the maximum dimension of the region defined by the geometry. This

parameter ultimately controls the speed of numerical convergence on a solution to the displacement equations. Block contacts are detected when block vertices are within 2.5 times the maximum displacement value. The recommended range for the maximum displacement value is between 0.001 and 0.01.

The dynamic and pseudo-static modes differ only by the block velocities used at the beginning of each time step. The dynamic mode preserves block inertia by using the computed block velocity from the previous time step, while the static mode resets all velocities to zero at the beginning of each time step. In this study, the dynamic mode is applied to rock debris runout models to generate more realistic kinematic results for rapid failure. The pseudo-static mode, which regulates the distribution of strain energy through the block system, enforces a slower deformation applicable to internal displacements in the head block expected to occur over several days to months. The effects of other parameters on the analyses are discussed below.

Two main analytical subroutines have been recently implemented: 1) a block rotation correction, and 2) a gravity turn-on phase algorithm. Because block rotation is approximated linearly, rapid growth in block area may result after each rotation increment. This problem is largely resolved by using an exact rotational post-correction. The gravity phase was developed in response to the gravity turn-on problem that results from elastic deformation and seating of block contacts from the sudden release of gravitational loading in initial time steps. This problem is partly resolved by enforcing a pseudo-static analysis with artificially high joint strength parameters on the block system

Figure 50. Application of block boundary conditions with fixed points, and measured points for monitoring block displacement through time.

prior to the initial time step until a specified tolerance is met. Once this occurs, the dynamic mode of analysis is turned on (MacLaughlin, 1997).

DDA Model Output

DDA analysis generates graphical output showing actual block deformation and kinematics through time. These results may be viewed numerically in output files once the analysis is completed. The output files provide data on monitored kinetic energy, virtual work, spring stiffness, time increments, open-close iterations, and open-close failures that may be plotted for visual inspection. If measured points are applied, total

block displacement, velocity, and acceleration may be post-processed from the output file.

Kinematics of Head Block Deformation

The structural geometry of the head block was modeled from the oblique intersection of the dominant discontinuities determined earlier with a line trending parallel to the upper extensometer wire (EXT 2) near the apex of the head block. Several bearings were shot along the lower portion of this wire where it was anchored to the head block throughout the remainder of 1998 following its acceleration in May. The average trend of S86W concurs with the dominant westward component tracked by GPS.

A topographic 1:1 structural cross-section was constructed from a 1:1200 scale (1 inch = 100 feet) contour map of the Mission Peak Landslide with 5-foot contour intervals. The topographic profile was then approximated by a series of connected line segments. The (x, y) coordinates of the two end points representing each line were then determined from the cross-section profile. The actual elevation is preserved in all coordinates so that modeled deformation and kinematics could be readily measured and correlated to field observations.

The head block boundaries and structural fabric were generated from the four dominant discontinuities established in Field Data: J1 (60/196), J2 (76/110), J3 (80/260), and J4 (35/260). Briones Sandstone bedding was included initially with a mean orientation of 42/11, though preliminary testing showed that its orientation only enhances stability. Furthermore, its intersection with other discontinuity sets generated block sizes

several magnitudes smaller than the largest blocks that frequently induced block penetration errors. Additionally, J3 was omitted since preliminary structural models using J3 paired with J1, J2, or both J1 and J2 also concluded that J3 was less influential in head block deformation and block kinematics. Sets parallel and interstitial to J1 and J2 were replicated to generate spacings of 1.5m, 3.0m, and 4.6m.

Head block deformation was modeled using four parameters: 1) joint friction, 2) joint spacing, 3) Young's Modulus, and 4) Poisson's Ratio. Each parameter was tested individually by holding the other parameters constant. The methods for testing each of these parameters is briefly discussed below.

Joint friction was tested using a joint spacing of $J1=J2= 4.6 \text{ m}$ (15 ft). This spacing generated 138 roughly equi-dimensional blocks, excluding those that intersected slope topography and the basal shear plane (J4). This structure was held constant for four separate trials using uniform friction values for all joint sets of $\varphi = 0^\circ, 25^\circ, 30^\circ, \text{ and } 45^\circ$. Shear forces along the basal shear plane (J4) were greatly dampened by assigning a friction of $\varphi_{\text{talus}} = 75^\circ$ for the talus block at the base of the head block. The effect of joint spacing on block kinematics and slope stability was observed by varying the joint spacing while holding joint friction constant at $\varphi_{\text{joint}} = 30^\circ$. Three structural models (modified from the model in Figure 55) were developed: 1) $J1 = 3\text{m}$ and $J2 = 4.6 \text{ m}$, 2) $J1 = 1.5 \text{ m}$ and $J2 = 4.6 \text{ m}$, and 3) $J1 = 4.6 \text{ m}$ and $J2 = 1.5 \text{ m}$. These structural configurations resulted in corresponding models sizes of 191, 315, and 268 blocks respectively. Models generally exceeding 300 blocks in size required 30 minutes to several hours per 1000 iterations.

Young's Modulus (E) and Poisson's Ratio (ν) are elastic constants used to quantify the relationship between stress and strain. DDA's current formulation assumes that blocks are linearly elastic, with stress in the third dimension held constant (MacLaughlin, 1997). DDA assigns default values of 1.0×10^6 psf and 0.49 to E and ν respectively. Because the numerical implementation of these parameters on multi-block systems is poorly understood, both parameters were tested only on a preliminary basis to observe analytical sensitivity to extreme, but reasonable, values for E and ν .

Values of Young's modulus of 1.0×10^8 psf, 1.0×10^{10} psf, and $\nu = 0.25$ (typical range: $0.25 \leq \nu \leq 0.33$) were tested separately while keeping the non-tested parameter at default. All three models use the original geometry (191 blocks) and joint friction ($\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$, $\varphi_{\text{talus}} = 45^\circ$) of Figure 57. The effects of E and ν on head block deformation are compared to the deformation results of Figure 58, where both values are held at default.

Head Block Deformation Results

The original head block structure used for the joint friction trials is shown in Figure 51. All results for joint frictions $\varphi = 0^\circ, 25^\circ, 30^\circ$, and 45° are shown in Figure 52, Rows 1-4, respectively. For $\varphi = 0^\circ$, the dominant mode of failure is sliding, with the greatest amount of displacement along the steeper-dipping J1 within the head block. The omission of friction at the base of the head block and talus block allowed for about 20 m of shear displacement along the basal failure plane. Multiple modes of failure are

apparent. Back-topple is evident at the tension crack and is transformed into a slumping mode at depth due to sliding on J1. Block slumping is most clearly shown at the front end of the head block, where a cluster of blocks behaving as one discrete body slumped approximately 4.6 m (15 ft.).

Analyses for $\varphi = 25^\circ$, 30° , and 45° use an artificial friction of $\varphi_{\text{talus}} = 75^\circ$ beneath the talus block to produce the interpreted lateral buttressing effect. In all three cases, the dominant mode of failure was a combination of sliding and toppling. The lowest friction model, $\varphi = 25^\circ$, showed shearing along multiple J1 surfaces as the dominant mode of failure, resulting in a pronounced opening of the tension crack above as a result. Models using $\varphi = 25^\circ$ and $\varphi = 30^\circ$ both exhibit block toppling at the slope face. In the final stages of deformation, sliding occurred on the over-inclined J1, promoting minor block fall at the scarp face. For $\varphi = 45^\circ$, a flexural toppling mode developed at 1000 iterations, and basal fracture developed by 1500 iterations, along a J1 surface extending from the top of the talus block to about 9 m (30 ft.) from the tension crack.

The dilation of the upper bounding tension crack was also markedly different in all four cases. In case 1, the back-topple of blocks generated a prominent bench where the crack would have otherwise developed. In cases 2-4, the tension crack varied in width and depth. Tension crack geometry appears to be hypothetically controlled by two factors: 1) the dampening of basal shear on J4, by application of artificially high friction to the talus block and 2) varied amounts of friction on J1, J2, and J4. In case 2, displacement along J1 created anomalous steps on the head block side of the crack and

Figure 51. Original geometry for joint friction sensitivity analysis. $J1 = J2 = 4.6$ m (15 ft.) and $J2 = 4.6$ m (15 ft.). E and ν are held at default values of 1.0×10^6 psf and 0.49 respectively. This configuration generates a total of 191 blocks.

Figure 52. Results of joint friction sensitivity analysis. Column A: 500 iterations; column B: 1000 iterations; column C: 1500 iterations. Row 1: $\varphi = 0$ for all joints; row 2: $\varphi_2 = \varphi_3 = \varphi_4 = 25^\circ$, $\varphi_{\text{talus}} = 75^\circ$; row 3: $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$, $\varphi_{\text{talus}} = 75^\circ$; row 4: $\varphi_2 = \varphi_3 = \varphi_4 = 45^\circ$, $\varphi_{\text{talus}} = 75^\circ$.

consequential asymmetry that is not recognized in the field. The tension crack dilated approximately 2.5 meters (8 ft.) in case 3 ($\varphi = 30^\circ$) after the first 500 iterations, and had not expanded 1000 iterations later.

The variation in joint spacing also had significant impact on block kinematics and deformation of the head block (Figures 53-58). Intuitively, this is expected because joint spacing ultimately determines block size, block geometry, and block kinematics. In all cases, joint friction is set to $\varphi = 30^\circ$, except at the base of the talus block, where $\varphi_{\text{talus}} = 45^\circ$. When $J1 = 3 \text{ m}$ (10 ft), and $J2 = 4.6 \text{ m}$ (15 ft.) (Figure 53), the apparent mode of failure is flexural toppling. Dilation occurs periodically about every 9 to 14 m (30 to 45 ft) on J2, causing a rib-like topography recognized in field as sackungen (Kieffer, 1998). Toppling has generated conditions for a substantially larger block failure to occur near the face, which has been recognized in the field. The benched topography of the head block is subtle but identifiable. These features are not regular as the analysis predicts, but do appear consistent with internal toppling based on deep fracture orientations measured below the apex extensometer (EXT 2).

For $J1 = 1.5 \text{ m}$ and $J2 = 4.6 \text{ m}$ (Figure 55), tabular block geometry enforces sliding on multiple planes of J1. The deflection of J2 is thus a direct result of shear displacement along J1. A new basal detachment surface becomes evident by 1000 iterations. This surface, delineated by deflection of J2, is steeply inclined in comparison to the basal shear plane (J4) (Figure 56). The overall deformation causes steepening of the slope face due to the creep-like transfer of rock mass from back to front. This process

Figure 53. Original geometry for joint spacing sensitivity analysis. $J1 = 3 \text{ m}$ (10 ft.) and $J2 = 4.6 \text{ m}$ (15 ft.). E and ν are held at default values of $1.0 \times 10^6 \text{ psf}$ and 0.49 respectively. This configuration generated a total of 191 blocks.

Figure 54. Results of joint spacing sensitivity analysis for $J1 = 3 \text{ m (10 ft.)}$ and $J2 = 4.6 \text{ m (15 ft.)}$. a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. ft) spacing. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$. appears to create a stabilizing effect by interlocking blocks from overburden.

For $J1 = 4.6$ m and $J2 = 1.5$ m (Figure 57), the mode of failure of individual blocks is ambiguous. Although the aspect ratio would suggest toppling, close examination shows discrete zones marked by alignment of $J2$ enclosing both flexural toppling and block slumping modes of failure. Flexural toppling is most pronounced at the scarp face (front) and tension crack (back) of the head block, where displacement along $J1$ appears negligible. Upslope and adjacent to this zone, individual blocks aligned along $J1$ interfaces appear back-tilted from the original geometry, suggesting slumping (Figure 58). The juxtaposition of discrete zones of flexural toppling to block slumping is expressed subtly as intermittent zones of obsequent scarps and smooth, concave depressions respectively. This geomorphic expression is recognized in the field.

The effects of Young's Modulus and Poisson's ratio on head block deformation and kinematics are more subtle than the effects of joint friction and spacing parameters. Sensitivity to both deformation parameters was analyzed using the original geometry and joint friction values shown in Figure 53. The dominant mode of failure is combined topple and sliding for $E = 1.0 \times 10^6$ psf (Figure 53), $E = 1.0 \times 10^8$ psf (Figure 59), and $E = 1.0 \times 10^{10}$ psf (Figure 60). Increasing values of E , however, promoted development of tension cracks within the head block, with measured dilations of 1-3 m and generally increasing depths towards the slope face. These tension cracks appear to diminish at the threshold value, $E = 1.0 \times 10^{10}$ psf, forcing large-scale block failures.

The effects of Poisson's ratio on head block deformation and kinematics appears negligible when the lower limit (Figure 61, $\nu = 0.25$) is compared to the highest limit

Figure 55. Original geometry for joint spacing sensitivity analysis. $J1 = 1.5$ m (5 ft.) and $J2 = 4.6$ m (15 ft.). E and ν are held at default values of 1.0×10^6 psf and 0.49 respectively. This configuration generates a total of 315 blocks.

Figure 56. Results of joint spacing sensitivity analysis for $J1 = 1.5 \text{ m (5 ft.)}$ and $J2 = 4.6 \text{ m (15 ft.)}$. a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. ft) spacing. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$.

Figure 57. Original geometry for joint-spacing sensitivity analysis. $J1 = 4.6$ m (15 ft.) and $J2 = 1.5$ m (5 ft.). E and ν are held at default values of 1.0×10^6 psf and 0.49 respectively. This configuration generated a total of 268 blocks.

Figure 58. Results of joint spacing sensitivity analysis for $J1 = 4.6$ m (15 ft.) and $J2 = 1.5$ m (5 ft.). a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. ft) spacing. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$.

Figure 59. The effect of Young's Modulus ($E = 1 \times 10^8$ psf) on head block deformation. a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$. The original geometry of Figure 5.4a is used.

Figure 60. The effect of Young's Modulus ($E = 1 \times 10^{10}$ psf) on head block deformation. a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$. The original geometry of Figure 5.4a is used.

Figure 61. The effect of Poisson's Ratio ($\nu = 0.25$) on head block deformation. a) 500 iterations, b) 1000 iterations, and c) 1500 iterations. A uniform joint friction of $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$ is applied, except $\varphi_{\text{talus}} = 45^\circ$. The original geometry of Figure 5.4a is used.

(0.49) for nearly incompressible rock (Figure 53). In general, the negligible deformation of individual blocks made analyses insensitive to extreme values of Poisson's ratio.

The effect of ν on head block deformation over time is difficult to model because of probable changes of stress or strain attributed to such factors as 1) change in loads applied to the rock mass by ground water, 2) change in head-scarp geometry, and 3) change in rock deformability properties by weathering processes (Goodman, 1980). DDA does not address these variables.

Runout Analysis Methods

DDA is used solely to examine block kinematics in a dynamic mode once gravitational loading is initiated and blocks are set in motion down-slope from the head block. The slope profiles were constructed from two plausible runout paths on a 1:1200 topographic map, based on the landslide's current geomorphology (Figure 62). The topographic profiles were estimated with a series of connected line segments that are represented as coordinates using real distances and elevations (Figure 63).

The head block geometry was slightly modified from that shown in Figure 53 with regards to the basal shear plane (J4) geometry. The deformation models showed J4 intersecting the slope line beneath the talus block to regulate its buttressing effect at the toe of the head block. Artificially high friction values at the base of the talus block still allowed for measurable shear displacement along the base. The basal shear plane was abruptly ended at the top of the talus cone so that stress from gravity loading is

Figure 62 . Two runout paths modeled in DDA. Path A-A and B-B are approximately 507 m (1,665 ft) and 510 m (1,675 ft) from the turning point at the arrow. This point marks the transition between rock fall, and runout. The total path lengths account for actual surface distance not horizontal length.

Figure 63. Original head block geometry with two runout paths. A.) runout path A-A has a total runout distance of about 507 m (1665 ft.) and vertical relief of 100 m (330 ft.) B.) runout path B-B has a total runout distance 510 m (1675 ft.) and vertical relief 84 m (275 ft.).

transferred more rapidly through the block system, imparting the initial energy needed to trigger rapid failure and more realistic block dynamics for slope debris flow.

Many runout models were initially tested using different head block structure, shear-plane geometry, and analytical parameters to understand the effect each had on the kinematics of modeled debris flow. The highly simplified head block structure largely eliminated problems with elastic rebound experienced from the instantaneous release of gravity loading in the initial phase of the dynamic analytical mode. Analysis sensitivity to slope surface roughness and geomorphic features such as the head-scarp graben and slope inclination were evaluated using a uniform joint friction of $\phi_j = 30^\circ$ and an average slope friction of 26° estimated from the energy-line method conducted by Geolith Consultants (1998). Both models were run for a total of 3000 time steps, and the graphic results were saved for 500, 1500, and 3000 iterations. Young's Modulus and Poisson's ratio were left at default values 1.0×10^6 psf and 0.49, respectively.

Runout Analysis Results

The total runout distances for slope profiles A-A and B-B are shown in Figures 64 and 65. The non-daylighted basal shear plane and moderate friction values prevented complete evacuation of the head block, which concurs with present field conditions. Complete head block failure is based on the underlying assumption that it is seismically induced under dry conditions such that buttressing support of the head-scarp graben block remains in place. DDA analysis in the dynamic mode, under non-daylighting conditions, resulted in failure of the upper two thirds of the head block along

J1. This pervasive joint set appears a likely candidate for larger block failures given its ubiquity within and around the head-scarp.

Several kinematic transitions are apparent between the head block and the terminal point of debris stream during the analysis. The onset of head block failure predicted a complex mode of flexural toppling combined with block sliding on the oversteepened, upper portions of the rock columns. Complete collapse of the toppling columns leads to combined sliding and rolling of base blocks on the newly daylighted J1 at the top of the talus cone. Small asperities generated by displacements at the intersections of J2 with J1 temporarily impede displacement of basal block clusters, creating ramps from which residual upper blocks could become airborne. Displacement downslope is kinematically separated into a lower block-sliding layer and an upper rolling and bouncing layer. Kinetic energy appeared to rapidly attenuate within the head-scarp graben. Two mechanisms appeared to be responsible for observed energy attenuation: 1) changes in surface relief, and 2) interaction between opposing kinematic block layers, where basal blocks generated sharp cavities between blocks and served to impede movement of upper blocks.

Finally, each model produced one or two lead blocks that appeared to move independently from the debris stream. The blocks appeared to move primarily by bouncing and rolling along the slope surface, which was assigned a uniform friction of $\varphi_{\text{slope}} = 26^\circ$. Closer examination of the kinematics of these blocks, however, revealed a single or several reversals in block rotation coincident with surface collision that violated the conservation of angular momentum.

Figure 64. Runout analysis using slope path A-A and joint friction values $\varphi_{\text{slope}} = 26^\circ$, $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$. A: 500 iterations; B: 1500 iterations; C: 3000 iterations. The maximum runout distance is determined by the most distal block.

Figure 65. Runout analysis using slope path B-B and joint friction values: $\varphi_{\text{slope}} = 26^\circ$, $\varphi_2 = \varphi_3 = \varphi_4 = 30^\circ$. A: 500 iterations; B: 1500 iterations; C: 3000 iterations. The maximum runout distance is determined by the most distal block.

Discussion and Conclusions

Sensitivity analyses conducted on the deformation of the head block offered some insight to how variables such as joint orientation, friction, spacing, and rock deformation parameters might affect overall head block deformation. When these variables cannot be well-established due to structural complexity and erosion, a reasonable range of values may be applied and the graphical kinematic results compared to those observed in the field. DDA has shown that even simple structural geometry may lead to complex modes of failure (multiple modes occurring at once) and that deformations are not intuitive.

The predicted initial dilation of the tension crack appears to be attributed entirely to shearing along J1 and flexural toppling (interlayer slip) along the rock column forming J3, which alternatively might be attributed to basal shear along the hypothetical J4. Field observation of ubiquitous dilation, development of such features as obsequent scarps (modeled in Figure 5.4b), and the lack of evidence for a major daylighting basal failure plane (J4) are interpreted as evidence in favor of minimal basal shear.

Minimal shear displacement on J4 could be the cause of both observed and predicted rock fall and block failure local to the steep slope face of the head block (Figure 54).

One of the main limitations of applying DDA to head block deformation is the inability to analyze more complex structures in three dimensions. Kinematics can only reasonably be estimated if the trend line roughly coincides with the plunge of pervasive structure. Displacements of the head block are dominantly downward and to the west (Appendix A), not parallel to the south-southwest trend of intersections formed by the pervasive J1 and conjugate joint sets. While a two-dimensional model is entirely limited

to displacement coincidental to the cross-section trend line, a three-dimensional model might offer complex modes of failure involving block rotation combined with sliding.

DDA's current geometry subroutine limits the user's ability to generate more complex structural models. Preliminary models in my study incorporated both random fracture sets superimposed on systematic joint sets (i.e. J1 and J2) and discontinuous systematic joint sets. The superposition of random fracture sets unavoidably generated block areas several magnitudes smaller than the maximum block promoting block penetration error during analyses. Small block areas were commonly generated at the intersection of three or more fracture sets, or at the head block boundaries. DDA's tree-cutting algorithm described by Yeung (1991) and MacLaughlin (1997), mathematically detects line segment intersections, such that segments with single intersections are trimmed away. Extraneous blocks generated above the head block boundaries from the over-extension of line segments (representing joint sets inside the head block) could only be eliminated by manual extrapolation of coordinates on graph paper or by trial and error.

Preliminary analyses incorporated numerous models with discontinuous J1, J2, and J4 sets to assess the overall effect on head block deformation and block kinematics. The single basal shear plane, (J4), was altered by incorporating several plausible step geometries. In theory, the discontinuous sets tested above should allow strain to propagate beyond the terminal point, across the rock bridges connecting parallel sets (Hoek and Bray, 1981). DDA is currently incapable of generating new fracture sets and crushing mechanisms (MacLaughlin, 1997)

The maximum rock fall runout distance predicted by DDA produced results similar to those determined by the energy-line method (Figure 66) conducted by Geolith Consultants, Inc. (1998). Geolith incorporated four turning points (changes in slope angle) in their energy-line model. They predicted a total rock debris runout distance range of 170 m (560 ft) to 350 m (1,146 ft), using an average friction of $\alpha = 24$ degrees, fall slope $\beta_1 = 43$ degrees, and runout slope $\beta_2 = 11$ degrees. DDA predicted maximum runout distances ranging from 230 m (755 ft) to 335 m (1,099 ft) (Figures 64 and 65), concurring with Geolith's results.

A comparison of DDA's predicted results to those of other rock fall runout models (Ritchie, 1963; Bozzolo and others, 1988; Pamini, and Hutter (1988), Pfeiffer and Higgins, 1989; Pfeiffer and Bowen, 1989; Kobayashi and others, 1990; Dade and Huppert, 1998) would require systematic comparison of error generated by DDA's linear approximation of block displacement to error generated by the analytical equations presented in the models above. This study would be similar to the kinematic testing of single-plane and bi-planar sliding failures (MacLaughlin, 1997), but would incorporate additional parameters affecting rapid block transport, such as angular momentum, dissipation of kinetic energy from linearly elastic collision between blocks, and sensitivity to modeled surface roughness.

Several factors currently render the DDA's predictions for maximum runout distances unreliable: 1) the inability to incorporate contrasting block sizes within the debris stream, where the smaller fragments behave as the transporting fluid (Hsu, 1975); 2) inability to model block shape and generate realistic surface roughness as

Figure 66. Established Energy Line and measured parameters for rock fall runout analysis modified after Geolith Consultants, Inc., 1998. Note that DDA's predicted total runout distances for runout paths A-A and B-B fall within their estimated maximum runout range.

prescribed by Kobayashi, et al. (1990); 3) violation of the conservation of angular momentum for free flying and rolling blocks; and 4) numerical creep generated by compression of the shear penetration springs along block boundaries during the final stages of runout when the block contact is seated (MacLaughlin, 1997).

CONCLUSIONS

The slope stability and block kinematics of the intensely fractured Briones Sandstone composing Mission Ridge appears to be structurally controlled by at least four pervasive discontinuities; bedding has negligible impact on slope processes because of its upslope dip. These discontinuities are highly dispersed, and generally plunge 15° - 30° steeper than the average slope face, rendering stability to the head scarp region until they are day-lighted or under-mined by removal of lateral support at the base of the ridge. The back rotation of the head scarp graben at the base of Mission Ridge during the 1998 Mission Peak landslide is stereographically shown to be the most likely cause for the brief period of acceleration of the head block and the onset of ravel that rapidly transformed the head scarp boundaries.

Block Theory was used to evaluate critically unstable blocks, termed key blocks, at the scarp face boundary. The underlying premise of this theory is that the failure of one relatively small block provides space for successive upslope blocks to move until a massive failure occurs. A relatively simple, tetrahedral block geometry was assumed based on the observed moulds preserved along the scarp. Several reasons advocate poor applicability of this stereographic application to the rock slope kinematics of Mission Ridge. 1) The inability to directly measure bounding joint surfaces of individual molds required the use of statistically averaged joint surfaces remote to the scarp face (free surface) being analyzed. The correlation of statistical orientations to actual block mould surfaces preserved in the scarp was difficult. 2) Block Theory assumes the existence of a relatively rigid and competent body of rock

with systematic fracture sets. While there did appear to be some degree of systematic fracturing in the Briones Sandstone, these fracture sets were frequently obscured by the superposition of discrete zones of intensely fractured and weathered rock. The intensely fractured nature of the Briones Sandstone likely contributes to slow deformation prior to instantaneous block failure. These conditions reduce the rock's rigidity and violate the supposition that no displacement or deformation of the rock may occur prior to the rock body being analyzed. 3) Joint surface properties needed more accurate characterization in order to assign realistic joint friction values to the failure surface(s).

DDA provided useful insight to the simultaneous interaction and kinematics of block systems. For relatively simple systems (small numbers of blocks), DDA was able to predict more complex modes of failure using the pseudostatic analytic mode (all block velocities are set to zero at the beginning of each time step). The pseudostatic mode forced the block system to deform slowly and smoothly along established discontinuities. Because the size of the head block was relatively small, actual linear elastic deformation, governed by Poisson's ratio and Young's Modulus of Elasticity, were insignificant for a wide range of values. Several general conclusions may be drawn from head block deformation analyses conducted in the pseudostatic mode. 1) Joint frictions close to $\phi_j = 30^\circ$ produced deformations and block kinematics compatible with observed evidence in the field, such as flexural topple and block topple combined with sliding. 2) Joint spacing, which varies the aspect ratio of individual blocks, appears to control which mode of failure will be most dominant. For example, when $J_1 < J_2$, blocks become tabular, forcing blocks

to slide along J1. When spacing is diminished for all sets, block kinematics and deformation is impeded largely by computational burden. Models exceeding 300 blocks generated errors which forced the program to stop. The kinematic interaction among vast numbers of blocks is not intuitive, and deserves further investigation once DDA has been modified to handle large models (exceeding 1000 blocks).

DDA also has the capacity to predict total runout distances in the event of larger catastrophic failures, such as the instantaneous release of the head block. To simulate realistic conditions, DDA's dynamic analytic mode (block velocities from previous time steps are used as initial velocities for proceeding timesteps) was applied. However, the dynamic mode generated numerical error from instantaneous gravity loading on the block system. The application of the gravity phase algorithm (MacLaughlin, 1997) converged on a solution only for very small numbers (< 200) while challenging computational capacity. The two runout models presented in this study generated distances that fell within range of those distances predicted by the energy-line method (Hsu, 1975). However, the credibility of these results is reduced by observed error in block kinematics. Numerical creep and violation of the laws of angular momentum likely generated erroneous distances.

The field work in this study served to establish structural trends that could be adapted to various models. The recognition of pervasive joint sets was aided by statistical analysis of joint poles and observation of repetitive structure in the field. It is assumed that these dominant discontinuity sets are continuous throughout the rock body, though this has not been strongly supported in the field. Future studies might include detailed joint trace maps to better establish patterns. Future kinematic models

might include base-friction modeling, and other numerical analyses. The underlying theory of DDA is readily equipped to facilitate three-dimensional analyses. Once a three-dimensional program is implemented, and computational efficiency enhanced, DDA may serve as a powerful tool for predicting the mechanisms governing the rock slope stability of Mission Ridge.

REFERENCES CITED

- Adhikary, D.P., Dyskin, A.V., Jewill, R.J., and Stewart, D.P., (1997). A Study of the Mechanism of Flexural Toppling Failure of Rock Slopes. *Rock Mechanics and Rock Engineering*, vol. 30, no. 2, pp. 75-93.
- Andrews, D.J., Oppenheimer, D.H., and Lienkaemper, J.J., (1992) The Mission Link Between the Hayward and Calaveras Faults: in Brocherdt and tohers, eds., *Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: CDMG Special Publication 113*, pp. 217-224.
- Bozzolo, D., Pamini, R. and Hutter, K. (1988). *Rockfall Analysis — A Mathematical Model and its Test with Field Data*. Proc. 5th International Symposium on Landslides, Lusanne. July 1988, vol. 1, pp. 555-560.
- Crane, R. C., (1988). *Geologic Map of the Niles Quadrangle, Alameda County, California* : in R.C. Crane, ed, *Geology of the San Ramon Valley and Environs: Northern California Geological Society*, San Ramon, 131p., 17 pl.
- Dade, B. W., and Huppert, H. E., (1998). *Long-runout Rockfalls*. *Geology*, v. 26, no. 9, pp. 803-806.
- Dibblee, T.W., (1980). *Preliminary Geologic Map of the Niles Quadrangle, Alameda County, California* , U.S. Geological Survey, Open File Report 80-533C.
- Geolith Consultants Inc. (1998). *Technical Report of Mission Peak Landslide, volume 2: Consultant s report for City of Fremont, CA..* 61 pp.
- Goodman, R. E., (1995). *Block Theory and its Application*. *Rock Mechanics Proceedings of the 35th Symposium*, J. K. Daemen and R. A. Schultz, editors. Balkema, pp. 1-15.
- Goodman, Richard E. and Gen-hua Shi (1985). *Block Theory and Its Application to Rock Engineering*. Prentice-Hall, Inc., New Jersey, 338 pp.
- Goodman, Richard E. (1980). *Introduction to Rock Mechanics*. John Wiley & Sons, New York, 478 pp.
- Graymer, R.W., Jones, E.B., and Helley, E.J., (1994). Preliminary Geologic Map of the Niles 7.5 Minute Quadrangle, Alameda County, California , U.S. Geological Survey Open File Report 94-132.

- Hall, Clarence A., Jr. (1958). *Geology and Paleontology of the Pleasanton Area; Alameda and Contra Costa Counties, California*. University of California Publications in Geological Sciences, v. 34:1, 89 pp.
- Hall, Clarence A., Jr. (1956). *The Geology of the Pleasanton Area; Alameda County, California*. Ph.D. Thesis in Geology, School of Mineral Sciences, Stanford University, 269 pp.
- Hatzor, Y. (1995). Application of Block Theory to Rock Slope Stability Studies. Mechanics Proceedings of the 35th U.S. Symposium, pp. 71-77.
- Hatzor, Yosef (1992). *Validation of Block Theory Using Field Case Histories*. Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley, 194 pp.
- Helly, E.J., Lajoie, K.R., and Burke, D.B., (1972). *Geologic Map of Late Cenozoic Deposit Alameda County, California*, U.S. Geological Survey Miscellaneous Field Studies Map MF-429.
- Herd, D.G., (1982). *Map of Principal Recently Active Faults in the San Francisco Bay Area, CA*: USGS Miscellaneous Field Studies Map.
- Hoek, E. and J. W. Bray (1981). *Rock Slope Engineering, 3rd edition*. Institution of Mining and Metallurgy, London, 402 pp.
- Hsu, Kenneth J., (1975). *Catastrophic Debris Streams (Sturzstroms) Generated by Rockfalls*. Geological Society of America Bulletin, v. 86, pp. 129-140.
- Keefer, David K. (1984) *Landslides Caused by Earthquakes*. Geological Society of America Bulletin, v. 95, pp. 406-421.
- Keefer, David K. (1984) *Rock Avalanches Caused by Earthquakes: Source Characteristics*. Science, v. 223, pp. 1288-1290.
- Kieffer, Daniel Scott (1998). *Rock Slumping: A Compound Failure Mode of Jointed Hard Rock Slopes*. Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley, 341 pp.
- Kobayashi, Y., Harp, E. L., and T. Kagawa, (1990). Simulation of Rockfalls Triggered by Earthquakes. Rock Mechanics and Rock Engineering, v. 23, no. 1, pp. 1-20.
- MacLaughlin, Mary M. (1997). *Discontinuous Deformation Analysis of the Kinematics of Landslides*. Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley, 117 pp.

- MacLaughlin, M.M. and N. Sitar (1995). *DDA for Windows*. UC-Berkeley Geotechnical Engineering Report No. UCB/GT/95-04, 23 pp.
- Mauldon, Mathew and Jorge Ureta (1995). Sliding Stability of Prismatic Blocks. Rock Mechanics Proceedings of the 35th U.S. Symposium, pp. 39-44.
- Nilsen, T.H., (1975). *Preliminary Photointerpretation Map of Landslide and Other Surficial Deposits of the Niles 7.5 minute Quadrangle, Alameda County, California*, U.S. Geological Survey Open File Report 75-277-40.
- Norrish, Norman I. and Duncan C. Wyllie (1996). Chapter 15: Rock Slope Stability Analysis in *Landslides: Investigation and Mitigation*, Transportation Research Board Special Report 247, A. Keith Turner and Robert L. Schuster, editors. National Academy Press, Washington, D.C., 673 pp.
- Oppenheimer, D.H., and MacGregor-Scott, N., (1992). *The Seismotectonics of the Eastern San Francisco Bay Region*: in Brocherdt and tohers, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: CDMG Special Publication 113, p. 11-16.
- Oppenheimer, D.H., Wong, I.G., and Klein, F. W., (1992). *The Seismicity of the Hayward Fault, California*: in Brocherdt and tohers, eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: CDMG Special Publication 113, pp. 91-100.
- Pfeiffer, T.J., and Bowen, T.D., (1989). *Computer Simulation of Rockfalls*. Bulletin of the Association of Engineering Geologists, vol. XXVI, No. 1, 1989 pp. 135-146.
- Pfeiffer, T. J., and Higgins, J.D., (1989). *Rockfall Hazard Analysis Using the Colorado Rockfall Simulation Program*: Transportation Research Record 1288, National Research Council, Washington D.C.
- Priest, S.D., and Hudson, J.A., (1981). *Estimation of Discontinuity Spacing and Trace Length Using Scanline Surveys*. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 18, pp. 183-197.
- Racbruch-Hall, D.H., (1974). *Map Showing Recently Active Breaks Along the Hayward Falult Zone and The Southern Part of the Calaveras Fault Zone, California* : U.S. Geological Survey Miscellaneous Investigations Map I-813.
- Ritchie, A.M. (1963). *Evaluation of Rockfall and its Control*, Highway Research Record No. 17, pp. 13-28.

- Rives, T., Razack, M., Petit, J. P., and Rawnsley, K. D. (1992). *Joint Spacing: Analogue and Numerical Simulations*. Journal of Structural Geology, vol. 14, no.8/9, pp. 925-937.
- Shi, Gen-hua (1988). *Discontinuous Deformation Analysis: A New Numerical Model for the Statics and Dynamics of Block Systems*. Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley, 378 pp.
- Yeung, Man-chu R. (1991). *Application of Shi's Discontinuous Deformation Analysis to the Study of Rock Behavior*. Ph.D Thesis, Department of Civil Engineering, University of California, Berkeley, 341 pp.

Appendix A: FIELD DATA

Field data were collected intermittently from June 1998 to December 2000. They have been reorganized according to the numerical location shown in figure 2.1 and compiled in strike/dip format (A-1). Briones bedding is recorded with corresponding elevation and shown separately. All orientations shown here were measured directly from the joint surface with a Brunton Compass and map board for averaging surface asperities. The accuracy of individual attitudes is about ± 5 degrees.

Additionally, provisional extensometer and Global Positioning System (G.P.S.) data have been provided by the U.S.G.S. These data provided a means to establish an approximate displacement vector of the large headblock, noted to have accelerated shortly after the partial reactivation of the landslide below on March 22, 1998. The collection of extensometer data evolved through two stages: 1) manual monitoring of displacement of an array of eight extensometer pins installed across the tension crack between 3/28 and 4/25 of 1998, and 2) two permanent recording wire extensometers, EXT 1 and EXT 2, installed on 4/25 and 6/16 of 1998 respectively. EXT 1 was installed across the base of the tension crack, and EXT 2 was installed at the extreme apex of the new headscarp. Recordings of EXT 2 were interrupted by several mechanical problems over a period of several months in the fall of 1998 before it was erected again. This array of extensometers uses a solar powered telemetry system which relays data to a remote computer. The resolved displacement vector provides only a crude estimate of horizontal movement. Real-time monitoring of displacements are provided at <http://daffy.wr.usgs.gov/mission/>.

Global Positioning System surveying was established on the headblock to obtain a three dimensional displacement vector with higher spacial resolution using satellite triangulation. The displacement vector is determined from the difference between a master station (MS) on stable ground near the ridge top, a remote instrument station (RS) down slope and just off the block, and a remote GPS antenna (RA) anchored on the scarp edge of the moving headblock as shown in the east view of the headblock below.

A-1: Provisional USGS Extensometer Data: Head Block Peak Acceleration

A-1. Provisional U.S.G.S. extensometer data showing head-block peak acceleration in early June of 1998. This occurred about 2.5 months after the partial reactivation on March 22.

A-1: USGS Provisional Extensometer Data: 1998-1999

A-2. GPS provisional data divided into horizontal (northings and eastings), and vertical components. This data was recorded from 01/31/00 to 2/5/01. The headblock is moving downward and nearly due west.

A-3: Mission Ridge Structural Data

Mission Ridge Joint Sets (Azimuth notation, right hand rule)											
entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.
1	68	103	46	85	241	91	85	202	136	44	125
2	67	104	47	65	202	92	69	192	137	88	290
3	55	140	48	88	128	93	43	106	138	63	105
4	70	111	49	81	299	94	70	206	139	80	332
5	56	121	50	85	207	95	67	92	140	80	115
6	72	136	51	86	305	96	71	204	141	29	187
7	76	126	52	78	300	97	55	100	142	86	241
8	84	122	53	72	227	98	39	97	143	84	267
9	59	181	54	90	122	99	86	264	144	87	260
10	76	201	55	72	216	100	66	91	145	88	267
11	82	132	56	80	292	101	63	192	146	39	188
12	85	266	57	56	183	102	68	190	147	55	182
13	70	213	58	85	296	103	73	176	148	64	266
14	74	187	59	67	203	104	57	205	149	70	297
15	81	247	60	89	286	105	65	141	150	61	196
16	80	243	61	68	195	106	66	191	151	83	309
17	80	221	62	66	307	107	44	199	152	56	208
18	70	190	63	72	205	108	58	194	153	44	217
19	80	197	64	61	312	109	58	320	154	64	305
20	86	273	65	80	208	110	59	305	155	67	120
21	60	186	66	67	304	111	83	343	156	47	253
22	53	189	67	73	213	112	86	125	157	73	133
23	74	102	68	73	140	113	83	323	158	50	159
24	89	96	69	85	225	114	55	207	159	73	246
25	60	173	70	75	255	115	86	268	160	87	132
26	66	107	71	69	195	116	83	293	161	89	149
27	77	104	72	70	207	117	64	207	162	42	244
28	87	255	73	86	128	118	80	309	163	75	133
29	70	190	74	77	120	119	51	195	164	85	240
30	61	176	75	70	192	120	78	118	165	72	127
31	74	170	76	78	204	121	40	264	166	90	91
32	68	173	77	75	200	122	63	126	167	50	172
33	82	250	78	60	181	123	74	120	168	75	177
34	87	260	79	74	93	124	69	140	169	78	196
35	66	197	80	52	179	125	53	209	170	80	98
36	69	105	81	76	92	126	65	226	171	81	191
37	76	275	82	69	138	127	73	117	172	77	133
38	57	197	83	72	208	128	37	254	173	73	138
39	61	147	84	71	112	129	88	320	174	53	170
40	71	200	85	69	200	130	89	252	175	69	163
41	70	199	86	64	95	131	50	233	176	82	260
42	89	314	87	87	309	132	64	223	177	71	283
43	60	197	88	43	184	133	52	130	178	66	187
44	83	259	89	71	205	134	52	118	179	84	318
45	82	316	90	72	107	135	56	132	180	77	146

Mission Ridge Joint Sets (Azimuth notation, right hand rule)											
entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.
181	55	195	226	85	236	271	60	100	316	74	54
182	50	183	227	55	205	272	78	170	317	49	56
183	68	305	228	88	239	273	84	143	318	84	50
184	44	169	229	36	155	274	77	256	319	76	42
185	89	284	230	78	251	275	84	177	320	50	8
186	54	200	231	45	137	276	51	90	321	59	76
187	71	190	232	87	258	277	72	239	322	41	48
188	76	103	233	50	199	278	62	100	323	40	35
189	64	193	234	70	294	279	45	107	324	77	71
190	76	101	235	53	111	280	67	248	325	57	67
191	62	173	236	70	222	281	39	247	326	64	49
192	55	161	237	77	98	282	89	201	327	86	1
193	84	276	238	64	193	283	73	164	328	73	77
194	58	203	239	64	271	284	55	148	329	71	70
195	51	202	240	60	206	285	64	272	330	45	39
196	83	250	241	83	253	286	45	155	331	84	52
197	49	202	242	84	329	287	47	152	332	84	50
198	89	265	243	80	245	288	27	213	333	88	50
199	81	180	244	85	316	289	82	77	334	75	79
200	85	172	245	65	180	290	72	28	335	83	51
201	88	110	246	78	105	291	70	17	336	84	67
202	85	297	247	66	191	292	78	69	337	62	72
203	67	140	248	85	288	293	75	74	338	72	60
204	85	205	249	79	180	294	79	23	339	56	87
205	86	150	250	63	170	295	26	23	340	73	86
206	43	228	251	87	307	296	68	81	341	48	70
207	55	189	252	58	207	297	77	82	342	68	70
208	74	279	253	77	303	298	66	80	343	79	75
209	52	180	254	52	192	299	78	75	344	80	42
210	73	257	255	83	258	300	78	85	345	90	63
211	38	238	256	60	201	301	83	82	346	77	29
212	74	101	257	71	285	302	90	87	347	59	17
213	81	267	258	84	143	303	88	50	348	64	22
214	62	178	259	80	247	304	87	82	349	70	57
215	76	345	260	62	268	305	66	83	350	53	15
216	77	289	261	72	139	306	55	87	351	78	69
217	51	189	262	55	172	307	54	75	352	78	59
218	79	281	263	45	193	308	57	29	353	71	80
219	69	287	264	67	328	309	55	89	354	71	58
220	74	182	265	70	332	310	90	21	355	78	67
221	66	194	266	75	322	311	59	85	356	66	89
222	45	200	267	44	194	312	57	82	357	72	35
223	73	117	268	55	305	313	57	70	358	54	73
224	57	183	269	74	161	314	53	60	359	45	2
225	56	167	270	76	271	315	68	70	360	63	84

Mission Ridge Joint Sets (Azimuth notation, right hand rule)											
entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.	entry no.	dip	dip dir.
361	42	86	406	53	164	451	53	223	496	53	183
362	80	87	407	76	258	452	61	103	497	73	290
363	62	299	408	81	274	453	41	186	498	67	234
364	56	182	409	54	146	454	64	87	499	45	208
365	59	196	410	86	87	455	35	183	500	57	250
366	55	85	411	59	302	456	74	91	501	79	282
367	42	315	412	65	207	457	82	42	502	79	98
368	87	288	413	75	87	458	71	300	503	71	237
369	63	192	414	80	323	459	61	323	504	88	289
370	53	100	415	78	253	460	60	115	505	50	201
371	89	209	416	51	180	461	70	31	506	72	324
372	75	92	417	79	299	462	57	77	507	85	73
373	54	185	418	69	192	463	87	11	508	46	187
374	76	220	419	47	286	464	89	285	509	64	348
375	48	94	420	64	195	465	72	182	510	48	311
376	40	308	421	43	46	466	70	135	511	76	109
377	54	84	422	64	101	467	74	21	512	55	302
378	82	0	423	72	285	468	71	258	513	71	78
379	59	88	424	64	239	469	67	59	514	54	229
380	89	25	425	75	305	470	60	173	515	57	185
381	70	139	426	88	124	471	62	224	516	86	260
382	73	58	427	87	133	472	70	37	517	87	245
383	89	31	428	71	271	473	80	62	518	57	175
384	72	185	429	46	358	474	40	206	519	40	37
385	57	177	430	41	310	475	76	344	520	84	246
386	85	38	431	49	39	476	71	219	521	53	345
387	84	106	432	81	272	477	83	224	522	69	175
388	74	272	433	40	183	478	85	272	523	75	139
389	68	145	434	35	42	479	58	189	524	62	195
390	68	142	435	85	152	480	89	249	525	58	298
391	60	242	436	43	196	481	62	269	526	75	139
392	75	128	437	83	80	482	74	152	527	86	239
393	67	190	438	56	154	483	80	76	528	52	336
394	79	93	439	85	86	484	73	120	529	89	51
395	63	187	440	60	200	485	41	168	530	76	202
396	44	173	441	68	320	486	50	181	531	79	307
397	75	90	442	61	79	487	73	85	532	80	90
398	63	175	443	46	213	488	53	191	533	77	277
399	54	209	444	58	317	489	65	247	534	66	279
400	56	162	445	37	210	490	61	138	535	54	182
401	88	245	446	77	110	491	84	66	536	67	60
402	67	289	447	76	108	492	78	314	537	79	268
403	62	224	448	40	355	493	75	60	538	77	185
404	69	267	449	41	180	494	72	135	539	56	185
405	75	212	450	76	113	495	68	199	540	60	317

Mission Ridge Joint Sets (Azimuth notation, right hand rule)		
entry no.	dip	dip dir.
541	83	197
542	67	311
543	80	196
544	71	332
545	83	287
546	52	190

Mission Ridge Bedding, Tbr (Azimuth notation, right hand rule)											
entry no.	dip	dip dir.	elev. (ft.)	entry no.	dip	dip dir.	elev. (ft.)	entry no.	dip	dip dir.	elev. (ft.)
1	21	256	1375	31	34	287	1525	61	18	273	1825
2	30	279	1375	32	31	281	1525	62	25	241	1825
3	21	256	1375	33	23	277	1540	63	31	295	1838
4	30	279	1375	34	27	293	1545	64	27	281	1840
5	27	291	1420	35	31	241	1545	65	25	285	1845
6	36	290	1420	36	22	260	1545	66	26	333	1845
7	26	283	1420	37	24	243	1545	67	25	277	1845
8	26	283	1425	38	23	288	1545	68	25	312	1848
9	28	295	1430	39	25	285	1560				
10	30	308	1440	40	23	283	1565				
11	24	315	1448	41	28	291	1570				
12	35	288	1450	42	30	299	1575				
13	35	275	1460	43	30	297	1575				
14	27	284	1465	44	35	310	1613				
15	25	260	1475	45	27	245	1645				
16	20	273	1475	46	27	250	1710				
17	20	272	1475	47	33	270	1710				
18	35	285	1475	48	26	311	1745				
19	25	270	1480	49	22	290	1750				
20	40	322	1490	50	49	295	1750				
21	42	281	1495	51	17	286	1750				
22	39	304	1495	52	35	287	1775				
23	25	270	1495	53	17	272	1775				
24	27	288	1495	54	20	287	1790				
25	34	285	1500	55	24	282	1750				
26	36	290	1500	56	52	296	1770				
27	30	275	1505	57	31	295	1810				
28	32	282	1510	58	23	273	1810				
29	40	312	1517	59	45	305	1815				
30	29	310	1520	60	21	295	1825				

Appendix B: Stereographic Analysis

B-1. Stereoplot modified after Hoek and Bray (1981) showing data required for wedge stability analysis. The angles measured from this plot were applied to a wedge stability calculation sheet formulated on an Microsoft Excel spread sheet (see B-2).

Wedge Stability Calculation Sheet		
Input Data	Function Value	Calculated Answer
$\Psi_a =$ $\Psi_b =$ $\Psi_5 =$ $\theta_{na \cdot nb} =$	$\cos \Psi_a =$ $\cos \Psi_b =$ $\sin \Psi_5 =$ $\cos \theta_{na \cdot nb} =$ $\sin \theta_{na \cdot nb} =$	$A = \frac{\cos \Psi_a - \cos \Psi (\cos \theta_{na \cdot nb})}{\sin \Psi_5 (\sin^2 \theta_{na \cdot nb})}$ $B = \frac{\cos \Psi_b - \cos \Psi (\cos \theta_{na \cdot nb})}{\sin \Psi_5 (\sin^2 \theta_{na \cdot nb})}$
$\theta_{24} =$ $\theta_{45} =$ $\theta_{2 \cdot na} =$	$\sin \theta_{24} =$ $\sin \theta_{45} =$ $\cos \theta_{2 \cdot na} =$	$X = \frac{\sin \theta_{24}}{(\sin \theta_{45})(\cos \theta_{2 \cdot na})}$
$\theta_{13} =$ $\theta_{35} =$ $\theta_{1 \cdot nb} =$	$\sin \theta_{13} =$ $\sin \theta_{35} =$ $\cos \theta_{1 \cdot nb} =$	$Y = \frac{\sin \theta_{13}}{(\sin \theta_{35})(\cos \theta_{1 \cdot nb})}$
$\varphi_A =$ $\varphi_B =$ $\gamma =$ $\gamma_w =$ $c_A =$ $c_B =$ $H =$	$\tan \varphi_A =$ $\tan \varphi_B =$ $\gamma_w / 2\gamma =$ $3 c_A / \gamma H =$ $3 c_B / \gamma H =$	$F = \frac{3c_A(X)}{\gamma H} + \frac{3c_B(Y)}{\gamma H} (A - \frac{\gamma_w}{2\gamma} \cdot X) \tan \varphi_A + (B - \frac{\gamma_w}{2\gamma} \cdot X) \tan \varphi_B$

B-2 Wedge stability calculation sheet template used in back-calculation analysis.

Appendix C: Critical Key Block Analysis

C-1 Dominant Discontinuities used in Critical Key Block Analysis

C-2 Removability and Mode of Failure analyses (Stereographic Projection)

A lower focal point, upper hemisphere stereographic projection is used by Block Theory. The projection unlike geologic applications, encompasses the entire reference sphere. The convention used here designates the region inside the projected horizontal reference circle as the upper hemisphere and the region outside the circle as the lower hemisphere. This space is utilized by projecting all structural features as entire great circles.

Figure C-2 shows an example of a stereoplot used for Block Theory analysis, generated from three joint planes (J1: 61/ 236, J2: 78/243, J3: 83/282) shown in solid line, and one excavation surface (80/267) shown in dashed line. The dip magnitude is directly proportional to the diameter such that shallowly dipping planes plot as small circles and vice versa. The true dip direction is measured in the projected lower hemisphere along an imaginary line connecting the centers of the reference circle and the great circle of the plane in question.

The intersection of the projected joint planes in Fig. 4.2 create numerous curved polygons denoted as joint pyramids (JP). Each JP is defined by a combination of upper and lower half-spaces corresponding to the planes involved. The upper and lower half-space of a plane refers to the space above and below it respectively. In the stereographic convention used here, the upper half-space is the region inside any great circle, and the region outside, the lower half-space. The JP formed by these combined half-spaces of respective planes is assigned a binary code given in the order that any group of joint planes are listed such that 0 represents all upper half-space regions and 1 represents

all lower half-space regions.

The projected excavation surface, which is a key element to the analysis, also possesses an upper and lower half space referred to as the space pyramid (SP) and excavation pyramid (EP) respectively. Physically, the SP represents all newly opened space for any removable potential key block to move into while the complementary EP represents the jointed rock mass. These spaces are separated stereographically by the bounding dashed line of the projected excavation surface. The JP 000 created by the upper half-spaces of all three joint planes is the only removable JP out of all projected JP s because its space is completely contained within the SP. The SP is complementary to the EP and provides the space for the block contained in the EP to move into.

Figure C-2. Stereographic projection for block removability

Figure C-2a. Removability analysis for critical key block JC 7 of excavation face
A. JP 101 is predicted to slide along the dip vector (44/250) of J3. This direction approximates the pervasive J4 controlling the western slope of Mission Ridge.

Figure C-2b. Removability analysis for critical key block JC 20 of excavation face B. JP 011 is predicted to slide along the dip vector (69/299) of J4. This direction is not coincidental with any of the dominant joint sets observed in the field.

Figure C-2c. Removability analysis for critical key block JC 2 of excavation face C. JP 011 is predicted to slide along the dip vector (39/186) of J1 only. This direction is sub-parallel and oblique to J4 controlling the west slope of Mission Ridge.

Figure C-2d. Removability analysis for critical key block JC 10 of Excavation face D. JP 001 is predicted to slide along the intersection of J3 and J4 ($I_{3,4}$) which has a plunge and trend of 59/154. This slide direction is oblique to the pervasive J1 (60/196).

Figure C-2e. Removability analysis for first critical key block JC 17 of Excavation face E. The hatch marked JP 000 is the only removable block. It slides on plane 1 only, with the same plunge and trend as plane 1 (61/236).

Figure C-2f. Removability analysis for critical key block JC 2 of excavation face F. JP 001 is predicted to slide along the dip vector (55/187) of J1. This direction nearly approximates the mean orientation of the pervasive J1.

C-3 Numerical Parameters used in Critical Key Block Analysis

The following tables contain data required to compute the JP shape parameter (K), and the block instability parameter F. The JC number, is used to label joint set combinations (JC s: i;j;k). The existence of a corresponding JP code for upper (0) and lower (1) half spaces of the combined joints composing the JP indicates that the JP is removable. No JP on the other hand indicates that no removability is present.

All existing modes of failure in this analysis are sliding on either single or double planes indicated by i or ij respectively. The numbers correspond to the order of the JC. For example, JC 3 of analysis A, fails on two planes (23) which are equivalent to joint planes 2 and 5. Note that in numerous cases, no MODE of failure exists even though the JP is removable. This implies that the block is stable in the absence of resisting forces, namely friction.

The JP shape parameter is defined the interplanar angles of each removable JP which was measured vectorally and checked stereographically for cases where the complementary angle ($180 - \theta$) was needed. Generally, obtuse angles form open JP s which have a shallow geometry relative to the excavation surface contributing to the likelihood of failure.

Finally, F_s^* is the computed sliding force of each block under limit equilibrium conditions ($F.S. = 1.0$). These values thus should not be misconstrued as factors of safety. The values in the following tables have not yet been converted into the stability parameter F.

Table 1: Analysis A: Location 35

JC (No.)	I;j;k	JP	MODE	A	B	C	F _s *
1	1;2;3	010	3	37	125	59	0.19
2	1;2;4	101	no MODE	X	X	X	X
3	1;2;5	001	23	143	63	36	-0.42
4	1;3;4	101	12	55	41	126	-0.10
5	1;3;5	001	2	125	63	94	0.19
6	1;4;5	001	no MODE	X	X	X	X
7	2;3;4	101	2	59	77	126	0.19
8	2;3;5	011	1	59	36	86	0.30
9	2;4;5	011	13	103	36	103	-0.42
10	3;4;5	011	1	126	94	103	0.19

Table 2: Analysis B: Location 34

JC (No.)	I;j;k	JP	MODE	A	B	C	F _s *
1	1;2;3	100	12	17	52	141	-2.47
2	1;2;4	010	13	17	89	76	0.42
3	1;2;5	101	12	17	71	116	-2.47
4	1;2;6	101	12	17	145	39	-2.47
5	1;3;4	100	3	52	91	40	0.66
6	1;3;5	100	no MODE	X	X	X	X
7	1;3;6	100	no MODE	X	X	X	X
8	1;4;5	101	2	91	71	137	0.68
9	1;4;6	001	12	89	35	107	0.42
10	1;5;6	110	no MODE	X	X	X	X
11	2;3;4	100	23	39	76	140	0.66
12	2;3;5	100	no MODE	X	X	X	X
13	2;3;6	100	no MODE	X	X	X	X
14	2;4;5	101	2	76	64	137	0.68
15	2;4;6	001	12	104	39	107	0.36
16	2;5;6	001	no MODE	X	X	X	X
17	3;4;5	101	2	40	30	137	0.68
18	3;4;6	001	12	140	77	107	0.66
19	3;5;6	001	no MODE	X	X	X	X
20	4;5;6	011	1	137	107	103	0.68

Table 3: Analysis C: Locations 23 and 24

JC (No.)	I;j;k	JP	MODE	A	B	C	F _s *
1	1;2;3	011	1	70	80	52	0.09
2	1;2;4	011	1	70	87	72	0.09
3	1;2;5	100	23	70	60	55	0.10
4	1;3;4	001	12	100	87	27	-0.24
5	1;3;5	010	1	80	115	64	0.09
6	1;4;5	010	1	87	115	90	0.09
7	2;3;4	001	no MODE	X	X	X	X
8	2;3;5	010	12	128	53	37	0.10
9	2;4;5	010	13	108	53	30	0.10
10	3;4;5	100	no MODE	X	X	X	X

Table 4: Analysis D: Locations 25, 27, and 33

JC (No.)	I;j;k	JP	MODE	A	B	C	F _s *
1	1;2;3	no JP	no MODE	X	X	X	X
2	1;2;4	100	23	37	102	41	-1.73
3	1;2;5	100	no MODE	X	X	X	X
4	1;3;4	100	23	78	102	55	-0.67
5	1;3;5	100	no MODE	X	X	X	X
6	1;4;5	001	no MODE	X	X	X	X
7	2;3;4	100	23	41	139	55	-0.12
8	2;3;5	no JP	no MODE	X	X	X	X
9	2;4;5	001	12	45	76	88	-1.73
10	3;4;5	001	12	55	117	92	-0.12

Table 5: Analysis E: Locations 28, 29, and 30

JC (No.)	I,j;k	JP	MODE	A	B	C	F ₈ *
1	1;2;3	no JP	no MODE	X	X	X	X
2	1;2;4	100	2	43	70	151	0.54
3	1;2;5	no JP	no MODE	X	X	X	X
4	1;2;6	101	2	43	93	125	0.54
5	1;2;7	101	no MODE	X	X	X	X
6	1;3;4	no JP	no MODE	X	X	X	X
7	1;3;5	000	13	122	89	141	0.25
8	1;3;6	100	no MODE	X	X	X	X
9	1;3;7	011	no MODE	X	X	X	X
10	1;4;5	000	13	110	89	150	0.25
11	1;4;6	100	no MODE	X	X	X	X
12	1;4;7	011	no MODE	X	X	X	X
13	1;5;6	001	12	89	87	147	0.25
14	1;5;7	001	12	89	72	156	0.25
15	1;6;7	001	no MODE	X	X	X	X
16	2;3;4	010	no MODE	X	X	X	X
17	2;3;5	000	1	162	131	141	0.54
18	2;3;6	011	no MODE	X	X	X	X
19	2;3;7	011	no MODE	X	X	X	X
20	2;4;5	000	1	151	131	150	0.54
21	2;4;6	100	no MODE	X	X	X	X
22	2;4;7	011	no MODE	X	X	X	X
23	2;5;6	001	1	131	125	147	0.54
24	2;5;7	001	1	131	114	156	0.54
25	2;6;7	001	no MODE	X	X	X	X
26	3;4;5	010	no MODE	X	X	X	X
27	3;4;6	100	no MODE	X	X	X	X
28	3;4;7	011	no MODE	X	X	X	X
29	3;5;6	000	no MODE	X	X	X	X
30	3;5;7	000	23	141	51	24	-3.18
31	3;6;7	001	no MODE	X	X	X	X
32	4;5;6	000	no MODE	X	X	X	X
33	4;5;7	000	23	150	39	24	-3.18
34	4;6;7	001	no MODE	X	X	X	X
35	5;6;7	010	13	147	24	21	-3.18

Table 6: Analysis F: Locations 31 and 32

JC (No.)	I;j;k	JP	MODE	A	B	C	F _s *
1	1;2;3	001	1	155	73	69	0.42
2	1;2;4	001	1	155	103	107	0.42
3	1;3;4	001	12	107	103	40	0.29
4	2;3;4	010	no MODE	X	X	X	X

C-4 Block Program Descriptions

All stereo plots were generated on DOS based Block Theory software developed by Shi and Goodman (1980). This software consists of numerous programs for stereographic and vectoral analysis of block stability, and kinematics along surface excavations and within tunnels. This analysis utilized programs B02, B03, B05, and B30 which are briefly described below:

B02.EXE: *Joint pyramids and kinematic modes:*

This program plots the great circles of all discontinuity planes, and excavation surfaces and identifies the upper and lower half spaces of all generated joint pyramids. Additionally, the failure mode of each joint pyramid is computed with respect to the resultant force vector input by the user.

B03.EXE: *Block Trace and three dimensional views of the block:*

This program can generate any three dimensional view of a specified removable block. If the block is not removable, an error message specifies the block edge found within the excavation pyramid (EP).

B05.EXE: *Stereographic projection and vector operations:*

This program will plot either an upper or lower hemisphere projection of all planes and vectors input by the user, and additionally provides vector operations such as planar intersections, angle between two planes, the normal vector of a plane, and angle between a vector and a plane. This program was useful for efficient computation of interplanar angles for the Critical Key Block Method.

B30.EXE: *The sliding force of a joint pyramid:*

This program requires additional joint friction values for each plane in order to compute the force required to keep the block from sliding for a factor of safety of unity. A number of other vector computations such as block edges, planar intersections, and modes of failure, are summarized in tables which may be easily toggled for viewing. This program is used to determine the instability parameter (F) in the Critical Key Block Analysis.

Appendix D: DDA Model and Analysis

DDA Geometry File Format

```
<?xml version="1.0" standalone="no"?>
<!DOCTYPE DDA SYSTEM "geometry.dtd">
<Berkeley:DDA xmlns:Berkeley="http://www.tsoft.com/~bdoolin/dda">
<!--Bogus comment to keep ddaml tree-stripping from seg faulting on bad child node.-->
```

```
<Geometry>
<Edgenodedist distance="0.00100000"/>
<Jointlist>
<!--topographic section A1A. 1665 ft runout-->
<Joint type="1">2100.00    961.00    2100.00    900.00</Joint>
<Joint type="1">2100.00    900.00    1792.00    993.00</Joint>
<Joint type="1">1792.00    993.00    1792.00    1070.00</Joint>
<Joint type="1">1792.00    1070.00    1871.00    1049.00</Joint>
<Joint type="1">1871.00    1049.00    1902.00    1029.00</Joint>
<Joint type="1">1902.00    1029.00    1972.00    1011.00</Joint>
<Joint type="1">1972.00    1011.00    2003.00    991.00</Joint>
<Joint type="1">2003.00    991.00    2034.00    980.00</Joint>
<Joint type="1">2034.00    980.00    2050.00    973.00</Joint>
<Joint type="1">2050.00    973.00    2100.00    961.00</Joint>

<Joint type="1">1792.00    993.00    1510.00    1030.00</Joint>
<Joint type="1">1510.00    1030.00    1510.00    1119.00</Joint>
<Joint type="1">1510.00    1119.00    1570.00    1100.00</Joint>
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<Joint type="1">1635.00    1088.00    1661.00    1080.00</Joint>
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<Joint type="1">1688.00    1081.00    1730.00    1080.00</Joint>
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<Joint type="1">1510.00    1030.00    1158.00    1118.00</Joint>
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<Joint type="1">1177.00    1257.00    1214.00    1241.00</Joint>
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<Joint type="1">1301.00    1209.00    1337.00    1191.00</Joint>
<Joint type="1">1337.00    1191.00    1372.00    1179.00</Joint>
<Joint type="1">1372.00    1179.00    1430.00    1157.00</Joint>
<Joint type="1">1430.00    1157.00    1492.00    1123.00</Joint>
<Joint type="1">1492.00    1123.00    1510.00    1119.00</Joint>

<Joint type="1">1158.00    1118.00    830.00    1200.00</Joint>
<Joint type="1">830.00    1200.00    830.00    1340.00</Joint>
<Joint type="1">830.00    1340.00    851.00    1339.00</Joint>
<Joint type="1">851.00    1339.00    863.00    1342.00</Joint>
<Joint type="1">863.00    1342.00    919.00    1335.00</Joint>
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<Joint type="1">1083.00    1290.00    1113.00    1277.00</Joint>
<Joint type="1">1113.00    1277.00    1141.00    1270.00</Joint>
<Joint type="1">1141.00    1270.00    1158.00    1261.00</Joint>

<Joint type="1">830.00    1200.00    514.00    1284.00</Joint>
<Joint type="1">514.00    1284.00    514.00    1400.00</Joint>
<Joint type="1">514.00    1400.00    559.00    1389.00</Joint>
<Joint type="1">559.00    1389.00    587.00    1379.00</Joint>
```

```

<Joint type="1">587.00    1379.00  602.00  1371.00</Joint>
<Joint type="1">602.00    1371.00  618.00  1367.00</Joint>
<Joint type="1">618.00    1367.00  633.00  1358.00</Joint>
<Joint type="1">633.00    1358.00  650.00  1355.00</Joint>
<Joint type="1">650.00    1355.00  682.00  1353.00</Joint>
<Joint type="1">682.00    1353.00  709.00  1358.00</Joint>
<Joint type="1">709.00    1358.00  731.00  1356.00</Joint>
<Joint type="1">731.00    1356.00  762.00  1350.00</Joint>
<Joint type="1">762.00    1350.00  830.00  1340.00</Joint>

```

<!-- headblock base/ BLOCK 6 -->

```

<Joint type="1">514.00    1284.00  0.00    1570.00</Joint>
<Joint type="1">0.00      1570.00  0.00    1850.00</Joint>
<Joint type="1">0.00      1850.00  57.00   1826.00</Joint>
<Joint type="1">57.00     1826.00  126.00  1776.00</Joint>

```

<!--headblock topographic surface -->

```

<Joint type="1">126.00    1776.00  273.00  1676.00</Joint>
<Joint type="1">273.00    1676.00  290.00  1670.00</Joint>
<Joint type="1">290.00    1670.00  342.00  1607.00</Joint>
<Joint type="1">342.00    1607.00  363.00  1517.00</Joint>
<Joint type="1">363.00    1517.00  370.00  1502.00</Joint>
<Joint type="1">370.00    1502.00  396.00  1475.00</Joint>
<Joint type="1">396.00    1475.00  464.00  1421.00</Joint>
<Joint type="1">464.00    1421.00  514.00  1400.00</Joint>

```

<!--big TENSION CRACK at 1776 ft elev. -->

```

<Joint type="3">126.00    1776.00  90.00   1650.00</Joint>

```

<!--planar NON-DAYLIGHTED shear surface DEEP-->

```

<Joint type="2">90.00     1650.00  363.00  1483.00</Joint>
<Joint type="2">363.00    1483.00  373.00  1510.00</Joint>

```

<!--jagged shear plane A2 of head block-->

```

<!--Joint type="2">90.00    1650.00  120.00  1620.00</Joint>
<Joint type="2">120.00     1620.00  140.00  1625.00</Joint>
<Joint type="2">140.00     1625.00  175.00  1604.00</Joint>
<Joint type="2">175.00     1604.00  250.00  1537.00</Joint>
<Joint type="2">250.00     1537.00  267.00  1540.00</Joint>
<Joint type="2">267.00     1540.00  464.00  1421.00</Joint-->

```

<!--pervasive J1 statistical orientation/CONTINUOUS SET 1 (60/196)-->

```

<Joint type="4">189.001590.80    90.20    1677.00</Joint>
<Joint type="4">275.80    1535.00  95.00    1696.40</Joint>
<Joint type="4">339.00    1502.20  99.00    1716.00</Joint>
<Joint type="4">369.00    1499.60  105.80   1733.00</Joint>
<Joint type="4">369.00    1519.80  113.00   1750.20</Joint>
<Joint type="4">363.00    1552.00  115.00   1772.40</Joint>
<Joint type="4">359.00    1576.00  155.00   1760.40</Joint-->

```

<!--pervasive J1 statistical orientation/CONTINUOUS SET 2-->

```

<Joint type="4">342.00    1601.60  240.00  1695.00</Joint>
<Joint type="4">347.50    1583.80  165.60  1742.00</Joint>
<Joint type="4">360.40    1558.00  121.00  1764.40</Joint>
<Joint type="4">364.00    1538.50  117.00  1754.00</Joint>
<Joint type="4">367.20    1520.00  115.00  1743.00</Joint>
<Joint type="4">376.00    1497.50  111.00  1733.60</Joint>
<Joint type="4">370.00    1488.00  107.60  1721.00</Joint>

```

```

<Joint type="4"> 315.00    1525.00  100.00  1710.00</Joint>
<Joint type="4"> 292.00    1530.50  96.00   1700.00</Joint>
<Joint type="4"> 219.00    1579.00  90.00   1690.00</Joint>
<Joint type="4"> 159.00    1617.00  90.00   1676.00</Joint>
<Joint type="4"> 123.00    1635.00  82.00   1670.00</Joint>

```

```

<!--Tension Crack parallel set 1 (76/110)-->

```

```

<!--Joint type="3">93.00    1637.00  133.00  1775.00</Joint>
<Joint type="3">102.00    1625.00  147.00  1767.00</Joint>
<Joint type="3">115.00    1623.00  160.00  1754.00</Joint>
<Joint type="3">128.00    1618.00  173.00  1748.00</Joint>
<Joint type="3">143.00    1615.00  188.00  1740.00</Joint>
<Joint type="3">158.00    1607.50  203.00  1730.00</Joint>
<Joint type="3">170.00    1597.00  213.00  1720.00</Joint>
<Joint type="3">186.00    1590.00  227.00  1708.00</Joint>
<Joint type="3">198.00    1573.00  241.00  1700.00</Joint>
<Joint type="3">210.00    1567.00  255.00  1693.00</Joint>
<Joint type="3">225.00    1558.00  269.00  1683.00</Joint>
<Joint type="3">238.00    1551.00  282.00  1674.00</Joint>
<Joint type="3">252.00    1539.00  296.00  1667.00</Joint>
<Joint type="3">269.00    1537.00  309.00  1652.00</Joint>
<Joint type="3">281.00    1526.00  320.00  1638.00</Joint>
<Joint type="3">296.00    1520.00  335.00  1628.00</Joint>
<Joint type="3">310.00    1510.00  345.00  1610.00</Joint>
<Joint type="3">323.00    1503.00  353.00  1590.00</Joint>
<Joint type="3">339.00    1497.52  359.00  1555.00</Joint>
<Joint type="3">353.00    1483.00  367.00  1517.00</Joint-->

```

```

<!--SET #2 (76/110)-->

```

```

<Joint type="3">98.50    1636.00  139.50  1772.00</Joint>
<Joint type="3">112.00    1635.00  156.00  1773.00</Joint>
<Joint type="3">123.00    1623.00  167.00  1754.00</Joint>
<Joint type="3">136.00    1616.00  181.00  1747.00</Joint>
<Joint type="3">151.00    1611.00  194.00  1735.00</Joint>
<Joint type="3">165.00    1602.00  207.00  1725.00</Joint>
<Joint type="3">178.00    1590.00  220.00  1713.00</Joint>
<Joint type="3">192.00    1584.00  233.00  1705.00</Joint>
<Joint type="3">205.00    1570.00  248.00  1696.00</Joint>
<Joint type="3">216.00    1557.00  262.00  1684.00</Joint>
<Joint type="3">230.00    1545.00  277.00  1680.00</Joint>
<Joint type="3">245.00    1540.00  290.00  1674.00</Joint>
<Joint type="3">259.00    1534.00  302.00  1660.00</Joint>
<Joint type="3">275.00    1534.00  317.00  1650.00</Joint>
<Joint type="3">290.00    1520.00  328.00  1632.00</Joint>
<Joint type="3">302.00    1514.00  339.00  1620.00</Joint>
<Joint type="3">315.00    1502.00  350.00  1600.00</Joint>
<Joint type="3">332.00    1497.00  353.00  1561.00</Joint>
<Joint type="3">345.00    1488.00  363.00  1533.00</Joint>

```

```

<!--FREE FACE joint SET #1 (84/251)-->

```

```

<!--Joint type="6">377.00  1460.00  363.00  1517.00</Joint>
<Joint type="6">351.00    1470.00  318.00  1650.00</Joint>
<Joint type="6">333.00    1480.00  297.00  1680.00</Joint>
<Joint type="6">317.00    1490.00  278.00  1690.00</Joint>
<Joint type="6">300.00    1500.00  259.00  1700.00</Joint>
<Joint type="6">280.00    1510.00  243.00  1710.00</Joint>
<Joint type="6">261.00    1520.00  225.00  1720.00</Joint>
<Joint type="6">248.00    1520.00  202.00  1740.00</Joint>
<Joint type="6">228.00    1530.00  187.00  1750.00</Joint>

```

```

<Joint type="6">213.00    1520.00  165.00  1770.00</Joint>
<Joint type="6">191.00    1550.00  148.00  1780.00</Joint>
<Joint type="6">174.00    1560.00  129.00  1790.00</Joint>
<Joint type="6">157.00    1570.00  119.00  1770.00</Joint>
<Joint type="6">138.00    1580.00  108.00  1750.00</Joint>
<Joint type="6">121.00    1580.00  95.00   1720.00</Joint-->

```

```

<!--Briones bedding /dip/dip dir =42/11 -->
<!--Joint type ="5">349.00    1487.00  373.00  1494.00</Joint>
<Joint type ="5">330.00    1500.00  381.00  1515.40</Joint>
<Joint type ="5">310.00    1513.40  371.00  1531.00</Joint>
<Joint type ="5">290.00    1523.00  370.00  1549.00</Joint>
<Joint type ="5">267.00    1535.20  361.40  1565.00</Joint>
<Joint type ="5">251.00    1548.40  357.00  1582.40</Joint>
<Joint type ="5">223.00    1560.80  351.00  1595.00</Joint>
<Joint type ="5">205.00    1574.40  347.00  1617.00</Joint>
<Joint type ="5">185.00    1587.00  327.00  1630.00</Joint>
<Joint type ="5">180.00    1602.00  315.00  1642.60</Joint>
<Joint type ="5">153.00    1610.00  305.00  1658.40</Joint>
<Joint type ="5">134.00    1620.40  294.00  1672.00</Joint>
<Joint type ="5">112.00    1633.00  270.00  1682.00</Joint>
<Joint type ="5">65.00     1640.00  249.00  1695.40</Joint>
<Joint type ="5">91.00     1667.50  226.00  1708.00</Joint>
<Joint type ="5">97.00     1685.00  208.00  1720.00</Joint>
<Joint type ="5">100.00    1705.00  190.00  1732.60</Joint>
<Joint type ="5">110.00    1727.00  176.00  1750.00</Joint>
<Joint type ="5">115.00    1747.20  152.00  1760.00</Joint-->
</Jointlist>

```

```

<Fixedpointlist>
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<Line>1820.00    1020.00  1820.00  1020.00</Line>
<Line>1760.00    1040.00  1760.00  1040.00</Line>
<Line>1540.00    1070.00  1540.00  1070.00</Line>
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<Line>1180.00    1180.00  1180.00  1180.00</Line>
<Line>1120.00    1200.00  1120.00  1200.00</Line>
<Line>860.00     1260.00  860.00   1260.00</Line>
<Line>800.00     1270.00  800.00   1270.00</Line>
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<Line>470.00     1350.00  470.00   1350.00</Line>
<Line>250.00     1470.00  250.00   1470.00</Line>
<Line>40.00      1580.00  40.00    1580.00</Line>
<Line>40.00      1790.00  40.00    1790.00</Line>
</Fixedpointlist>

```

```

<Measuredpointlist>
<!--Point>350.00    1520.00  350.00  1520.00</Point>
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<Point>140.00     1750.00  140.00  1750.00</Point>
<Point>330.00     1610.00  330.00  1610.00</Point-->
</Measuredpointlist>

```

```

</Geometry>
</Berkeley:DDA>

```

DDA Analysis File

```

#!0xDDA-v1.5
# This file was automatically produced by
# DDA for Windows, a project of the University
# of California, Berkeley. Geotechnical Program,
analysisflags
0 # rotation: 0 linear 1 trig
0 # gravity: 0 off 1 on
1 # auto time step flag: 0 off 1 on
1 # auto penalty (set at 1)
0 # 0 plane stress, 1 plane strain
analysisparameters
1 # analysis type: 1 dynamic 0 static
500 # number of time steps
1 # number of block materials
5 # number of joint materials
0.001000 # maximum displacement
0.010000 # maximum time steps size
14 # number of time dependent points (fixed + load)
9.810000 # gravitational acceleration (not used)
timedeppoints
# fixed points
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
0
# number of values in time dependent loading
# load point values
blockmaterials
# density, unit weight, elastic mod. poisson's ratio
2.650000 135.000000 10000000.000000 0.490000
# \sigma_{11}, \sigma_{22}, \sigma_{12}
0.000000 0.000000 0.000000
# \tau_{11}, \tau_{22}, \tau_{12}
0.000000 0.000000 0.000000
# v_x, v_y, v_r (rotation)
0.000000 0.000000 0.000000
jointmaterials
# \phi, cohesion, tensile strength
26.000000 0.000000 0.000000
# \phi, cohesion, tensile strength
30.000000 500.000000 0.000000
# \phi, cohesion, tensile strength
30.000000 0.000000 0.000000
# \phi, cohesion, tensile strength
0.000000 0.000000 0.000000
# \phi, cohesion, tensile strength
45.000000 0.000000 0.000000

```