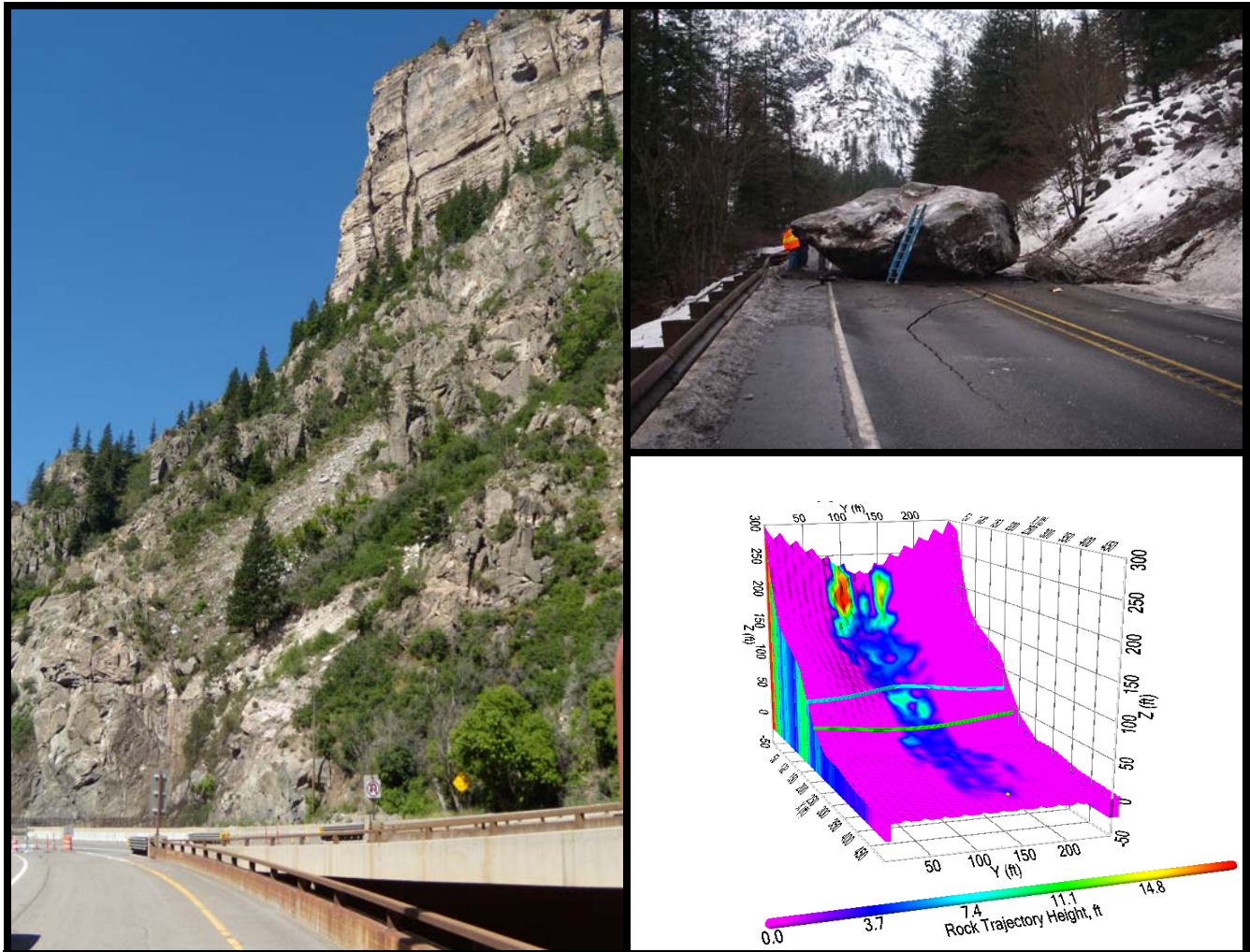


# CRSP-3D USER'S MANUAL

## Colorado Rockfall Simulation Program

Publication No. FHWA-CFL/TD-12-007

February 2012



U.S. Department  
of Transportation  
**Federal Highway  
Administration**

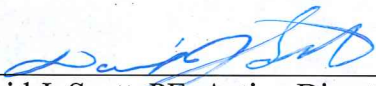


**Central Federal Lands Highway Division**  
12300 West Dakota Avenue  
Lakewood, CO 80228

## FOREWORD

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Rockfall protection is becoming more important as populations and travel in mountainous areas increase. Computer programs that model rockfall on measured slope profiles have become an effective tool in evaluating rockfall hazards and in mitigation design. The main objective of this work is to update the current CRSP (4.0) program and provide a reliable tool for estimating rockfall behavior. This is achieved by using advanced mathematical modeling techniques to simulate the interaction of rock and slope. In addition, the program can be run with a 2D or 3D slope profile. The new approach is believed to provide a more realistic model of rockfall movement on a slope surface. This report provides background on CRSP-3D, and a user's guide for incorporating the program as an effective tool in estimating rockfall behavior.



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David J. Scott, PE, Acting Director of Project Delivery  
Federal Highway Administration  
Central Federal Lands Highway Division

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16. Abstract <p>Rockfall is a natural result of weathering, erosion, and gravity on steep natural rock slopes and rock cuts. When rocks become loosened from a steep slope, they may travel down the slope in a combination of rolling, bouncing, sliding, launching, and free fall. When rockfall comes in contact with roads, structures or railroads, it can cause destruction to property and becomes a safety issue. As traffic and building developments increase in volume in mountainous areas, the need to protect people and structures from rockfall increases in importance.</p> <p>The original Colorado Rockfall Simulation Program (CRSP) was a 2D model developed for modeling rocks rolling and bouncing down slopes. It has been used to predict the behavior of rockfall, determine the need for rockfall mitigation, and aid in the design of mitigation. New numerical techniques that can be applied to modeling of rockfall movement have become available since CRSP was first written in the mid 1980's. CRSP-3D uses the Discrete Element Method and provides a theoretically more representative dynamic simulation of rock and slope interaction using the equations of motion than the approach employed by previous versions of CRSP. In addition, CRSP-3D includes an option where the slope profile can be loaded from scanned slope data, such as LIDAR. CRSP-3D estimates preferred rockfall paths, distribution on the slope, rock bounce height, rock velocity, rock kinetic energy and rock rollout distances.</p> <p>This user's manual presents the theoretical basis for the computer program, discusses program execution including inputs and outputs, and includes examples to demonstrate use of the program.</p>					
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**CRSP-3D USER'S MANUAL – TABLE OF CONTENTS**

<b>SI* (MODERN METRIC) CONVERSION FACTORS</b>				
<b>APPROXIMATE CONVERSIONS TO SI UNITS</b>				
<b>Symbol</b>	<b>When You Know</b>	<b>Multiply By</b>	<b>To Find</b>	<b>Symbol</b>
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa
<b>APPROXIMATE CONVERSIONS FROM SI UNITS</b>				
<b>Symbol</b>	<b>When You Know</b>	<b>Multiply By</b>	<b>To Find</b>	<b>Symbol</b>
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals			

\*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

**TABLE OF CONTENTS**

CHAPTER 1 – BACKGROUND AND METHODOLOGY ..... 1

INTRODUCTION ..... 1

PURPOSE ..... 1

LIMITATIONS ..... 2

PREVIOUS CRSP VERSIONS ..... 2

    Development of CRSP..... 3

CRSP-3D ..... 3

    Discrete Element Method ..... 3

    Contact Mechanics Between Falling Rock and a Slope ..... 6

    Stiffness and Damping (Slope Hardness)..... 8

SYSTEM REQUIREMENTS ..... 10

INSTALLATION ..... 10

    CD Installation..... 10

    Internet Installation..... 11

FUTURE VERSIONS OF CRSP-3D..... 11

CHAPTER 2 - GENERAL PROGRAM EXECUTION ..... 13

STARTING CRSP-3D ..... 13

MAIN MENU..... 14

    File Menu Item ..... 14

    Units Menu Item..... 15

    Help Menu Item..... 15

TOOLBAR ..... 16

TABS..... 17

    Project Tab..... 17

    Slope Geometry Tab..... 18

    Slope Mechanical Properties Tab ..... 27

    Analysis Partitions Tab..... 30

    Falling Rock Parameters Tab ..... 33

---

Simulation Tab .....	34
Output Tab.....	35
DELETING FILES.....	39
CALIBRATION.....	39
CHAPTER 3 – WORKED EXAMPLES .....	41
TUTORIAL EXAMPLE .....	41
Creating a New Project.....	41
Slope Geometry .....	42
Slope Mechanical Properties .....	44
Analysis Partitions.....	47
Falling Rock Parameters.....	49
Simulation.....	50
3D LIDAR EXAMPLE .....	52
Slope Geometry .....	52
Slope Mechanical Properties .....	56
Analysis Partitions.....	57
Falling Rock Parameters.....	58
Simulation.....	59
Output.....	60
2D EXAMPLE .....	62
Slope Geometry .....	62
Slope Mechanical Properties .....	63
Analysis Partitions.....	65
Falling Rock Parameters.....	65
Simulation.....	66
Statistics.....	68
CHAPTER 4 – ROCKFALL FIELD EVALUATION .....	69
PARAMETERS.....	69
Slope Profile .....	69

---

Zone Boundary Selection ..... 70

Rock Size and Shape ..... 71

Slope Surface Roughness ..... 73

Slope Hardness Coefficient ..... 74

CALIBRATION ..... 75

    Rock Trajectory and Height ..... 76

    Rock Runout ..... 76

REFERENCES ..... 77

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES ..... 79

APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES ..... 97

    TUTORIAL EXAMPLE #1 ..... 97

    CANYON LIDAR 3D SPHERE EXAMPLE #2 ..... 113

    CANYON 2D SPHERE EXAMPLE #3 ..... 127

**LIST OF FIGURES**

Figure 1. Schematic. Blocks in contact..... 5

Figure 2. Schematic. Visco-elastic contact model in normal direction. .... 7

Figure 3. Schematic. Elastic contact model in the tangential direction. .... 8

Figure 4. Screenshot. CRSP-3D start-up splash screen. .... 13

Figure 5. Screenshot. Main Menu..... 14

Figure 6. Screenshot. File Menu Item..... 14

Figure 7. Screenshot. Units Menu..... 15

Figure 8. Screenshot. Help Menu. .... 16

Figure 9. Screenshot. Example of Build version. .... 16

Figure 10. Screenshot. Toolbar..... 16

Figure 11. Screenshot. Tabs..... 17

Figure 12. Screenshot. Project Tab..... 17

Figure 13. Screenshot. Slope Geometry Tab. .... 18

Figure 14. Screenshot. Surface Points Tab. .... 19

Figure 15. Screenshot. Select Excel Spreadsheet X, Y, Z Coordinate Data..... 19

Figure 16. Screenshot. Highlight Paste Zone in CRSP-3D. .... 19

Figure 17. Screenshot. Pasted X, Y, Z Coordinate Data..... 20

Figure 18. Screenshot. Initialize scrollbars..... 20

Figure 19. Screenshot. Moving and deleting points on the screen. .... 21

Figure 20. Screenshot. Graphic rotation and translation controls..... 21

Figure 21. Screenshot. Image Rotation..... 22

Figure 22. Screenshot. LIDAR Preprocessor..... 22

Figure 23. Diagram. The maximum surface roughness of 6 feet generated by spheres with centers 12 feet apart. .... 24

Figure 24. Screenshot. Surface Resolution Selection. .... 25

Figure 25. Screenshot. Specifying Surface Resolution, Offsets and Spin value when loading a LIDAR file. .... 25

Figure 26. Screenshot. Use of the *Spin* control to place the view in the X-Z plane. .... 26

Figure 27. Screenshot. Select *Refresh* on the Slope Geometry Tab to create a slope surface. .... 27

Figure 28. Screenshot. Select a slope material. .... 27

Figure 29. Screenshot. Enter roughness and hardness values associated with a slope material type..... 28

Figure 30. Screenshot. Identify the material type under the Slope Mechanical Properties tab..... 29

Figure 31. Screenshot. Place points around the perimeter of the identified material. .... 29

Figure 32. Screenshot. Place points around the perimeter of the first material. .... 29

Figure 33. Screenshot. Boulder field zone (magenta) drawn on the screen using the mouse. 30

Figure 34. Screenshot. Enter partition name, direction, and location..... 31

Figure 35. Screenshot. X and Z coordinates of the Partition. .... 32

Figure 36. Screenshot. Dragging a Partition..... 32

Figure 37. Screenshot. The spherical elements and tubular connectors that make up various rock shapes. .... 33

Figure 38. Screenshot. Falling Rock Parameters Input..... 34

Figure 39. Screenshot. Magnified Simulation Tab Controls. .... 35



---

Figure 40. Screenshot. CRSP-3D Simulation graphic screen.....	35
Figure 41. Screenshot. Rock Trajectory Height simulation output for each rock passing Analysis Partition BP-1.....	36
Figure 42. Screenshot. Rock Trajectory Height Frequency output for Partition BP-1 as presented in the Report option.....	36
Figure 43. Screenshot. Checkboxes that select various image views in the simulation report.....	37
Figure 44. Screenshot. Simulation Report.....	38
Figure 45. Screenshot. Print controls for CRSP-3D Report.....	38
Figure 46. Screenshot. Select File → New.....	41
Figure 47. Screenshot. Create and name a new folder.....	42
Figure 48. Screenshot. Fill in project information.....	42
Figure 49. Screenshot. Cut and paste data from Excel spreadsheet.....	43
Figure 50. Screenshot. Graphic rendition of slope geometry.....	44
Figure 51. Screenshot. Use mouse to delineate Boulder Field.....	45
Figure 52. Screenshot. Delineate Talus.....	46
Figure 53. Screenshot. Completed geometry.....	47
Figure 54. Screenshot. Define and locate Analysis Partitions.....	48
Figure 55. Screenshot. Locations of Analysis Partitions.....	49
Figure 56. Screenshot. Parameter values for Boulder Field.....	50
Figure 57. Screenshot. Software disclaimer.....	50
Figure 58. Screenshot. Rock trajectory height traces generated by the rockfall simulation...	51
Figure 59. Screenshot. Original LIDAR file in .txt format.....	52
Figure 60. Screenshot. Excel spreadsheet.....	53
Figure 61. Screenshot. Adding headers to spreadsheet.....	53
Figure 62. Screenshot. File opened in text editor.....	54
Figure 63. Screenshot. Ensuring all field delimiters are spaces.....	54
Figure 64. Screenshot. AutoCalc Transform box and Load File button.....	55
Figure 65. Screenshot. Loading a LIDAR file.....	55
Figure 66. Screenshot. Generated LIDAR profile.....	56
Figure 67. Screenshot. Defining materials zone and adding mechanical properties information.....	57
Figure 68. Screenshot. Selected analysis partitions.....	58
Figure 69. Screenshot. Falling rock parameters (release zone shown in green).....	59
Figure 70. Screenshot. Velocity traces of 15 ft diameter round rocks falling down slope....	60
Figure 71. Screenshot. Frequency information for all velocities calculated at Analysis Partition 1.....	61
Figure 72. Screenshot. Rotated view of slope geometry with slope coordinates showing how a virtual 2D geometry is created from an inherently 3D model.....	63
Figure 73. Screenshot. View showing slope mechanical properties and graphic rendering...	64
Figure 74. Plot. Material profile down slope (ft). Each point represents a change in slope material.....	64
Figure 75. Screenshot. Location of analysis partitions.....	65
Figure 76. Screenshot. Falling rock parameters.....	66
Figure 77. Screenshot. Rotated simulation view showing rockfall kinetic energy.....	66
Figure 78. Screenshot. Simulation showing virtual 2D view.....	67

---

---

Figure 79. Screenshot. Histogram showing kinetic energy frequency for simulation.....	68
Figure 80. Schematic. Slope profile identifying launch points and source areas (after Brawner, 1994). .....	70
Figure 81. Schematic. Volumetric Joint Count ( $J_v$ ). Measurements are made normal to the direction of joint set. Line 1 intersects 5 joints, line 2 intersects 6 joints, and line 3 intersects 4 joints.....	73
Figure 82. Photograph. Moist Soft Soil. ....	79
Figure 83. Photograph. Moist Soft Soil. ....	80
Figure 84. Photograph. Soft Soil Indentation. ....	81
Figure 85. Photograph. Dry Soft Soil. ....	82
Figure 86. Photograph. Intermediate Soil. ....	83
Figure 87. Photograph. Moderately Soft Soil. ....	84
Figure 88. Photograph. Firm Soil. ....	85
Figure 89. Photograph. Firm Soil. ....	86
Figure 90. Photograph. Firm Soil. ....	87
Figure 91. Photograph. Gravel to Cobble Talus. ....	88
Figure 92. Photograph. Gravel to Cobble Talus. ....	89
Figure 93. Photograph. Gravel to Cobble Talus. ....	90
Figure 94. Photograph. Boulder Talus.....	91
Figure 95. Photograph. Boulder Talus.....	92
Figure 96. Photograph. Boulder Talus.....	93
Figure 97. Photograph. Hard Bedrock. ....	94
Figure 98. Photograph. Hard Bedrock.....	95

**LIST OF TABLES**

Table 1. Procedures for editing slope points..... 44  
Table 2. Rock-Mass Description (ISRM Working Group, 1978, 1981)..... 72  
Table 3. Typical rock unit weights and densities (After: Hoek and Bray, 1981). .... 73  
Table 4. Preliminary roughness values. .... 74  
Table 5. Preliminary hardness values and associated hardness measure..... 75

**LIST OF SYMBOLS AND ABBREVIATIONS**

2D	two dimensional
3D	three dimensional
Caltrans	California Department of Transportation
CFLHD	Central Federal Lands Highway Division (FHWA)
CDOT	Colorado Department of Transportation
COR	Coefficient of Restitution
COTR	Contracting Officer's Technical Representative
CRSP	Colorado Rockfall Simulation Program
CSM	Colorado School of Mines
DEM	Discrete Element Method
DR	Dynamic Relaxation
EFLHD	Eastern Federal Lands Highway Division (FHWA)
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
kip	kilo pound (1000 pounds)
kJ	kilo Joules
lbm	pounds mass
lbf	pounds force, pounds weight
lb	pounds force, pounds weight
LIDAR	Light Detection and Ranging
ODOT	Oregon Department of Transportation
OTS	Office of Technical Services (FHWA)
psi	pounds per square inch
s	second
SI units	International System of units (e.g. m, N, kPa, etc.)
US units	United States customary units (e.g., ft, lbf, psi, etc.)
WFLHD	Western Federal Lands Highway Division (FHWA)
X,Y,Z	Cartesian coordinate system

## ACKNOWLEDGMENTS

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## CHAPTER 1 – BACKGROUND AND METHODOLOGY

### INTRODUCTION

When designing rockfall protective structures such as ditches, berms, fences, and walls, it has become common practice to first model the rockfall trajectory using computer simulations and then assign barrier location(s) and design guidelines based on program output. Computer modeling of rockfall trajectory is helpful in estimating how rockfall parameters such as bounce height, velocity, kinetic energy, and rollout distance change along the slope length.

Current programs used for modeling rockfall trajectory require input of a 2D slope profile, slope characteristics, and typical rockfall size. 2D modeling causes problems when simulating the rotation and slope interaction of non-spherical rocks because obscure rock shapes have different modes of rotation depending on velocity. For example, at high speeds a cylindrical shaped rock will roll end-over-end, and act more like a sphere, while at slower speeds these rocks will tumble and roll along the long axis. This may result in inaccurate estimates of rockfall properties, especially rock rollout and bounce height. Additionally, current programs use a stochastic semi-empirical approach which does not directly address the fundamental physics of falling rock interaction with a slope face.

CRSP-3D uses the Discrete Element Method for dynamic model simulation using the equations of motion, which provide a more accurate approximation of rock and slope interaction than the methods employed by previous versions of CRSP. CRSP-3D uses 3D slope geometry to achieve a more accurate approach in modeling the interaction and movement of rockfall on a slope surface. The use of a 3D slope provides the ability to model different possible rockfall paths on a section of slope, and has the capability to model the rotational movement of non-spherical rocks.

This manual is intended to provide the user with the background required to apply CRSP-3D to rockfall hazards studies.

### PURPOSE

The CRSP-3D program is intended to provide an up-to-date analytical tool for evaluating existing or potential rock fall events and to provide data to be used in the design of rockfall fences, rockfall attenuators, catch ditches, catch berms and other rockfall protection structures. The goal has been to improve the accuracy of rockfall simulations, in particular to improve predictions of rock bounce heights and rock runout distance at the base of a slope.

Some specific features:

- CRSP-3D uses a new approach which applies the Discrete Element Method to rock-slope interaction and directly models interactions such as impact, rolling, launching, sliding, and damping during a rockfall event.

- The slope hardness is represented using one numerical input value (hardness coefficient) instead of two (tangential and normal coefficients of restitution) as in previous versions.
- The slope roughness coefficient in CRSP-3D is dependent only on lateral variations normal to the slope, rather than on both lateral variations and the size of the falling rock as in previous versions of CRSP.

Finally, added input features include the following:

- The slope profile can be displayed either as apparent 2D or full 3D. The code is actually 3D only; the 2D effect is obtained by looking at a section through the slope.
- The user can build rocks of several shapes: spherical, cylindrical, discoidal, tetrahedral and prismatic (blocky).
- Analysis Partition parameters (e.g. equivalent to barrier height and position, if barrier position is being modeled) can be input into the slope profile and kinetic energy of the falling rock can be obtained.

## LIMITATIONS

This program has been tested and is believed to be a reliable engineering tool; however, it should be recognized that this is first version of an entirely new code. No responsibility is assumed by the authors; Summit Peak Technologies, Yeh & Associates, the Federal Highway Administration (FHWA), The Colorado Department of Transportation (CDOT), the Colorado School of Mines (CSM) or any employees of the above for any errors, mistakes or misrepresentations that may occur from any use of this program.

## PREVIOUS CRSP VERSIONS

The original CRSP version 1.0 was written by Timothy J. Pfeiffer for a Master of Engineering thesis in Geological Engineering at CSM in 1988. It was originally developed for CDOT for use in conjunction with the construction of I-70 through Glenwood Canyon, Colorado. A reasonable estimate of probable bounce height and velocity of rockfall events was needed in order to design rockfall fences and alternative catchment ditches. CRSP was developed to simulate rockfall events at a site based on estimates of slope profile, slope irregularities, slope material properties and rockfall size. The project was supervised by Dr. Jerry Higgins and the research was partially funded by CDOT. Later versions included:

- Version 2.1 (1991) manual revised by Richard D. Andrew and program revised by Robert Beck (CDOT).
- Version 3.0 (1993) manual revised by Richard D. Andrew and Robert Beck and program revised by Richard J. Schultz, Timothy J. Pfeiffer, Richard D. Andrew, and Robert B. Beck (CDOT).
- Version 3.0a (1995) program revised by Richard D. Andrew (CDOT).
- Version 4.0 (2000) manual and program revised by Christopher L. Jones (CSM), Jerry D. Higgins, (CSM) and Richard D. Andrew (CDOT).



## Development of CRSP

From version 1.0 through version 4.0, the CRSP algorithm did not change. Version 4.0 was produced to be compatible with Windows 95 and Windows NT, it was reprogrammed using Visual Basic, and the input/text editor section was modified to increase user-friendliness. The input coefficients (normal coefficient of restitution and tangential coefficient of frictional resistance) were recalibrated through the accumulation of rock rolling data provided by Caltrans and the original CRSP calibration effort. The Caltrans data consisted of seven sets of data. Six of the data sets are from Monterey County, CA (Duffy and Hoon, 1996; Duffy, 1996; Smith and Duffy, 1990). The other set was collected in Switzerland (Duffy, 1992).

## CRSP-3D

The CRSP-3D algorithm is a departure from previous versions of CRSP which were semi-empirical in nature to a more fundamental physical computational model approach. The new algorithm uses a combination of the general equations of motion and the Discrete Element Method (DEM) to simulate rock velocity and the contact forces between rock and slope. DEM assumes a linear elastic contact force-displacement relationship between two impact bodies. The normal contact formulation is linear elastic with a viscous damping coefficient characterized by two parameters; normal stiffness and viscosity. The tangential force depends on the coefficient of restitution (COR) and the relative tangential velocity of the two contact objects. An explanation of the program algorithm is included below.

In CRSP-3D, the definition of surface roughness has changed so that only one value is needed to model the surface roughness for all rock sizes. The surface roughness is no longer dependent on falling rock size. Additionally, CRSP-3D uses one input value, the hardness coefficient, to model slope material properties. The hardness coefficient is a function of the coefficient of restitution, which is a measure of the elasticity of the collision between a falling rock and the slope, and a damping coefficient which models how much tangential resistance the rock is subjected to upon sliding on the slope. A discussion of the equations behind CRSP-3D rockfall modeling is included in the following section.

## Discrete Element Method

The Discrete Element Method (DEM) is a numerical technique designed to solve problems in applied mechanics that exhibit gross discontinuous material and geometrical behavior. DEM is used to analyze multiple interacting rigid or deformable bodies undergoing large dynamic or pseudo static, absolute or relative motion, governed by complex constitutive behavior.

DEM essentially is based on the numerical solution of the equation of motion and the principle of dynamic relaxation. Kinematics equations are established for each discrete body. The velocities, accelerations, and positions of the bodies are updated by calculating the contact forces between them. Depending on different physical problems, DEM programs should at least include the following three aspects:

- Representation of contact, which attempts to establish a correct contact constitutive model between discrete bodies.

- Representation of the properties of materials, which defines the particles or blocks to be rigid or deformable.
- Contact detection and revision of contacts, which attempts to establish certain data structures and algorithms to assess the contacts and the contact types, such as whether the vertex, edge or face of one polyhedron will touch a corresponding entity on a second polyhedron.

The following section discusses the discrete element method specifically related to CRSP-3D, which discretizes the particles as three-dimensional spheres that contact each other at their surfaces. Some general features of DEM are also included in this section.

### *Equation of Motion*

Figure 1 shows two blocks **I** and **II** in contact. Their positions are defined by vectors  $\mathbf{R}_I$  and  $\mathbf{R}_2$ . The blocks have masses  $m_1$  and  $m_2$ , linear velocity vectors  $\mathbf{v}_1$  and  $\mathbf{v}_2$ , and angular velocity vectors  $\omega_1$  and  $\omega_2$ , respectively. The equation of motion for element  $i$  at discretized time step  $n$  is:

$$\mathbf{M}\mathbf{a}_n^i + \mathbf{C}\mathbf{v}_n^i + \mathbf{P}_n^i(\mathbf{x}_n^i) = \mathbf{f}_n^i \quad (1)$$

where:

$\mathbf{x}_n^i$ ,  $\mathbf{v}_n^i$  and  $\mathbf{a}_n^i$  are the position, velocity and acceleration vectors of the  $i$ th element at the  $n$ th time step. The 3D case results in:

$$(\mathbf{x}_n^i)^T = [\mathbf{x}_n^i, \mathbf{y}_n^i, \mathbf{z}_n^i, \theta_n^i]$$

$$(\mathbf{v}_n^i)^T = [\dot{\mathbf{x}}_n^i, \dot{\mathbf{y}}_n^i, \dot{\mathbf{z}}_n^i, \dot{\theta}_n^i]$$

$$(\mathbf{a}_n^i)^T = [\ddot{\mathbf{x}}_n^i, \ddot{\mathbf{y}}_n^i, \ddot{\mathbf{z}}_n^i, \ddot{\theta}_n^i]$$

(2)

where:

$\mathbf{M}$  – mass matrix, ( $kg, lbm$ )

$\mathbf{C}$  – damping matrix, ( $kg/s, lbm/s-g_c$ ), where  $g_c$  is the gravitational constant.

$\mathbf{P}_n^i$  – resultant contact force vector applied on the  $i$ th element at the  $n$ th step ( $N, lbf$ )

$\mathbf{f}_n^i$  – the boundary force or body force vector applied on the  $i$ th element at the  $n$ th step ( $N, lbf$ )

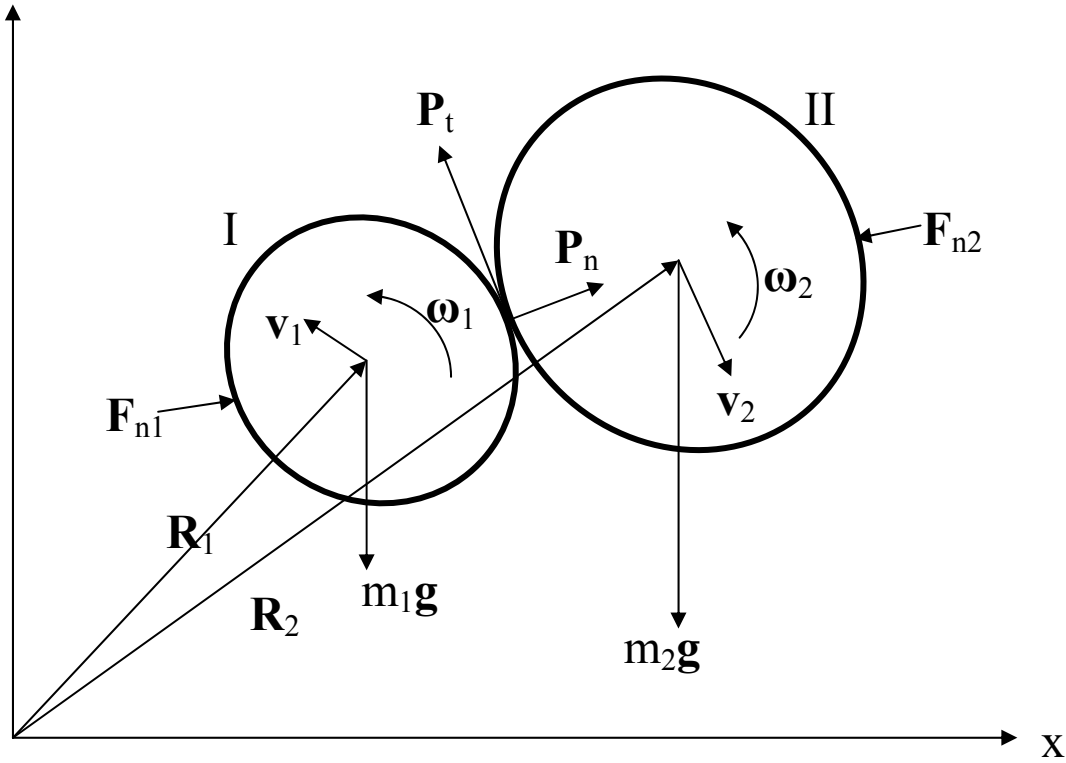


Figure 1. Schematic. Blocks in contact.

Numerically solving equation (1) in the time domain gives accelerations, velocities, displacements and resultant forces. The stress/strain relationship inside of the discrete assembly is obtained by an averaging method. The *average stress tensor* of the volume  $V$  of the *representative of volume element* (RVE) can be obtained by:

$$\sigma_{ij} = \frac{1}{V} \sum_{p=1}^N \sum_{c=1}^{m_p} \mathbf{x}_i^c \mathbf{F}_j^c \quad (3)$$

where:

$\mathbf{x}_i^c$  is position vector at contact point  $c$

$\mathbf{F}_j^c$  is contact force vector at contact point  $c$

$N$  is the particle number in RVE

$m_p$  is the number of contact points for particle  $p$

Similarly, the *average strain* of the RVE defined for infinite deformation can be written (by the Average Displacement Gradient Algorithm) as:

$$\bar{\varepsilon}_{ij} = \frac{1}{2} (\mathbf{F}_{ij} + \mathbf{F}_{ji}) \quad (4)$$

where

$\mathbf{F}_{ij}$  is contact force.

### ***Numerical Integration Algorithms***

There are different numerical integration algorithms for solving equation (1). The explicit integration algorithm is among the most used schemes in current discrete element analysis. For CRSP-3D, the central difference explicit expression used for the *acceleration* at time step  $n$  and interval  $h$  is given by:

$$\mathbf{a}_n = \frac{1}{h}(\mathbf{v}_{n+1/2} - \mathbf{v}_{n-1/2}) \quad (5)$$

where:

$h$  – time interval between time step  $n$  and  $n + 1$

$$\mathbf{v}_{n-1/2} = \frac{1}{h}(\mathbf{x}_n - \mathbf{x}_{n-1}) \quad (6)$$

The *velocity* at time step  $n$  is given by:

$$\mathbf{v}_n = \frac{1}{2}(\mathbf{v}_{n-1/2} + \mathbf{v}_{n+1/2}) \quad (7)$$

The *velocity update equation* is obtained by substituting equation (5) and equation (7) into equation (1) to give :

$$\mathbf{v}_{n+1/2} = \frac{(M/h - C/2)}{(M/h + C/2)} \mathbf{v}_{n-1/2} + \frac{\mathbf{f}_n - \mathbf{P}}{(M/h + C/2)} \quad (8)$$

where:

$\mathbf{P} \equiv \mathbf{P}_n^i(\mathbf{x}_n^i)$  from equation (1)

$\mathbf{f}_n$  = body force from equation (1)

The *displacement update equation* is:

$$\mathbf{x}_{x+1} = \mathbf{x}_n + h\mathbf{v}_{n+1/2} \quad (9)$$

The explicit integration algorithm used in DEM analysis is simple and straightforward compared to implicit schemes. It achieves fast and accurate solutions for dynamic problems such as rockfall, impact, and granular flow problems. However, this algorithm is only conditionally stable. The time step must be adequately small to maintain stability conditions. In CRSP-3D, the time step is automatically set and adjusted by the program. When the algorithm is used to solve static (or pseudo static) problems, dynamic relaxation procedures (DR) must be performed in order to achieve rapid convergence.

### **Contact Mechanics Between Falling Rock and a Slope**

The visco-elastic contact model, illustrated in Figure 2 as a spring and dashpot, is the most popular constitutive contact model used in DEM analysis. Because of its simplicity, the calculations are very efficient. The assumption of a linear elastic contact force-displacement relationship between two impact bodies is a good approximation, and is still widely used in engineering.

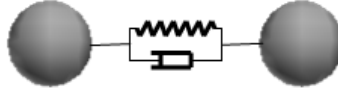


Figure 2. Schematic. Visco-elastic contact model in normal direction.

The normal contact formulation is linear elastic with a viscous damper characterized by two parameters: *normal stiffness*  $k_n$  and *viscosity*  $C$ . The model works for both compression and tension forces based on the relative distance between the two contact points. The *normal force* is defined by:

$$\mathbf{N} = \begin{cases} \frac{1}{2} k_n \varepsilon_n \bullet \mathbf{n} + C \mathbf{v}_{rn} & \varepsilon \geq 0 \parallel \varepsilon \geq -\varepsilon_{\max} \\ 0 & \varepsilon < -\varepsilon_{\max} \end{cases} \quad (10)$$

where:

$\varepsilon_n$  = penetration distance between two contact points. (For two spheres,  $\varepsilon_n$  equals the sum of the radii minus the distance between the two contact sphere centers.)

$-\varepsilon_{\max}$  = maximum tension distance between two neighboring particles. (If negative penetration is larger than this value, the connection between the two particles is disconnected, and the tension force between these two particles is set to be zero.)

$\mathbf{n}$  = normal unit vector at the contact point.

$\mathbf{v}_{rn}$  = normal relative velocity vector at the contact point.

$k_n$  = normal contact stiffness.

$C$  = viscosity of the material

The tangential force depends on the friction of the material and the relative tangential velocity of the two contact particles. The formula for the *tangential force* is defined as:

$$T = \begin{cases} \text{sign}(v_{rs}) \frac{1}{2} k_s \varepsilon_t \bullet s & \frac{1}{2} k_s \cdot \varepsilon < f |N| \\ \text{sign}(v_{rs}) f |N| \bullet s & \frac{1}{2} k_s \cdot \varepsilon \geq f |N| \end{cases} \quad (11)$$

where:

$k_s$  = shear contact stiffness

$f$  = coefficient of static friction

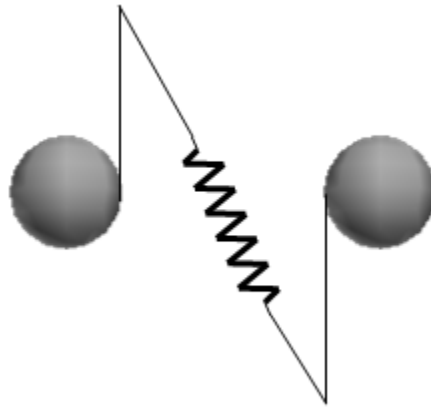
$v_{rs}$  = tangential relative velocity vector at the contact point

$\varepsilon_t$  = relative displacement of falling rock and slope

$N$  = Normal force

$S$  = tangential unit vector

The direction of the tangential force is the reverse of the tangential relative velocity. The magnitude of the tangential force is equal to the relative displacement of the falling rock and the slope ( $\varepsilon_t$ ) times the shear contact stiffness, which is the first term of Equation 11. The second term of Equation 11 refers to the case when the maximum static friction force is larger than the Coulomb friction force (threshold or maximum friction at which movement between surfaces can commence). This mechanical model is shown in Figure 3.



**Figure 3. Schematic. Elastic contact model in the tangential direction.**

There may be *three cases* influencing the tangential force and rotation of the falling rock. When the tangential force is less than the Coulomb frictional force, the rock is either in a *static state or rolling without sliding* on the slope. When the tangential force is equal to or greater than the Coulomb frictional force, the rock may *slide without rolling, or slide while rolling* on the slope. Since the DEM numerical scheme is based on integrating the equation of motion, the *velocity, position, and rock rotation angle* is updated based on the calculation of resultant forces on the rock in each case.

### **Stiffness and Damping (Slope Hardness)**

The key to successful modeling using DEM is proper selection of the stiffness and damping coefficients. Theoretically, the *damping coefficient*  $C$  can be derived from material properties such as the coefficient of restitution:

$$C = 2 \ln\left(\frac{1}{e}\right) \sqrt{\frac{k_n m_i m_j}{(m_i + m_j) \pi^2 + [\ln(1/e)]^2}} \quad (12)$$

where:

$m_i$  and  $m_j$  = the masses of particles  $i$  and  $j$ , respectively.

$e$  = restitution coefficient of the material.

$k_n$  = the normal contact stiffness.

For the falling rock problem,  $m_j$  is the mass of the slope element, which can be assumed to be infinite. Equation 12 may be rewritten as:

$$C = 2 \ln\left(\frac{1}{e}\right) \sqrt{\frac{k_n m}{\pi^2 + [\ln(1/e)]^2}} \quad (13)$$

where:

$$m = \frac{m_i m_j}{m_i + m_j}$$

Since the damping coefficient and the COR are directly related to the hardness coefficient, they are used in calculating effects of rock and slope interaction. The damping and COR have an inverse linear relationship. For example, a hard slope will have a relatively high COR and a low damping value while a soft soil slope will have a low COR and a high damping value.

Slope and roadway materials have been grouped under general descriptions (Soft Clay, Hard Clay, Sand, Gravel, Soft Bedrock, Hard Bedrock, Boulder Field, Talus, Concrete Road and Asphalt Road). Because of the large range in hardness coefficient values observed in some materials, the hardness coefficient overlap between different slopes under the same material description was used to construct a table of recommended ranges of hardness coefficient values. This table, shown in *Material Descriptions* in the CRSP-3D Help, is to be used as a starting point for choosing hardness coefficient values.

During CRSP-3D rockfall simulations, the hardness coefficient values, for example, may need to be calibrated to produce accurate output. This calibration process entails running rockfall simulations of existing rockfalls (calibration sites) and comparing the output to observed rockfall parameters at the existing sites. In this manner input parameters such as slope hardness, roughness and boulder size at a required location can be estimated more accurately. An automatic calibration mode capability is included in the advanced upgrade version of CRSP-3D.

## SYSTEM REQUIREMENTS

### Minimum System Requirements:

2.0 GHz or faster processor

Intel Pentium 4, Penium M, Pentium D processor or better, or AMD K-8 (Athlon) or better

4 GB internal RAM

Windows 7, Windows Vista, Windows XP Professional or Windows XP Home

NVIDIA GeForce FX 5200, ATI Radeon 9600, or better graphics card

### Recommended Requirements:

2.5 GHz or faster processor

Core 2 Duo or Athlon X2.

8 GB internal RAM

Windows 7, Windows Vista

NVIDIA GeForce 8000, ATI Radeon 9600, or better graphics card with 512 MB dedicated RAM

## INSTALLATION

CRSP-3D is a fully encapsulated executable file, which may be installed from the accompanying CD ROM disk, or installed from an internet web link. For either method, two files should be copied: this “*CRSP-3D User’s Manual*” and the zipped program file package of “*CRSP3D\_ZIP*”. Before installing CRSP-3D, ensure that you have at least a minimum recommended free space of 400 MB.

After the files are copied, save the encapsulated executable zipped file *as-is* to any user-specified location on the computer. Since there is no modification to the registry, no special administrator privileges are required for installation. Uninstalling is similarly simple, in that the executable file can just be deleted.

Once saved to the user designated location, the user can easily manually create a shortcut to the Windows desktop or any other location

All data input files used by CRSP-3D must reside in a subdirectory of, or in the same directory (folder) as, the CRSP-3D executable program (the .exe file).

CRSP-3D generates a file called *project.txt* which contains all the data input into the code for a particular simulation. When a project file is saved, this file is the critical file saved within a folder bearing the project name.

### CD Installation

From your CD drive, select, copy, and then paste the files named “*CRSP-3D User’s Manual*” “*CRSP3D\_ZIP*” into a folder on your hard drive. A suggestion would be *C:\Crsp3D*. Unzip and install the CRSP-3D program files with a left double click on “*CRSP3D\_ZIP*” accepting the recommended default directory of *C:\Crsp3D* by clicking on the Unzip button. Under this initial installation CRSP-3D starts automatically. To run it again later, the application file is titled, “*CSPR-3D*”. For convenience you can create a desktop shortcut to “*CRSP-3D*”.



### **Internet Installation**

This public version of CRSP-3D can be found at [www.cflhd.gov/programs/techDevelopment/geotech/CRSP-3D](http://www.cflhd.gov/programs/techDevelopment/geotech/CRSP-3D).

Individually right click on "*Entire Document - CRSP-3D User's Manual, Colorado Rockfall Simulation Program*" and "*Self-Extracting Executable Program – CRSP-3D, Colorado Rockfall Simulation Program*" then "save" them onto your hard drive. Once copied, follow the *CD Installation* directions shown above.

### **FUTURE VERSIONS OF CRSP-3D**

Currently no additional revisions of CRSP-3D are under development though discussion is in progress at FHWA with respect to the future of the program. It is possible that versions of the code will be developed that incorporate changes and any corrections. Improvement to the capabilities of the code may also be considered.

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## CHAPTER 2 - GENERAL PROGRAM EXECUTION

## STARTING CRSP-3D

Double-click on the CRSP-3D desktop icon to start CRSP. The program may take several minutes to start up. A splash screen (Figure 4) is displayed during program initialization each time the program runs; a *Loading* progress indicator is shown.

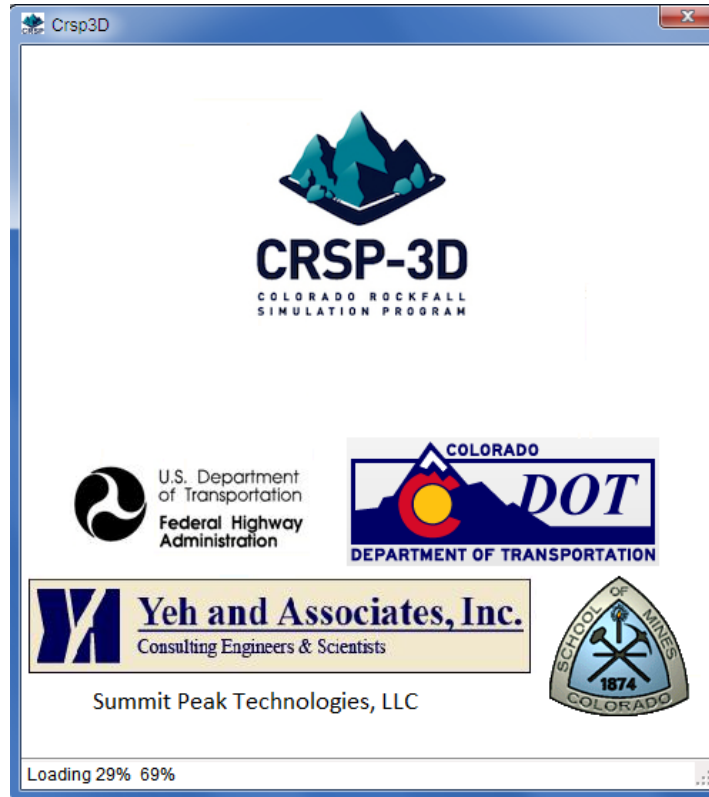


Figure 4. Screenshot. CRSP-3D start-up splash screen.

Thereafter, a *Browse for Folder* screen will open up requesting the user to *Select a Project Folder* (an existing saved run) or *Make a New Folder* (for a new run). Once this has been accomplished the splash screen will disappear for as long as 2 minutes before another screen opens.

Note: though there is no physical indication on the screen that CRSP-3D is running at this point, it is processing in the background and a startup screen (possibly minimized) will appear in a minute or so.

## MAIN MENU

The main menu in CRSP-3D (Figure 5) consists of three options: **File**, **Units**, and **Help**.

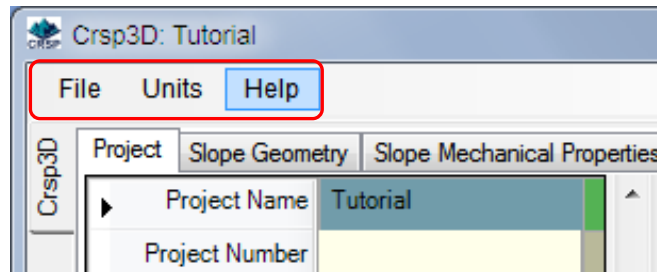


Figure 5. Screenshot. Main Menu.

### File Menu Item

*File* has a drop down menu (Figure 6) with the following options:

**New:** Creates a new project

**Open:** Opens an existing project

**Save:** Saves current project

**Save As:** Saves current project under a different name; user *must* use the menu that opens to create a new folder name

**Clear Data:** Erases all data in current project

**Exit:** Ends the application

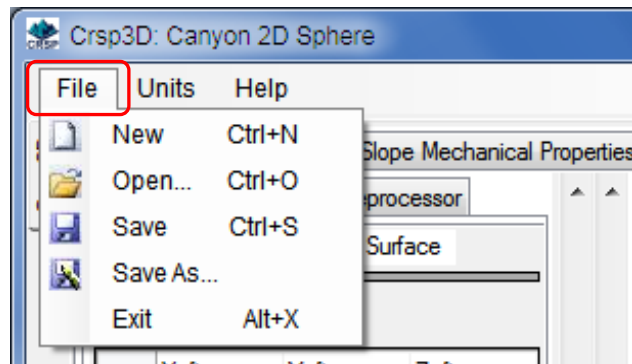


Figure 6. Screenshot. File Menu Item.

## Units Menu Item

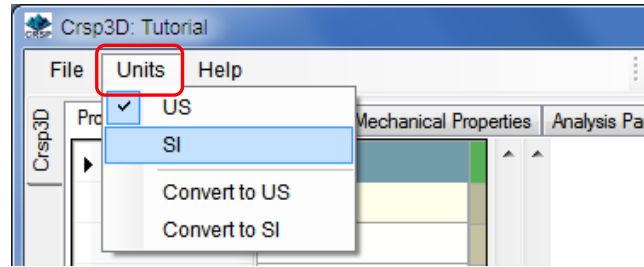


Figure 7. Screenshot. Units Menu.

The *Units* menu (Figure 7) allows the user to enter data in either customary US units (i.e. ft, lb, etc.) or SI units (i.e. m, kN, etc.). The default setting for a new project is in customary US units. If the user has input data in SI units, and accidentally enters those values while the units are set to US units, then the user can simply select “SI” from the units menu. The input values will remain the same, but the program will perform calculations in SI units.

*Convert to US* and *Convert to SI* are used when a user has entered data in one unit and then wishes to see the equivalent problem in the other unit. The SI units’ designation in the top part of the menu will automatically be checked, indicating the current unit in use.

**Units->US:** Use English US units, with no unit conversions.

**Units->SI:** Use metric SI units, with no unit conversions.

**Units->Convert to US:** Convert all current SI units to US units.

**Units->Convert to SI:** Convert all current US units to SI units.

Slight round-off errors may occur during conversions. Multiple conversions between units will increase the magnitude round-off errors. The use of these menu items is discouraged for design work. All US and SI units are displayed in the Report.

## Help Menu Item

Selecting *Help* will open the Help file’s *Table of Contents* (Figure 8). The help function is navigated by clicking on links in the Table of Contents listing, and clicking on *Return to Table of Contents* and other links within each Help section. To hide Help, drag the frame all the way to the right side of the screen:

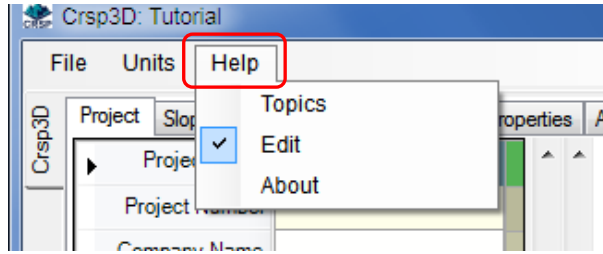


Figure 8. Screenshot. Help Menu.

**Help->Topics:** Opens the Table of Contents.

**Help->Edit:** Enables editing of Help content. Any changes to Help should be saved, since all changes will be overwritten after the program updates.

**Help->About:** Displays application version and build information (Figure 9). The version build is in year.month.day.hour.minute format.

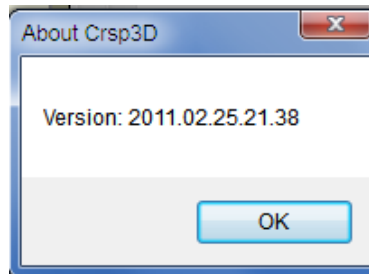


Figure 9. Screenshot. Example of Build version.

## TOOLBAR

The toolbar is located to the right of the *Menu*, with icons corresponding to File menu items. The toolbar (Figure 10) at the top of the screen gives you shortcut access to common menu options that also appear under the *File* menu. From left to right:

- New
- Open
- Save
- Save As
- Help

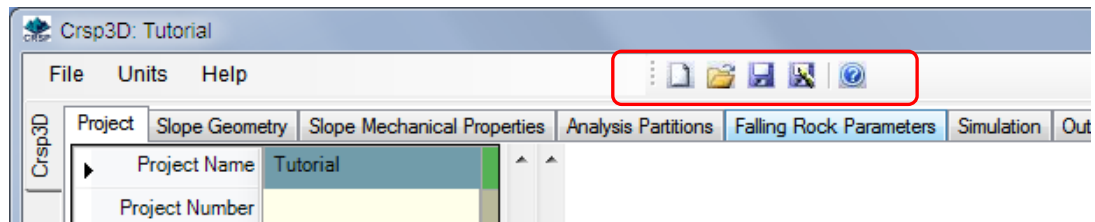


Figure 10. Screenshot. Toolbar.

## TABS

Input parameters and output results in CRSP-3D are organized into the following tabs (Figure 11):

- Project Tab
- Slope Geometry Tab
- Slope Mechanical Properties Tab
- Analysis Partitions Tab
- Falling Rock Parameters Tab
- Simulation Tab
- Output Tab

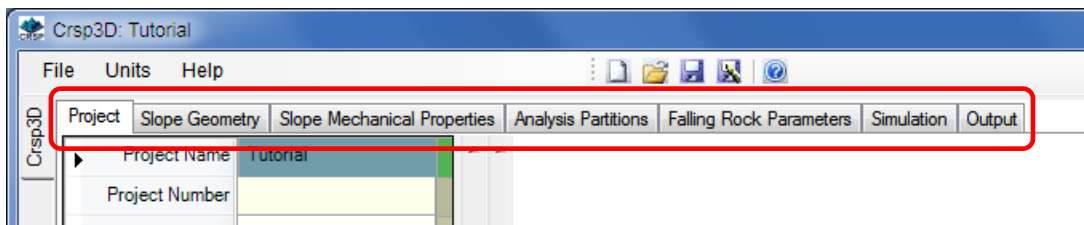


Figure 11. Screenshot. Tabs.

### Project Tab

Basic project information such as *Project Name*, *Project Number*, *Company Name*, *Location*, *Map Coordinates*, etc., is input under the *Project Tab* (Figure 12). The Project Name field will be displayed over the slope image on the screen graphic as a title to identify the project. The information entered into the Project Tab appears in the *Report* in order to identify the project, data set and the analysis.

Project	Slope Geometry	Slope Mechanical Properties
Project Name	Tutorial	
Project Number	2010-05-17	
Company Name	GAP Engineering	
Location	Denver, CO	
Map Coordinates	39° 44' 21" N / 104° 59' 3" W	
Designer	Alan Rock	
Reviewer	Dr. Runing Zhang	
Date	May 17, 2010	

Figure 12. Screenshot. Project Tab.

## Slope Geometry Tab

Slope surface geometry is input using the *Slope Geometry Tab* (Figure 13). Coordinates are entered as X-Y-Z spatial coordinates of points that define the slope surface. In a CRSP-3D graphic slope representation, the X-axis (slope length projected onto the horizontal plane) represents the horizontal component of the slope cross-section and the Z-axis (slope height) represents the vertical component of the slope cross-section. In 3D, the Y-axis (slope face width) forms the slope face. A virtual 2D project geometry, therefore, is entered in X-Z coordinates, though a constant Y coordinate has to be input to maintain compatibility with the program requirements (the view is rotated into the X-Z plane for a 2D effect).

Surface Points may be entered in the following ways:

via the *Surface Points* sub-tab:

- cut and paste from an Excel spreadsheet,
- entered manually via the keyboard,
- entered graphically with the mouse by clicking location on the slope, or

via the *Lidar Preprocessor* sub-tab:

- imported from a LIDAR slope geometry file.

The *Refresh* button is used to update the graphic once the data points have been entered or if changes are made to the graphic

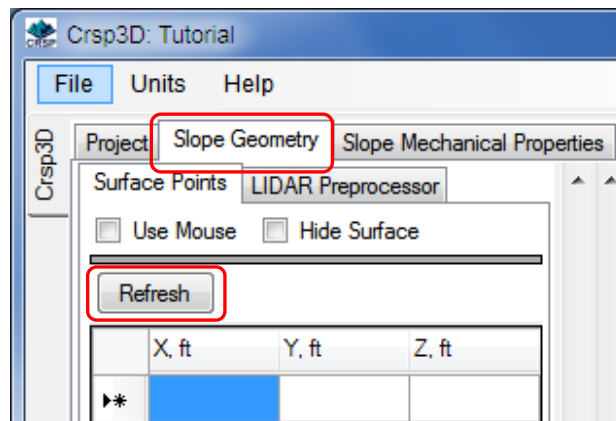


Figure 13. Screenshot. Slope Geometry Tab.

## Surface Points Sub-Tab

Surface Points refer to the X-Y-Z spatial coordinates of points on a slope surface. The user defines the surface geometry of the slope being investigated using these surface coordinates. Surface points (Figure 14) can be entered in several ways



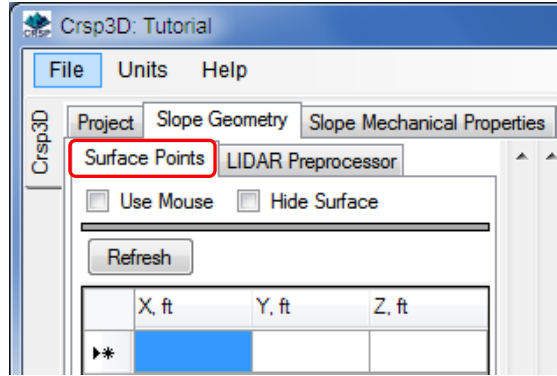


Figure 14. Screenshot. Surface Points Tab.

**Pasting Points from an Excel Spreadsheet:**

- First, select the (X,Y,Z) point coordinates in Excel (Figure 15):

500	0	0
401	0	4.26
279.66	0	0
330.09	0	14.7
232.7	0	37.31
192.69	0	79.05
168.87	0	115.57
103.99	0	138.18
58.77	0	160.79
30.95	0	214.71
0	0	300
330.31	125	9.76

Figure 15. Screenshot. Select Excel Spreadsheet X, Y, Z Coordinate Data.

- Type Ctrl-C to copy to the clipboard.
- Next, click the top row of cells (X, Y and Z) so they appear solid blue (Figure 16).

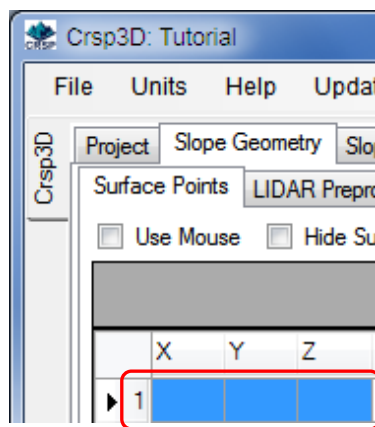


Figure 16. Screenshot. Highlight Paste Zone in CRSP-3D.

- Then, type Ctrl-V to paste the points (Figure 17):

	X, ft	Y, ft	Z, ft
1	500	0	0
2	401	0	4.3
3	279.7	0	0
4	330.1	0	14.7
5	232.7	0	37.3
6	192.7	0	79.1
7	168.9	0	115.6
8	104	0	138.2
9	58.8	0	160.8

Figure 17. Screenshot. Pasted X, Y, Z Coordinate Data.

**Enter Points With The Mouse:**

- First, position the scrollbars as follows (Figure 18):

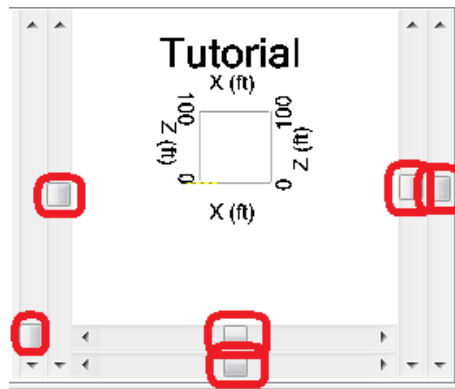


Figure 18. Screenshot. Initialize scrollbars.

- Next, left-click the mouse and move points to the desired location (Figure 19).
- Points may be deleted by right-clicking the point, *or* selecting the row of the grid and pressing the Delete key.

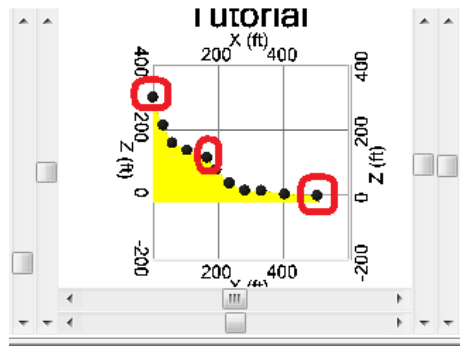


Figure 19. Screenshot. Moving and deleting points on the screen.

The slope graphic may be rotated and translated using the screen slider controls identified as follows (Figures 20 and 21):

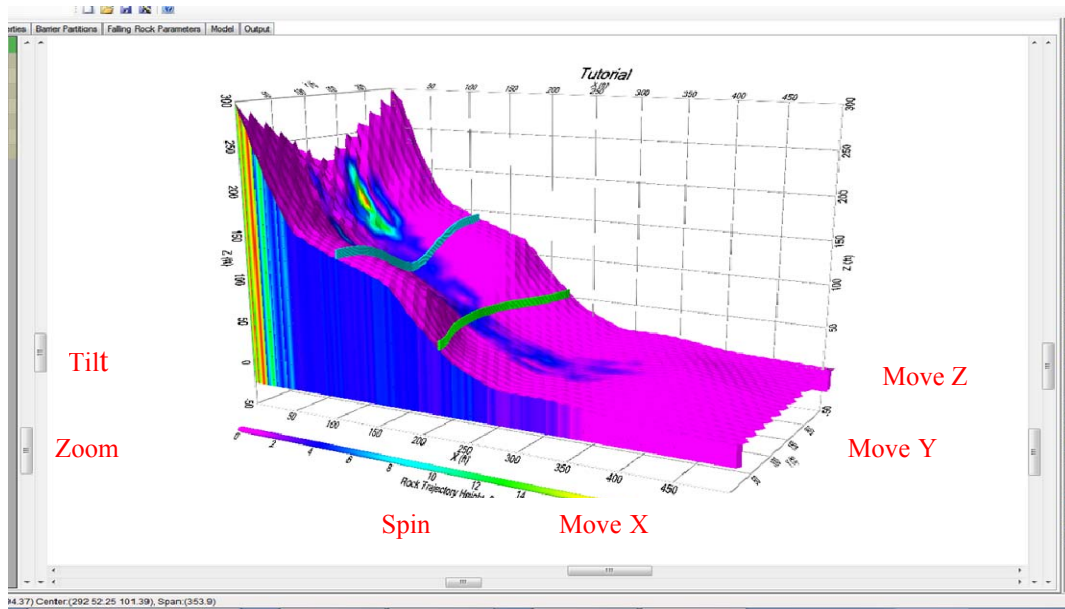


Figure 20. Screenshot. Graphic rotation and translation controls.

- Tilt** control - rotates the graphic about the horizontal x- axis
- Spin** control - rotates the graphic about the vertical z-axis
- Move X** control - moves graphic parallel to the x axis direction
- Move Y** control - moves graphic parallel to the y axis direction
- Move Z** control - moves graphic parallel to the z axis direction
- Zoom** control - enlarges or reduces the image.

The image may be rotated to make sure the points are correct on the slope:

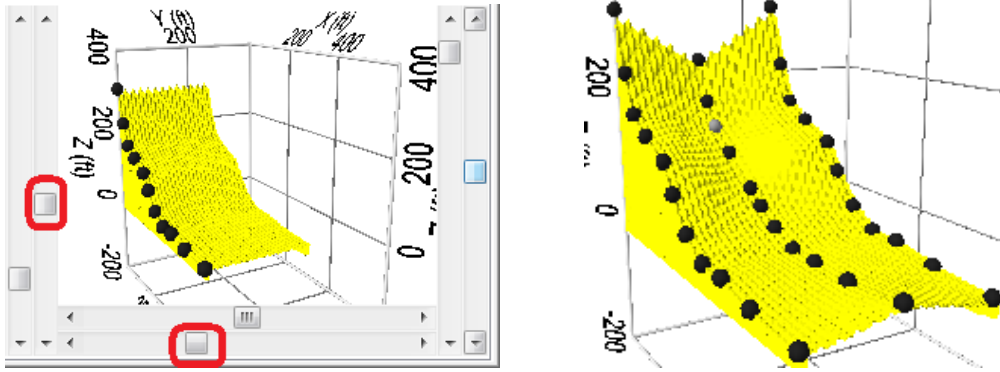


Figure 21. Screenshot. Image Rotation.

***LIDAR Preprocessor Sub-Tab***

This tab is used to import slope geometry data from a LIDAR file (Figure 22).

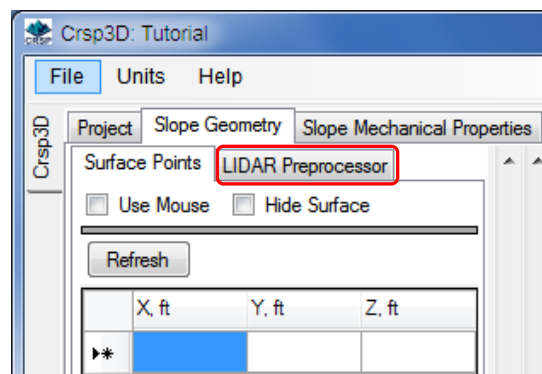


Figure 22. Screenshot. LIDAR Preprocessor.

**Data Format:**

CRSP-3D currently supports two ASCII text file formats for slope geometry input (file extension **.asc** or **.txt**). These two file formats are current standards used by the Federal Highway Administration (FHWA). CRSP-3D allows the user to convert the data from SI units to US units, or from US units to SI units, after importing the data file.

The first file format contains a header section of any content and length (which is ignored), followed by the line "X Y Z" (uppercase separated by spaces only), followed by data points in the form "Easting Northing Elevation" (separated by spaces) as shown below.

SLIDE AREA 1

US State Plane 1983, Colorado Central 0502, NAD 83  
US Survey Feet

X Y Z

2938198.64 1679321.49 9114.45  
 2938199.59 1679321.55 9114.40  
 2938200.75 1679321.17 9114.25

Note: Be certain that only "space" delimiters are used.

The second file format contains a header section of any content and length (which is ignored), followed by the line "X Y Z R G B" (uppercase separated by spaces only), followed by data points in the form "Easting Northing Elevation Red Green Blue" (separated by spaces only), with Red, Green, and Blue referring to color components from 0-255) as shown below:

SLIDE AREA 1

US State Plane 1983, Colorado Central 0502, NAD 83  
 US Survey Feet

X Y Z R G B  
 2938198.64 1679321.49 9114.45 0 0 4  
 2938199.59 1679321.55 9114.40 131 59 21  
 2938200.75 1679321.17 9114.25 5 0 4

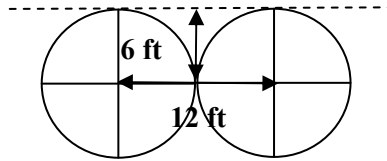
A LIDAR text file with a large number of X Y Z records will run slowly and may be prone to crashes. A solution is to "thin out" the raw LIDAR data to a fewer number of records using software specifically designed for this. Another option to thin out the number of records is to increase the surface resolution value (see Figure 24 and the discussion under *Surface Resolution*). This will reduce the number of data records to a more manageable size. Input reading time with a file size of five thousand records can be very slow (CRSP-3D was intended for sizes between 500 and 2000 records). A thousand records seem to be a good compromise between accuracy and execution time though the user should experiment to determine what file-size *versus* execution-time compromise is acceptable.

Once a LIDAR file is received it can initially be reviewed, edited and saved using a suitable text editor (e.g. a freeware text editor like *Crimson Editor* works well). The edited file can then be manipulated in spreadsheet program like Microsoft Excel which provides the capability to perform data operations that an editor is not intended for. This pre-processed file can then be saved as a text file (.txt, space delimited). Before proceeding to load the file into CRSP-3D it is imperative that the file be reviewed in a text editor like *Crimson Editor* to make certain that the file contains only blank space field delimiters. At this point, heading and X Y Z lines can be added to the beginning of the file. Once saved this file is ready to be loaded into CRSP-3D.

**Slope Surface Roughness:**

The slope surface roughness is simulated using virtual spheres to create the surface. In order to create the slope surface, CRSP-3D assumes a fixed 12 feet lateral spacing between sphere centers regardless of the diameter of the spheres. These virtual spheres are constrained to vary in radius between a minimum of 6 feet and a maximum of 60 feet which, respectively, correspond to a surface roughness or amplitude of 6 feet over a base length of 12 feet (the maximum roughness possible) and an approximately smooth surface. It is this variation in radius that creates the variation in slope surface roughness. Roughness is defined as the perpendicular

distance between the intersection of two adjacent virtual spheres and a tangent line to the two spheres as shown below in Figure 23.



**Figure 23. Diagram. The maximum surface roughness of 6 feet generated by spheres with centers 12 feet apart.**

### Surface Resolution:

CRSP-3D uses a fixed 12 feet center-to-center distance for modeling a slope surface when surface coordinates are cut and paste from a spreadsheet, entered manually or inserted graphically. This is also the case for a LIDAR file regardless of the spacing of data points contained in the file. This 12 feet spacing controls the roughness of the generated slope surface and is referred to as the *resolution* when processing a LIDAR file. Therefore, using a surface resolution of 12 ft when importing a LIDAR file will create a slope surface with the same roughness as that generated by CRSP-3D when creating a slope surface created using manually inserted coordinates. Loading a LIDAR file and specifying a resolution value less than 12 ft (a higher resolution) will only degrade performance with no other improvements. Using a surface resolution value greater than 12 ft (a lower resolution) will reduce rockfall simulation time and will reduce the uploaded file size (the number of LIDAR records will be "thinned out"), but will cause CRSP-3D to interpolate between points to achieve a virtual 12 ft surface resolution resulting in a smoothing of the model slope surface.

CRSP-3D will maintain a constant surface point spacing (points that define the surface of the slope being analyzed) of 12 feet - either by extrapolating new point data points from data originally provided at a greater spacing than 12 feet or by thinning the number of data points provided at a closer spacing than 12 feet. For example, on a 1000 foot by 1000 foot slope there will be approximately 7000 surface points spaced 12 feet apart. CRSP-3D will reduce the number of surface data points to 7000 for large input data files or increase the number of surface data points to 7000 for small input data files.

By *increasing the Surface Resolution value* to greater than 12 (see Figure 24), one is increasing the spacing between points that define the surface and therefore *decreasing the surface resolution*. For example, by increasing the surface resolution value to 48, the total number of surface points defining a 1000 foot by 1000 foot slope will reduce to about 450.

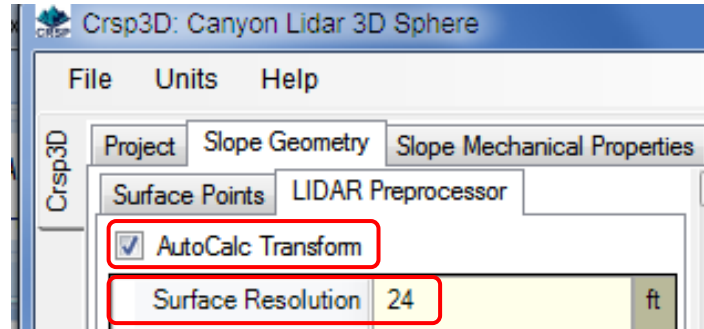


Figure 24. Screenshot. Surface Resolution Selection.

Users should use their judgment to define the surface resolution when processing LIDAR files. For example, for smooth planar slopes, selecting a surface resolution of 48 feet will have little impact on simulated slope topography compared to selecting a 12 feet surface resolution. Conversely, on very rough slopes, a 12 feet surface resolution will show more representative slope topography compared to choosing a 48 feet surface resolution. Surface resolution is set at the time of upload, and cannot be adjusted after the file has been uploaded in CRSP-3D.

Note: Use multiples of 12 when changing surface resolution values e.g. 12, 24, 36, 48, etc. (shown in order of decreasing surface resolution).

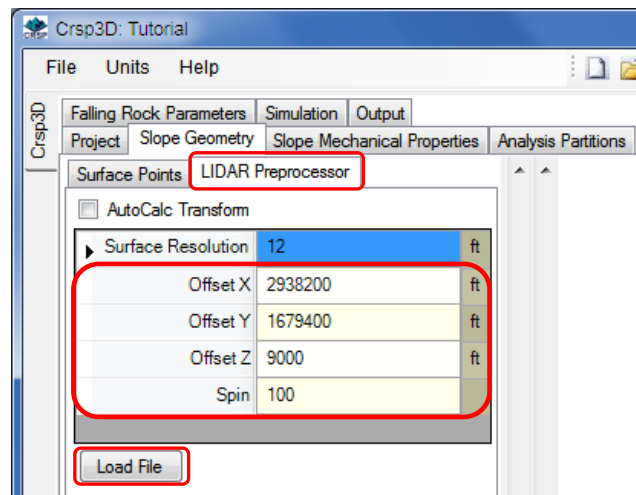


Figure 25. Screenshot. Specifying Surface Resolution, Offsets and Spin value when loading a LIDAR file.

**Offsets:**

The leading digits that are common to each of the coordinate values can be eliminated for purposes of analysis of a local feature like a slope. These are referred to as *offsets* and can be removed in two different ways; (1) manually (Figure 25) as described in the following paragraph or (2) via the *Autocalc Transform* option (see Figure 24), which will perform the appropriate offset calculations automatically without the need to select offsets.

Enter X, Y and Z offsets to reduce the number of digits that need to be stored in the geometry file. When the file is loaded, these values will be subtracted from the X (Easting), Y (Northing), and Z (Elevation) coordinates in the file, thereby defining position in local coordinates.

Note: The screen graphics rendering does not support coordinate values with more than 5 digits, so removing offsets may be necessary in order to reduce the number of coordinate digits to no more than 5 to avoid potential display problems.

**Spin:**

A rotation angle may be entered for Spin to rotate the image about the Z-axis in order to align the fall line of slope along the X-Axis (Figure 26). Increments of 90 degrees should be used to achieve this.

**Load File:**

Clicking the *Load File* button imports the LIDAR data into the *Surface Points Tab* (Figure 25).

**Refresh:**

Select *Refresh* (Figure 27) on the *Slope Geometry Tab* to create or to update the slope surface if slope coordinate data has been newly input or modified.

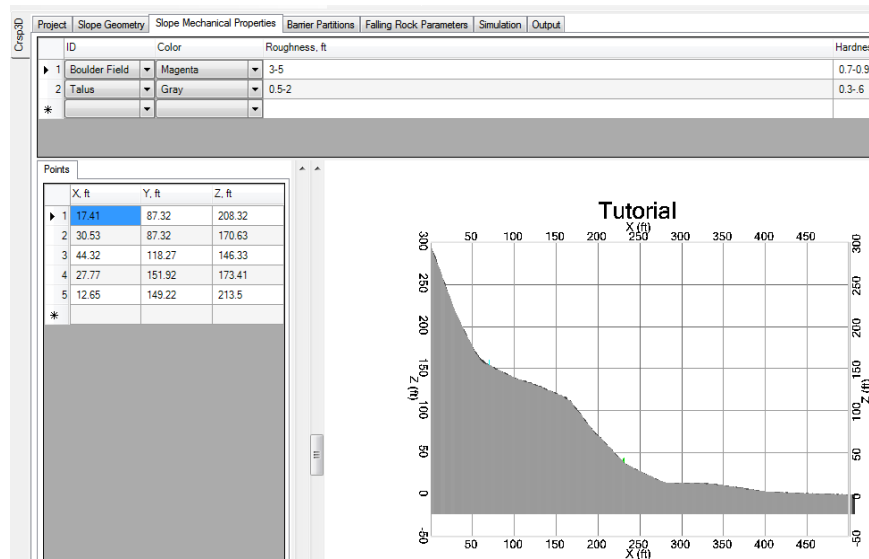


Figure 26. Screenshot. Use of the *Spin* control to place the view in the X-Z plane.



15	499.5	125	1
16	232.8	125	26
17	194.3	125	45.2
18	165.5	125	63.7
19	101.2	125	100.7
20	55.4	125	131.7
21	28.8	125	165
22	2.2	125	224.8
23	500	250	1
24	401.4	250	4.3

Refresh

Figure 27. Screenshot. Select *Refresh* on the Slope Geometry Tab to create a slope surface.

### Slope Mechanical Properties Tab

The *Slope Mechanical Properties* Tab (Figure 28) allows different materials to be specified on the slope, as well as the roughness and hardness values for each material zone.

#### Select a Slope Material Type

- A slope material may be selected by clicking the down-arrow icon in the ID cell (Figure 28):

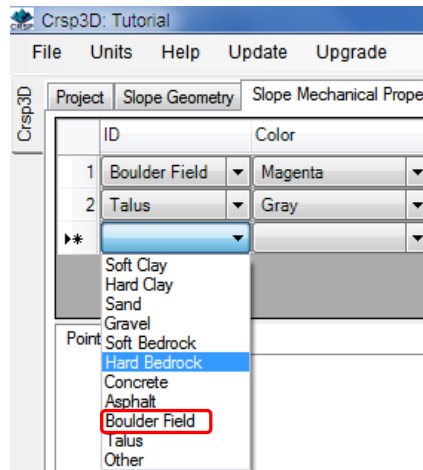


Figure 28. Screenshot. Select a slope material.

- Select the material *ID* or type in a name manually, by double clicking a cell. Double-clicking the cell allows a more descriptive name to be entered, if desired (e.g., Large Boulders). The material *ID* field must be populated before the program will allow the user to double-click the cell and manually enter a user-defined material ID. The default material types are included just as examples; users can specify any material they wish by overwriting the default types.

Note: There are only nine colors that can be used to represent zones and correspondingly there are only nine material IDs that can be used on a single slope. The first nine colors that appear in the drop down box are available - the remaining gradient color options that show are disabled.

- Enter *Roughness* values or ranges (Figure 29). *Roughness* values between 0.01 (smooth) and 6 (rough) can be entered. Some judgment as to the selection of this value is recommended since the numbers represent the amplitude of the roughness measured in feet with respect to a flat surface over a reference distance of 12 feet. See the discussion on slope *Surface Roughness* presented in previously.
- Enter *Hardness* values or Ranges (Figure 29). *Hardness* varies between 0.01 and 1 and represents the amount of energy that is transmitted between bodies during impact. Hardness also correlates to the degree of damping i.e. a high hardness will have low damping ratio and *vice versa* since the damping coefficient and the coefficient of restitution (COR) are directly related to the hardness coefficient as discussed previously in Chapter 1.

Note: The surface roughness, when entered into the program as a single number, such as 2.0, will result in a constant surface roughness being modeled in the program. If a range of surface roughness is input, such as 0.1 - 2.0, the program will randomly choose roughness values between 0.1 and 2.0 for each element location on the slope. The user can also use a range for the hardness coefficient, which is entered the same way as the roughness. A range of hardness values can be used to simulate dispersed trees and large boulders on the slope.

ID	Name	Color	Roughness, ft	Hardness
1	Boulder Field	Magenta	3-5	0.7-0.9
2	Talus	Gray	0.5-2	0.3-6
*				

Figure 29. Screenshot. Enter roughness and hardness values associated with a slope material type.

### *Locate the Material Type on the Slope*

This can be done entering coordinates manually or by using the mouse. The following method uses the mouse.

Note: A detailed description of the manual input of coordinates to define slope properties is discussed for the 2D Example in Chapter 3 - Worked Examples.

The mouse location is shown along the bottom of the program window. Several coordinates are listed:

- Mouse: (mouse coordinates)
- Surface: (coordinates of mouse projected on the slope surface). Use surface coordinates for placing points on the slope surface.
- Center: (coordinates of viewing center)
- Span: (horizontal width of view, similar to zoom)

Note: When placing points near the edges or top of the slope using a mouse, the points are sometimes set far behind the slope surface. To alleviate this problem, rotate the slope image to look straight down on the slope (similar to an aerial view) and then place the points.

- Select the material from the drop down menu (Figure 30).

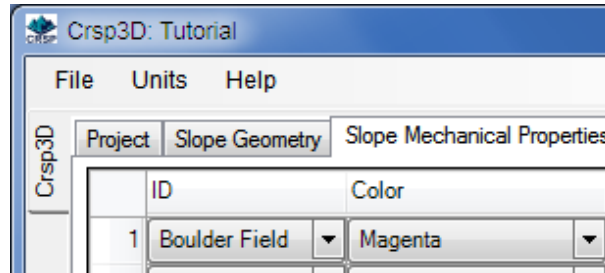


Figure 30. Screenshot. Identify the material type under the Slope Mechanical Properties tab.

- Click on the slope in regions where this material may be found (Figure 31).

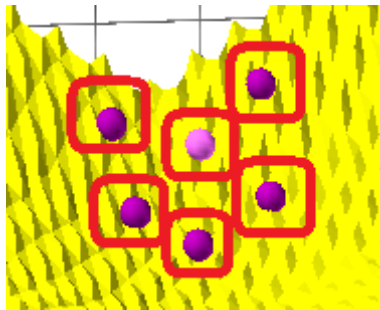


Figure 31. Screenshot. Place points around the perimeter of the identified material.

- Select the next material and define its extent (Figure 32). Click on the appropriate material and then click the mouse on the slope at points corresponding to locations of this material on the slope.

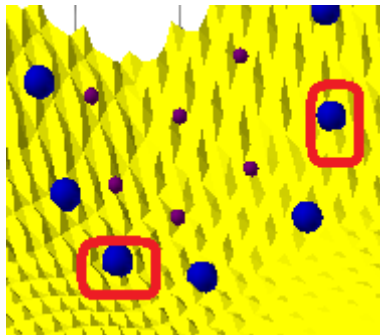


Figure 32. Screenshot. Place points around the perimeter of the first material.

To draw a zone on the display, simply use the left mouse button to create a series of points along the perimeter of the zone. Points can be deleted by placing the cursor on the point to be deleted and clicking the right mouse button. Points can be dragged by holding the left mouse button on the point and dragging it to the desired location. The zone within two perimeters or between a perimeter and the boundary of the model (depending on which is applicable) will be assigned the input roughness and hardness values.

After entering a set of mechanical properties data click *Build* to update the slope (Figure 33).

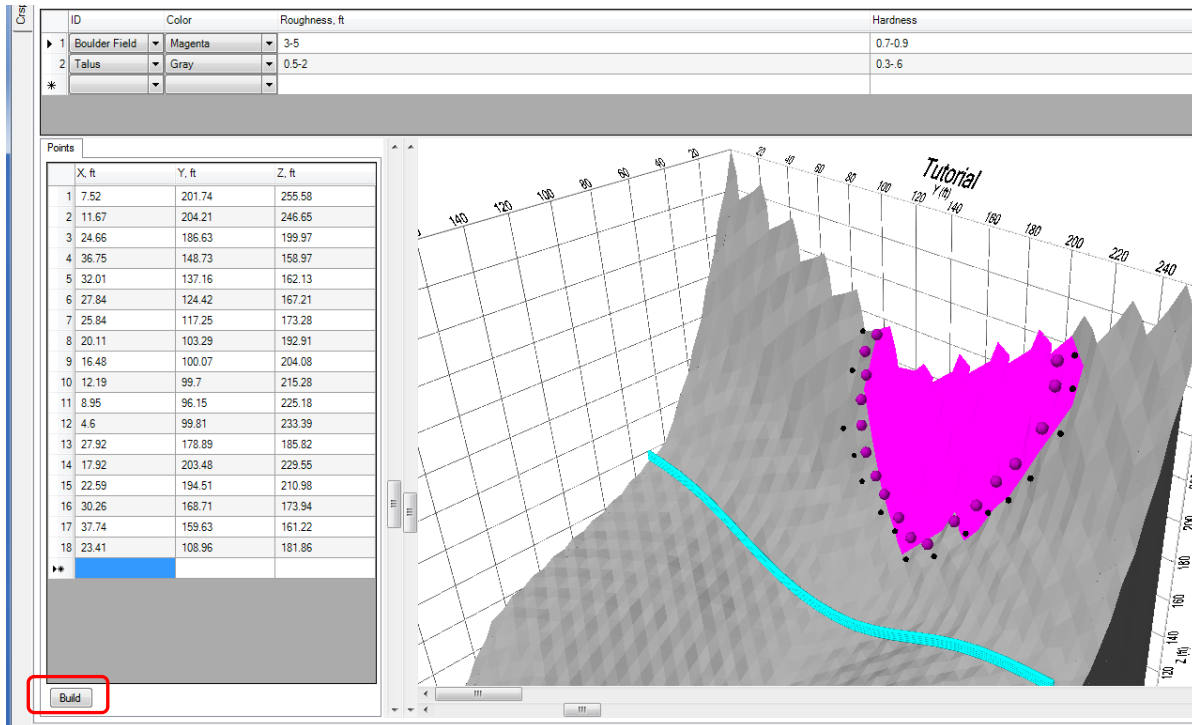


Figure 33. Screenshot. Boulder field zone (magenta) drawn on the screen using the mouse.

### Analysis Partitions Tab

Analysis Partitions are used to simulate the position of a barrier or define a physical location where parameters such as *Rock Trajectory Height*, *Rock Velocity* and *Rock Kinetic Energy* may be determined during simulation runs. They are defined by entering the elevation (Z-coordinate) of the top of the partition or the position (X coordinate) across the slope face. Providing just the X coordinate, fixes the X coordinate across the slope and allows the Z coordinate to vary. Alternatively, the Z coordinate can input which then defines the top of the partition and allows the x coordinate to vary in order to maintain the fixed Z coordinate condition or an existing X partition can be changed to a Z partition by clicking on the Direction box and selecting Z. Rocks can be retained by a barrier, but rocks can also pass a barrier by bouncing over, passing beneath (attenuator) or breaking the barrier.

Note: The partition does not act as a physical barrier. Also note that the number of partitions generally should not exceed four because this may increase execution time significantly and create high graphics memory demand which may lead to program instability.

Partitions can be located where observed rockfall bounce heights (tree scars) or rollouts were measured or where rock fall experimental data are available. This information can then be used to calibrate the model to the observed rockfall parameters (see Calibration later in this document).

- Select the *Analysis Partition tab* to enter locations of analysis partitions on the slope.
- Enter a partition name under ID (e.g., BP-1) (Figure 34).

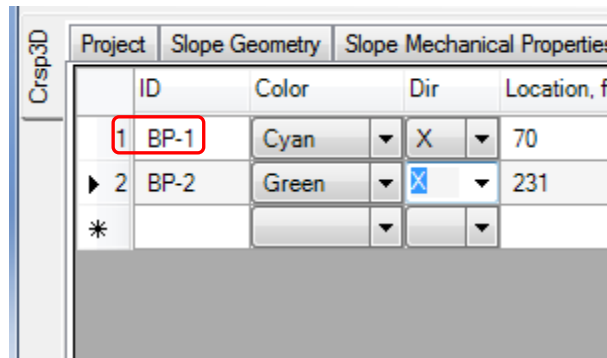


Figure 34. Screenshot. Enter partition name, direction, and location.

- Enter the location of the partition

The location of the analysis partition can be entered by manually entering a position on the slope face as represented by a fixed horizontal X coordinate or by entering a fixed height Z (the elevation of the top of the partition across the slope). See Figure 35. CRSP-3D requires only the coordinate of the partition to be entered (either the fixed X coordinate of the partition across the slope face or Z for the fixed elevation of the top of the partition).

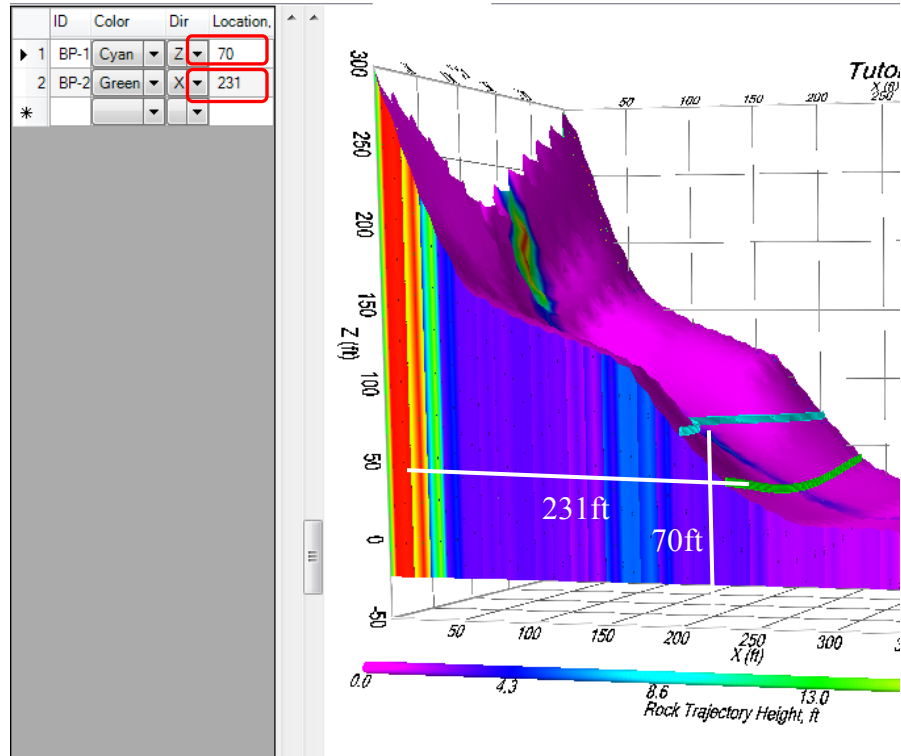


Figure 35. Screenshot. X and Z coordinates of the Partition.

- Alternatively, clicking the right mouse button on the desired location on the slope will add points representing the position of a partition.

CRSP-3D will calculate *Kinetic Energy*, *Velocity* and *Rock Trajectory Height* (bounce height) for falling rocks at the location of each partition (rocks must actually pass the partition for the energy and height calculations to be performed). Partitions can be deleted by clicking the right mouse button on the base of the Partition to be deleted. They can be dragged up and down the slope by holding the left mouse button on the base of the Partition and dragging it to the desired location (see Figure 36).

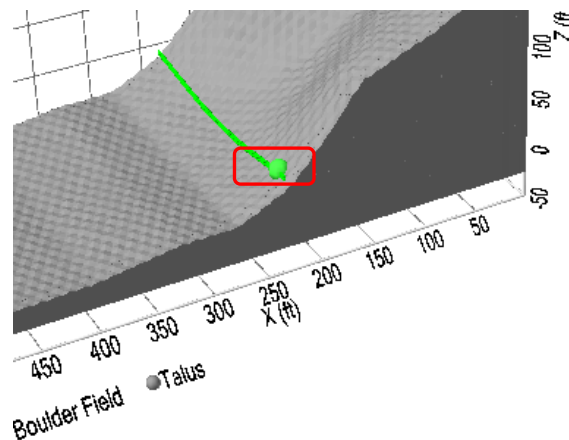
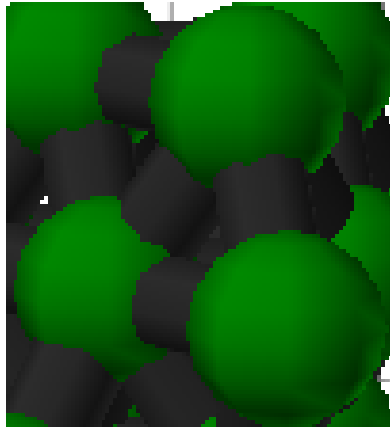


Figure 36. Screenshot. Dragging a Partition.

### Falling Rock Parameters Tab

The *Falling Rock Parameters* tab is used to enter parameters (Figure 38) for the CRSP-3D simulation comprising:

- the *zone* where rocks are released (the program will randomly choose rockfall starting locations within the material zone designated as the release zone),
- the *number* of rocks to release,
- the *unit weight* of the rock,
- the *shape* of the rocks defined by the number of spherical elements combined to create each rock shape. See Figure 37. Number of spherical elements to create a falling rock shape: one spherical element = sphere, two spherical elements = cylinder, three spherical elements = triangular disc, four spherical elements = tetrahedron, eight spherical elements = cube), and
- the *size* of the falling rock defined in terms the characteristic dimension for each shape. In the case of:
  - (1) a single element sphere, size is the diameter;
  - (2) a two-element cylinder, size is the length of the cylinder;
  - (3) a three element triangular disc, size is the triangular side length;
  - (4) a four element tetrahedron, size is the height; and
  - (5) an eight element cube, size is the length of the side of the cube.



**Figure 37. Screenshot. The spherical elements and tubular connectors that make up various rock shapes.**

Rock size can be entered as a single number if the simulated rock(s) will be equidimensional. If a range of rock sizes (e.g. 1- 4.5 feet) are to be simulated, a range of rock sizes are randomly selected within the designated range. This rock size corresponds to the characteristic dimension of the rock shape specified.

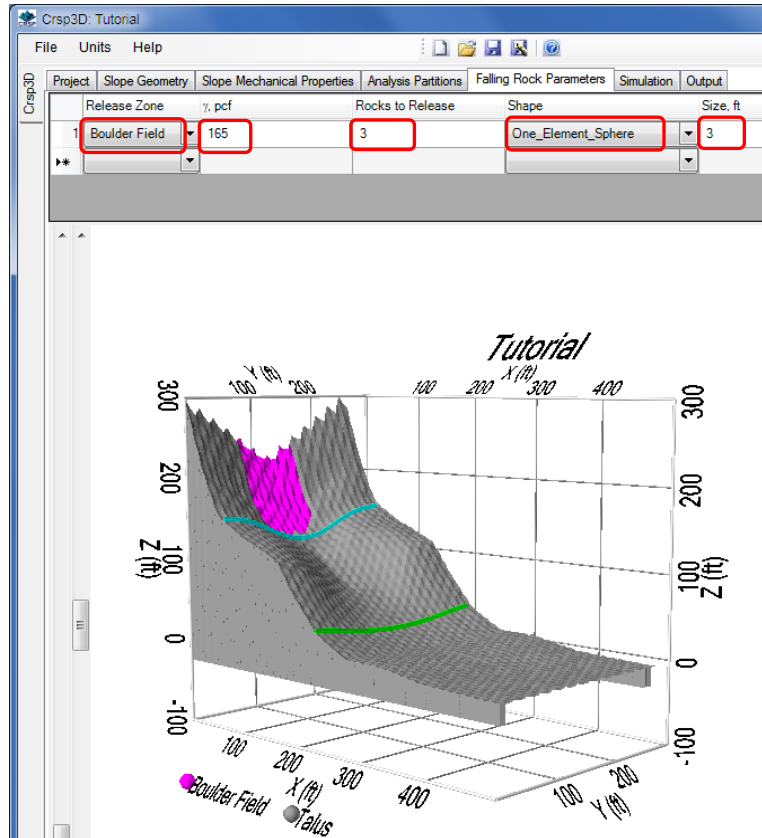


Figure 38. Screenshot. Falling Rock Parameters Input.

Rock size and shape can have an effect on output parameters such as runout distance, bounce height, velocity, and kinetic energy. CRSP-3D does not output the simulated rock size or shape in the *Stats* tab (see Figure 41); however, this information is displayed in the *Report* if the user chooses to generate it. CRSP-3D simulates rocks and outputs the results in the *Stats* tab in the order that they are entered in the *Falling Rock Parameters* tab. The user can model several different rock shapes and sizes in one rockfall simulation and observe the difference in output by using the numbers listed on the left hand column of the *Stats* tab.

### Simulation Tab

The *Simulation* tab performs the actual execution of the simulation. The rockfall simulation model is run from the Simulation tab. See Figures 39 and 40.



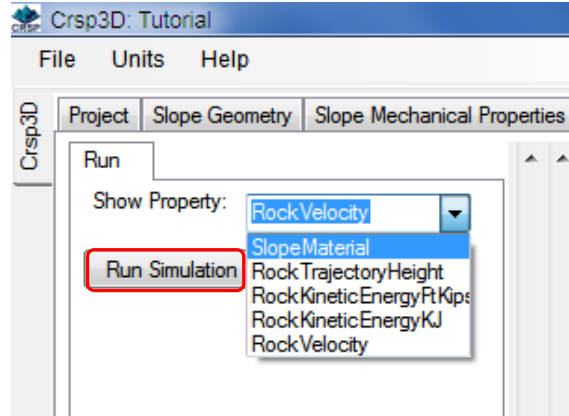


Figure 39. Screenshot. Magnified Simulation Tab Controls.

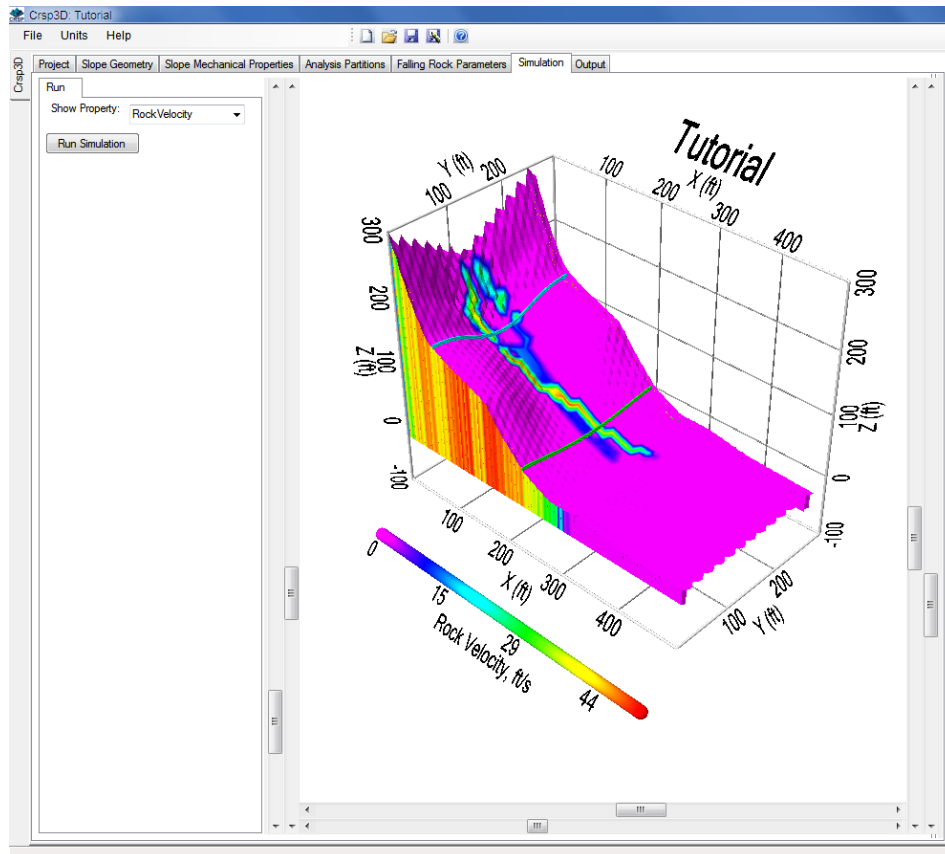


Figure 40. Screenshot. CRSP-3D Simulation graphic screen.

### Output Tab

The *Output* tab contains a *Stats* and a *Report* sub-tab.

**Stats Sub-Tab**

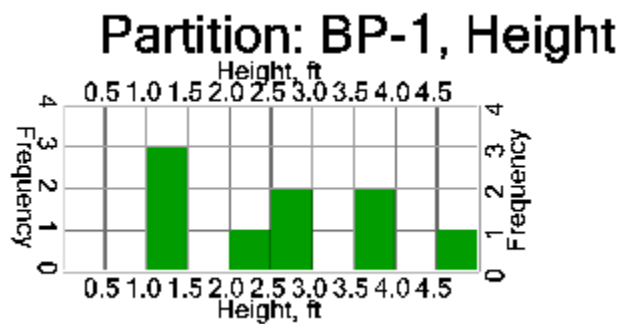
Output of the rockfall simulation can be viewed under the *Stats* sub-tab (Figure 41). Output can only be viewed at barrier Partitions, so at least one partition must be included to view output.

- The *Stats* sub-tab displays various rockfall properties for each rock at each Analysis Partition.
- The numbers down the left-hand column of the *Stats* sub-tab represent the simulation sequence numbers of each rock rolled in the analysis. CRSP-3D first simulates the rockfall identified by data input in the first row under the *Falling Rock Parameters* tab and thereafter simulates rockfalls sequentially as identified by the data input in each succeeding row.

	Barrier ID	Height, ft	KE, ft-kips	KE, kJ	StopX, ft	StopZ, ft
1	BP-1	2.3	183	248	356	14
2	BP-1	0.0	0	0	-1	143
3	BP-1	1.4	217	294	333	11
4	BP-1	1.1	170	230	333	12
5	BP-1	1.5	467	633	362	15
6	BP-1	3.8	155	210	328	10
7	BP-1	4.8	274	372	330	10

**Figure 41. Screenshot. Rock Trajectory Height simulation output for each rock passing Analysis Partition BP-1.**

- Clicking on a cell in the *Stats* grid displays a histogram of the selected rockfall property at the selected Analysis Partition (Figure 42).



**Figure 42. Screenshot. Rock Trajectory Height Frequency output for Partition BP-1 as presented in the Report option.**

- Checkboxes allow various image views and rockfall properties to be specified to show in the *Stats* and *Report* (Figure 43).

Note: It is advisable to check only those boxes of direct interest (generally  $\leq 5$ ), otherwise the volume of data to display can overwhelm the amount of graphics memory available leading to program instability.

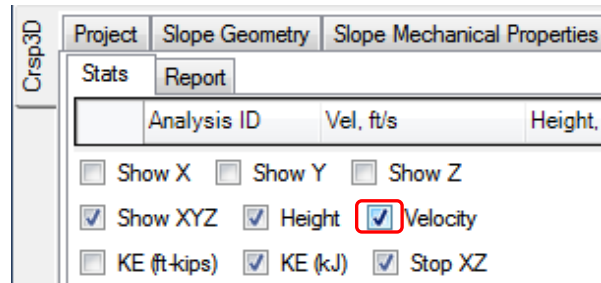


Figure 43. Screenshot. Checkboxes that select various image views in the simulation report.

### ***Report Tab***

The *Report* tab provides the option to automatically generate a report of a simulation run complete with graphics. This report can be cut-and-paste into another document using the options provided.

Note: The model display should be rotated and translated to the desired viewing position before generating the *Report* under the *Report Sub-Tab*.

- Select *Generate* to create a report (see Figure 44)  
Generating a report may require several minutes to build tables, collect statistics, and insert images into the report. The report generation status is shown in the status bar at the bottom of the application window.

The report will automatically generate after a delay. Different tabs will be selected and images will appear on the screen during this process. Check the status at the bottom of the screen.

Note: The report may take 5 or more minutes to process depending on computer hardware characteristics and on occasion may appear to have stop working. It is important not to click on any other tabs or buttons during this time. The *Report* tab will be automatically selected when the report completes.

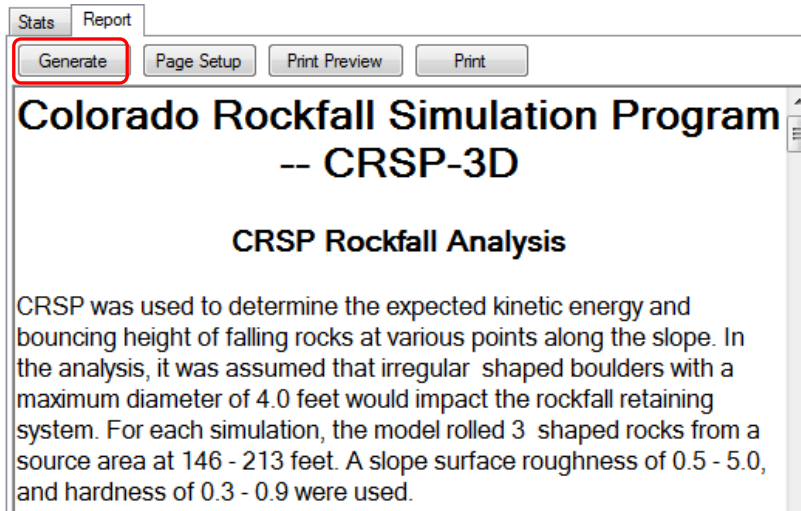


Figure 44. Screenshot. Simulation Report.

- To *Print* the report use the print buttons at the top of the *Report* tab (Figure 45).

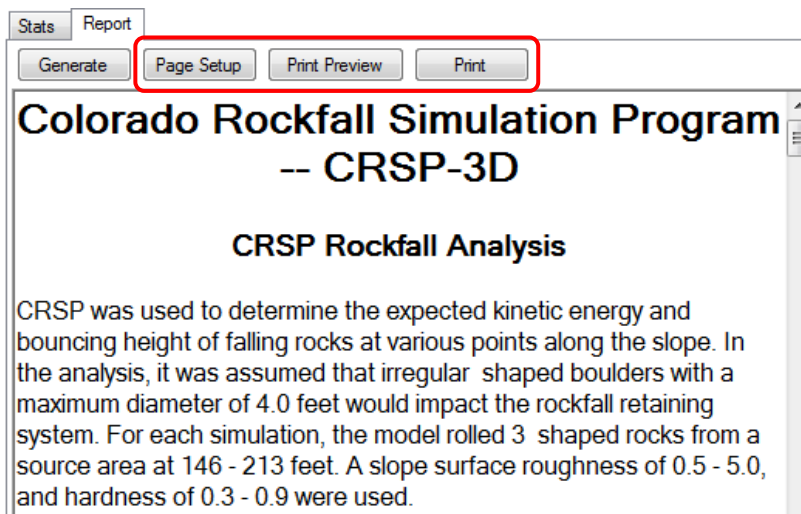


Figure 45. Screenshot. Print controls for CRSP-3D Report.

- To cut and paste the entire report into another document, click in the Report body and then:
  - (1) to select all  
type Ctrl-A,
  - (2) to copy  
type Ctrl-C, and
  - (3) to paste into a MS-Word document  
type Ctrl-V.

## DELETING FILES

To delete unwanted CRSP-3D rockfall simulation files, go to the drive and folder location where the files are saved and delete them. CRSP-3D does not have an option to delete files within the program.

## CALIBRATION

CRSP-3D rockfall simulations may need to be calibrated to produce acceptable output. The calibration process entails running rockfall simulations of existing monitored/measured rockfalls (calibration sites) and comparing the simulation output parameters to observed rockfall parameters obtained at these sites. In this manner, input parameters, such as slope hardness and roughness, at a required location can be adjusted to simulate a rockfall more accurately.

The hardness coefficient and roughness values can be calibrated by entering candidate roughness and hardness values and comparing the output of the simulation to the observed bounce height or runout distance at a specific location on the slope (with the Analysis Partition positioned as appropriate for simulation). The input values are adjusted until the resulting simulated bounce height and runout values correspond to actual measured values.

Rock shape and size variables can be added to bounce height and runout distance to improve the calibration, if desired. Rock size and shape can have an effect on output parameters such as runout distance, bounce height, velocity, and kinetic energy. CRSP-3D does not output the simulated rock size or shape in the *Stats* tab; this information is displayed in the *Report*.

CRSP-3D simulates rocks and outputs the results in the *Stats* tab in the order that they are entered in the *Falling Rock Parameters* tab. As indicated previously the user can model several different rock shapes and sizes in one rockfall simulation and observe the difference in output by using the numbers listed on the left hand column of the *Stats* tab

Actual velocity and kinetic energy values may require a rock rolling experiment, possibly with the use of high speed cameras and reference lines. Bounce height and runout distance can be measured on a natural slope with rockfall accumulation.

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## CHAPTER 3 – WORKED EXAMPLES

The examples following are intended to help familiarize the user with CRSP-3D. It is suggested that the user go through each step of these examples using the program and compare their results with the output results presented. Data entry for all simulation runs goes from left-to-right following the order of the Tabs. All selections within each Tab are addressed at the time the Tab is being processed.

Note: When installing the provided files, all input files must reside in a subdirectory of, or in the same directory as, the executable program.

### TUTORIAL EXAMPLE

This example can be loaded at program startup by selecting the *Tutorial* folder when the *Select Project Folder* window opens. A complete copy of the CRSP-3D report output for this example can be found in Appendix B.

### Creating a New Project

To create a new, blank project:

- Select *File* → *New* (Figure 46)

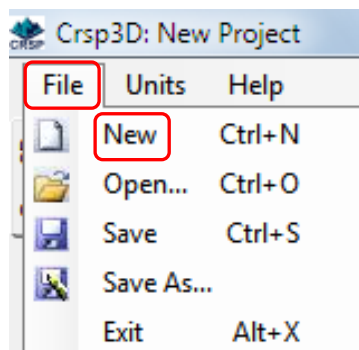


Figure 46. Screenshot. Select File → New.

You can browse to the location where you would like your new project to be stored.

- Select *Make New Folder* to make a new project. A new project folder will appear.
- Type in a project name (e.g., *Tutorial*), and click OK (Figure 47).

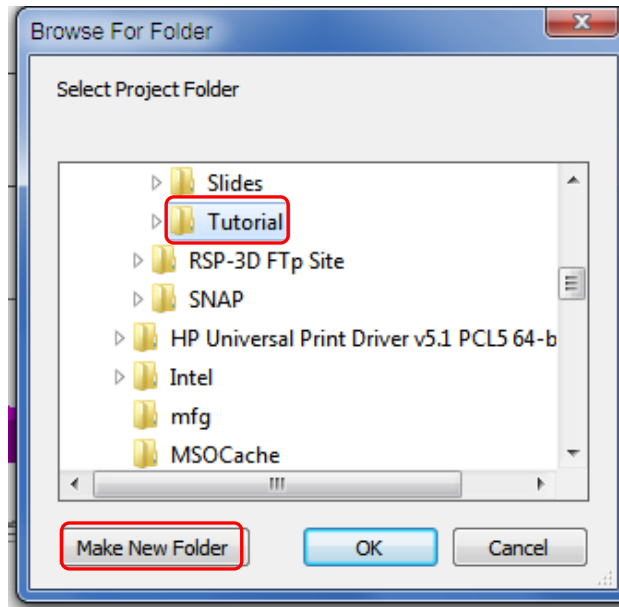


Figure 47. Screenshot. Create and name a new folder.

A new window opens up at a blank *Project* tab which can then be filled with the appropriate identifying project information (Figure 48).

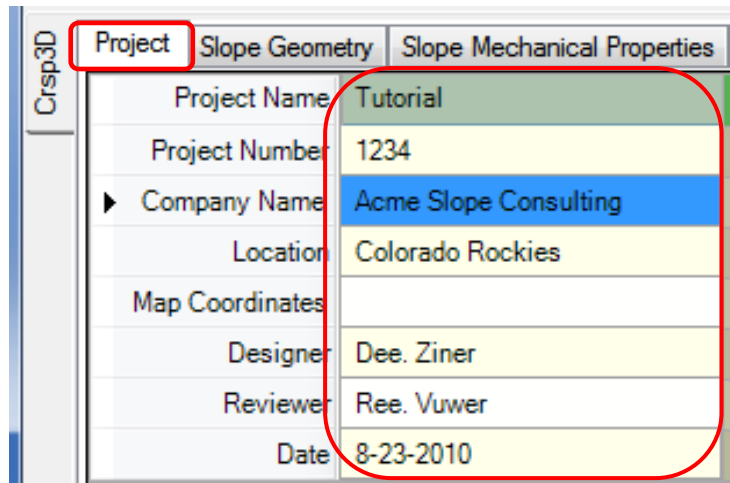


Figure 48. Screenshot. Fill in project information.

### Slope Geometry

In this example, slope geometry data are cut from an Excel spreadsheet and pasted directly into *Surface Points*, as shown in Figure 49.

Note: That the graphic display routine is not always stable with coordinate values expressed in more than 5 digits. This should be confirmed by trial and error.



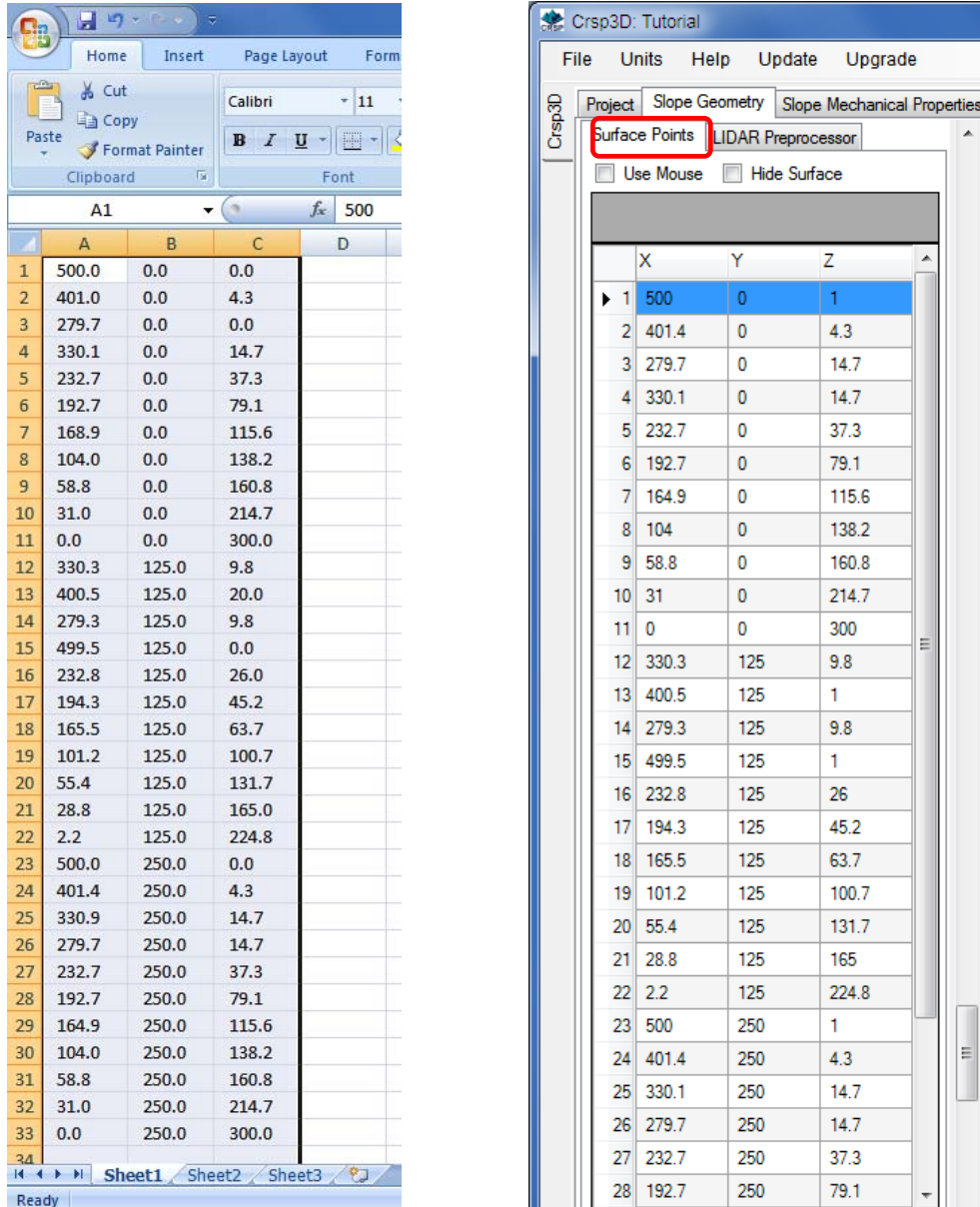


Figure 49. Screenshot. Cut and paste data from Excel spreadsheet.

Once the geometry data has been pasted, click *Refresh* to create the solid geometry. A graphic model will be generated, as shown in Figure 49.

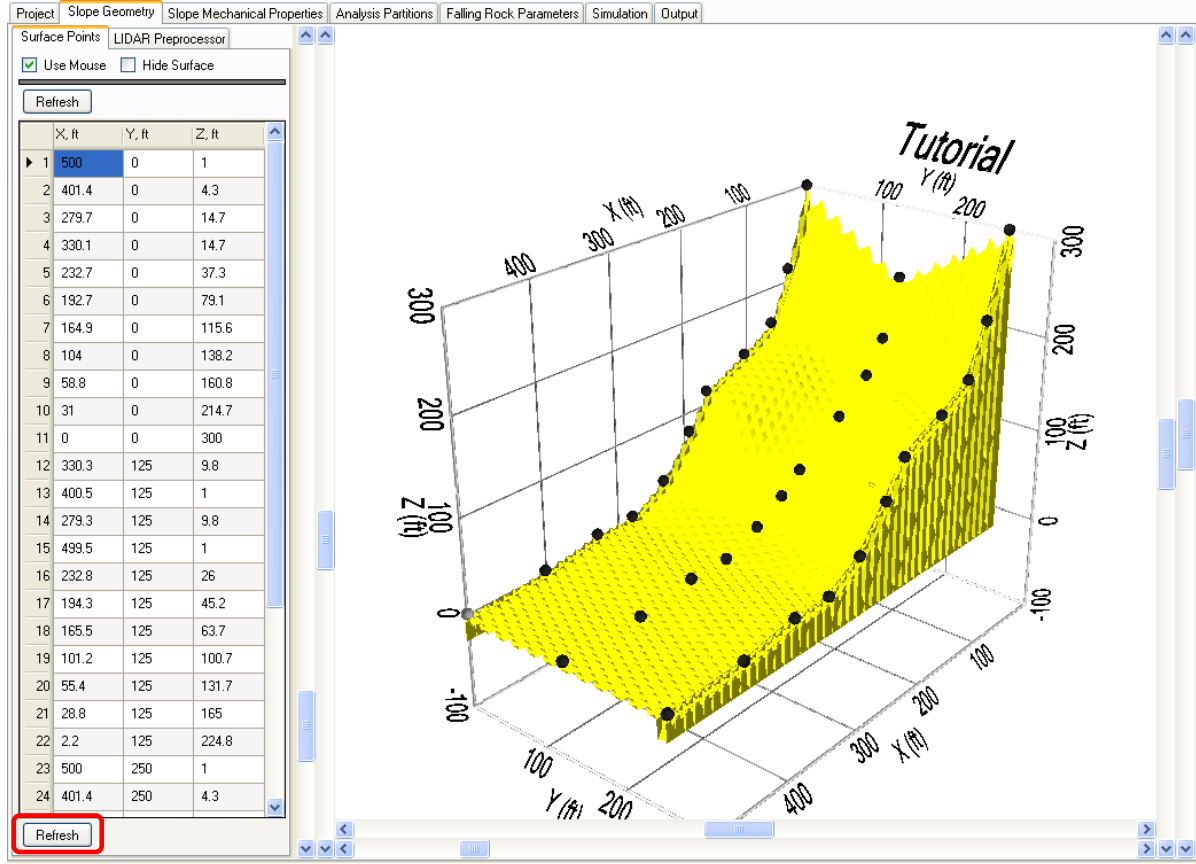


Figure 50. Screenshot. Graphic rendition of slope geometry.

Table 1. Procedures for editing slope points.

Function	Procedure
Add point	Place the mouse cursor on the slope at the required location and left-click the mouse.
Delete Point	Place the mouse cursor on the point to be deleted and right - click the mouse
Move Point	Manually adjust the coordinates, or press and hold the left mouse button on the point in the profile screen, then drag the point to the desired location.

### Slope Mechanical Properties

Select the *Slope Mechanical Properties* tab to (1) define the various rock material zones and (2) to input the roughness and hardness values for each zone.

Before drawing a zone boundary point on the display, make sure the appropriate row is selected. This can be done by clicking on the number within the row number area to the left of the

material ID, or clicking a grid cell in the desired row. There is a drop-down menu of material types (which can easily be typed over with an alternative user-defined description, if desired), as well as an adjacent drop-down color palette that associates a material type with a colored area on the screen graphic.

In this example (Figure 51) two material types are being modeled, *Boulder Field* and *Talus*:

- *Boulder Field* is represented by magenta coloring and *Talus* represented by gray.

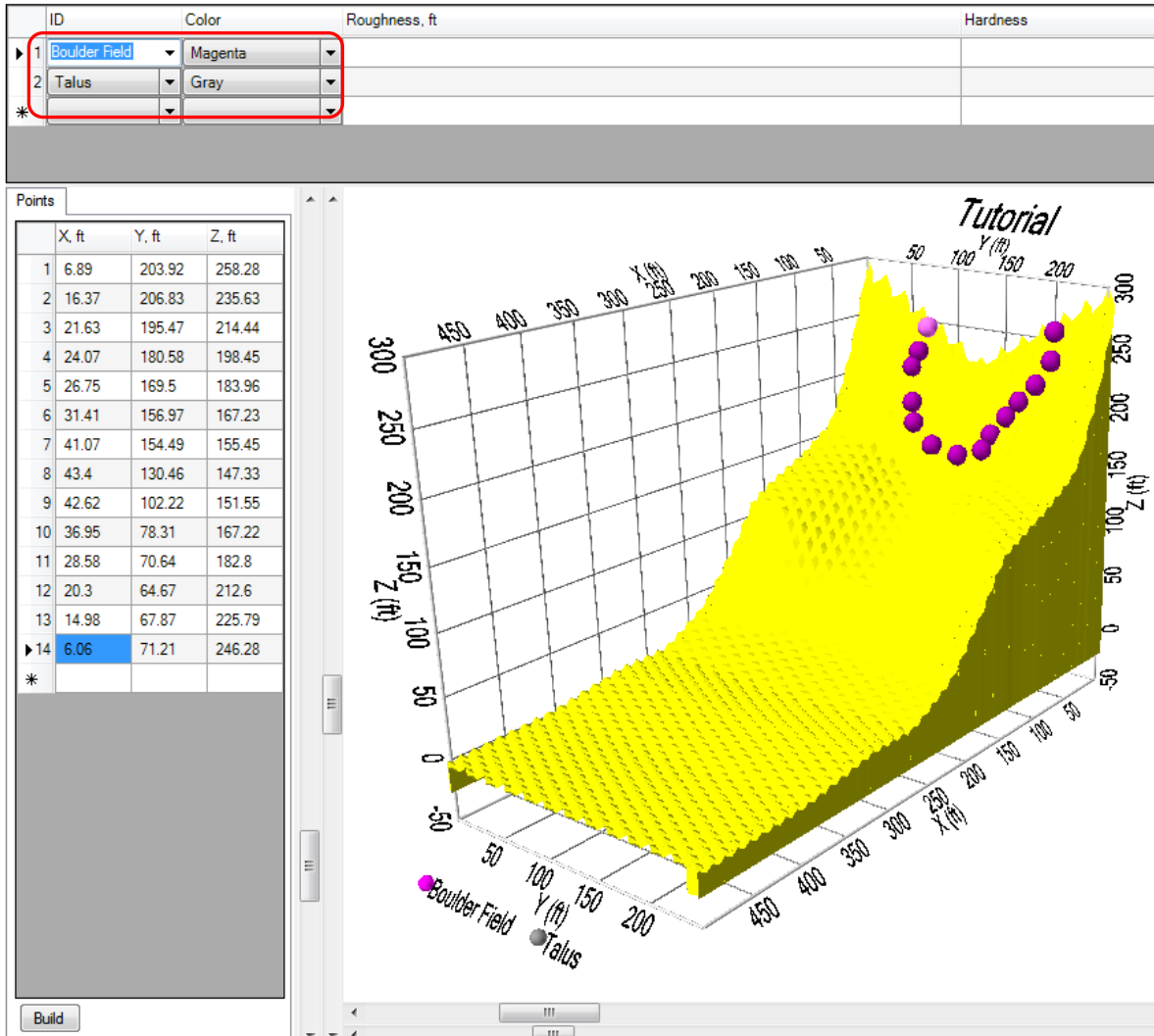


Figure 51. Screenshot. Use mouse to delineate Boulder Field

- *Boulder Field* has arbitrarily been assigned a hardness of 0.7-0.9 and the *Talus* has been assigned a hardness of 0.3-0.6. *Talus* has arbitrarily been assigned a roughness of 0.3-0.5 and the *Talus* has been assigned a roughness of 0.3-0.6 (see Figure 52).

Note: *Hardness* and *Roughness* values can be manually calibrated from known rockfall information in order to obtain realistic rockfall response data, as previously described in this manual.

Note: If a range of values are input (e.g., 0.1-2.0 for surface roughness), the program will randomly choose roughness values between 0 and 2.0 for each element location on the slope within the zone occupied by that material.

The area within the zone will be assigned the input roughness and hardness values.

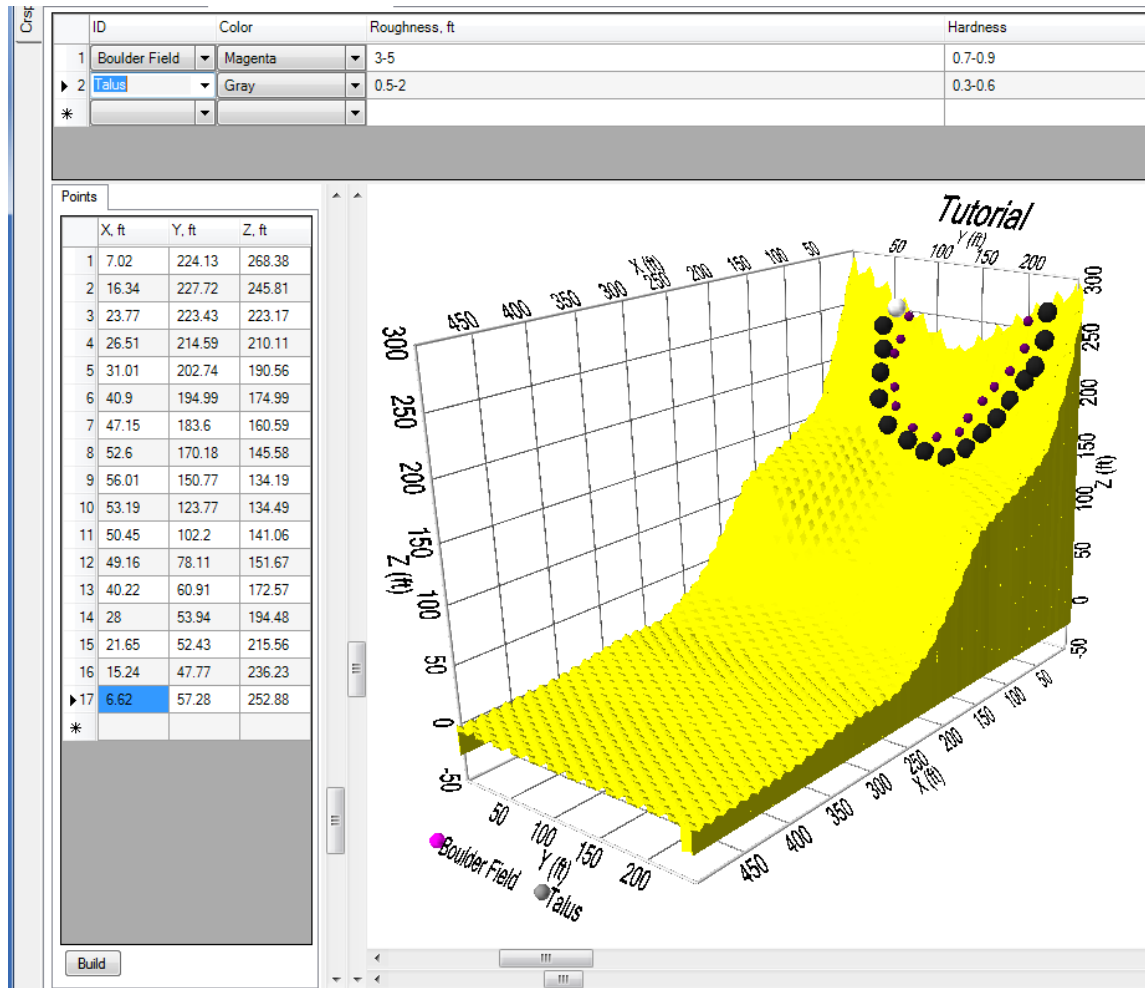


Figure 52. Screenshot. Delineate Talus.

- Press *Build* to update the graphic to show the distribution of the material types on the slope (Figure 53).

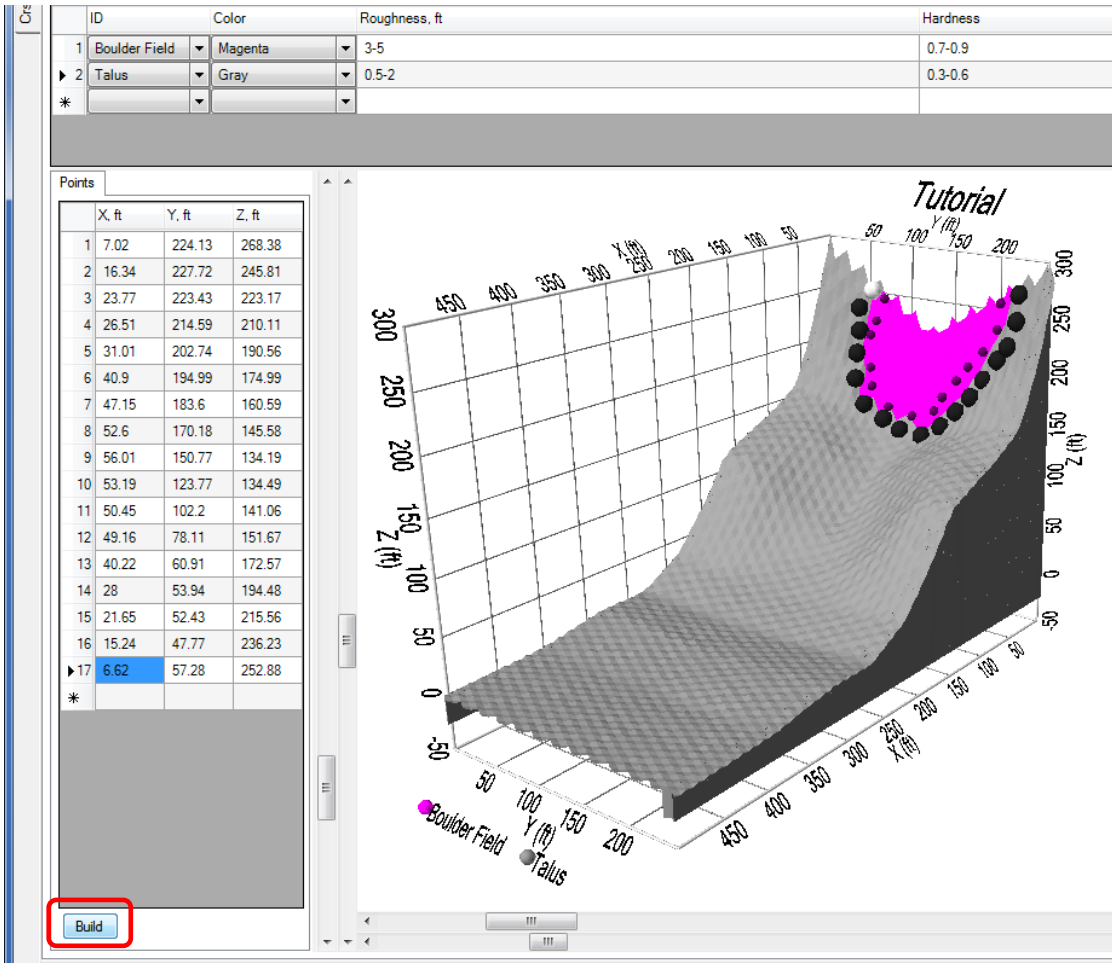


Figure 53. Screenshot. Completed geometry.

### Analysis Partitions

Select the *Analysis Partition* tab to enter locations of analysis partitions on the slope. The user enters a partition name under ID (Figure 54). Thereafter (Figure 55):

- Enter the location of the analysis partition by either clicking the left mouse button on the profile or manually entering the coordinates. The location of the partition can be entered by *manually entering* a position across the slope face as represented by a fixed X coordinate.

Note: Partitions can be deleted by clicking the right mouse button on the base of the partition to be deleted. Partitions can be dragged up and down the slope by holding the left mouse button on the base of the partition and dragging it to the desired location.

or:

- Enter a fixed height Z of the top of the barrier (the elevation) coordinate above the slope. Alternatively, clicking the left mouse button on the desired location on the slope will add a point representing the position of a partition. Give the partition a name (such as BP-1) and a Z coordinate height of the top of the partition (such as 70 ft). Add another partition called BP-2 and select a horizontal X coordinate position on the slope face of 231 ft.

Note: CRSP-3D requires only the coordinate of the partition to be entered (either X for location on slope face or Z for the fixed elevation of the top of the barrier). CRSP-3D will calculate rockfall kinetic energy, velocity and bounce height for rocks as they fall past the partition locations.

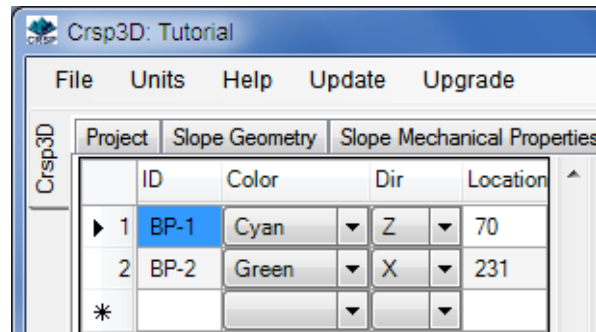


Figure 54. Screenshot. Define and locate Analysis Partitions.

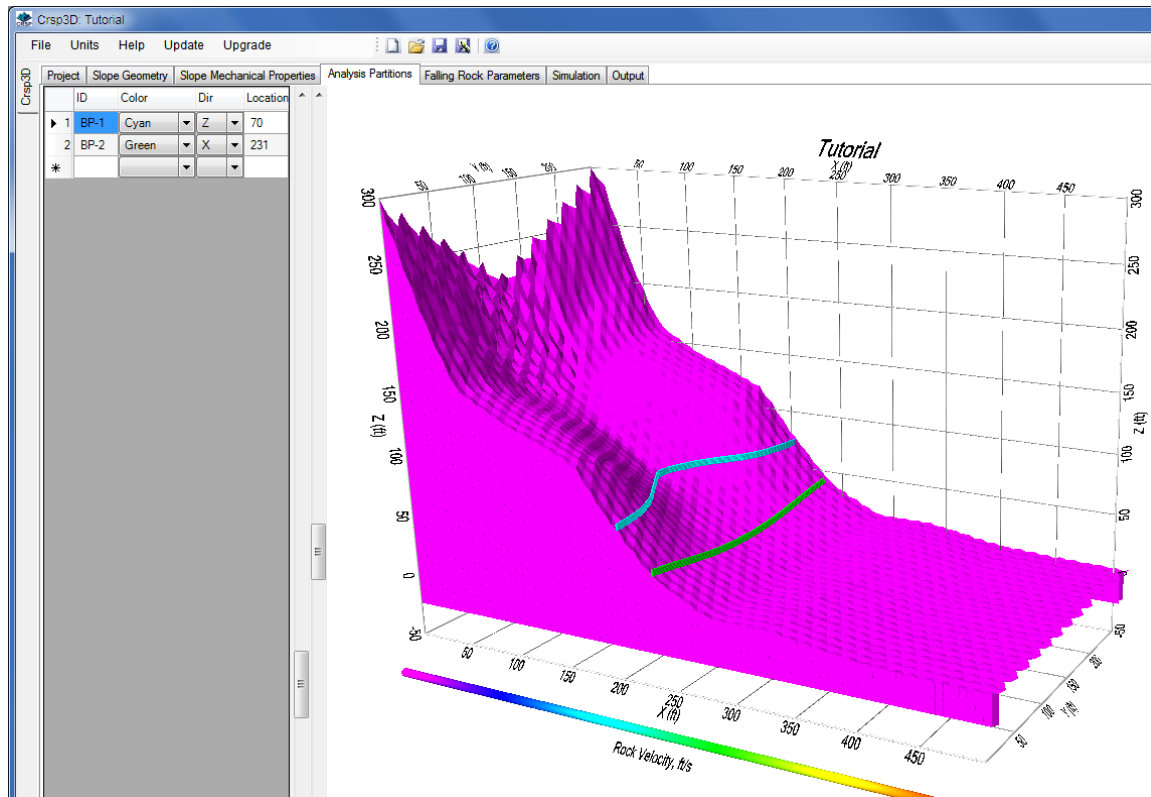


Figure 55. Screenshot. Locations of Analysis Partitions.

### Falling Rock Parameters

The *Falling Rock Parameters* tab is used to enter parameters for the simulation comprising:

Values for these parameters are shown in Figure 56. CRSP-3D will randomly choose rockfall starting locations within the designated material zone.

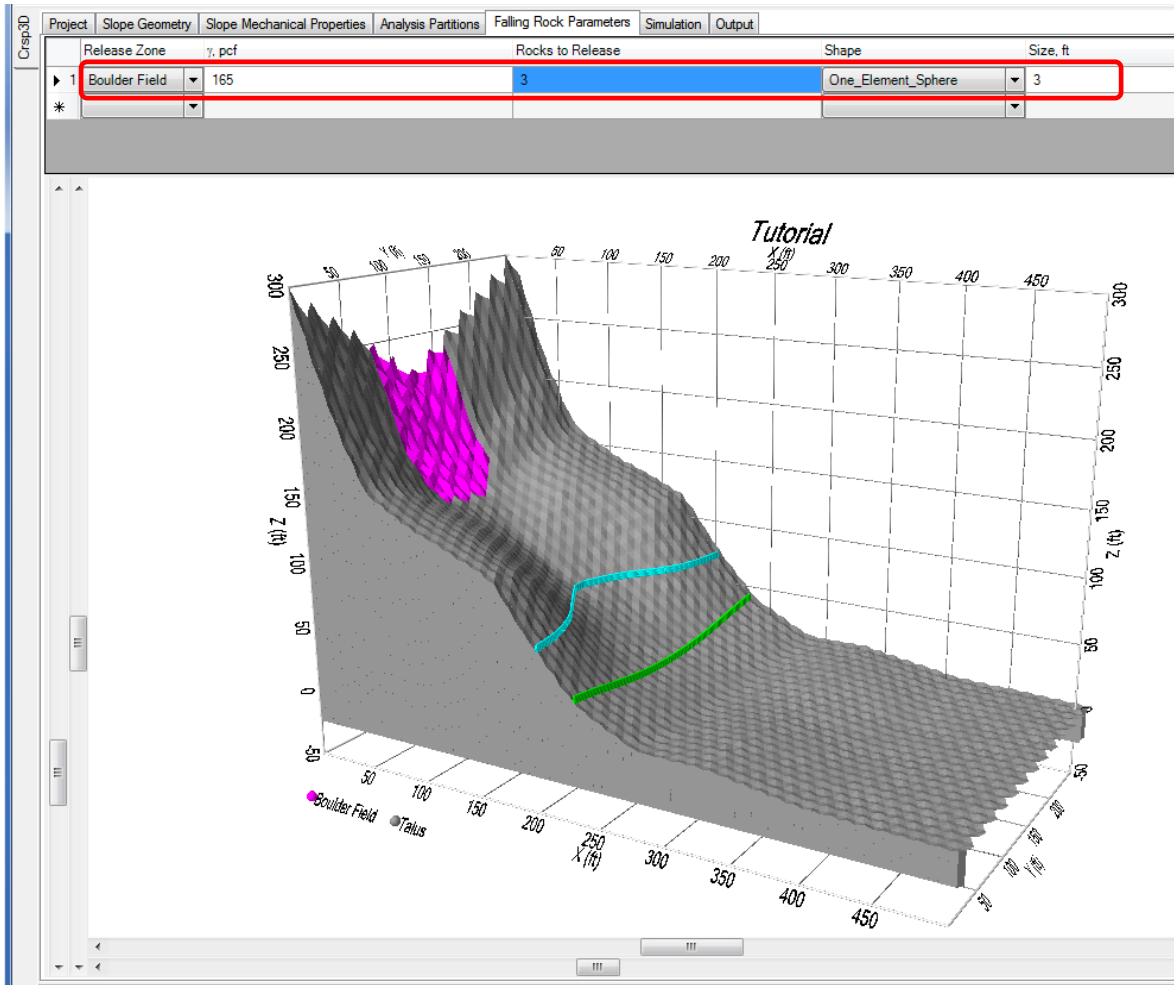


Figure 56. Screenshot. Parameter values for Boulder Field.

### Simulation

Click *Run Simulation* to execute (Figure 58). A disclaimer precedes each run (Figure 57).

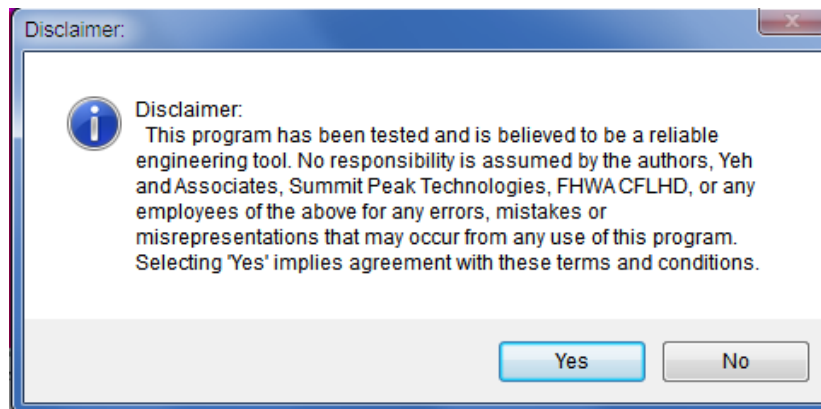


Figure 57. Screenshot. Software disclaimer.



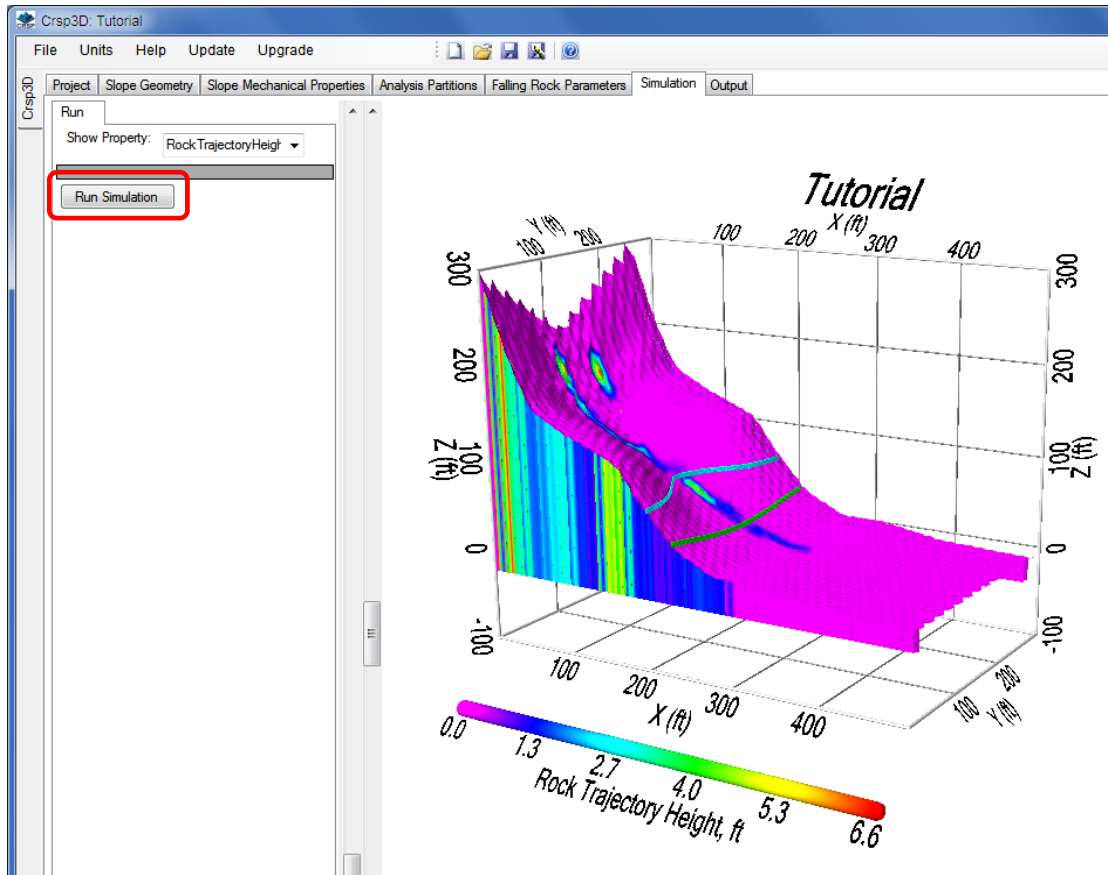


Figure 58. Screenshot. Rock trajectory height traces generated by the rockfall simulation.

### 3D LIDAR EXAMPLE

The following example is a 3D simulation of a rockfall using LIDAR data. The LIDAR information is read into CRSP-3D using built-in program features; however, some pre-processing of the LIDAR data is required prior to downloading the data to the program. The steps involved in creating a new project folder are not repeated here since they are common to all simulations and have been presented previously.

This example can be loaded at program startup by selecting the *Canyon LIDAR 3D Sphere* folder when the *Select Project Folder* window opens. A complete copy of the CRSP-3D report output for this example can be found in Appendix B.

### Slope Geometry

LIDAR data requirements are specific and should be followed carefully. The LIDAR data need to be formatted as described in Chapter 2, LIDAR Preprocessor Sub-Tab.

The following provides a step-by-step procedure that was used to manipulate a LIDAR file to be uploaded by CRSP-3D. Not all LIDAR files may be created the same, so the procedure may differ on occasion. The LIDAR file is initially in .txt format, but had commas used as delimiters (see Figure 59).

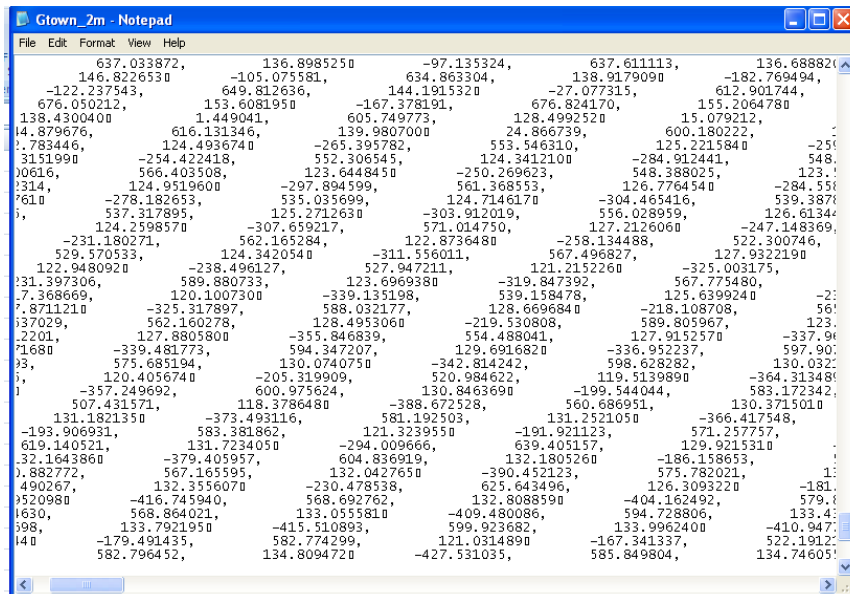


Figure 59. Screenshot. Original LIDAR file in .txt format.

1. To remove the comma delimiters, upload the .txt file into Microsoft Excel by choosing the *Data* tab and then choosing *From Text* (Figure 60). This will upload the .txt file into Microsoft Excel with the ability to remove the comma delimiters.

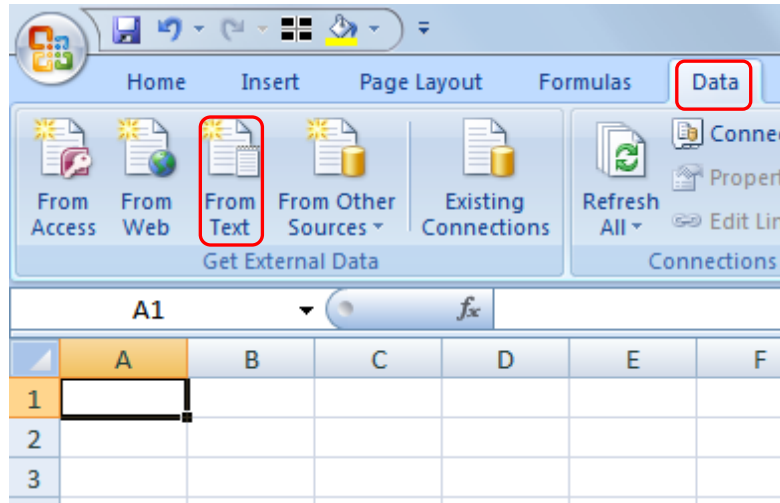


Figure 60. Screenshot. Excel spreadsheet.

2. Once the LIDAR points are showing on the Excel screen, make sure two significant digits or less are used for the LIDAR points. Also, add X Y Z on the top of each column, and add a title for project tracking (Figure 61). Save the file as a .txt file.

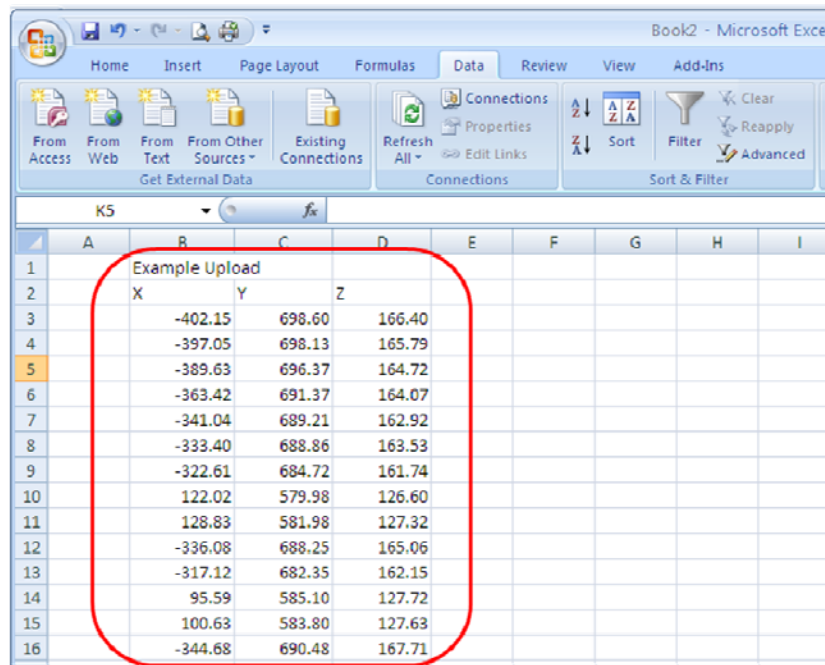


Figure 61. Screenshot. Adding headers to spreadsheet.

3. Now use the text editor (in this example *Crimson Editor* is used) to upload the .txt file and view the delimiters in the file (Figure 62).

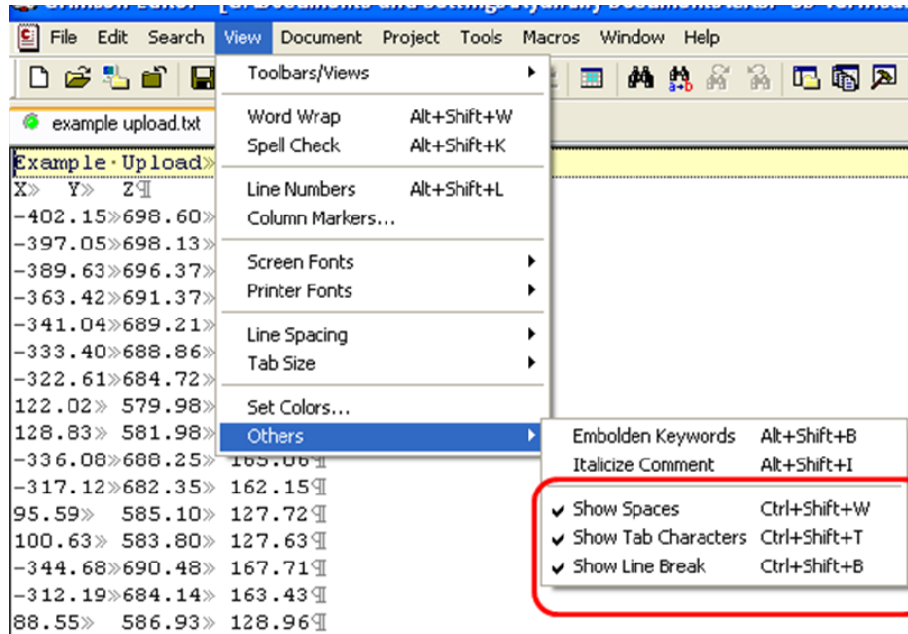


Figure 62. Screenshot. File opened in text editor.

4. Make sure all delimiters are set to spaces (Figure 63). Save the file as a .txt file. The saved file will now be ready for upload to CRSP-3D.

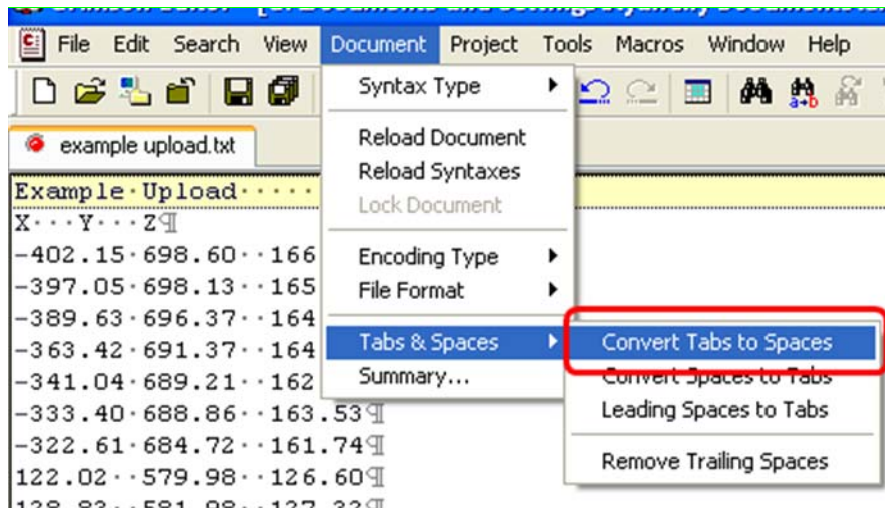


Figure 63. Screenshot. Ensuring all field delimiters are spaces.

### ***LIDAR Preprocessor Sub-Tab***

The saved ASCII file is loaded into the program using the *LIDAR Preprocessor Sub-tab* and clicking the *Load File* button (Figure 64).

By checking the AutoCalc Transform box (Figure 64), the program automatically calculates the X, Y and Z offsets, which is usually the best approach to follow, though the user may choose to leave it unchecked and provide the offsets manually.

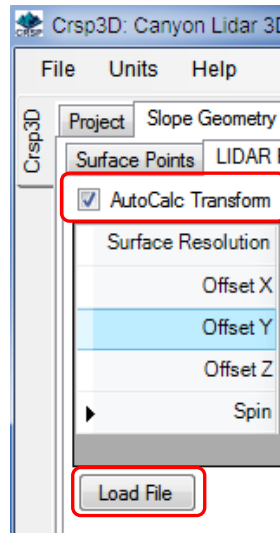


Figure 64. Screenshot. AutoCalc Transform box and Load File button.

To load the file, the *Load File* button is clicked and the program will request the location and the name of the file to load (Figure 65).

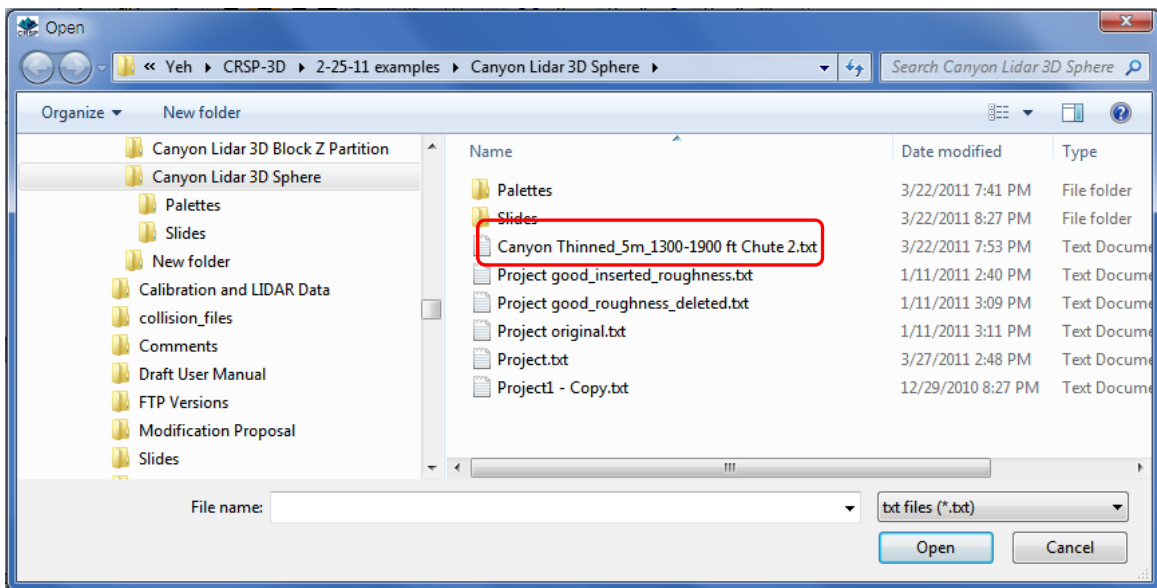


Figure 65. Screenshot. Loading a LIDAR file.

Once the file loads successfully, the calculated offsets will be displayed (if the AutoCalc Transform box was checked), the X, Y, Z coordinates of the surface will be displayed, and a graphic rendition of the slope geometry will appear (see Figure 66).

Note: This may take several minutes to appear depending on the size of the file being processed.

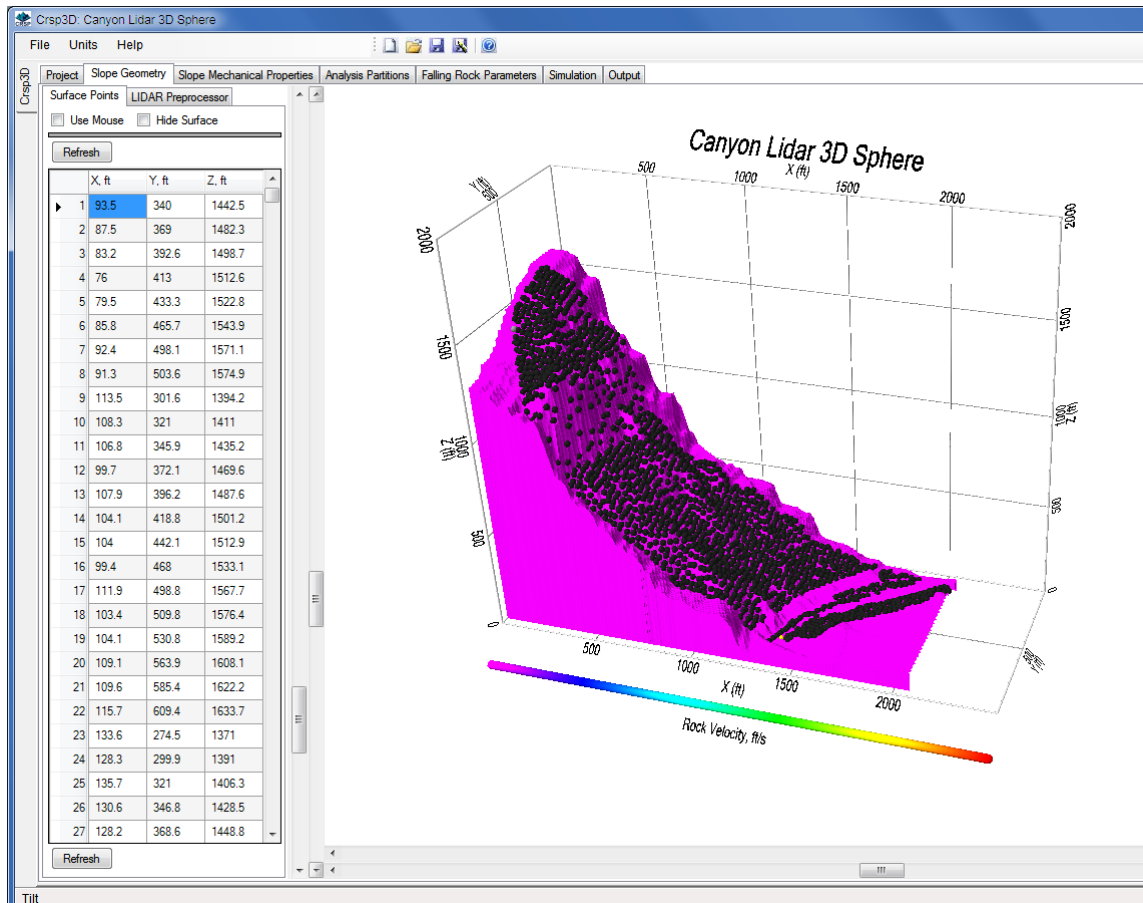


Figure 66. Screenshot. Generated LIDAR profile.

### Slope Mechanical Properties

On entering this screen, a graphical slope profile and a blank table of X, Y, Z surface coordinates is displayed along with blank fields for Material ID, Color, Roughness and Hardness. These blank fields are filled with user-defined surface material zones and slope mechanical properties information. *Arbitrarily* assigned values for Roughness and Hardness are shown below. The model surface shown is generated when *Build* is clicked (see Figure 67).

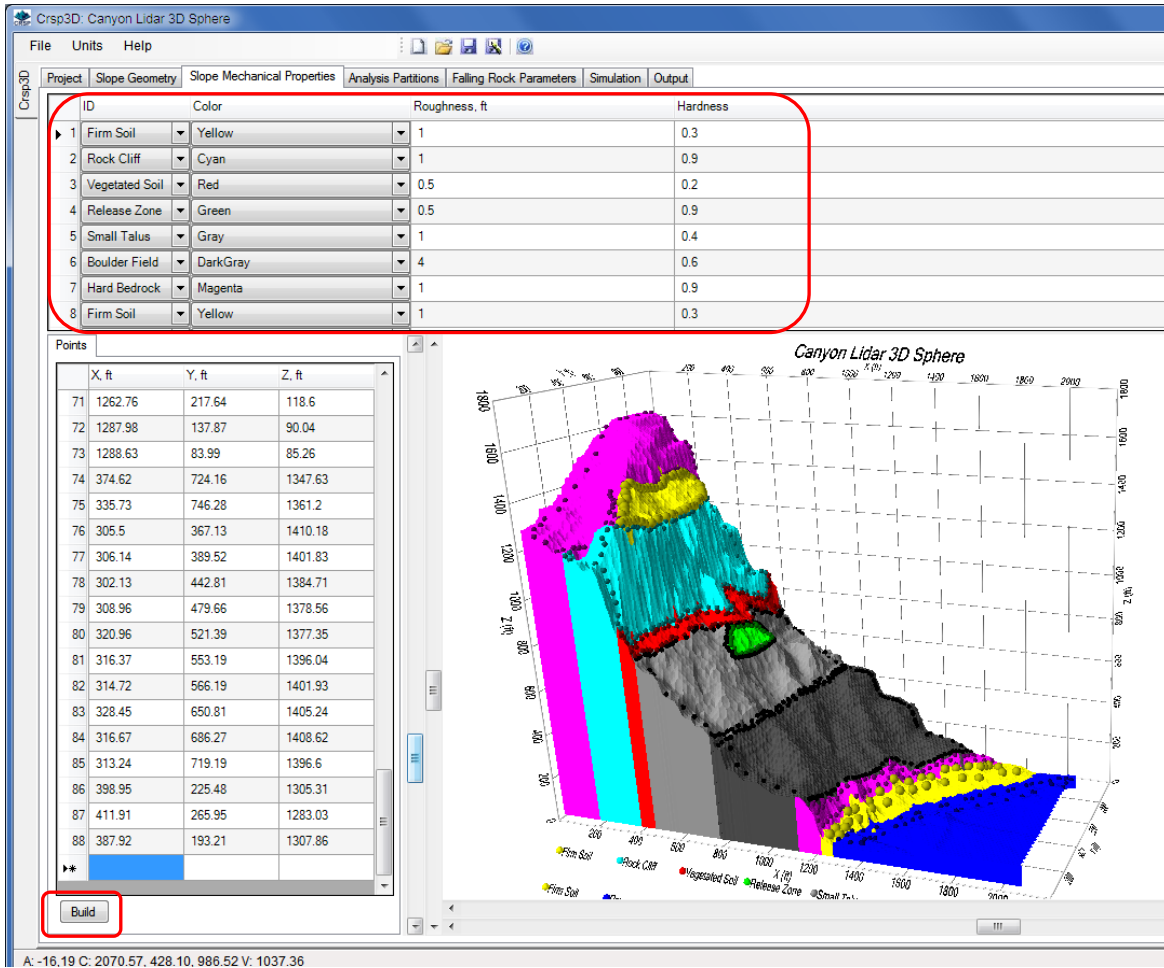


Figure 67. Screenshot. Defining materials zone and adding mechanical properties information.

### Analysis Partitions

For this example four locations (in blue) on the slope were analyzed as indicated in Figure 68. These analytical partitions were defined using the X-coordinate option to locate them across the slope face.

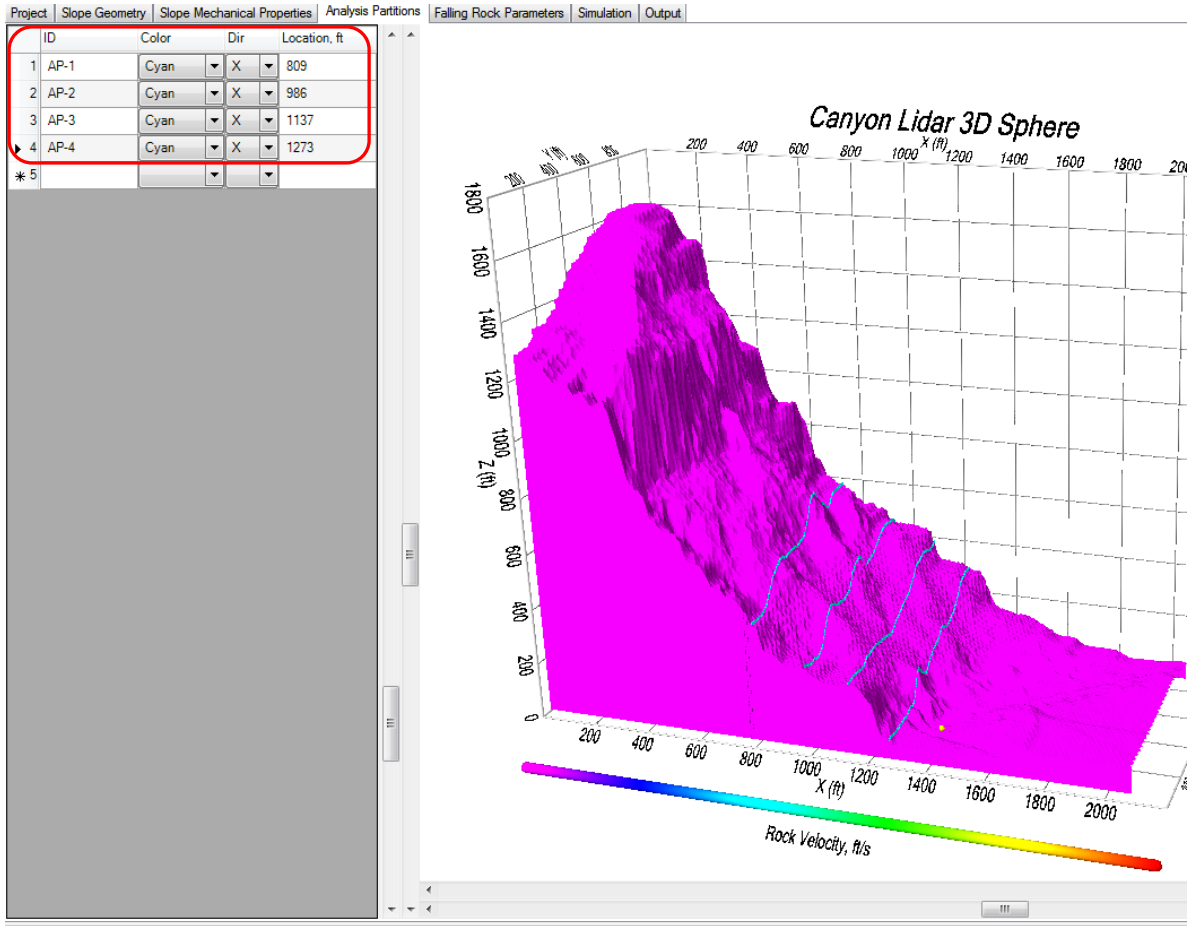


Figure 68. Screenshot. Selected analysis partitions.

### Falling Rock Parameters

Rock Parameters that define the unit weight of the rock, the number of falling rocks to simulate and the geometry of the falling rocks were input as indicated in Figure 69.



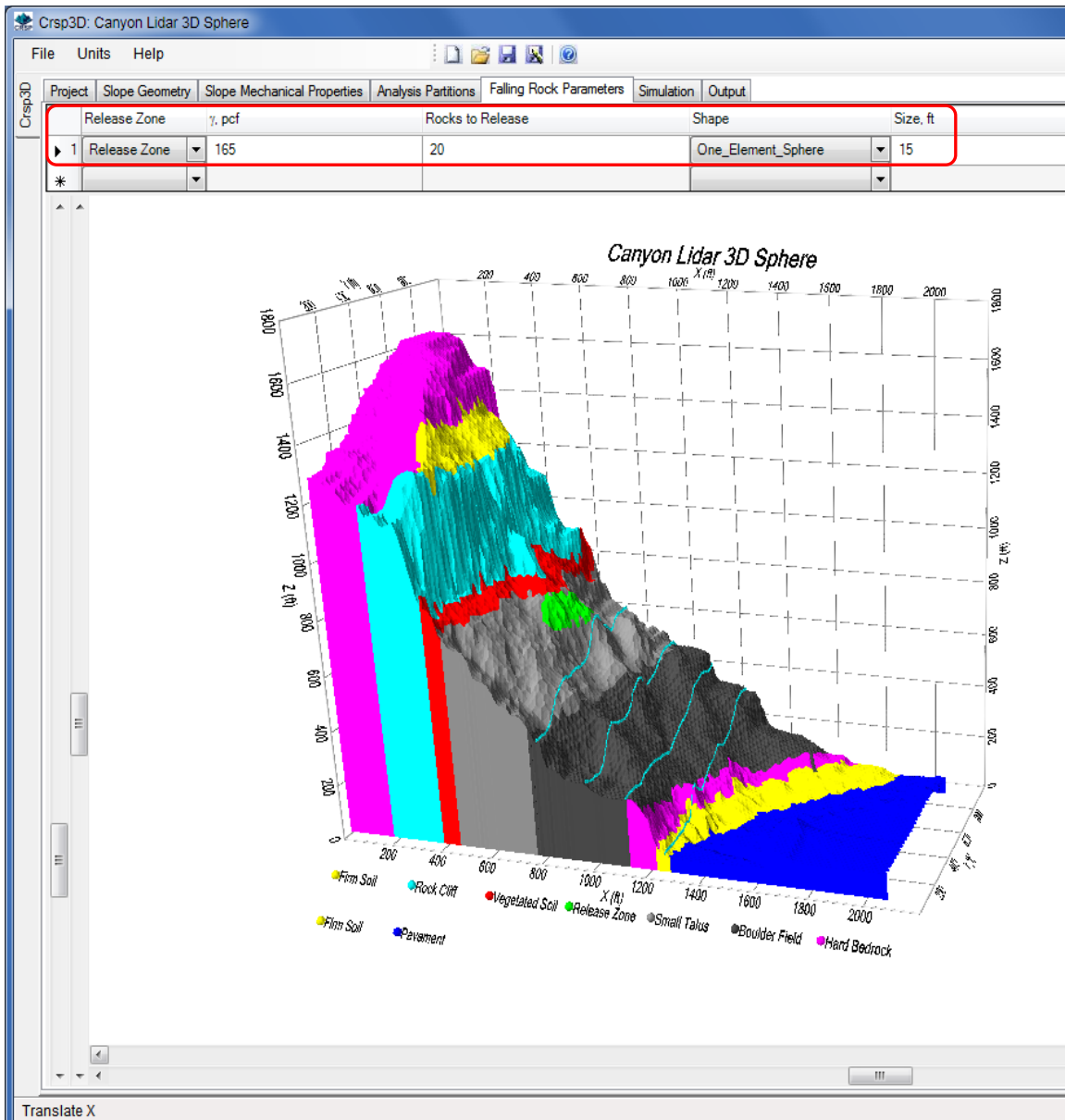


Figure 69. Screenshot. Falling rock parameters (release zone shown in green).

### Simulation

Simulation of twenty round rocks, each of 15 feet in diameter, falling from random locations within the identified green release zone was performed. The combined *velocity traces* showing both velocities and rockfall path for all of the 20 rockfalls are presented in Figure 70.

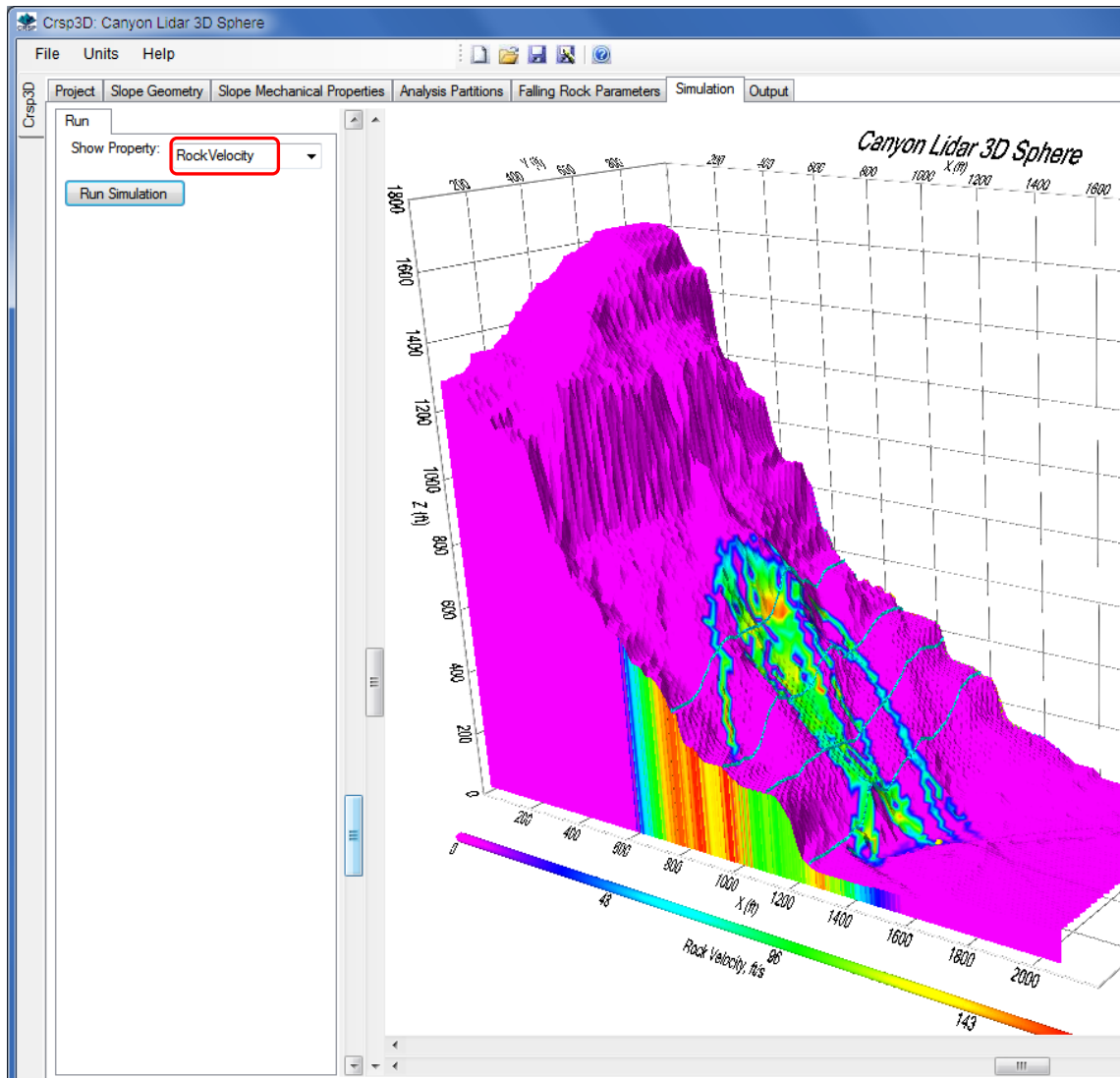


Figure 70. Screenshot. Velocity traces of 15 ft diameter round rocks falling down slope.

## Output

### *Statistics*

Statistical information gathered during the simulation is presented under the *Stats* tab. Histograms of all the values of a parameter of interest in a particular analysis partition can be displayed by highlighting (see in blue) the specific parameter as indicated out in Figure 71.

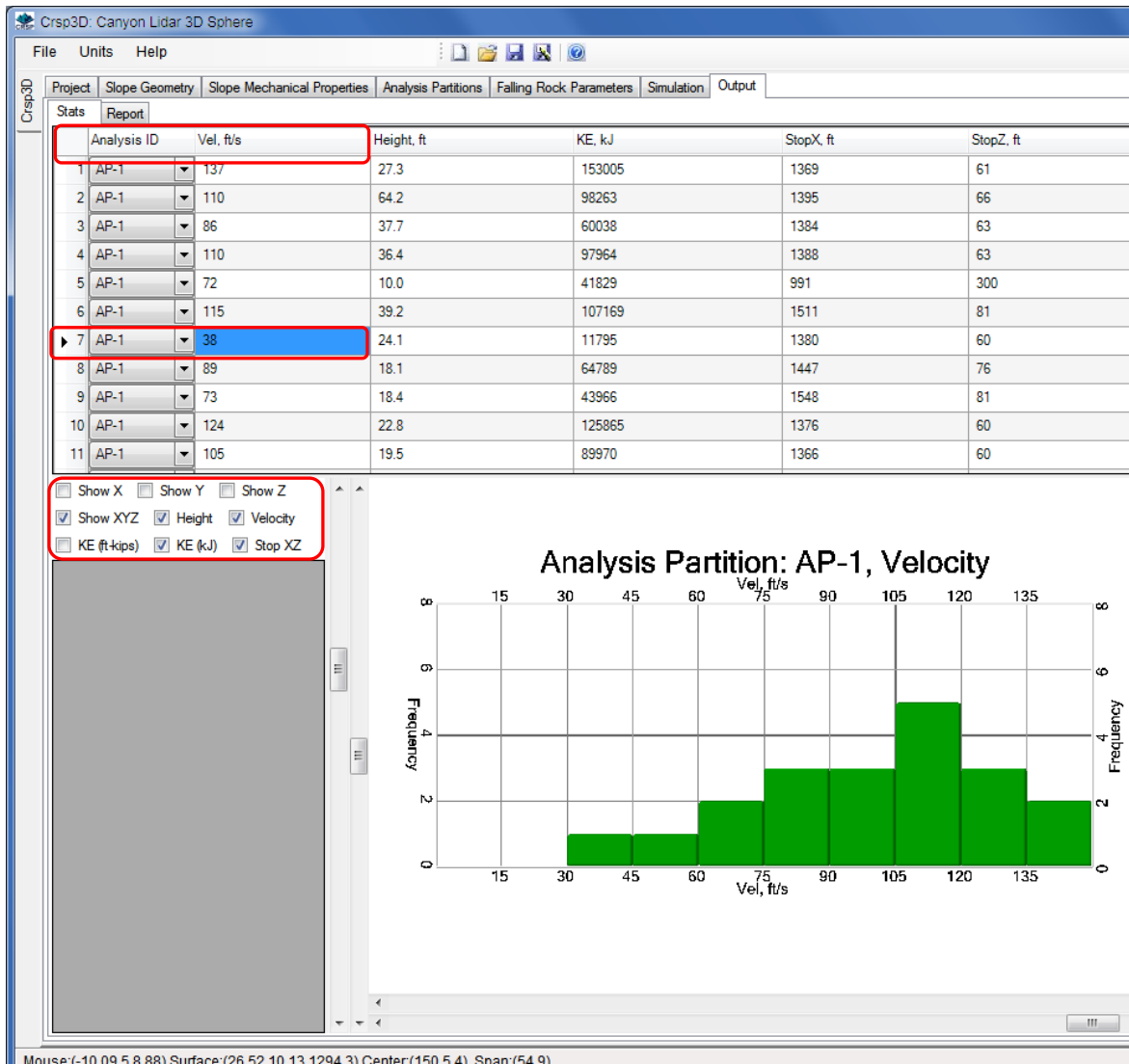


Figure 71. Screenshot. Frequency information for all velocities calculated at Analysis Partition 1.

## 2D EXAMPLE

The following example is a 2D simulation of a rockfall using manually input slope geometry data. The steps involved in creating a new project folder are not repeated here since they are common to all simulations and have been presented previously.

This example can be loaded at program startup by selecting the *Canyon 2D Sphere* folder when the *Select Project Folder* window opens. A complete copy of the CRSP-3D report output for this example can be found in Appendix B.

### Slope Geometry

In this example the slope geometry being considered is two-dimensional. Since CRSP-3D is inherently three-dimensional, two-dimensional analysis can be accommodated by rotating the profile of the slope into the X-Z plane.

In a CRSP-3D graphic slope representation, the X-axis (slope length projected onto the horizontal plane) represents the horizontal component of the slope cross-section and the Z-axis (slope height) represents the vertical component of the slope cross-section. In 2D the Y-axis (slope face width) is normal to the screen or printout. A 2D geometry, therefore is entered in X, Z coordinates. In order to maintain compatibility with the 3D program requirements, a constant Y coordinate is required. A fixed slope face width is calculated if a constant Y coordinate is entered as part of each X Y Z set of coordinates (Figure 72).

In the current example, slope geometry data was input *manually* using slope coordinates from an X, Z coordinate table.

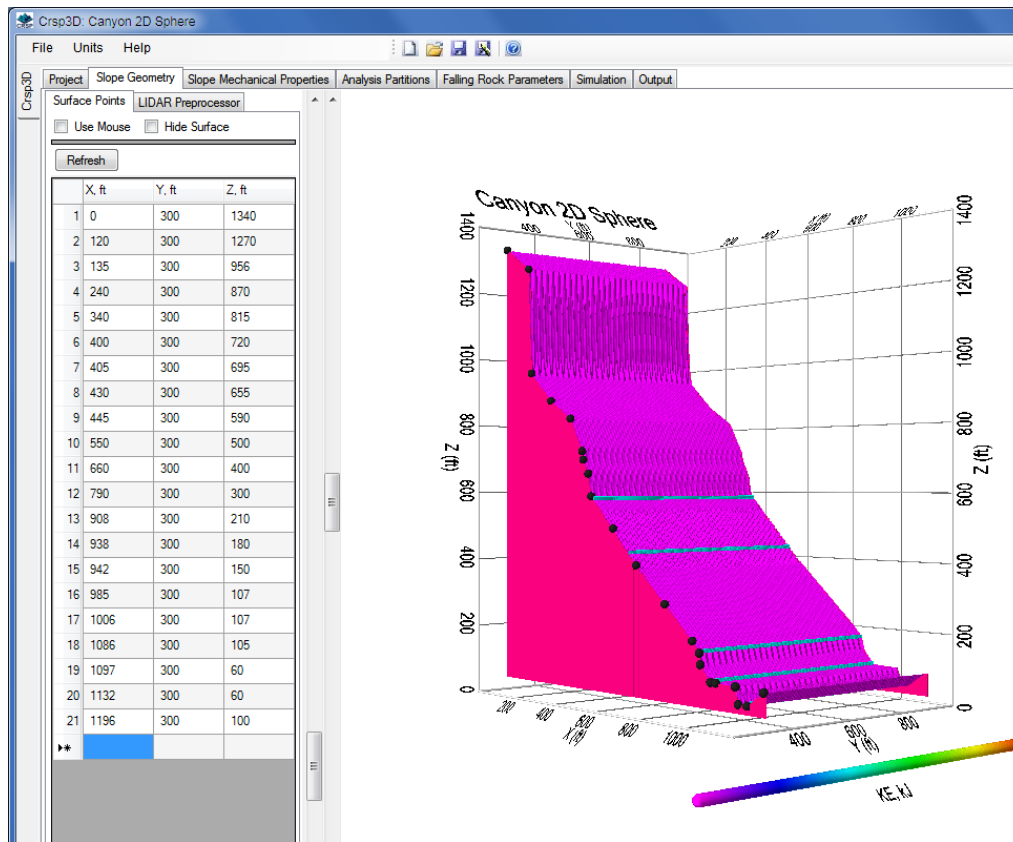


Figure 72. Screenshot. Rotated view of slope geometry with slope coordinates showing how a virtual 2D geometry is created from an inherently 3D model.

### Slope Mechanical Properties

For the current example, arbitrarily assigned values for Roughness and Hardness are shown (Figure 73). In a 2D simulation, slope mechanical properties that are input manually are added sequentially from either the top or bottom of the slope. These values mirror the slope geometry *but* differ in that only boundaries between slope material types are input. Assuming that the slope properties are plotted in the Z-X plane and start from the top of the slope the process is as follows:

- Coordinates are entered for the crest of the slope i.e. the highest elevation (largest Z coordinate) and the corresponding X coordinate (lowest X coordinate).
- The next pair of X, Z coordinates corresponds to the lower edge of the uppermost material zone.
- The following pair of X, Z coordinates represents the next lowermost boundary and so on for each consecutive material zone down the slope. This process is repeated until the bottom of the slope is reached. See the generated profile in Figure 74.

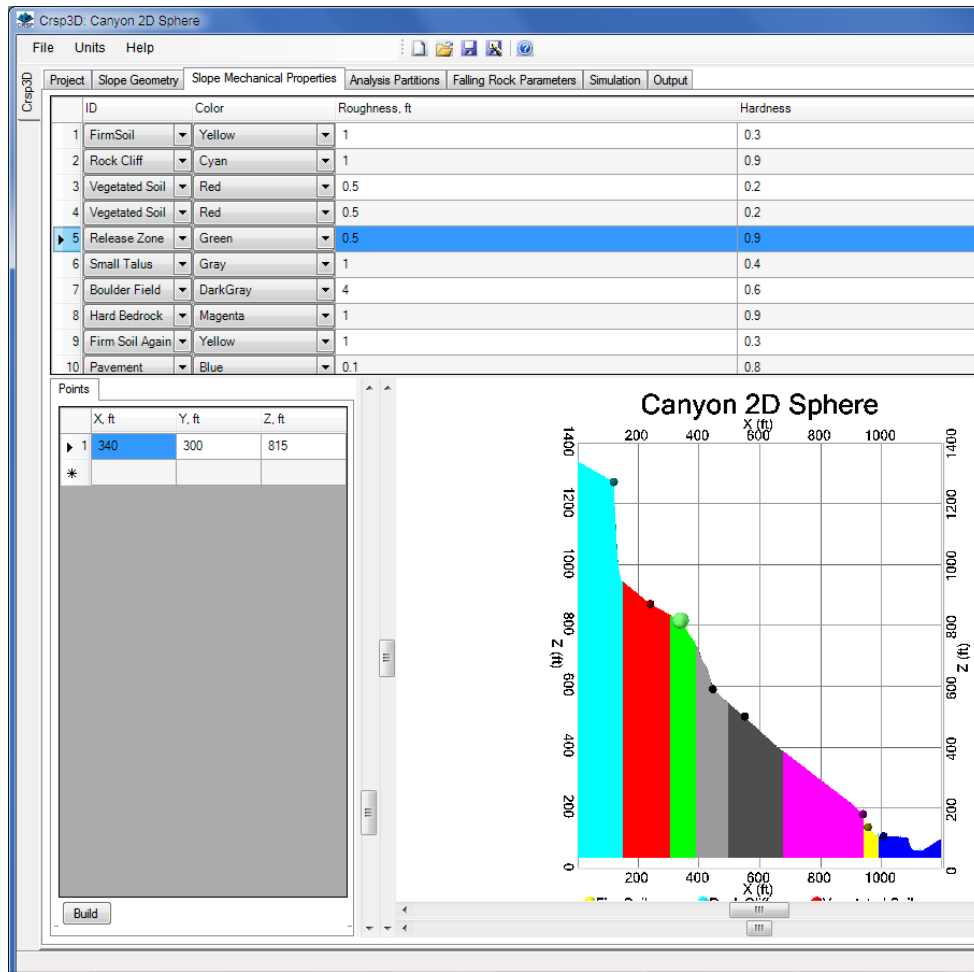


Figure 73. Screenshot. View showing slope mechanical properties and graphic rendering.

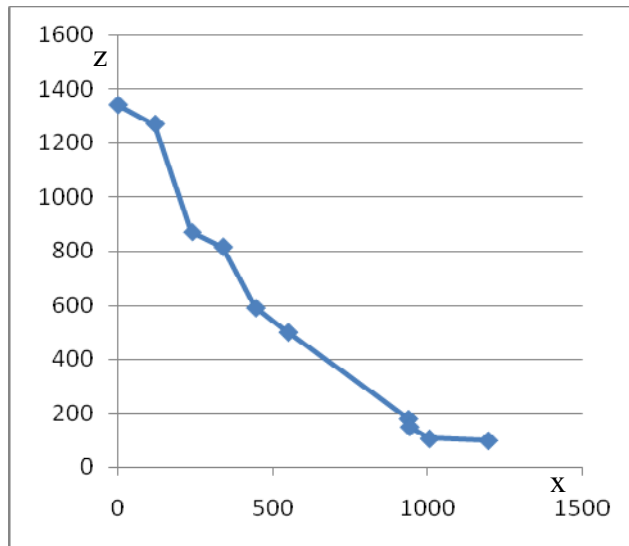


Figure 74. Plot. Material profile down slope (ft). Each point represents a change in slope material.

### Analysis Partitions

The selected partitions are identified in Figure 75 (blue lines)

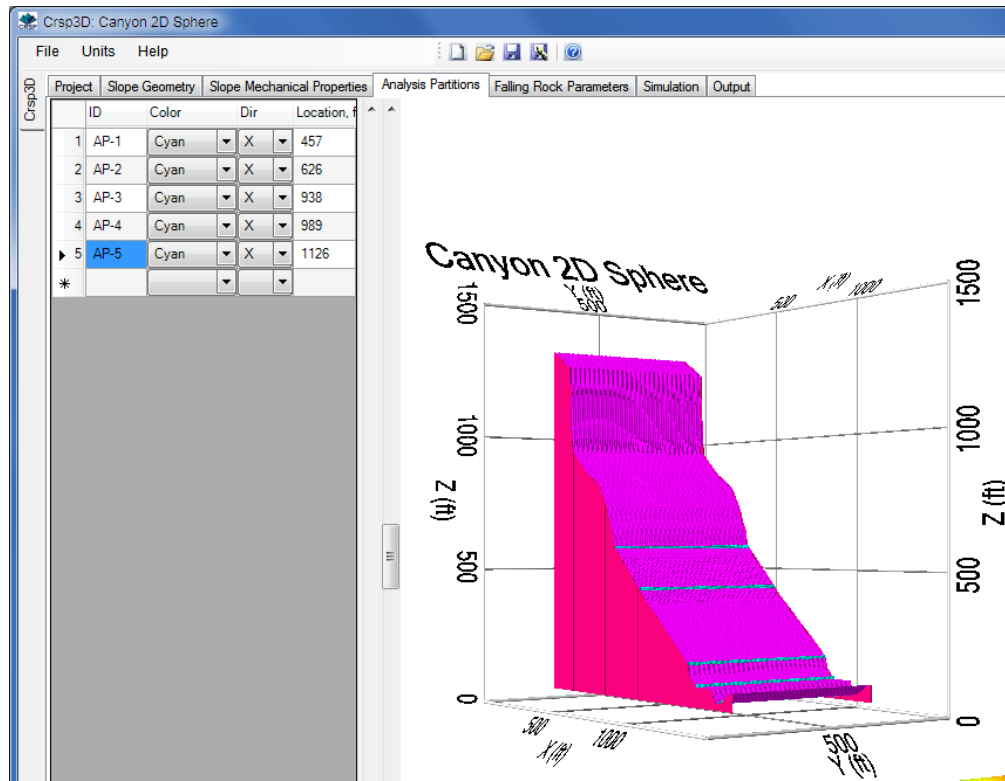


Figure 75. Screenshot. Location of analysis partitions.

### Falling Rock Parameters

The release zone and related rock parameters are shown in Figure 76.

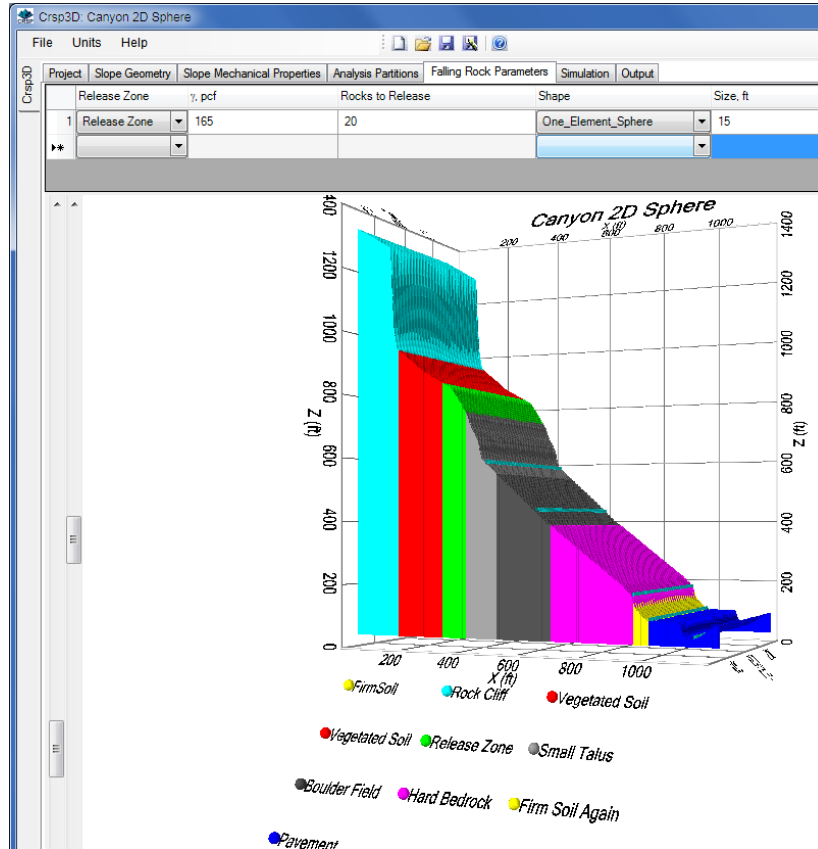


Figure 76. Screenshot. Falling rock parameters.

### Simulation

Kinetic Energy simulation results are shown graphically in Figure 77.

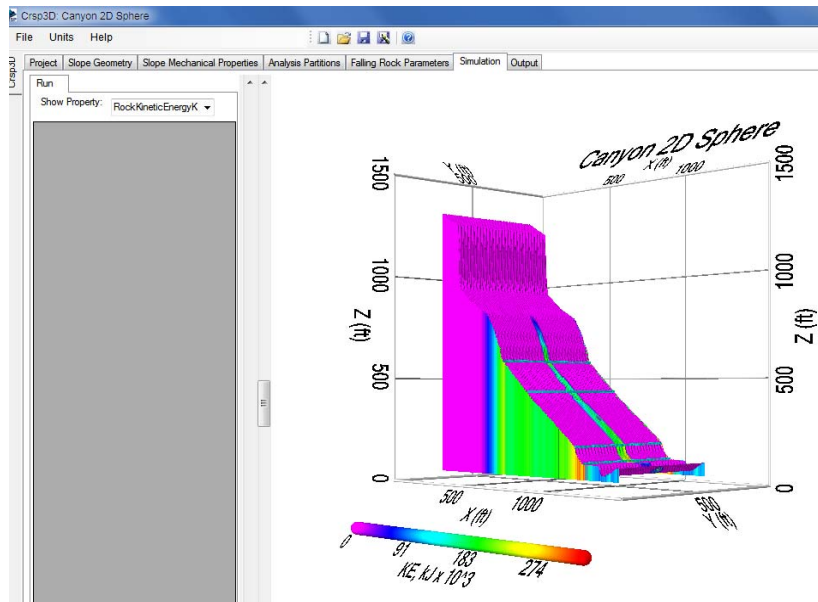


Figure 77. Screenshot. Rotated simulation view showing rockfall kinetic energy.



The virtual 2D view is shown in Figure 78.

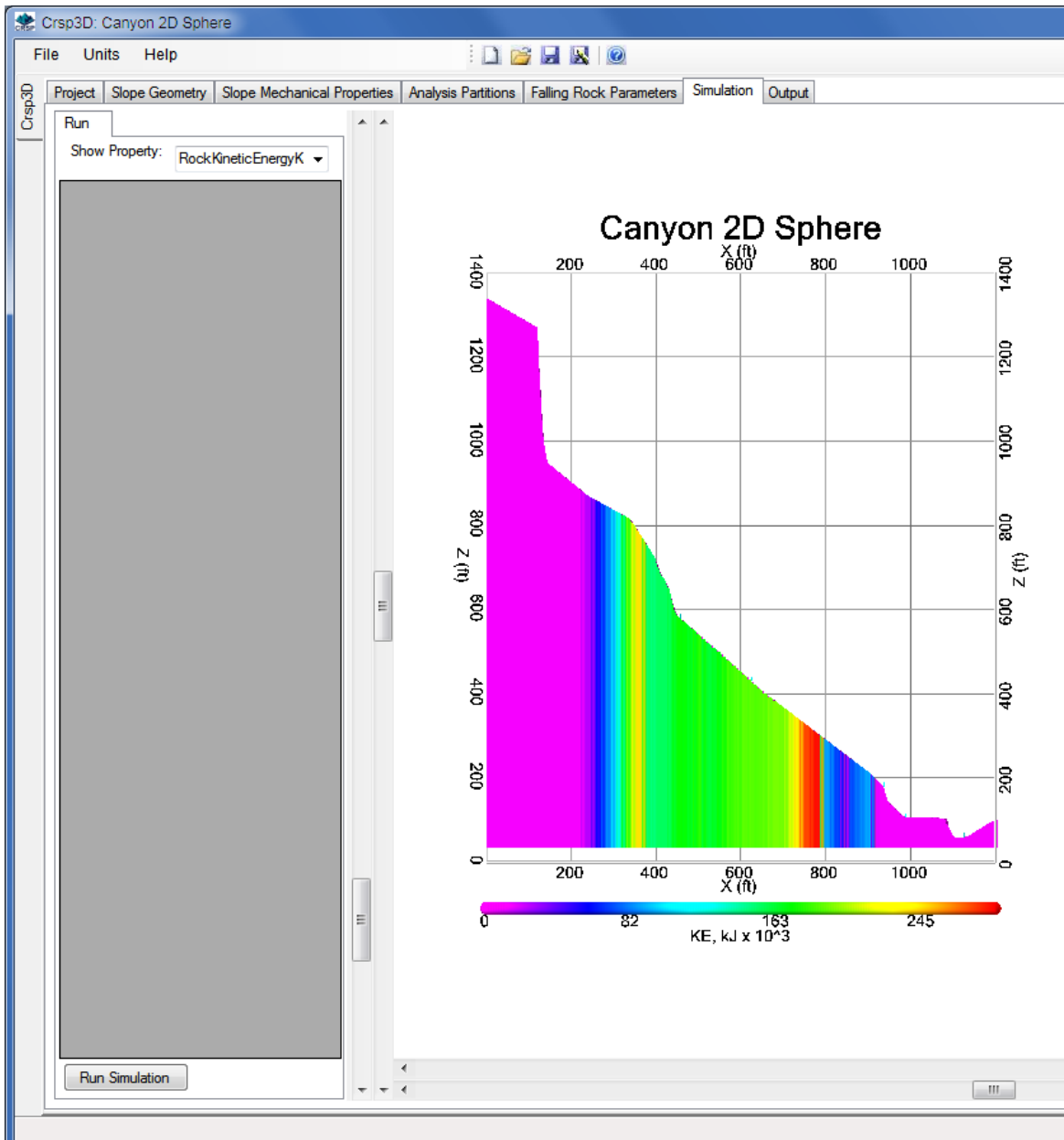


Figure 78. Screenshot. Simulation showing virtual 2D view.

Statistics

Figure 79 shows a sample of the statistical output from CRSP-3D consisting of a histogram showing the distribution of kinetic energies for each rock that was simulated falling down the slope.

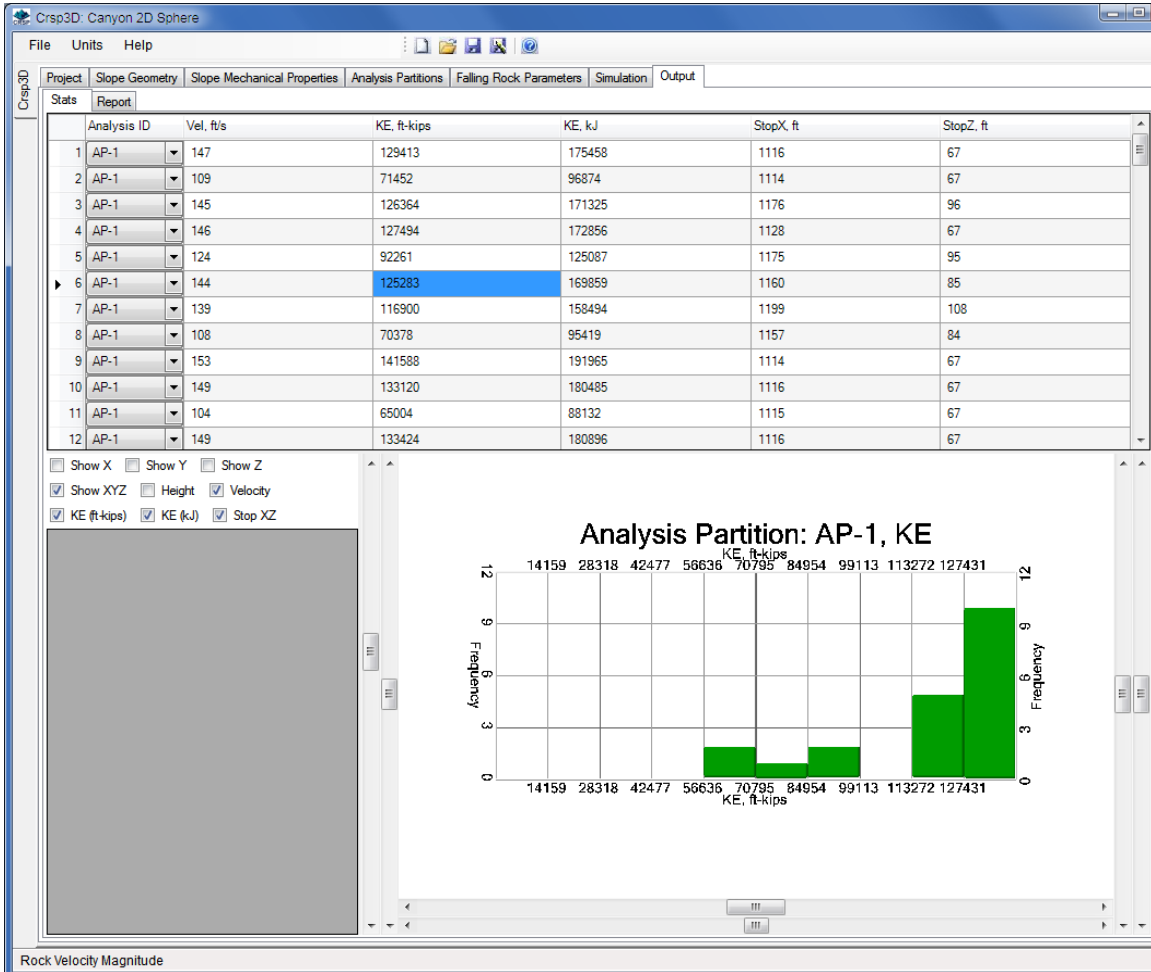


Figure 79. Screenshot. Histogram showing kinetic energy frequency for simulation.

## CHAPTER 4 – ROCKFALL FIELD EVALUATION

Predicting trajectories of rolling and bouncing rocks can be a challenging process for many rockfall prone areas. It has become clear from comparison of previous modeling work with actual rockfall measurements that the mechanics of contact between different materials needs to be incorporated into a rockfall model to account for discrepancies between predicted and measured events. CRSP-3D attempts to accommodate these concerns by including the mechanics of impact between falling rock and a multiple material slope surface having variable hardness and roughness.

Historically field studies have evaluated both the coefficients of restitution and rolling friction. These, together with the geometries of both the slope and falling rocks are the parameters conventionally used to simulate rockfall behavior.

### PARAMETERS

For the purposes of performing rockfall analysis CRSP-3D requires the following input:

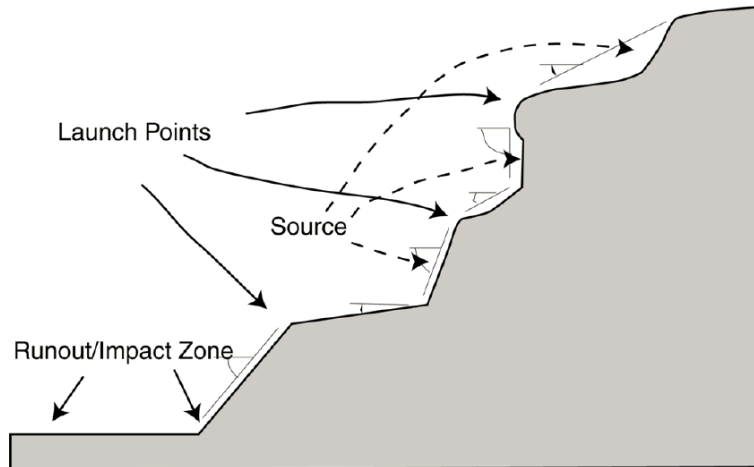
1. Slope profile, input as a series of X, Y, and Z Cartesian coordinates. In addition to conventional survey data or existing topographic data these coordinates may also be derived from a scanned survey (e.g. LIDAR);
2. Estimation or measurement of the roughness of the slope surface within each zone;
3. Estimation of the slope hardness coefficient within each slope zone;
4. Number, starting location, density, shape, size distribution of rocks comprising the rockfall events; and
5. At least one analysis partition on the slope must be input to view output of rock velocity, kinetic energy, and bounce height.

### Slope Profile

An initial requirement for rock fall modeling is the generation of a topographic profile of a slope showing the profile from launch zone through to runout zone (Figure 80). Similarly surface properties along the profile need to be identified and grouped to form zones. Topographic profiles can be developed from existing topographic maps or survey information, or in the case of 3D representations, from LIDAR scans or other 3D topographic information.

Launch (source) areas and their related runout zones should be identified in the field. Impact locations on structures, trees, or in soft ground observed in the field can be used to approximate bounce heights and launch points.

For 2D rockfall analysis, simple slope profiles are acceptable. 3D models, however, require more extensive topographic data in order to provide a suitable 3D representation of a rock slope.



**Figure 80. Schematic. Slope profile identifying launch points and source areas (after Brawner, 1994).**

As already indicated, a critical part of rock fall modeling is the generation of a slope profile defined topographically by X and Y coordinates in the case of 2D profiles or by X, Y and Z coordinates in the case of 3D profiles. Generally a slope can be divided into three areas, each displaying differing behavior during a rockfall event. Ideally, these zones will be separate, but on many slopes, boundaries of the zones can overlap. The first zone is the rockfall source area typically located near the top of the slope composed of bedrock outcrops, cut rock slopes, or coarse surficial deposits. The middle zone is referred to as the travel path and represents the course that the rock will follow after separating from the source zone. The runout zone is the area of deceleration and stopping for rockfall and can be located on slope or at the base of the slope.

Since CRSP-3D only performs 3D analyses, X, Y and Z coordinates are mandatory though the Y coordinate (laterally across the face of the slope) can be set to a fixed value, equal to roughly half to a third the height of the slope, to allow what is effectively a 2D analysis. To perform what is effectively a 2D analysis, only a 2D (X-Z) geometry profile needs to be surveyed/measured since the third dimension (Y) is provided as a user-estimated constant value. The slope may then be viewed in 2D so that the slope cross-section has only X and Z Cartesian coordinates visible.

### **Zone Boundary Selection**

Slopes are divided into different material zones that identify areas of differing properties. Properties that are generally of significance to rockfall sites are the relative hardness of both the source rocks and various slope zones as well as the surface roughnesses of each of these zones.

Surface materials along the rockfall profile should be identified in the field in order to define property characteristics required for modeling. Some indication of the relative “hardness” of the surface and description of the surface material is required including amount of exposure as a percentage the slope surface being surveyed.

In the field, the location zone boundaries can effectively be established by measuring the slope angle and length and width of a zone. Various methods can be used to achieve this. CRSP-3D,

however, has limits to the number of zones that can be employed during a single simulation. The number of possible zones is controlled by the number of unique material ID values representing these zones that are available in CRSP-3D.

### **Rock Size and Shape**

Rock size and shape influence the degree to which slope surface roughness affects rockfall behavior. Rockfall data show that spherical or near spherical rocks move faster downslope than other irregular shapes. Large rocks tend to have longer runout because of their greater kinetic energy.

Rock shapes can be generalized as “spherical”, “tabular”, or “discoidal” etc. to facilitate analysis. These shapes can have a large effect on the rock trajectory during a rockfall. Spheres generally represent a worst case scenario since they comprise the greatest mass for a given size and tend to accelerate faster and decelerate slower than angular rocks. Elongated shapes, such as cylinders, normally take a longer slope distance to reach high velocities and have shorter runout distances compared to spherical rocks. At high velocities, elongated rocks act much like spherical rocks because they are rotating end-over-end so the rock contacts the slope at just two points. During acceleration and deceleration, angular rocks tend to tumble and fall while spherical rocks roll without needing to overcome any undulation in their rock surface, resulting in a longer runout distance.

Any disintegration of rocks as they fall tends to dissipate energy, so disintegration can influence modeling results. Furthermore rock sizes that accumulate at the toe of rockfall zones in the runout area may not be representative of the initial rock sizes at launch or early in their trajectories.

Although falling rocks may break up during descent, the largest rocks found at the base of the rockfall path that can be identified as having fallen from the source area may be considered a reasonable representation of a maximum rock size case for CRSP-3D modeling. If no rocks are available at the base of the path, then rock size can be established by measuring joint spacing in the source area and estimating a probable size for falling rock.

CRSP-3D allows spherical, cylindrical, discoidal, tetrahedral and cube-shaped rocks. The investigator should choose the appropriate rock shape for CRSP-3D rockfall simulation. To represent the probable worst case on a slope, a spherical rock shape can be used.

### ***Block Size***

The discontinuity orientation and number of sets determine the shape of the blocks, which may resemble cubes, rhombohedrons, tetrahedrons, sheets, or irregular shapes. The block size and inter-block shear strength determine the mechanical behavior of a rock mass. ISRM Working Groups (1978, 1981) suggest standard terminology for field descriptions of rock masses to enable evaluations of block size and shape (see Table 2).

Table 2. Rock-Mass Description (ISRM Working Group, 1978, 1981).

Descriptive Term	Definition
Massive	Few joints or very wide spacing
Blocky	Approximately equidimensional
Tabular	One dimension considerably smaller than the other two
Columnar	One dimension considerably larger than the other two
Irregular	Wide variation of block size and shape
Crushed	Heavily jointed to “sugar cube”

Block size ( $I_b$ ) can be estimated by selecting several typical in-situ blocks, measuring them and establishing an average size (ISRM Working Group, 1978). An alternate method of describing block size is use of the Volumetric Joint Count method (ISRM Working Group, 1978, 1981). A volume joint count ( $J_v$ ) is defined as the sum of the number of joints *per meter* for each joint set (by definition  $J_v$  is metric). The number of joints of each set should be counted along a 5-10 m (16-32 ft) sampling interval along a line that runs perpendicular to each set.

The procedure for calculating  $J_v$  is illustrated in Figure 81. The rock mass has three discontinuity sets, and thus the joints belonging to each set are counted along three sampling lines; two lines (lines 1 and 2) are 10 m (32 ft) long, and one line (Line 3) is 7 m (23 ft) long.

As shown in Figure 81, the joint counts were: Line 1 = 5, Line 2 = 6, and Line 3 = 4. Then the calculation for  $J_v$  is performed as shown:

$$J_v = 5/10 + 6/10 + 4/7$$

$$J_v = 0.5 + 0.6 + 0.6 = 1.7 \text{ joints /meter}^3$$

Using Table 2, the example rock mass is composed of large blocks based on a  $J_v$  value of 1.7.

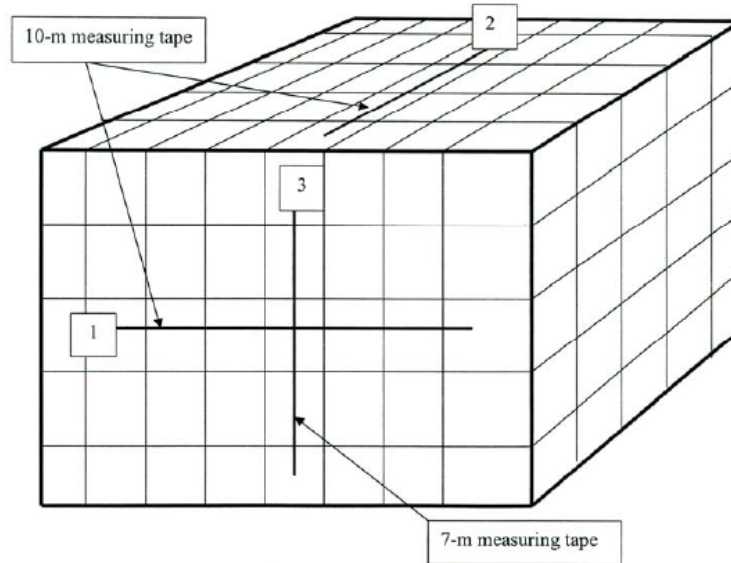


Figure 81. Schematic. Volumetric Joint Count ( $J_v$ ). Measurements are made normal to the direction of joint set. Line 1 intersects 5 joints, line 2 intersects 6 joints, and line 3 intersects 4 joints.

**Rock Density**

The rock density was found to have little effect on CRSP-3D output. A value of 165 lb/ft<sup>3</sup> is a good average that produces acceptable CRSP-3D output and is the default in this program. If a more precise estimate of density is desired, Table 3 can be used.

Table 3. Typical rock unit weights and densities (After: Hoek and Bray, 1981).

ROCK TYPE	U.S UNITS: UNIT WEIGHT (lb/ft <sup>3</sup> )	METRIC UNITS: DENSITY (kg/m <sup>3</sup> )
Hard igneous rocks – granite, basalt, porphyry	160 to 190	2550 to 3060
Metamorphic rocks – quartzite, gneiss, slate	160 to 180	2550 to 2850
Hard sedimentary rocks – limestone, dolomite, sandstone	150 to 180	2340 to 2850
Soft sedimentary rocks – sandstone, coal, chalk, shale	110 to 150	1730 to 2340

**Slope Surface Roughness**

The most accurate program output was found to be obtained when a surface roughness of about 2.0 is used. Although the actual slope surface roughness is often less than 2.0, this value was

found to be appropriate for modeling the proper amount of rock and slope interaction, though other experience may differ. Table 4 provides some suggestions on roughness values to be input in CRSP-3D.

Note: It is emphasized that these values are, at best, preliminary starting points and should not be relied on - there are no substitutes for calibration analyses and judgment.

It should be recognized that the surface roughness, when entered into the program as a single number such as 2.0, will result in a constant surface roughness being modeled on the slope surface. If a range of surface roughness is input, such as 0.5 - 2.0, the program will randomly choose roughness values between 0.5 and 2.0. Single roughness values were found to produce accurate results for all slope types, and should be used in the initial rockfall simulations to establish suitable roughness values that result in acceptable rockfall simulation output values.

Note: The program can be sensitive to the roughness value used, and starting with a range of roughness values without previously establishing acceptable output can result in erroneous results.

**Table 4. Preliminary roughness values.**

Roughness Value	Comments
3.0 and above	Generally only used for very rough slope surfaces where high bounce heights are predicted or have been observed.
1.0 - 2.0	Generally for use on most slope surfaces with most falling rock geometries, even if the slope is relatively smooth. This compensates for the non-uniformity in most rock shapes and slope surfaces.
0.1 - 1.0	Use judiciously. Roughness values below 2.0 may produce higher than expected values when modeling spherical rocks.

**Slope Hardness Coefficient**

The hardness coefficient is a numerical representation of the slope material properties used to estimate the amount of energy transferred from the rock to the slope surface upon impact; values range from 0.01 to 1.0. A value of 1.0 represents no transfer of elastic energy and essentially does not exist in real situations. Conversely a value of 0.0 would represent a total transfer of energy and similarly does not exist in real situations.

Table 5 provides a method for determining hardness values in the field for various slope materials. The hardness of the slope material can be estimated using a firm blow with the pick end of a rock hammer. During CRSP-3D rockfall simulations, the hardness coefficient may need to be adjusted to achieve acceptable output. Example photographs of slopes in each hardness range are provided in Appendix A.

Note: It is emphasized that these values are, at best, preliminary starting points and should not be relied on - there are no substitutes for calibration analyses and judgment.



The current program allows modeling of a hardness range or a single hardness value. A single hardness value is used the majority of the time, and should always be used for the initial rockfall simulations in order to get the model to calibrate satisfactorily. Only after an acceptable hardness coefficient resulting in accurate calibrated program output has been established should a range of hardness values be input to perform sensitivity analyses.

A hardness range could be used to model trees or boulders on a slope. For example, for a slope with an estimated hardness of 0.5 that also has trees, instead of using a single hardness value of 0.2 to account for the cumulative effect of trees, use a hardness range of 0.1 - 0.5 to more accurately model the random affect of trees. Each time a rock is rolled down the slope, the hardness of the slope will vary randomly from 0.1 - 0.5, simulating a rock occasionally glancing off of trees or hitting them directly as it bounces down the slope.

CRSP-3D maps the input hardness value to the tangential damping coefficient and the coefficient of restitution (COR) values. The damping and COR have an inverse linear relationship. For example, a hard slope will have a relatively high COR and a low damping value while a soft soil slope will have a low COR and a high damping value. Slope and roadway materials have been grouped under few general descriptions (Soft Clay, Hard Clay, Sand, Gravel, Soft Bedrock, Hard Bedrock, Boulder field, Talus, Concrete Road and Asphalt Road) which were then used to construct a table of preliminary roughness and hardness coefficient values (Table 5). This table is provided only as a starting point for choosing hardness coefficient values.

**Table 5. Preliminary hardness values and associated hardness measure.**

<b>SLOPE MATERIAL TYPE</b>	<b>MATERIAL DESCRIPTION</b>	<b>HARDNESS RANGE</b>	<b>HARDNESS MEASURE</b>
SOFT	Soft clay Loose sand	0.1-0.3	>100% rock pick penetration. Footprints left in soil.
INTERMEDIATE	Medium clay	0.3-0.5	75% - 100% rock pick penetration.
FIRM	Hard clay Soft bedrock	0.4-0.7	50-75% rock pick penetration.
GRAVEL TO COBBLE TALUS	Gravel Cobbles	0.2-0.6	Talus covers >40% of slope.
BOULDER TALUS	Boulder field	0.5-0.8	Talus cover >40% of slope.
HARD BEDROCK	Fresh hard rock	0.7-0.9	-

**CALIBRATION**

The calibration process entails running rockfall simulations of existing monitored/measured rockfalls (calibration sites) and comparing the simulated output parameters (e.g. rollout, bounce

height, velocity) to observed rockfall parameters obtained at these sites. In this manner, input parameters, such as slope hardness and roughness can be adjusted to simulate a rockfall more accurately.

Two main approaches can be used to calibrate numerical models:

- Simulation of existing natural rockfall events
- Controlled field testing

Simulation of existing natural rockfall (commonly referred to as "back-analysis") is a common calibration procedure. This technique is used to simulate the characteristics of rockfall such as bounce height and runout. Simulated bounce height and runout distance can be compared with measured values on a natural slope with rockfall accumulation.

Full-scale field experiments, using carefully controlled rock shapes, sizes and slope conditions may be performed. Velocity values can be measured with the use of high speed cameras or other methods. These velocity values in conjunction with the size, shape and mass of individual falling rocks can be used to calculate kinetic energy values which can then be compared with values generated from simulations.

### **Rock Trajectory and Height**

Rockfall simulation aids in determining the trajectories and kinetic energies of falling rocks for the purposes of evaluating rockfall hazard and providing input to the design of rockfall mitigation measures. The variability in trajectory and bounce height observed during actual rockfall results from variations in the size, shape, and properties of falling rock, slope material properties, and slope geometry. This variations make selecting representative properties for modeling a challenge.

### **Rock Runout**

Runout (also referred to as "rollout") distance, is the distance rockfall travels from the source area to its stopping location. Field measurement is possible on undisturbed slopes, where rockfall has not been moved. Rock runout establishes rockfall distribution and possibly rock size for the slope, provided rock does not breakup appreciably as it falls. For the purposes of categorization when performing field evaluation of rockfall events, a rock of rockfall origin can be defined as located completely on top of the soil. Rocks that are completely or partly buried in the soil should be assumed to be deposited by other processes.

Since rocks may break up into smaller pieces as they tumble down a slope, the size as observed at or near the bottom of a slope may not be a true indicator of the original rock size. This version of CRSP-3D does not account for rock breakage as it falls downslope. One approach to accommodating this would be to simulate a variety of rock sizes from a variety of launch positions and determine from the results which conditions generate the most critical rockfall concerns and evaluate risk and mitigation design accordingly. Some additional simple statistical analysis of the results data may also prove useful.

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APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
SOFT	0.1-0.3	>100% rock pick penetration. Footprints left in soil.



Figure 82. Photograph. Moist Soft Soil.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
SOFT	0.1-0.3	>100% rock pick penetration. Footprints left in soil.



Figure 83. Photograph. Moist Soft Soil.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
SOFT	0.1-0.3	>100% rock pick penetration. Footprints left in soil.



Figure 84. Photograph. Soft Soil Indentation.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
SOFT	0.1-0.3	>100% rock pick penetration. Footprints left in soil.



Figure 85. Photograph. Dry Soft Soil.



**APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES**

<b>SLOPE MATERIAL TYPE</b>	<b>HARDNESS RANGE</b>	<b>MATERIAL DESCRIPTION</b>
INTERMEDIATE	0.3-0.5	75% - 100% rock pick penetration.



**Figure 86. Photograph. Intermediate Soil.**

**APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES**

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<b>SLOPE MATERIAL TYPE</b>	<b>HARDNESS RANGE</b>	<b>MATERIAL DESCRIPTION</b>
MODERATELY SOFT	0.3-0.5	75% - 100% rock pick penetration.



**Figure 87. Photograph. Moderately Soft Soil.**

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
FIRM	0.4-0.6	50-75% rock pick penetration.



Figure 88. Photograph. Firm Soil.

**APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES**

<b>SLOPE MATERIAL TYPE</b>	<b>HARDNESS RANGE</b>	<b>MATERIAL DESCRIPTION</b>
FIRM	0.4-0.6	50-75% rock pick penetration.



**Figure 89. Photograph. Firm Soil.**

**APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES**

<b>SLOPE MATERIAL TYPE</b>	<b>HARDNESS RANGE</b>	<b>MATERIAL DESCRIPTION</b>
FIRM	0.4-0.6	50-75% rock pick penetration.



**Figure 90. Photograph. Firm Soil.**

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
GRAVEL TO COBBLE TALUS	0.2-0.6	Talus covers > 40% of slope.



Figure 91. Photograph. Gravel to Cobble Talus.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
GRAVEL TO COBBLE TALUS	0.2-0.6	Talus covers > 40% of slope.



Figure 92. Photograph. Gravel to Cobble Talus.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
GRAVEL TO COBBLE TALUS	0.2-0.6	Talus covers > 40% of slope.



Figure 93. Photograph. Gravel to Cobble Talus.



APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
BOULDER TALUS	0.5-0.8	Talus covers > 40% of slope.



Figure 94. Photograph. Boulder Talus.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
BOULDER TALUS	0.5-0.8	Talus covers > 40% of slope.



Figure 95. Photograph. Boulder Talus.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
BOULDER TALUS	0.5-0.8	Talus covers > 40% of slope.



Figure 96. Photograph. Boulder Talus.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
HARD BEDROCK	0.7-0.9	Hard rock



Figure 97. Photograph. Hard Bedrock.

APPENDIX A - EXAMPLE PHOTOGRAPHS OF MATERIAL HARDNESS TYPES

SLOPE MATERIAL TYPE	HARDNESS RANGE	MATERIAL DESCRIPTION
HARD BEDROCK	0.7-0.9	Hard rock



Figure 98. Photograph. Hard Bedrock.

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APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES

TUTORIAL EXAMPLE #1

REPORT

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## Colorado Rockfall Simulation Program -- CRSP-3D

### CRSP Rockfall Analysis

CRSP was used to determine the expected kinetic energy and bouncing height of falling rocks at various points along the slope. In the analysis, it was assumed that irregular- shaped boulders with a maximum diameter of 3.0 feet would impact the rockfall retaining system. For each simulation, the model rolled 3 shaped rocks from a source area at 146 - 214 feet. A slope surface roughness of 0.5 - 5.0, and hardness of 0.3 - 0.9 were used.

### PROJECT INFORMATION

Project Name	Tutorial
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### Material Properties

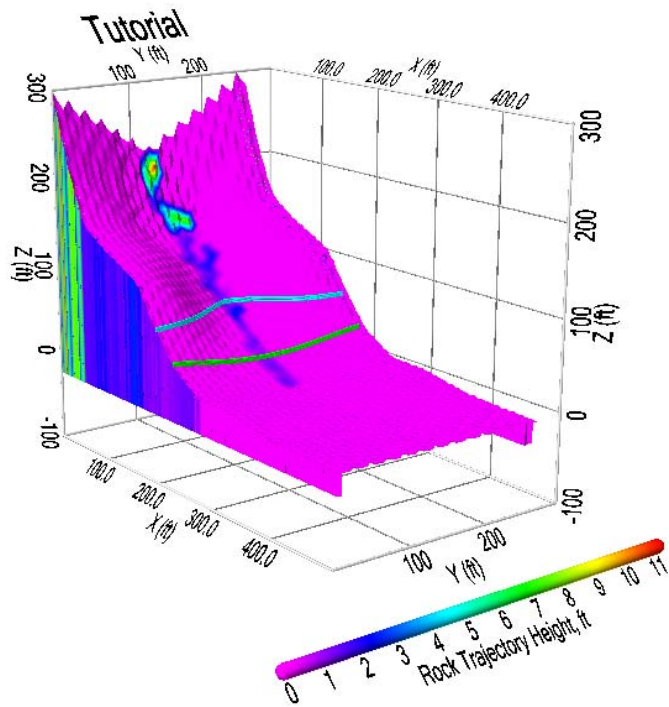
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Material 1	<i>ID</i>	Boulder Field		<i>Boulder Field</i>	
	<i>Color</i>	Magenta		<i>Magenta</i>	
	<i>Roughness</i>	3-5	ft	<i>0.91-1.52</i>	<i>m</i>
	<i>Hardness</i>	0.7-0.9		<i>0.7-0.9</i>	
Material 2	<i>ID</i>	Talus		<i>Talus</i>	
	<i>Color</i>	Gray		<i>Gray</i>	
	<i>Roughness</i>	0.5-2	ft	<i>0.15-0.61</i>	<i>m</i>
	<i>Hardness</i>	0.3-.6		<i>0.3-.6</i>	

### Analysis Partition Properties

		English	Units	SI	Units
Analysis Partition 1	<i>ID</i>	BP-1		<i>BP-1</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	Z		<i>Z</i>	
	<i>Location</i>	70	ft	<i>21</i>	<i>m</i>
Analysis Partition 2	<i>ID</i>	BP-2		<i>BP-2</i>	
	<i>Color</i>	Green		<i>Green</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	231	ft	<i>70</i>	<i>m</i>

### Rockfall Parameters

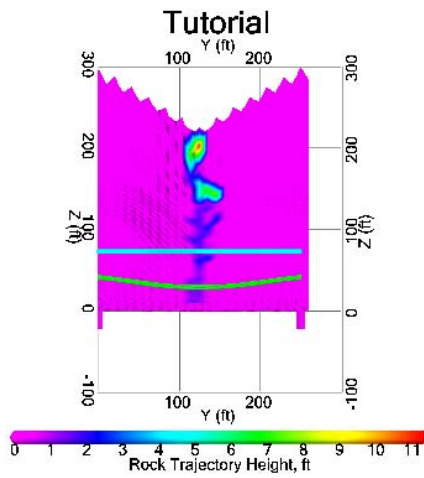
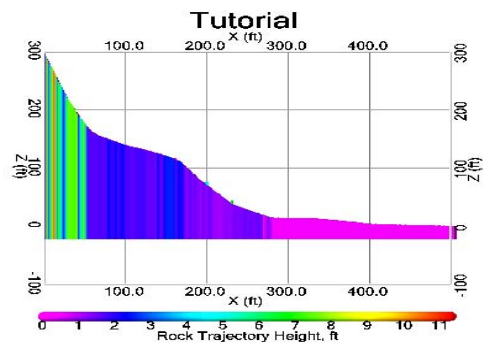
		English	Units	SI	Units
Rockfall Parameter 1	<i>Release Zone</i>	Boulder Field		<i>Boulder Field</i>	
	<i>γ</i>	165	pcf	25.9	kN/m <sup>3</sup>
	<i>Rocks to Release</i>	3		3	
	<i>Shape</i>	One_Element_Sphere		<i>One_Element_Sphere</i>	
	<i>Size</i>	3	ft	0.9144	m



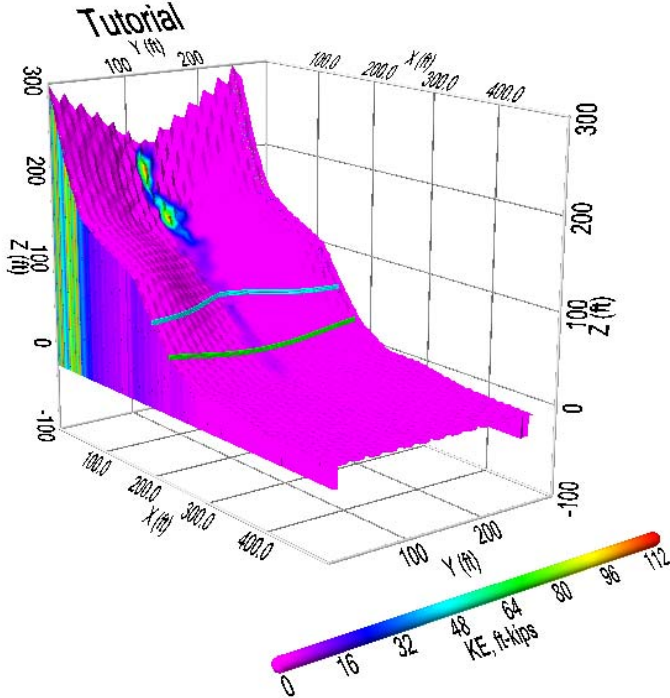
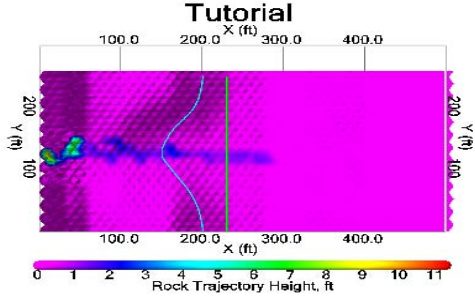


APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1

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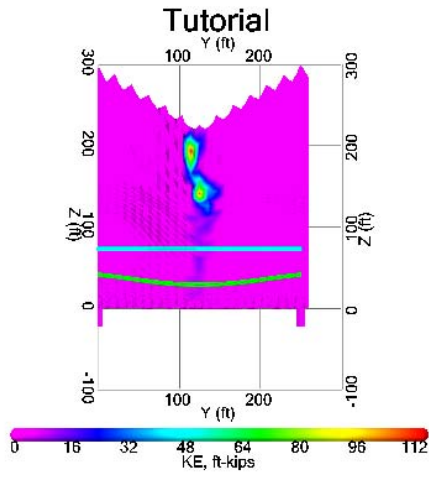
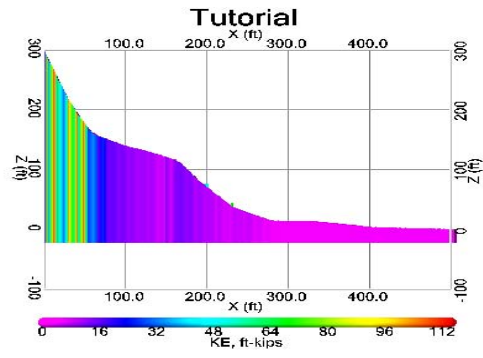


APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1

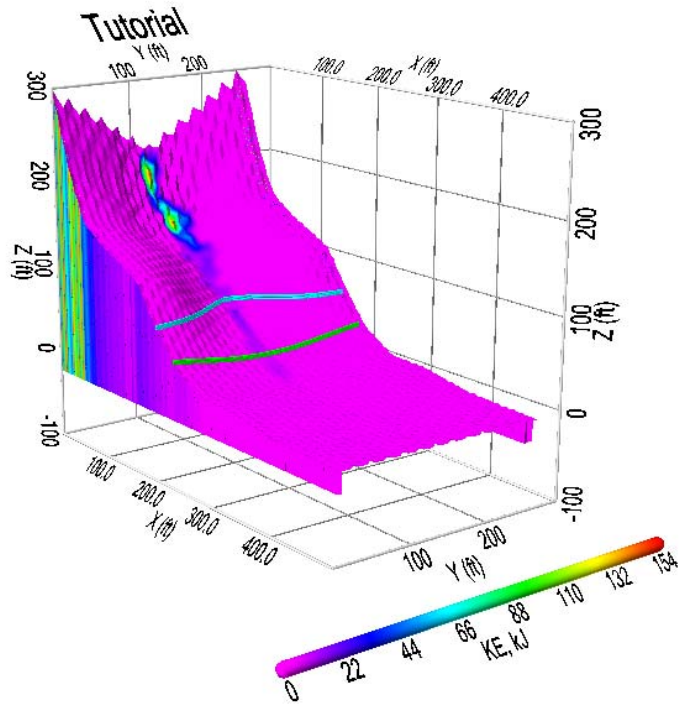
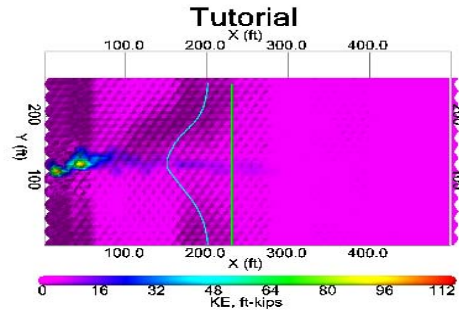


APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1

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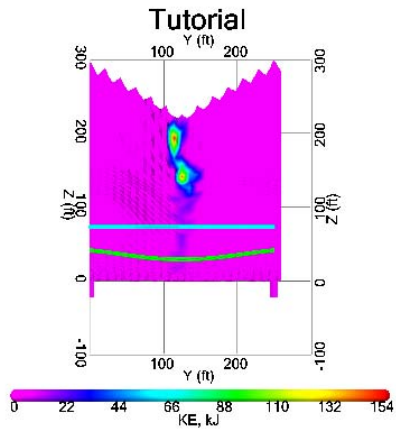
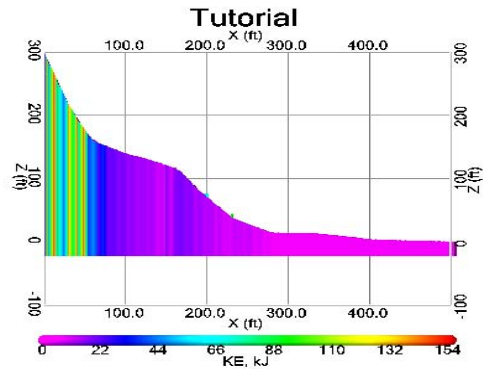


APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1



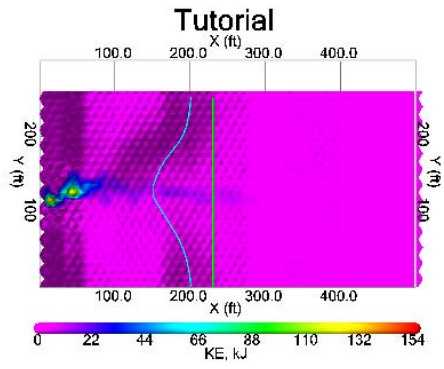
APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1

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APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
TUTORIAL EXAMPLE #1

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## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Tutorial

### CRSP Rockfall Results for Analysis Partition BP-1

#### Summary of Results

Max Bounce Ht, ft	Max Energy, ft-kips	Max Energy, kJ	Percent Passing
1	3	4	67%

#### Cumulative Probability

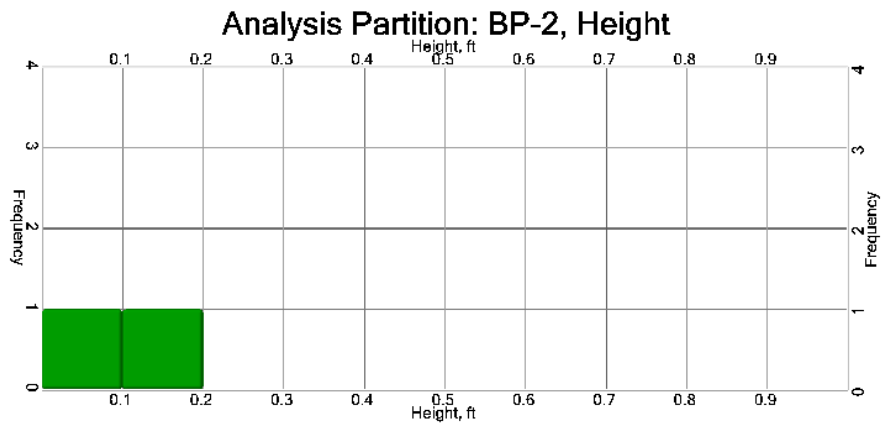
Cumulative Probability	<i>Bounce Ht, ft</i>	Energy, ft-kips	Energy, kJ	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
50%	0.0	3	4	282	9
75%	0.1	3	4	290	12
90%	0.1	3	4	298	14
95%	0.1	3	4	302	14
98%	0.1	4	5	307	15

## Colorado Rockfall Simulation Program -- CRSP-3D

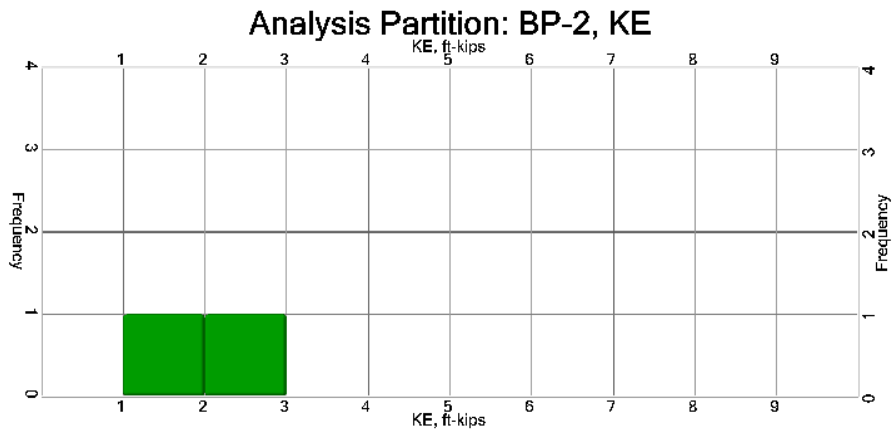
Project Name: Tutorial

### CRSP Rockfall Results for Analysis Partition 1

Height (ft)

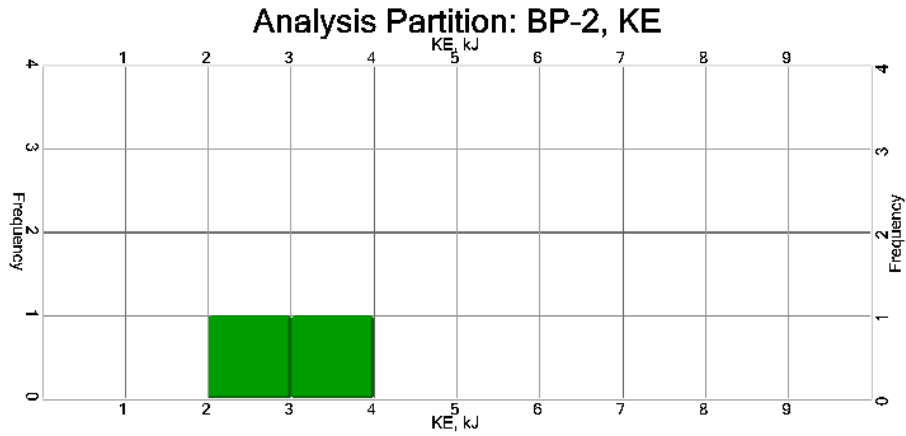


### Kinetic Energy (ft-kips)

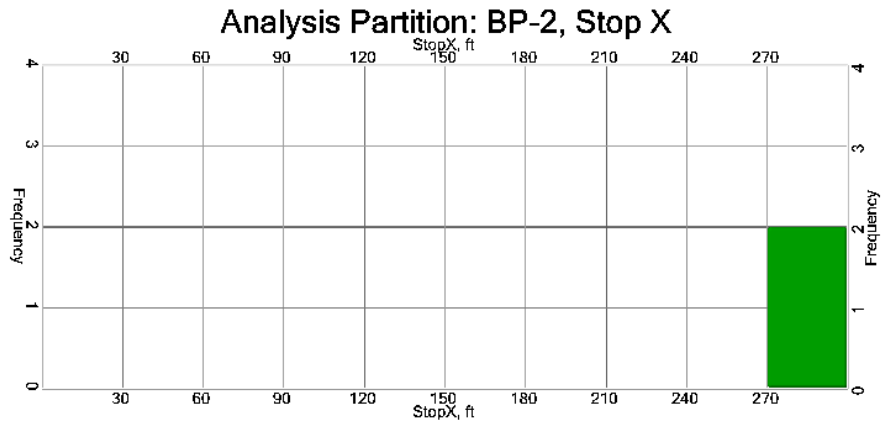


### Kinetic Energy (kJ)

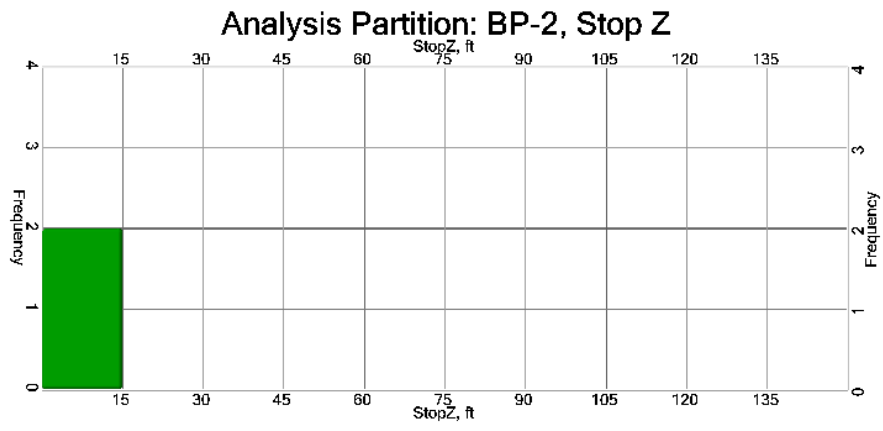




Rollout Stop X (ft) for rocks passing Analysis Partition 1



Rollout Stop Z (ft) for rocks passing Analysis Partition 1



# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Tutorial

## CRSP Rockfall Results for Analysis Partition BP-2

### Summary of Results

Max Bounce Ht, ft	Max Energy, ft-kips	Max Energy, kJ	Percent Passing
1	3	4	67%

### Cumulative Probability

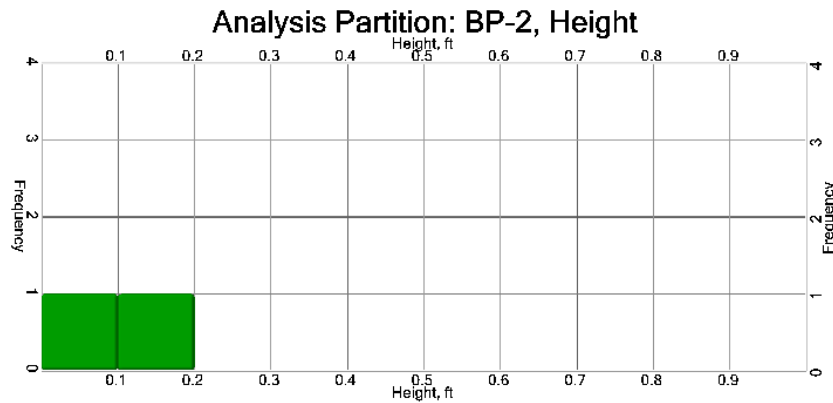
Cumulative Probability	Bounce Ht, ft	Energy, ft-kips	Energy, kJ	Rollout X, ft	Rollout Z, ft
50%	0.1	2	3	282	9
75%	0.2	3	4	290	12
90%	0.2	3	4	298	14
95%	0.2	3	4	302	14
98%	0.2	3	4	307	15

# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Tutorial

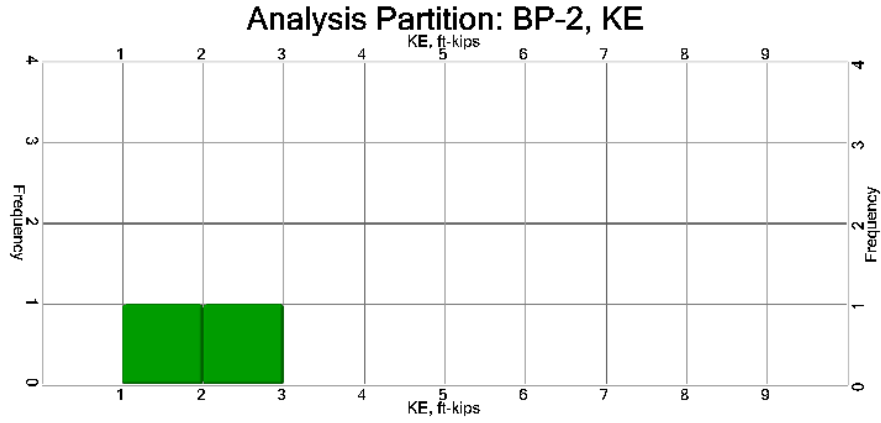
## CRSP Rockfall Results for Analysis Partition 2

### Height (ft)

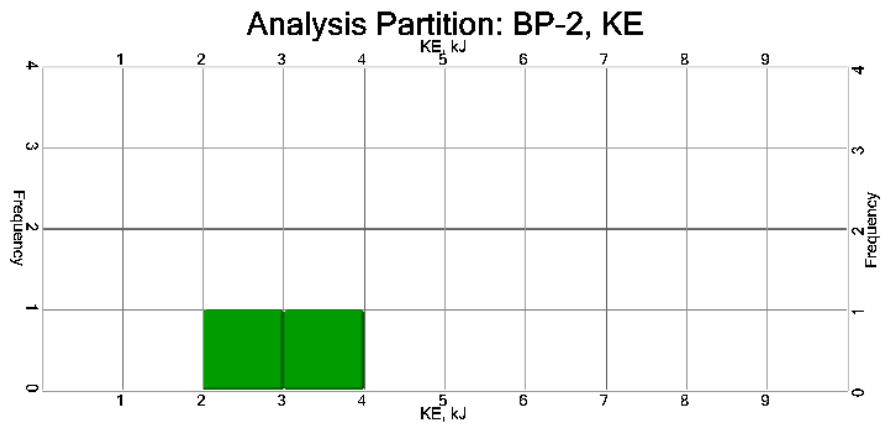


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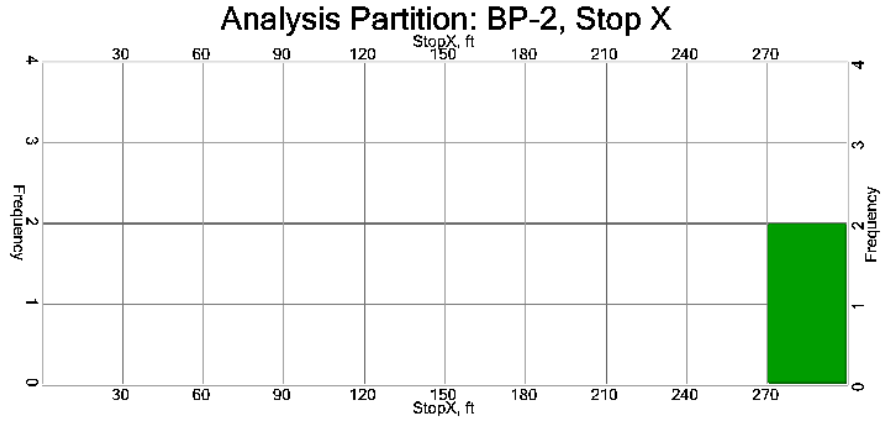
## Kinetic Energy (ft-kips)



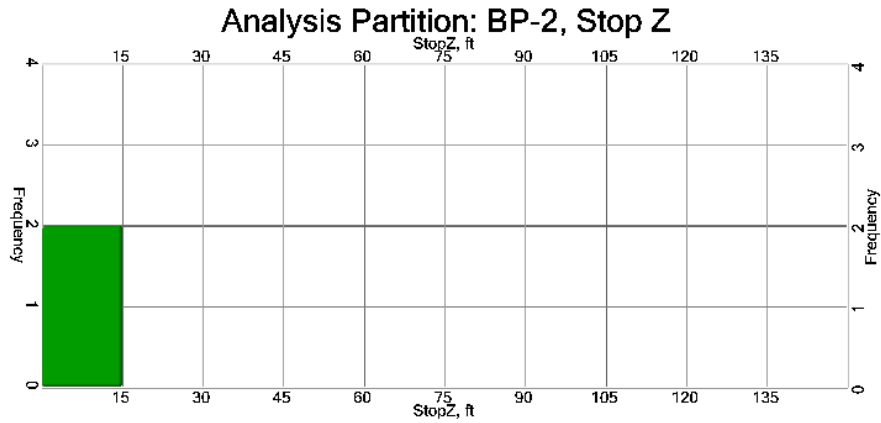
## Kinetic Energy (kJ)



Rollout Stop X (ft) for rocks passing Analysis Partition 2



Rollout Stop Z (ft) for rocks passing Analysis Partition 2



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CANYON LIDAR 3D SPHERE EXAMPLE #2

REPORT

Colorado Rockfall Simulation Program -- CRSP-3D

CRSP Rockfall Analysis

CRSP was used to determine the expected kinetic energy and bouncing height of falling rocks at various points along the slope. In the analysis, it was assumed that irregular shaped boulders with a maximum diameter of 15.0 feet would impact the rockfall retaining system. For each simulation, the model rolled 20 shaped rocks from a source area at 701 - 812 feet. A slope surface roughness of 0.1 - 4.0, and hardness of 0.2 - 0.9 were used.

**PROJECT INFORMATION**

Project Name	Canyon Lidar 3D Sphere
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**Material Properties**

		English	Units	SI	Units
Material 1	<i>ID</i>	Firm Soil		<i>Firm Soil</i>	
	<i>Color</i>	Yellow		<i>Yellow</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.3		<i>0.3</i>	
Material 2	<i>ID</i>	Rock Cliff		<i>Rock Cliff</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 3	<i>ID</i>	Vegetated Soil		<i>Vegetated Soil</i>	
	<i>Color</i>	Red		<i>Red</i>	
	<i>Roughness</i>	0.5	ft	<i>0.15</i>	<i>m</i>
	<i>Hardness</i>	0.2		<i>0.2</i>	
Material 4	<i>ID</i>	Release Zone		<i>Release Zone</i>	
	<i>Color</i>	Green		<i>Green</i>	
	<i>Roughness</i>	0.5	ft	<i>0.15</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 5	<i>ID</i>	Small Talus		<i>Small Talus</i>	
	<i>Color</i>	Gray		<i>Gray</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.4		<i>0.4</i>	
Material 6	<i>ID</i>	Boulder Field		<i>Boulder Field</i>	

**APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 3D SPHERE EXAMPLE #2**

	<i>Color</i>	DarkGray		<i>DarkGray</i>	
	<i>Roughness</i>	4	ft	<i>1.22</i>	<i>m</i>
	<i>Hardness</i>	0.6		<i>0.6</i>	
Material 7	<i>ID</i>	Hard Bedrock		<i>Hard Bedrock</i>	
	<i>Color</i>	Magenta		<i>Magenta</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 8	<i>ID</i>	Firm Soil		<i>Firm Soil</i>	
	<i>Color</i>	Yellow		<i>Yellow</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.3		<i>0.3</i>	
Material 9	<i>ID</i>	Pavement		<i>Pavement</i>	
	<i>Color</i>	Blue		<i>Blue</i>	
	<i>Roughness</i>	0.1	ft	<i>0.03</i>	<i>m</i>
	<i>Hardness</i>	0.8		<i>0.8</i>	

**Analysis Partition Properties**

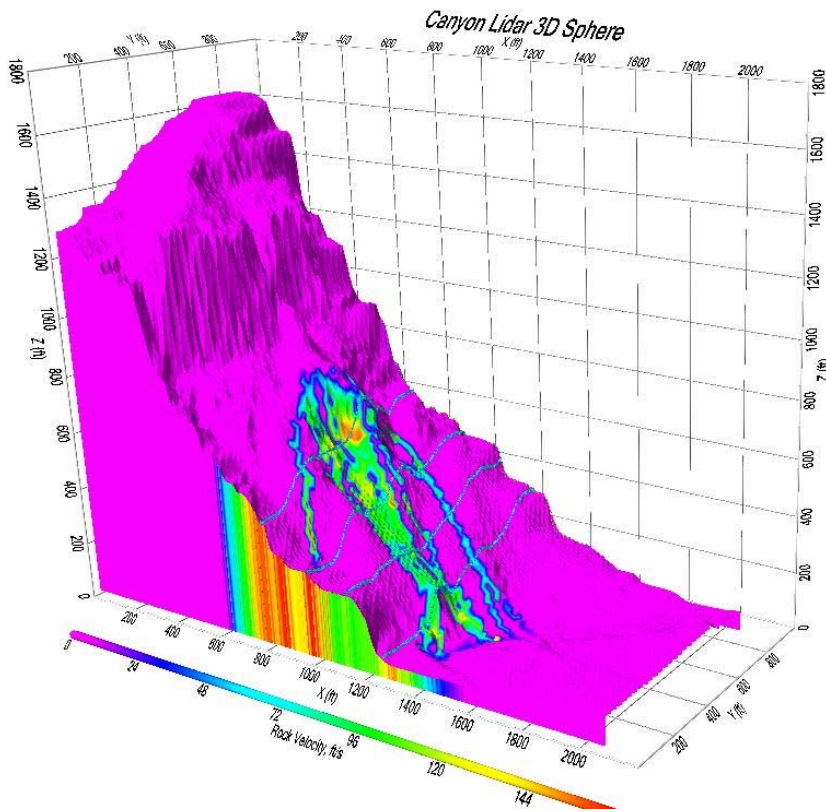
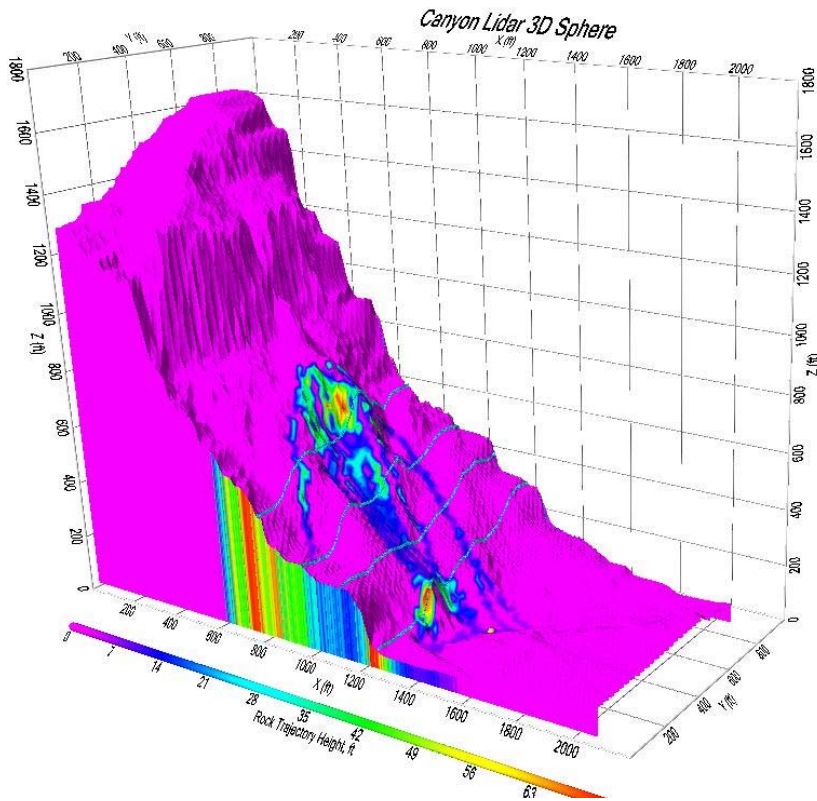
		English	Units	<i>SI</i>	<i>Units</i>
Analysis Partition 1	<i>ID</i>	AP-1		<i>AP-1</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	809	ft	<i>247</i>	<i>m</i>
Analysis Partition 2	<i>ID</i>	AP-2		<i>AP-2</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	986	ft	<i>301</i>	<i>m</i>
Analysis Partition 3	<i>ID</i>	AP-3		<i>AP-3</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	1137	ft	<i>347</i>	<i>m</i>
Analysis Partition 4	<i>ID</i>	AP-4		<i>AP-4</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	1273	ft	<i>388</i>	<i>m</i>

**Rockfall Parameters**

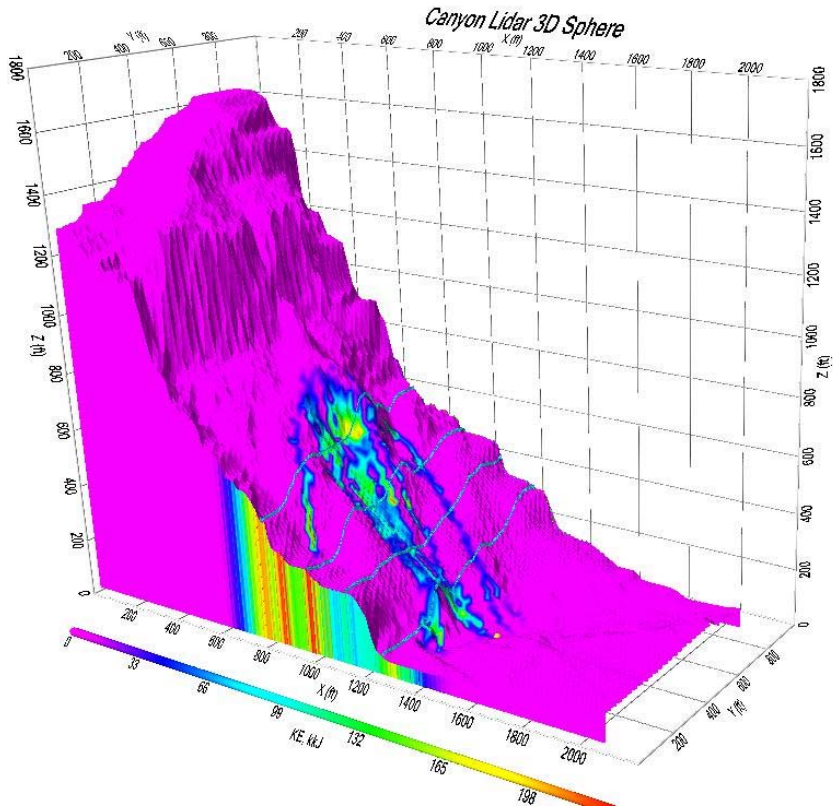
		English	Units	<i>SI</i>	<i>Units</i>
Rockfall Parameter 1	<i>Release Zone</i>	Release Zone		<i>Release Zone</i>	
	<i>γ</i>	165	pcf	<i>25.9</i>	<i>kN/m<sup>3</sup></i>
	<i>Rocks to Release</i>	20		<i>20</i>	
	<i>Shape</i>	One_Element_Sphere		<i>One_Element_Sphere</i>	
	<i>Size</i>	15	ft	<i>4.572</i>	<i>m</i>



APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 3D SPHERE EXAMPLE #2



APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 3D SPHERE EXAMPLE #2



# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

## CRSP Rockfall Results for Analysis Partition AP-1

### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
69	143	121768	165092	100%

### Cumulative Probability

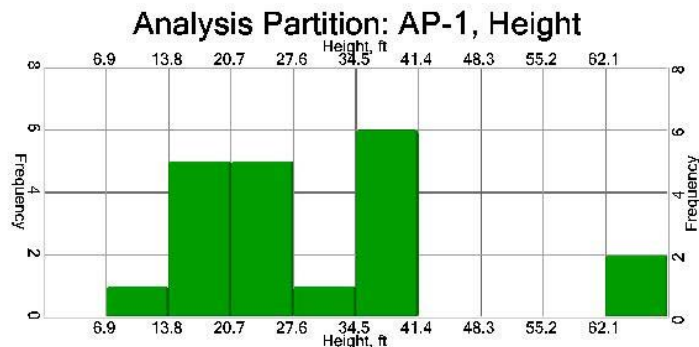
Cumulative Probability	Bounce Ht, ft	Velocity, ft/s	Energy, ft-kips	Energy, kJ	Rollout X, ft	Rollout Z, ft
50%	26.5	106	68374	92704	1412	68
75%	37.0	119	85361	115735	1479	81
90%	52.6	132	104479	141656	1545	94
95%	66.3	140	117386	159074	1582	237
98%	69.3	145	123231	167081	1621	304

# Colorado Rockfall Simulation Program -- CRSP-3D

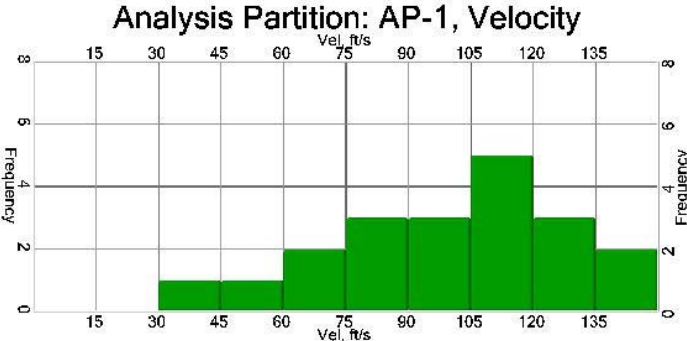
Project Name: Canyon Lidar 3D Sphere

## CRSP Rockfall Results for Analysis Partition 1

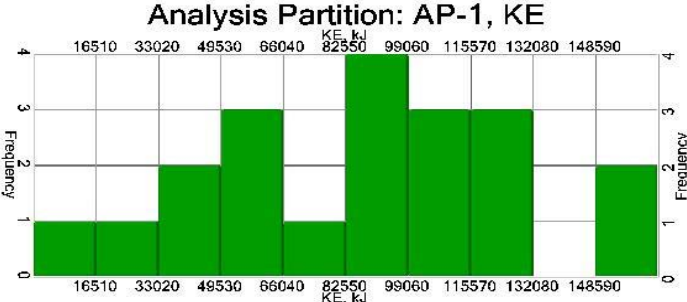
### Height (ft)



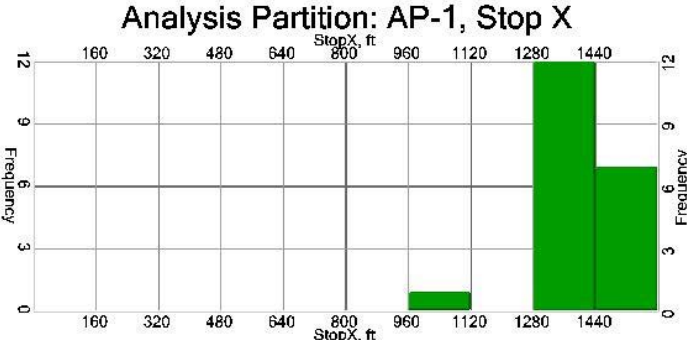
**Velocity (ft/s)**



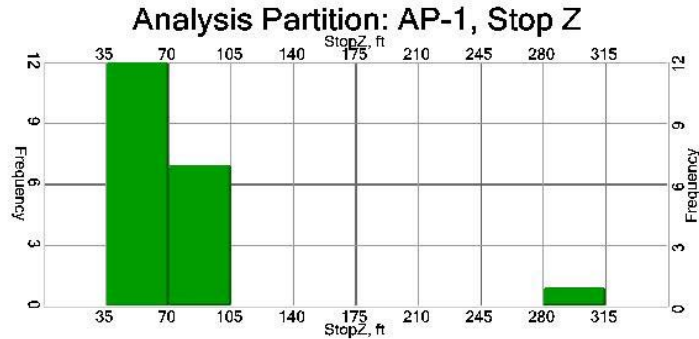
**Kinetic Energy (kJ)**



**Rollout Stop X (ft) for rocks passing Analysis Partition 1**



## Rollout Stop Z (ft) for rocks passing Analysis Partition 1



## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

### CRSP Rockfall Results for Analysis Partition AP-2

#### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
48	146	128104	173683	100%

#### Cumulative Probability

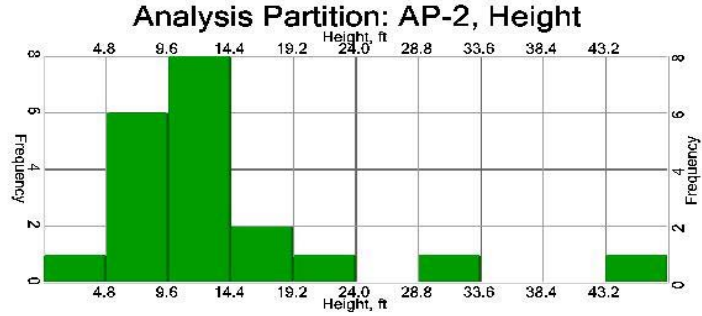
Cumulative Probability	Bounce Ht, ft	Velocity, ft/s	Energy, ft-kips	Energy, kJ	Rollout X, ft	Rollout Z, ft
50%	11.9	88	46888	63571	1412	68
75%	15.4	99	58354	79116	1479	81
90%	25.9	115	78852	106906	1545	94
95%	41.3	132	115491	156582	1582	237
98%	48.0	147	129455	175514	1621	304

## Colorado Rockfall Simulation Program -- CRSP-3D

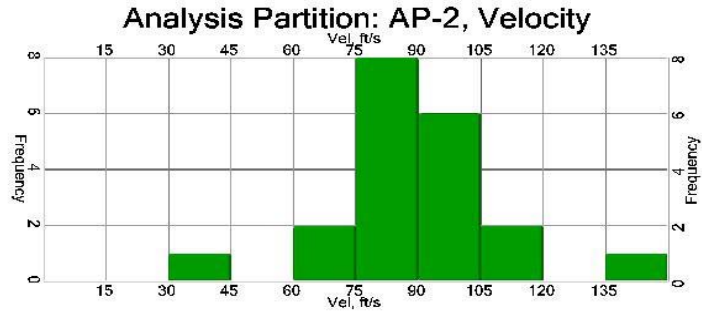
Project Name: Canyon Lidar 3D Sphere

## CRSP Rockfall Results for Analysis Partition 2

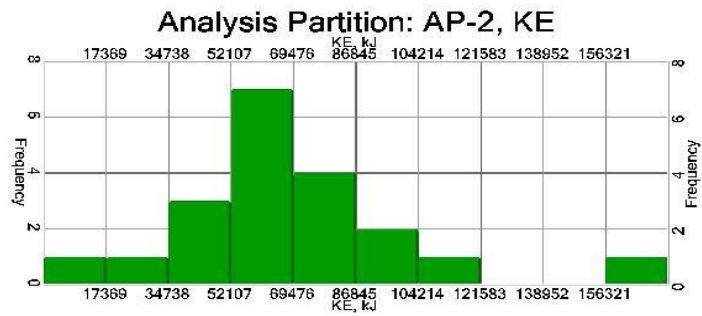
### Height (ft)



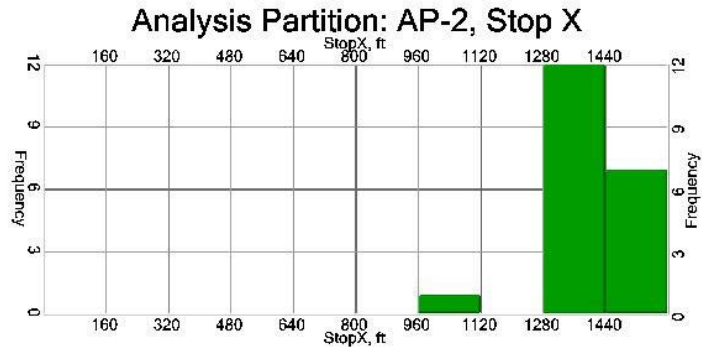
### Velocity (ft/s)



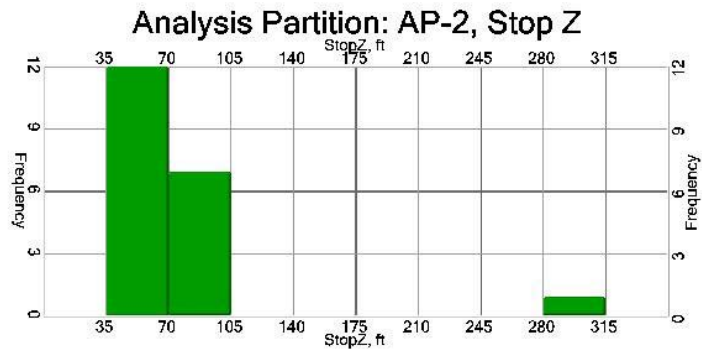
### Kinetic Energy (kJ)



Rollout Stop X (ft) for rocks passing Analysis Partition 2



Rollout Stop Z (ft) for rocks passing Analysis Partition 2



# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

## CRSP Rockfall Results for Analysis Partition AP-3

### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
21	114	78031	105795	95%

### Cumulative Probability

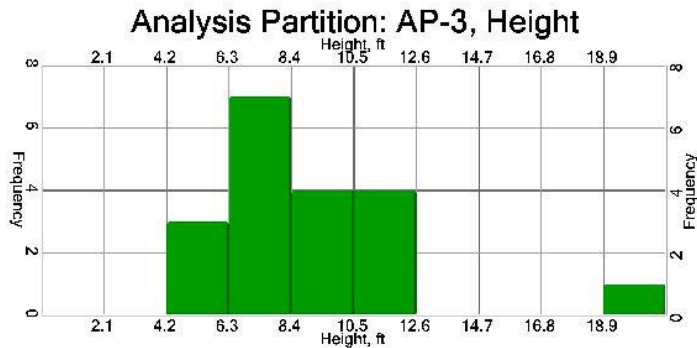
Cumulative Probability	Bounce Ht, ft	Velocity, ft/s	Energy, ft-kips	Energy, kJ	Rollout X, ft	Rollout Z, ft
50%	8.6	71	29577	40098	1418	67
75%	10.9	85	43156	58507	1483	78
90%	12.3	97	54940	74483	1547	88
95%	18.9	107	72928	98870	1584	94
98%	20.5	116	79016	107123	1623	101

# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

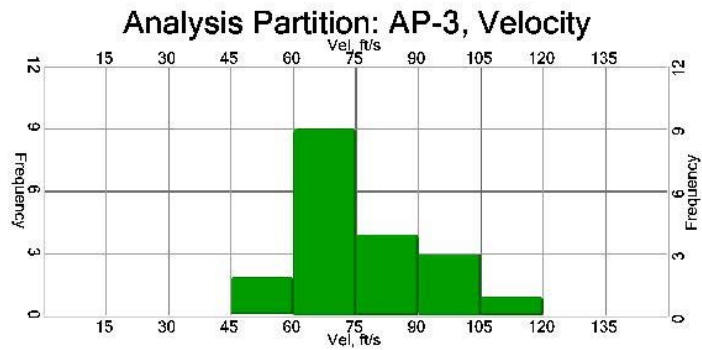
## CRSP Rockfall Results for Analysis Partition 3

### Height (ft)

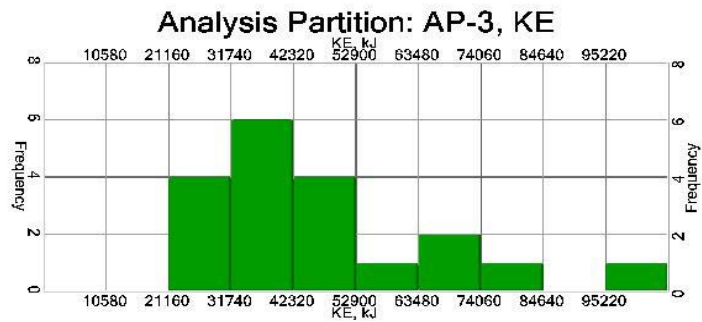




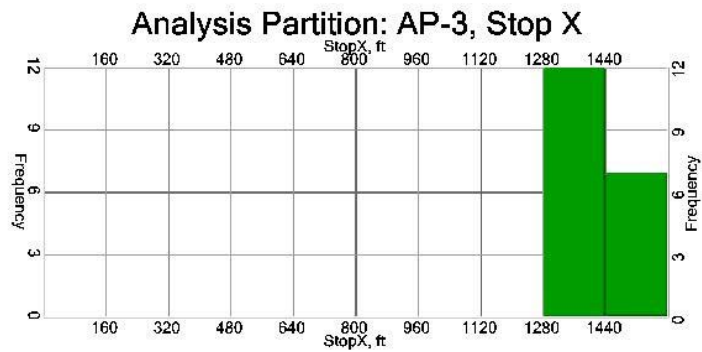
### Velocity (ft/s)



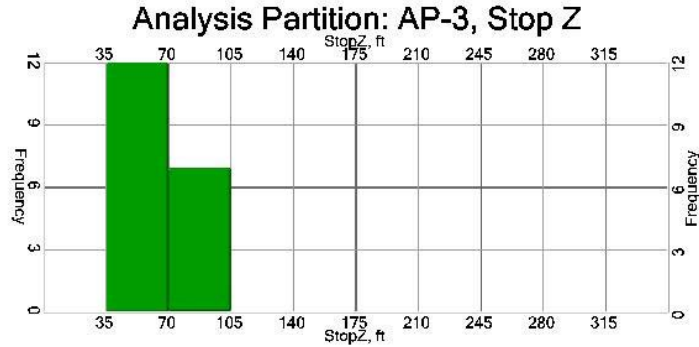
### Kinetic Energy (kJ)



### Rollout Stop X (ft) for rocks passing Analysis Partition 3



Rollout Stop Z (ft) for rocks passing Analysis Partition 3



Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

CRSP Rockfall Results for Analysis Partition AP-4

Summary of Results

Max Bounce Ht, ft	Max Velocity, ft/s	Max Energy, ft-kips	Max Energy, kJ	Percent Passing
67	109	71368	96760	95%

Cumulative Probability

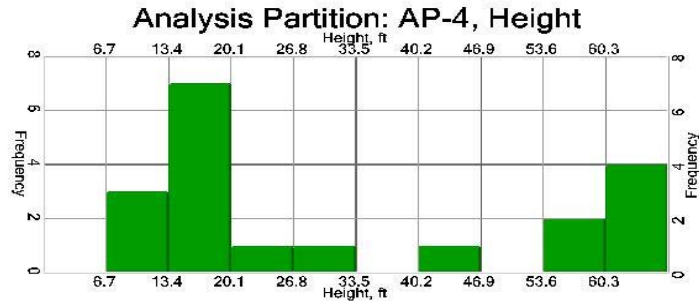
Cumulative Probability	Bounce Ht, ft	Velocity, ft/s	Energy, ft-kips	Energy, kJ	Rollout X, ft	Rollout Z, ft
50%	20.2	77	36220	49106	1418	67
75%	59.0	88	44999	61007	1483	78
90%	64.7	97	55133	74747	1547	88
95%	66.6	104	66695	90422	1584	94
98%	68.3	111	72262	97970	1623	101

# Colorado Rockfall Simulation Program -- CRSP-3D

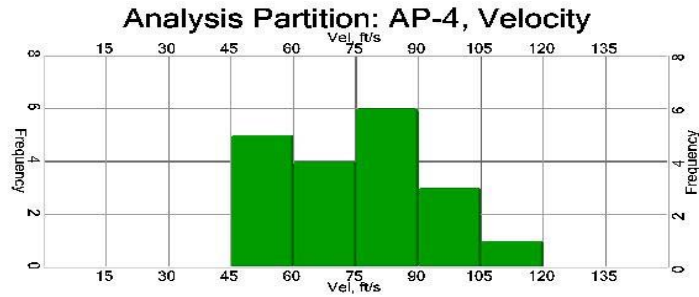
Project Name: Canyon Lidar 3D Sphere

## CRSP Rockfall Results for Analysis Partition 4

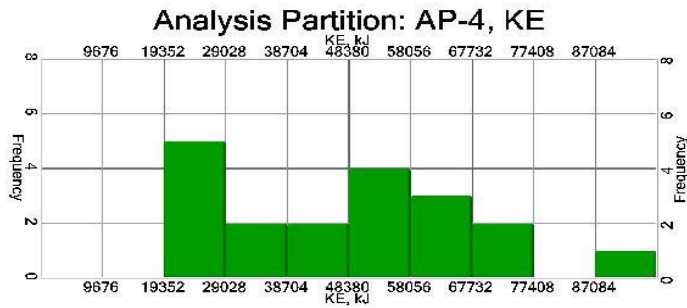
### Height (ft)



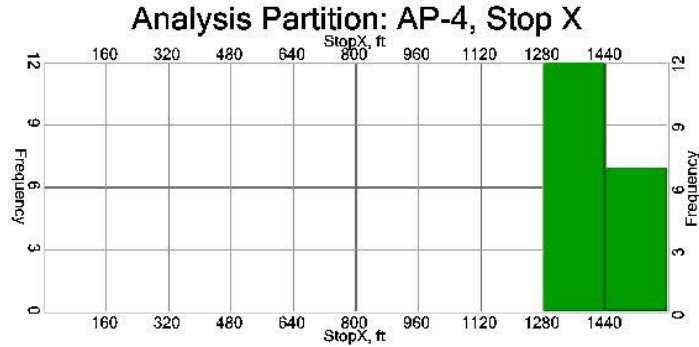
### Velocity (ft/s)



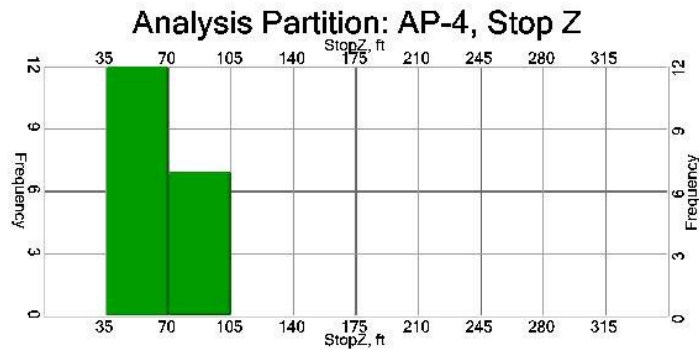
### Kinetic Energy (kJ)



Rollout Stop X (ft) for rocks passing Analysis Partition 4



Rollout Stop Z (ft) for rocks passing Analysis Partition 4



Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon Lidar 3D Sphere

CANYON 2D SPHERE EXAMPLE #3

REPORT

# Colorado Rockfall Simulation Program -- CRSP-3D

## CRSP Rockfall Analysis

CRSP was used to determine the expected kinetic energy and bouncing height of falling rocks at various points along the slope. In the analysis, it was assumed that irregular shaped boulders with a maximum diameter of 15.0 feet would impact the rockfall retaining system. For each simulation, the model rolled 20 shaped rocks from a source area at 815 feet. A slope surface roughness of 0.1 - 4.0, and hardness of 0.2 - 0.9 were used.

### PROJECT INFORMATION

Project Name	Canyon 2D Sphere
Project Number	1235
Company Name	Acme Slope Consulting
Location	Colorado
Designer	D. Ziner
Reviewer	R. Viewer
Date	2-25-11

### Material Properties

		English	Units	SI	Units
Material 1	<i>ID</i>	FirmSoil		<i>FirmSoil</i>	
	<i>Color</i>	Yellow		<i>Yellow</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.3		<i>0.3</i>	
Material 2	<i>ID</i>	Rock Cliff		<i>Rock Cliff</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 3	<i>ID</i>	Vegetated Soil		<i>Vegetated Soil</i>	
	<i>Color</i>	Red		<i>Red</i>	
	<i>Roughness</i>	0.5	ft	<i>0.15</i>	<i>m</i>
	<i>Hardness</i>	0.2		<i>0.2</i>	
Material 4	<i>ID</i>	Vegetated Soil		<i>Vegetated Soil</i>	
	<i>Color</i>	Red		<i>Red</i>	
	<i>Roughness</i>	0.5	ft	<i>0.15</i>	<i>m</i>

**APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 2D SPHERE EXAMPLE #3**

	<i>Hardness</i>	0.2		<i>0.2</i>	
Material 5	<i>ID</i>	Release Zone		<i>Release Zone</i>	
	<i>Color</i>	Green		<i>Green</i>	
	<i>Roughness</i>	0.5	ft	<i>0.15</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 6	<i>ID</i>	Small Talus		<i>Small Talus</i>	
	<i>Color</i>	Gray		<i>Gray</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.4		<i>0.4</i>	
Material 7	<i>ID</i>	Boulder Field		<i>Boulder Field</i>	
	<i>Color</i>	DarkGray		<i>DarkGray</i>	
	<i>Roughness</i>	4	ft	<i>1.22</i>	<i>m</i>
	<i>Hardness</i>	0.6		<i>0.6</i>	
Material 8	<i>ID</i>	Hard Bedrock		<i>Hard Bedrock</i>	
	<i>Color</i>	Magenta		<i>Magenta</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.9		<i>0.9</i>	
Material 9	<i>ID</i>	Firm Soil Again		<i>Firm Soil Again</i>	
	<i>Color</i>	Yellow		<i>Yellow</i>	
	<i>Roughness</i>	1	ft	<i>0.3</i>	<i>m</i>
	<i>Hardness</i>	0.3		<i>0.3</i>	
Material 10	<i>ID</i>	Pavement		<i>Pavement</i>	
	<i>Color</i>	Blue		<i>Blue</i>	
	<i>Roughness</i>	0.1	ft	<i>0.03</i>	<i>m</i>
	<i>Hardness</i>	0.8		<i>0.8</i>	

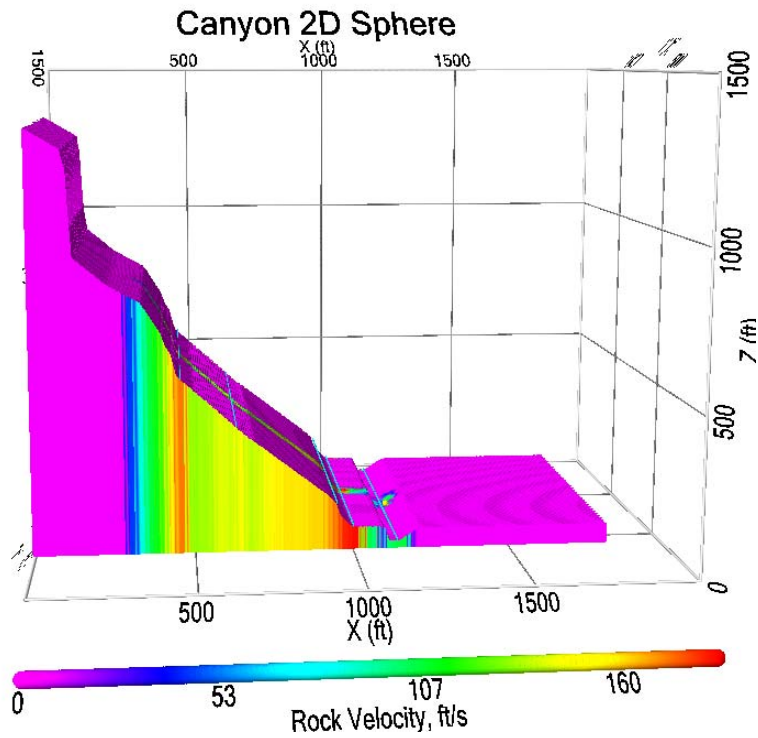
**Analysis Partition Properties**

		English	Units	<i>SI</i>	<i>Units</i>
Analysis Partition 1	<i>ID</i>	AP-1		<i>AP-1</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	457	ft	<i>139</i>	<i>m</i>
Analysis Partition 2	<i>ID</i>	AP-2		<i>AP-2</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	626	ft	<i>191</i>	<i>m</i>
Analysis Partition 3	<i>ID</i>	AP-3		<i>AP-3</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	938	ft	<i>286</i>	<i>m</i>
Analysis Partition 4	<i>ID</i>	AP-4		<i>AP-4</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	989	ft	<i>301</i>	<i>m</i>
Analysis Partition 5	<i>ID</i>	AP-5		<i>AP-5</i>	
	<i>Color</i>	Cyan		<i>Cyan</i>	
	<i>Dir</i>	X		<i>X</i>	
	<i>Location</i>	1126	ft	<i>343</i>	<i>m</i>

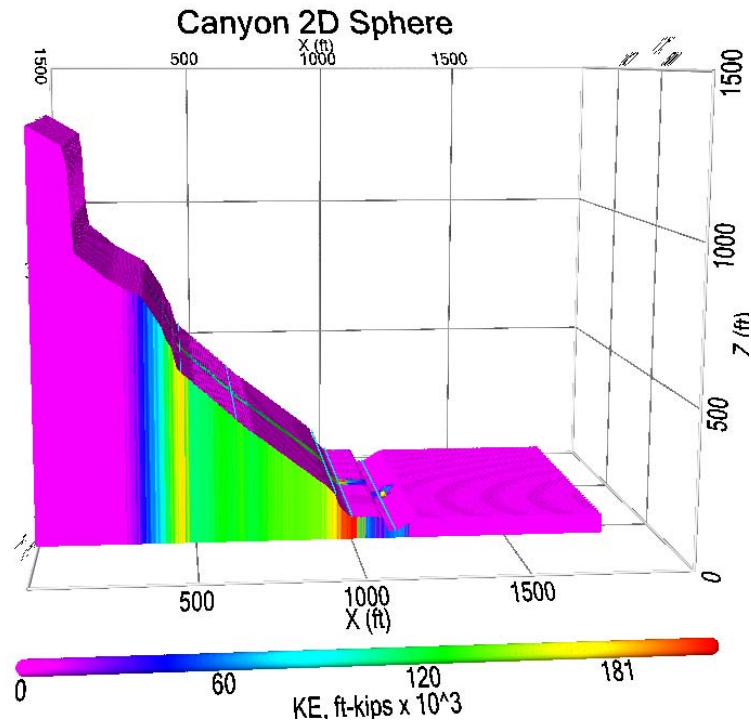
**Rockfall Parameters**

		English	Units	<i>SI</i>	<i>Units</i>
Rockfall Parameter 1	<i>Release Zone</i>	Release Zone		<i>Release Zone</i>	
	<i>γ</i>	165	pcf	<i>25.9</i>	<i>kN/m<sup>3</sup></i>
	<i>Rocks to Release</i>	20		<i>20</i>	
	<i>Shape</i>	One_Element_Sphere		<i>One_Element_Sphere</i>	
	<i>Size</i>	15	ft	<i>4.572</i>	<i>m</i>

RockVelocity



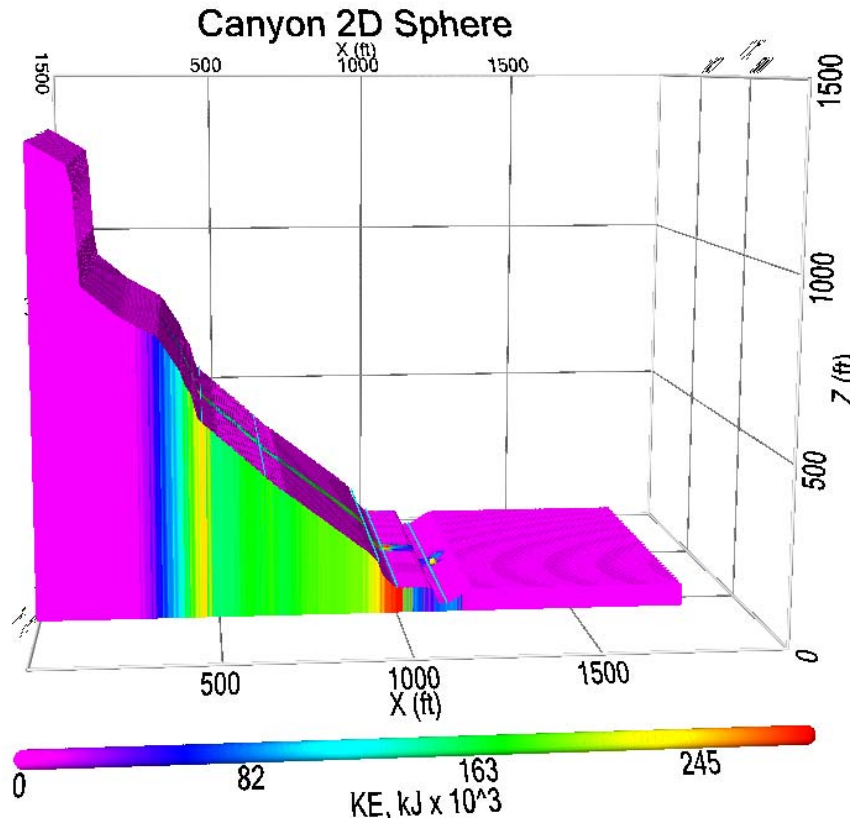
RockKineticEnergyFtKips



RockKineticEnergyKJ



APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 2D SPHERE EXAMPLE #3



## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

11

### CRSP Rockfall Results for Colorado and Analysis Partition AP-1

#### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
<i>56</i>	<i>152</i>	<i>138899</i>	<i>188319</i>	<i>100%</i>

#### Cumulative Probability

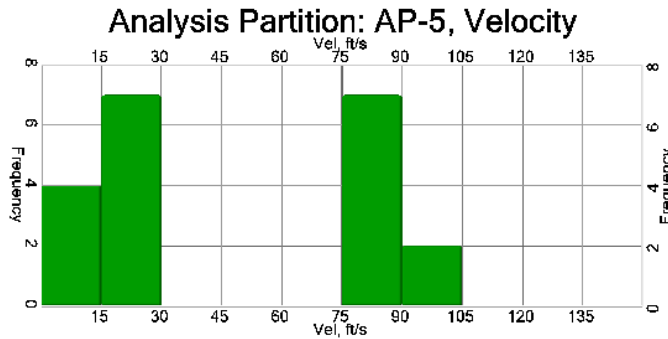
<i>Cumulative Probability</i>	<i>Bounce Ht, ft</i>	<i>Velocity, ft/s</i>	<i>Energy, ft-kips</i>	<i>Energy, kJ</i>	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
<i>50%</i>	<i>48.1</i>	<i>137</i>	<i>116607</i>	<i>158095</i>	<i>1129</i>	<i>68</i>
<i>75%</i>	<i>51.8</i>	<i>146</i>	<i>126677</i>	<i>171748</i>	<i>1163</i>	<i>74</i>
<i>90%</i>	<i>54.2</i>	<i>153</i>	<i>133205</i>	<i>180599</i>	<i>1193</i>	<i>81</i>
<i>95%</i>	<i>55.5</i>	<i>156</i>	<i>137025</i>	<i>185778</i>	<i>1212</i>	<i>86</i>
<i>98%</i>	<i>56.9</i>	<i>160</i>	<i>141331</i>	<i>191616</i>	<i>1233</i>	<i>92</i>

# Colorado Rockfall Simulation Program -- CRSP-3D

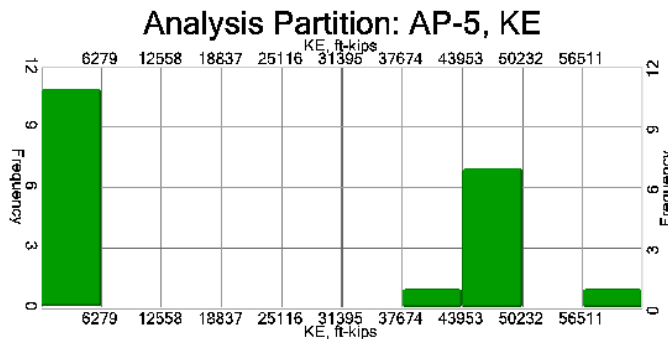
Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-11

## CRSP Rockfall Results for Station Colorado and Analysis Partition 1

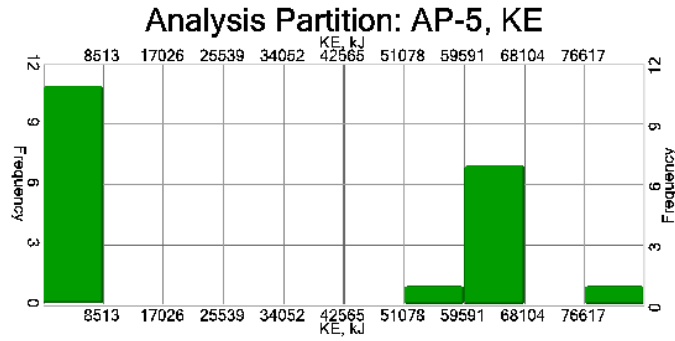
### Velocity (ft/s)



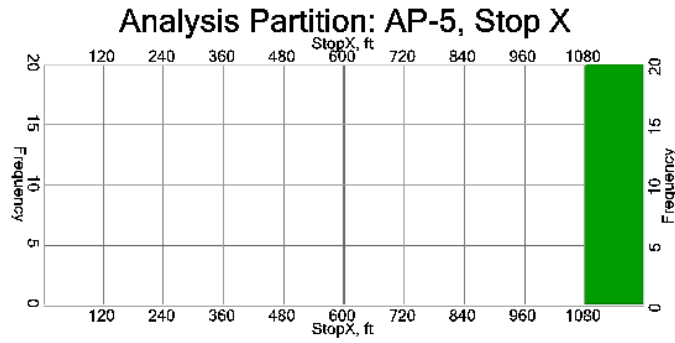
### Kinetic Energy (ft-kips)



### Kinetic Energy (kJ)



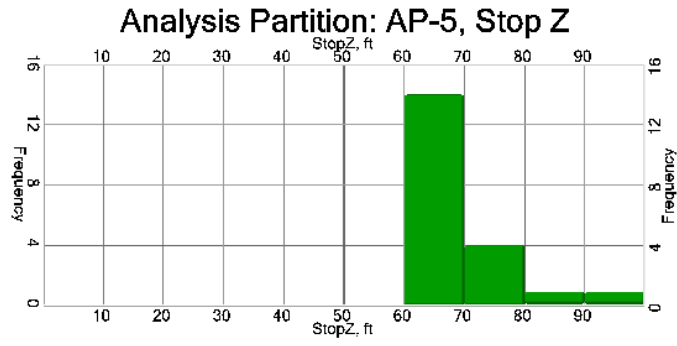
### Rollout Stop X (ft) for rocks passing Analysis Partition 1



### Rollout Stop Z (ft) for rocks passing Analysis Partition 1

APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 2D SPHERE EXAMPLE #3

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## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

11

### CRSP Rockfall Results for Colorado and Analysis Partition AP-2

#### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
<i>10</i>	<i>138</i>	<i>113398</i>	<i>153745</i>	<i>100%</i>

#### Cumulative Probability

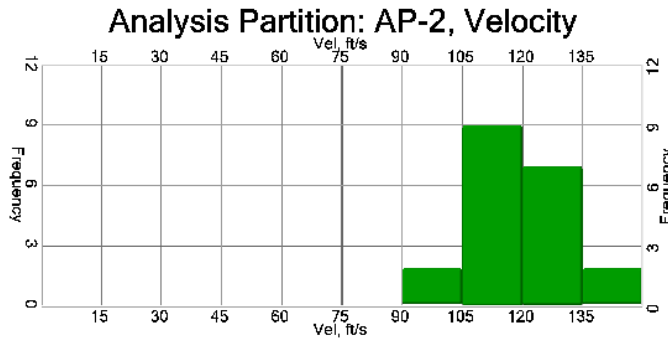
<i>Cumulative Probability</i>	<i>Bounce Ht, ft</i>	<i>Velocity, ft/s</i>	<i>Energy, ft-kips</i>	<i>Energy, kJ</i>	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
<i>50%</i>	<i>8.4</i>	<i>119</i>	<i>84256</i>	<i>114236</i>	<i>1129</i>	<i>68</i>
<i>75%</i>	<i>8.8</i>	<i>130</i>	<i>102457</i>	<i>138913</i>	<i>1163</i>	<i>74</i>
<i>90%</i>	<i>9.2</i>	<i>137</i>	<i>110678</i>	<i>150060</i>	<i>1193</i>	<i>81</i>
<i>95%</i>	<i>9.4</i>	<i>140</i>	<i>113854</i>	<i>154365</i>	<i>1212</i>	<i>86</i>
<i>98%</i>	<i>9.6</i>	<i>144</i>	<i>116859</i>	<i>158439</i>	<i>1233</i>	<i>92</i>

# Colorado Rockfall Simulation Program -- CRSP-3D

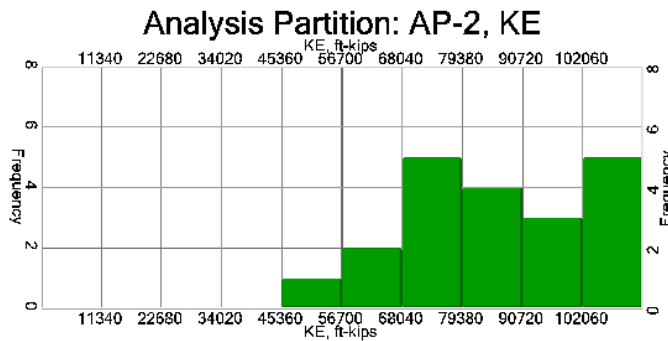
Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-11

## CRSP Rockfall Results for Station Colorado and Analysis Partition 2

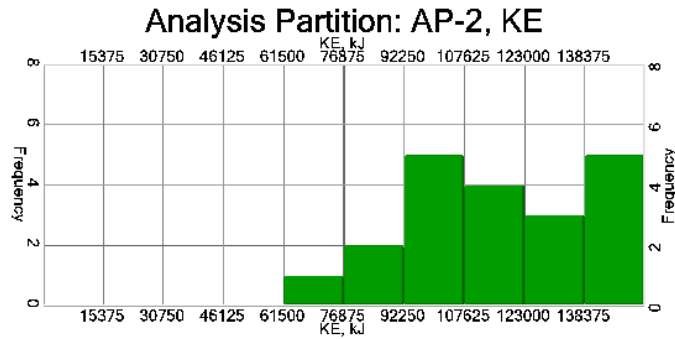
### Velocity (ft/s)



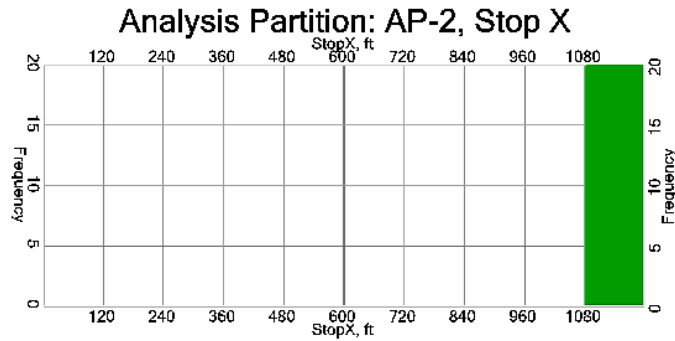
### Kinetic Energy (ft-kips)



### Kinetic Energy (kJ)



### Rollout Stop X (ft) for rocks passing Analysis Partition 2

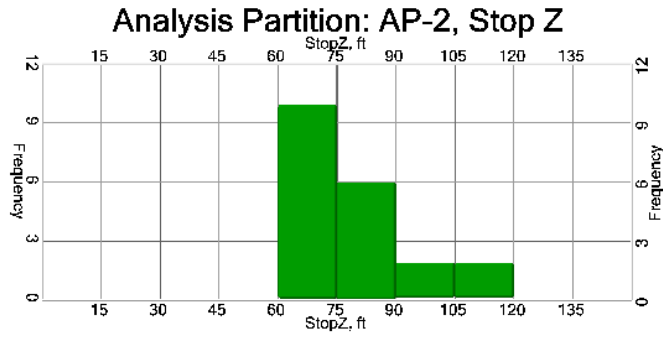


### Rollout Stop Z (ft) for rocks passing Analysis Partition 2



APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 2D SPHERE EXAMPLE #3

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## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

11

### CRSP Rockfall Results for Colorado and Analysis Partition AP-3

#### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
<i>16</i>	<i>162</i>	<i>156924</i>	<i>212758</i>	<i>100%</i>

#### Cumulative Probability

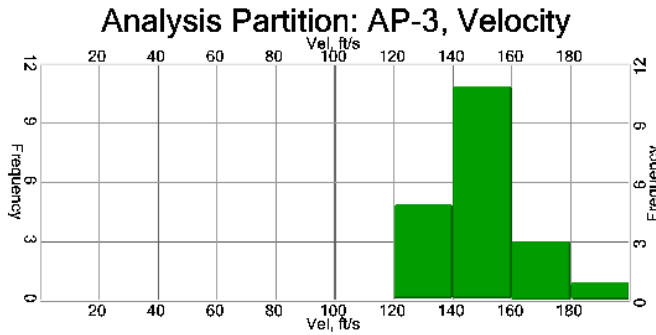
<i>Cumulative Probability</i>	<i>Bounce Ht, ft</i>	<i>Velocity, ft/s</i>	<i>Energy, ft-kips</i>	<i>Energy, kJ</i>	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
<i>50%</i>	<i>13.7</i>	<i>149</i>	<i>133469</i>	<i>180952</i>	<i>1129</i>	<i>68</i>
<i>75%</i>	<i>14.6</i>	<i>156</i>	<i>143669</i>	<i>194782</i>	<i>1163</i>	<i>74</i>
<i>90%</i>	<i>15.3</i>	<i>162</i>	<i>151673</i>	<i>205633</i>	<i>1193</i>	<i>81</i>
<i>95%</i>	<i>15.8</i>	<i>166</i>	<i>156145</i>	<i>211696</i>	<i>1212</i>	<i>86</i>
<i>98%</i>	<i>16.3</i>	<i>170</i>	<i>160696</i>	<i>217866</i>	<i>1233</i>	<i>92</i>

# Colorado Rockfall Simulation Program -- CRSP-3D

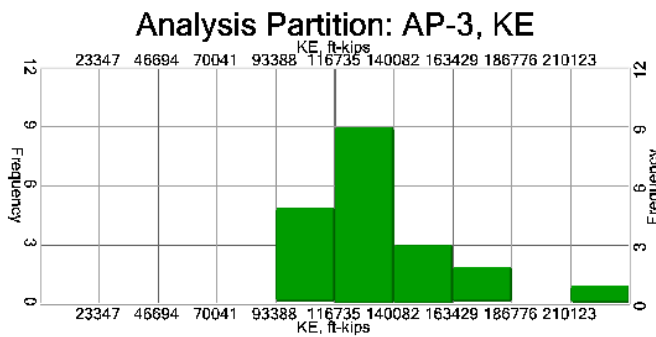
Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-11

## CRSP Rockfall Results for Station Colorado and Analysis Partition 3

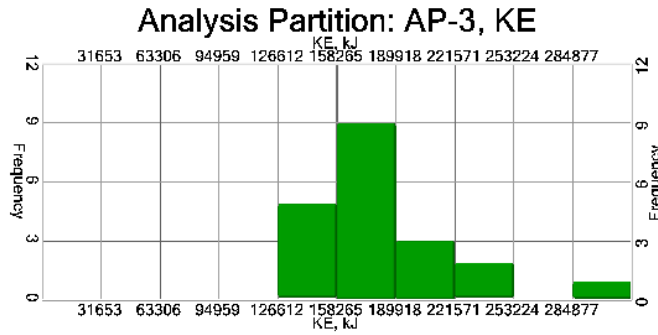
### Velocity (ft/s)



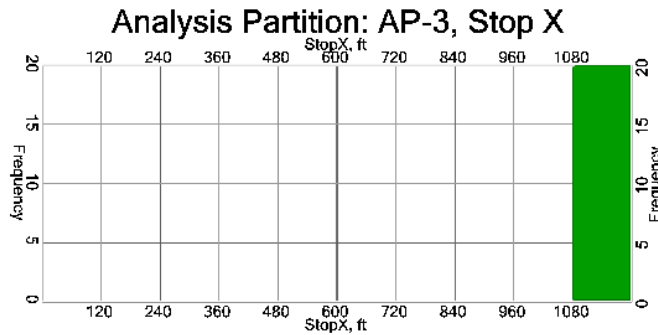
### Kinetic Energy (ft-kips)



### Kinetic Energy (kJ)



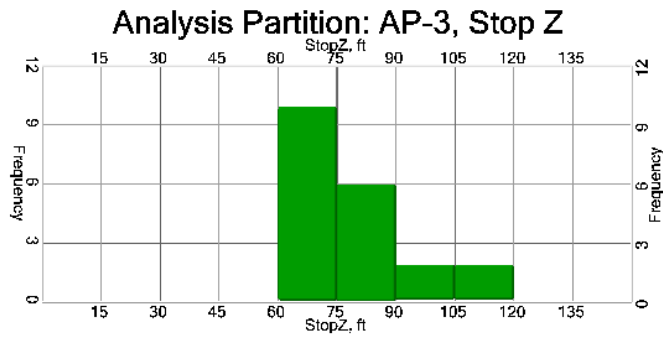
### Rollout Stop X (ft) for rocks passing Analysis Partition 3



### Rollout Stop Z (ft) for rocks passing Analysis Partition 3

APPENDIX B – CRSP-3D REPORT OUTPUT FOR EXAMPLES  
CANYON LIDAR 2D SPHERE EXAMPLE #3

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## Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

11

### CRSP Rockfall Results for Colorado and Analysis Partition AP-4

#### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
43	182	197839	268230	100%

#### Cumulative Probability

Cumulative Probability	Bounce Ht, ft	<i>Velocity, ft/s</i>	Energy, ft-kips	Energy, kJ	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
50%	33.4	171	175484	237920	1129	68
75%	36.5	177	185376	251332	1163	74
90%	38.9	183	193883	262865	1193	81
95%	40.7	187	198631	269303	1212	86
98%	42.7	191	203676	276143	1233	92

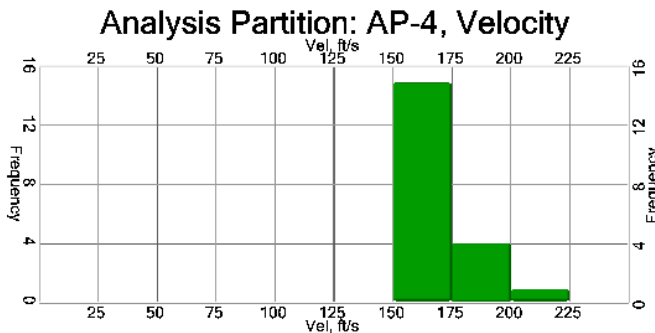
# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

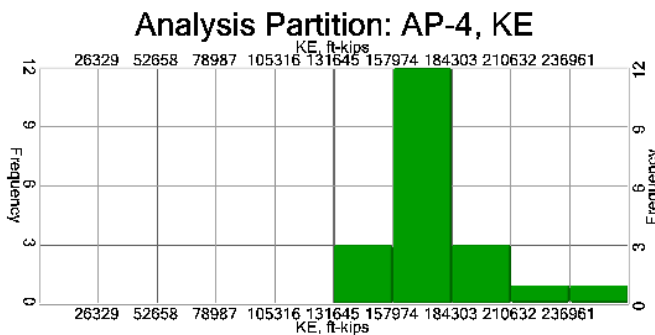
11

## CRSP Rockfall Results for Station Colorado and Analysis Partition 4

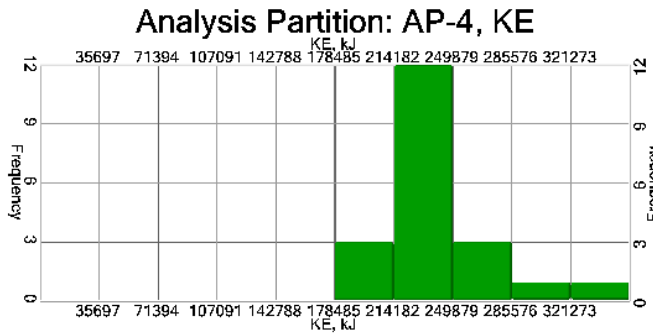
### Velocity (ft/s)



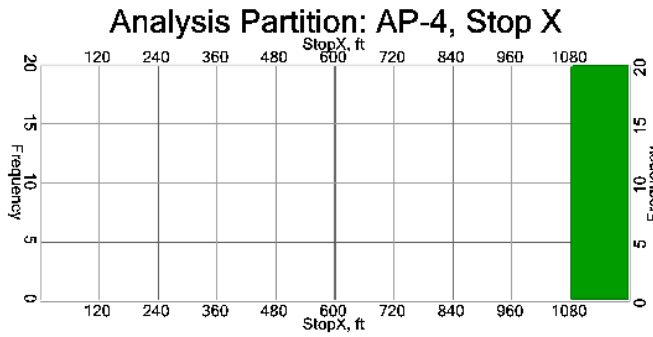
### Kinetic Energy (ft-kips)



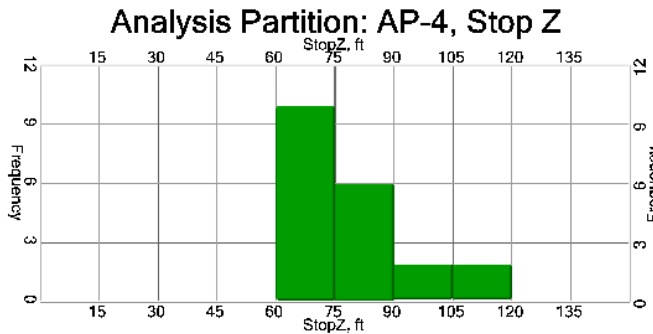
Kinetic Energy (kJ)



Rollout Stop X (ft) for rocks passing Analysis Partition 4



Rollout Stop Z (ft) for rocks passing Analysis Partition 4





# Colorado Rockfall Simulation Program -- CRSP-3D

Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope  
 Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-

11

## CRSP Rockfall Results for Colorado and Analysis Partition AP-5

### Summary of Results

<i>Max Bounce Ht, ft</i>	<i>Max Velocity, ft/s</i>	<i>Max Energy, ft-kips</i>	<i>Max Energy, kJ</i>	<i>Percent Passing</i>
39	103	62784	85122	100%

### Cumulative Probability

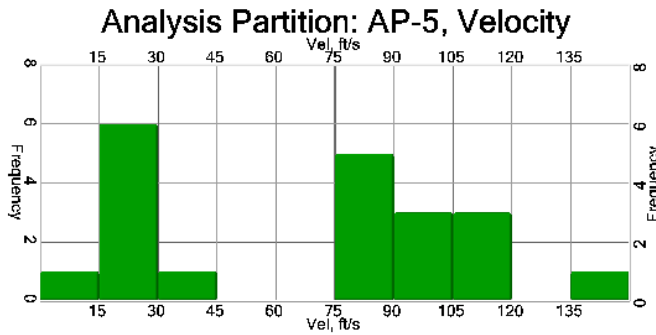
Cumulative Probability	Bounce Ht, ft	<i>Velocity, ft/s</i>	Energy, ft-kips	Energy, kJ	<i>Rollout X, ft</i>	<i>Rollout Z, ft</i>
50%	8.4	32	39275	53249	1129	68
75%	24.4	88	46779	63422	1163	74
90%	31.9	95	50577	68572	1193	81
95%	35.7	99	59745	81001	1212	86
98%	39.1	104	63732	86407	1233	92

# Colorado Rockfall Simulation Program -- CRSP-3D

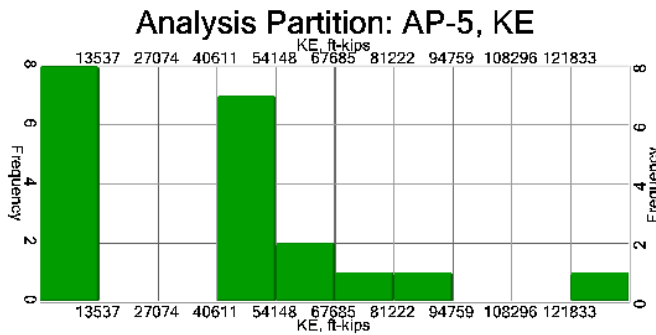
Project Name: Canyon 2D Sphere Project Number: 1235 Company Name: Acme Slope Consulting Location: Colorado Designer: D. Ziner Reviewer: R. Viewer Date: 2-25-11

## CRSP Rockfall Results for Station Colorado and Analysis Partition 5

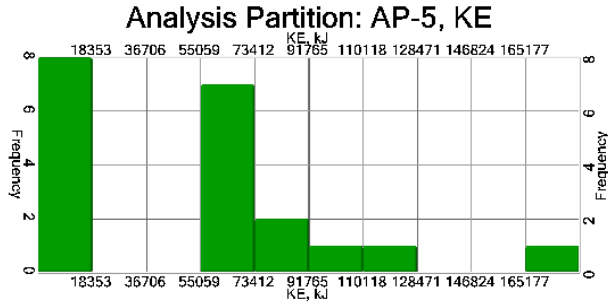
### Velocity (ft/s)



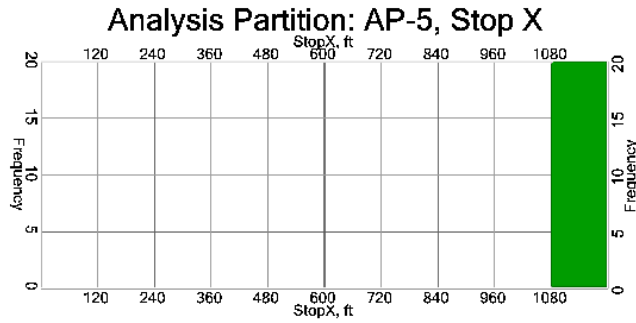
### Kinetic Energy (ft-kips)



### Kinetic Energy (kJ)



### Rollout Stop X (ft) for rocks passing Analysis Partition 5



### Rollout Stop Z (ft) for rocks passing Analysis Partition 5

