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Project Title

A RATIONAL PROCEDURE FOR ROCK SLOPE DESIGN FOR WESTERN PENNSYLVANIA

Supplement to Project Report

DESIGN GUIDANCE MANUAL

December 31, 2008

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COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 510601
WORK ORDER # PIT 005

A RATIONAL PROCEDURE FOR ROCK SLOPE DESIGN FOR WESTERN PENNSYLVANIA

PennDOT Work Order No. 5

Design Guidance Manual

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12/31/2008

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INTRODUCTION

This manual provides guidance and suggestions on rock slope design with the aid of Colorado Rockfall Simulation Program (CRSP). It encompasses the field data collection, program input data selection and typical run interpretation. In this manual, the suggested procedures are detailed first, followed by a detailed application example: S.R. 0028 Southbound, Segment 251 within Allegheny County, Pennsylvania, which is also denoted as Slope 3 in the following text as well as in the report of Work Order No. 5. Additionally, the same procedure is depicted for: Slope 5, S.R. 0051 Southbound Segment 741, Allegheny County, PA, and Slope 7, S.R. 0060 Eastbound, Segment 180, Beaver County, PA.

Overview of CRSP and the required input can be found in the report of Work Order No. 5, as well as in the CRSP user manual (included in the CRSP software package). The present Guidance Manual only describes how the input to the program may be obtained and how the analysis might be carried out. It is important to state at the outset that to properly carry out an analysis requires an assembly of a competent team that comprises seasoned engineering geologists as well as experienced geotechnical engineers.

1. COMPILATION OF BASE MAPPING DATA

The first step of the investigation consists of a literature search which consists of gathering and reviewing the site soils, geology, topographic data, and any relevant geotechnical engineering reports. In the event that site specific survey data are not available, a potential source of high resolution data of the studied area may be obtained from the Pennsylvania Department of Conservation and Natural Resources (DCNR) Website where high resolution topographic data obtained via Light Detection and Ranging (LiDAR) surveys may be downloaded (http://www.dcnr.state.pa.us/topogeo/pamap/lidarprog.aspx). It is important to verify that the site has not been modified after the LiDAR surveys were completed. Another alternative is to digitalize the profile of a site from a topographic survey map of high resolution. It is also important to note that the survey data, LiDAR Data, or other types of data are important because during the field collection of the CRSP data, existing slopes are sometimes inaccessible or simply far too dangerous to walk on to gather site specific geometric data. The actual thicknesses of bedrock units and existing slope angles can be estimated in the field and are further refined based on the various survey data. These survey data form the basis for generating the input geometry data to CRSP and should be as accurate as possible. Geological mapping and the site stratigraphy should be consulted to determine the stratigraphic bedrock and soils units. The geologic mapping may provide preliminary regional information of joint trends, bedrock structure, and locations of bedrock units which may be prone to rapid weathering or other stability issues. The geologic mapping will provide insight during the field activities for the identification of potential problem zones. The geological stratigraphy of

Allegheny County is presented in Appendix A of the Work Order No. 5 report, and the data used for example 3 is presented below.

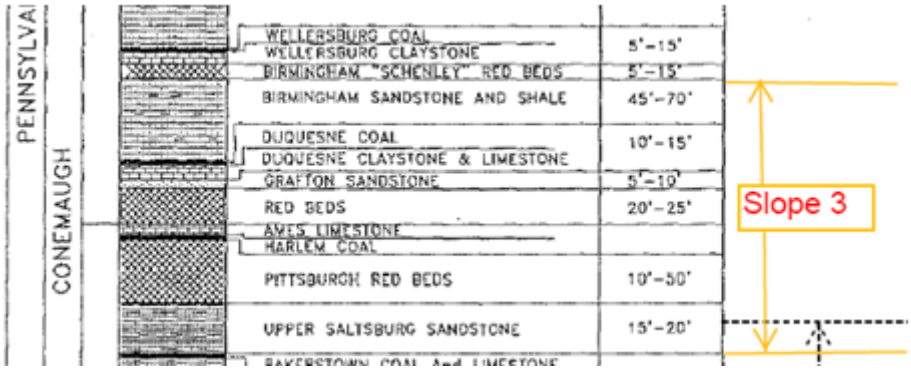


FIGURE 1-1. SLOPE 3 ON THE STRATIGRAPHY PROFILE OF ALLEGHENY COUNTY.

FIGURE 1-2. LIDAR DATA SUPERIMPOSED OVER THE AERIAL PHOTO FOR THE EXAMPLE SITE.

2. COLLECTION OF FIELD DATA

The following data forms were created to ensure that the field work generated the necessary information required by CRSP and provided uniform assessment across multiple sites. Refer to Appendix A for blank field data collection sheets. The data sheets were designed to document the collection of the following data:

- Slope Stratigraphy and Cross Sectional Information
- Slope, bedrock, and Joint Orientations
- Catchment Basin & Barrier Information
- CRSP Input Parameters.

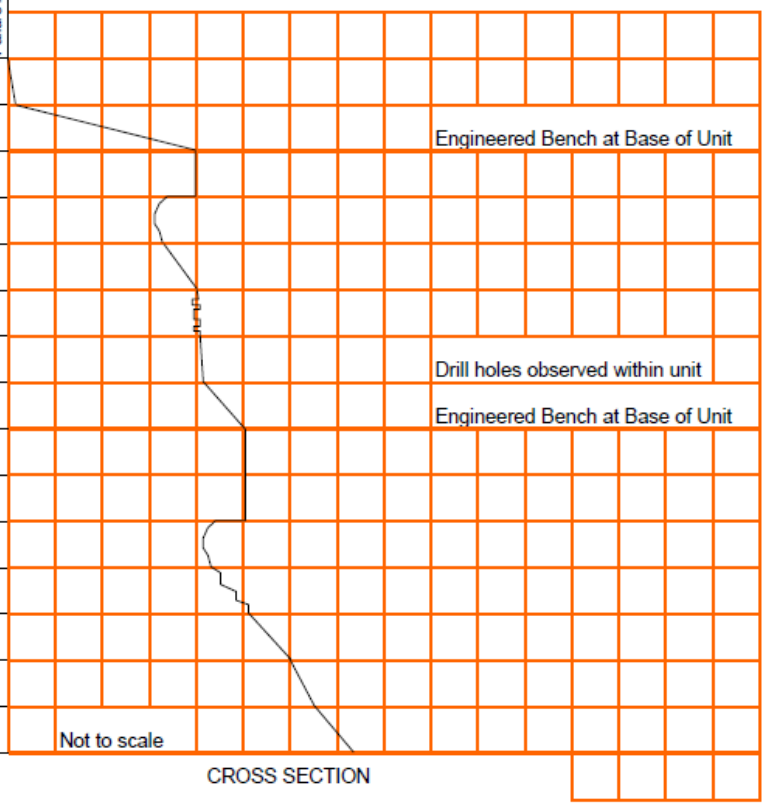
While working on the slope cross section description in the field, one should recognize the layered structure and identify every possible change of material and/or surface inclination. This information is to be recorded into the form "Step 1 Slope Cross Section" (Figure 3) and it's level of acuracy strongly affects the outcome of a CRSP analysis and the projected rockfalls. Figure 4 shows how the slope profile is perceived by the geologist during the field work of Slope. Likewise, it is important to describe in detail the toe characteristics and/or the containment ditch/basin, if any. This information is recorded into the form "Step 2 Containment Ditch and Barrier Cross Section" (Figure 5).

Step 1 Slope Cross Section

Slope Cross Section Slope # 3 Sheet 1 of 1

Stratigraphic Sequence Initial Design Degree of cut slope:

Rock Type	Unit Thickness (1)	Degree of Weathering (2)	Weathering Rate (3)	Est. Largest Block Diameter (ft)	Face Angle (4)	Overhanging (5)	Fall Potential (6)	CRSP Cell #	Failure Mode(7)
Sandstone (Massive)	40.0	M		10.0	75	N	Y	1	J
Talus	6.0	C		0.6	20	N	N	2	F
Sandstone (Massive)	20.0	M		10.0	90	O	Y	3	J/U
Claystone (Redbeds)	7.0	H		0.5	90	P	Y	4	F
Mudstone	8.0	M		3	55	N	P	5	F/J
Sandstone w/Int. Mudstone	8.0	M		2.0	85	N	Y	6	F
Sandstone (Massive)	10.0	S		3.0	85	N	Y	7	J
Talus	8.0	C		1.0	51	N	Y	8	F
Sandstone (Massive)	4.0	S		10.0	90	Y	Y	9	J/U
Sandy Shale	7.0	S		20.0	90	P	Y	10	J
Mudstone	5.0	M		6.0	62	P	Y	11	F/J
Claystone (Redbeds)	25.0	H		6.0	62	N	Y	12	F/J
Talus	10.0	C		1.5	52	N	Y	13	F
Sandstone (Massive)	6.0	S		1.5	65	N	Y	14	J
Talus (Excavated)	5.0	C		0.5	50	N	N	15	F



*Unit observed on the ground

(1) Unit thickness based on vertical height in feet.
(2) Value based on visual inspection of unit (H=Highly, M=Moderately, S=Slightly,U=Unweathered, C=Completely)
(3) Weathering rate is based on extent of unit weathering as compared to the unit with least weathering within the same slope.
(4) Face Angle is existing outcrop slope angle.
(5) Indicates unit is overhanging other units, O=Overhanding other units, P=Protected by above overhanging unit, N=Not Overhanging, N/A=Not Applicable)
(6) Indicates whether material will reach the ground from this unit (Y=Yes, N=No, P=Partially Buried in Talus)
(7) How pieces detach from the slope (F=Flaking (Freeze/Thaw), J=Joint Intersections, U=Undercutting, W=Water Transported)

FIGURE 2-1. SLOPE CROSS SECTION DESCRIPTION FOR SLOPE 3.

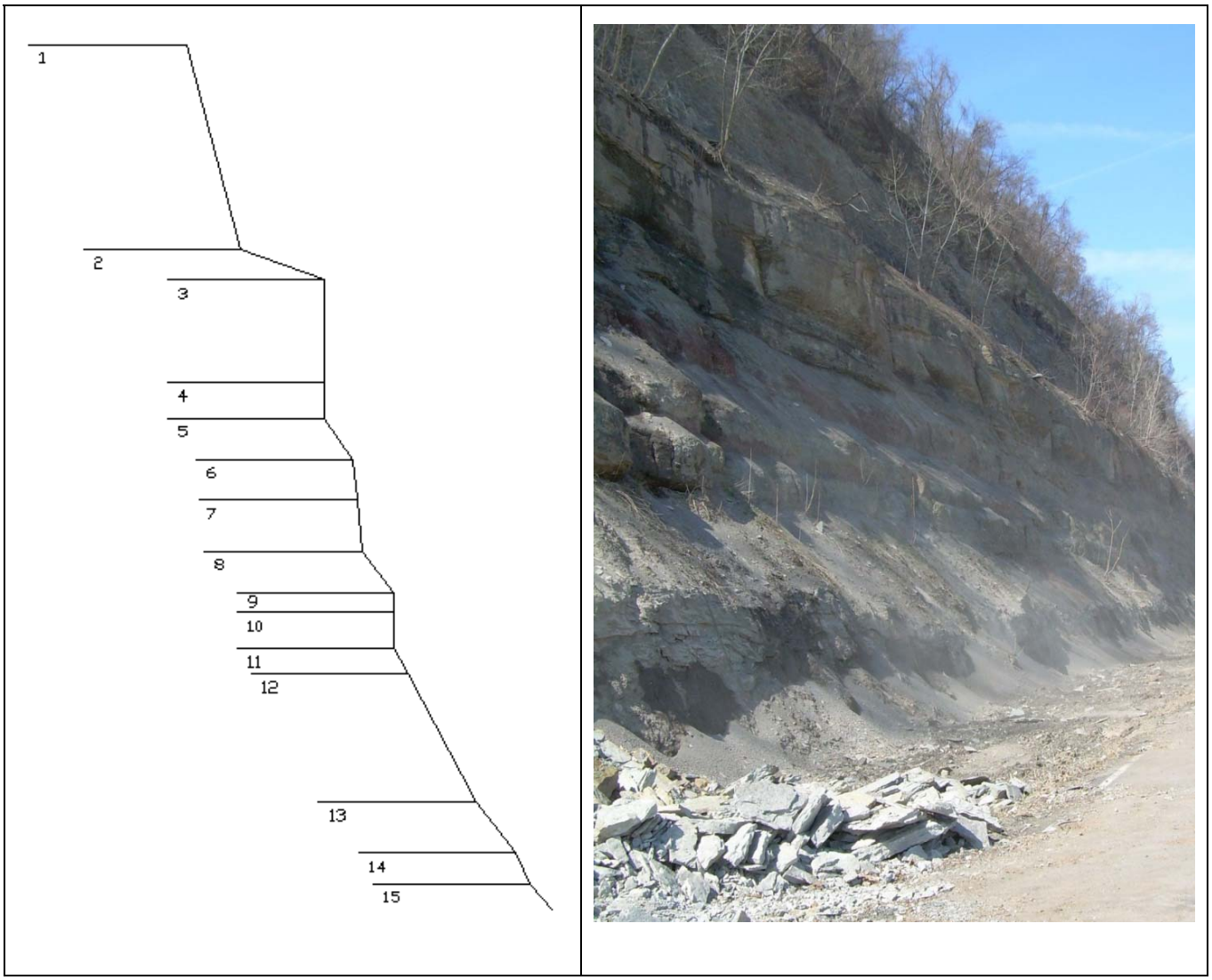


FIGURE 2-2. MAPPING IN THE FIELD, SLOPE 3.

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section Slope # 3 Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

26 feet

Barrier type and dimensions None

Depth of ditch 2.5' recently excavated

Plot distribution of material within ditch. Use CRSP Cell # when possible

Failure Mode: ___ Shatters on impact

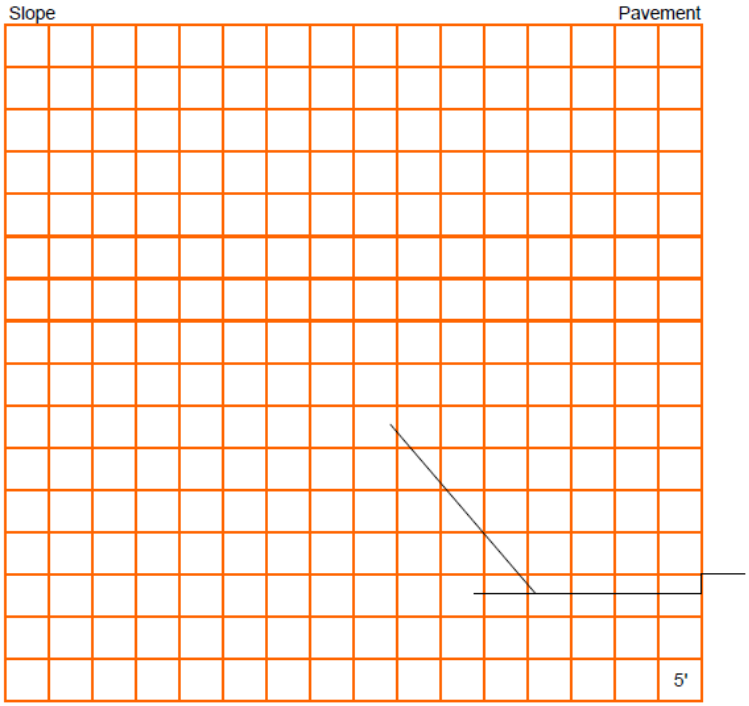
X Falls with subsequent weathering

___ Other (Describe)

Performance ___ Material contained with ditch

X Material on pavement or shoulder

● Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

FIGURE 2-3. COLLECTION OF CATCHMENT DITCH & BARRIER INFORMATION FOR SLOPE 3.

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # 3 Sheet 1 of 1

CRSP Cell # _____

Existing Slope Angle (based off LiDAR) _____

Slope Strike 16

Slope Dip _____

Bedding Strike _____

Dip _____

Road Strike 16

Valley Strike N/A

					RMR Rating					
Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?
1	16	90		3 to 5						
2	274	90		30						
3	240	90		20 to 40						
4	0	90		20 to 100						
5	290	90		3 to ?						

FIGURE 2-4. COLLECTION OF BEDDING, SLOPE, AND DISCONTINUITY ORIENTATION FOR SLOPE 3

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 3
Date: 4/7/2008

					Tangential Coefficient (Rt)				Normal Coefficient (Rn)								Rock Hardness (pcf)			
Cell #	Description	Rock Size (R) Radius (ft)	Surface Roughness (S) (ft) (in one Rock Radius)	Maximum Varation in Slope Angle θ=tan-1 (S/R)	Smooth Hard Surfaces (.9 to 1.0)	Most Bedrock and Boulder Fields (.75 to 0.95)	Talus and firm soil slopes (.65 to .95)	Soft soil slopes (.5 to .8)	Smooth Hard Surfaces (.6 to 1.0)	Most Bedrock and Boulder Fields (.15 to 0.35)	Talus and firm soil slopes (.12 to .2)	Soft soil slopes (.1 to .2)	Begin X	Begin Y	End X	End Y	Hard Sed (150 to 180)	Soft Sed (110 to 150)	Brush Covered Slopes Percent	Rock Shape Spherical (S), Disk (D), or Cylindrical (C)
1	Sandstone (Massive)	5	5			X				X							X			S
2	Talus	0.3	0.5					X				X						X		S
3	Sandstone (Massive)	5	5		X				X								X			S
4	Claystone (Redbeds)	0.25	2					X				X						X		S
5	Mudstone	1.5	2				X				X							X		S
6	Sandstone w/int. Mudstone	1	1.5			X				X								X		S
7	Sandstone (Massive)	1.5	1		X				X								X			S
8	Talus	0.5	1.5					X				X						X		S
9	Sandstone (Massive)	5	1		X				X								X			S
10	Sandy Shale	10	1.5			X				X								X		C
11	Mudstone	1	1.5				X				X							X		S
12	Claystone (Redbeds)	3	5					X				X						X		S
13	Talus	1.25	0.5					X				X						X		S
14	Sandstone (Massive)	0.75	1.5		X				X								X			S
15	Talus (Excavated)	0.25	1					X				X						X		S

FIGURE 2-5. CRSP INPUT PARAMETER COLLECTION FOR SLOPE 3.

Figure 6 depicts the form where bedding, slope, and discontinuity orientation data is recorded. Furthermore with the joint spacing and inclination, one may able to determine possible block sizes that may separate from the slope to produce a rock fall event.

Once the information about a slope is collected, the final "Step 4 CRSP parameters form" (Figure 7) is filled out. This form gathers all the CRSP input variables necessary for each layer composing the cross section profile for analysis. For a detailed explanation of these parameters, please refer to CRSP manual, or the report of Work Order No. 5.

A slope is divided into cells based on the observation of the site stratigraphy. Each cell represents one lithologic unit, either a soil or a rock. It is important to note that stratigraphic sequence of the slope should be based on existing conditions. Talus deposits on a slope should be noted and assigned a separate cell number ignoring the bedrock buried by the talus. AS the presence of a talus deposit changes the restitution characteristics of an impact rock block. The exact starting and ending coordinates of each cell is determined based on the available survey data and is explained below. In addition to the field forms, as many photographs as possible of the site showing the slope profile should be acquired. Refer to the report of Work Order No. 5 for photographs of the study. The field mapping should be doubled checked with other sources of information, such as photos of the site or construction records to provide increase the accuracy of the data.

3. MERGING THE FIELD PROFILE WITH THE SURVEY PROFILE

The field recorded profile needs to be merged with the detailed survey profile before an analysis can be carried out. This task involves correlating the field documented stratigraphic units with the topographic elevations of the survey profile. Less weathered resistant bedrock units will maintain their post construction shape better than those that are more weathered. By locating the less weathered resistant bedrock units on the survey profile, one can estimate the location and slope angle of the more resistant units based on the slope stratigraphic sequence. Note that for bedrock units which weather rapidly and actually undercut less resistant units are sketched as a vertical line on the survey profile. This task is very tedious and care must be given to ensure proper placement of the stratigraphic units. The LiDAR profile on the right below shows a large undulation on the top of the slope because of the presence of trees.

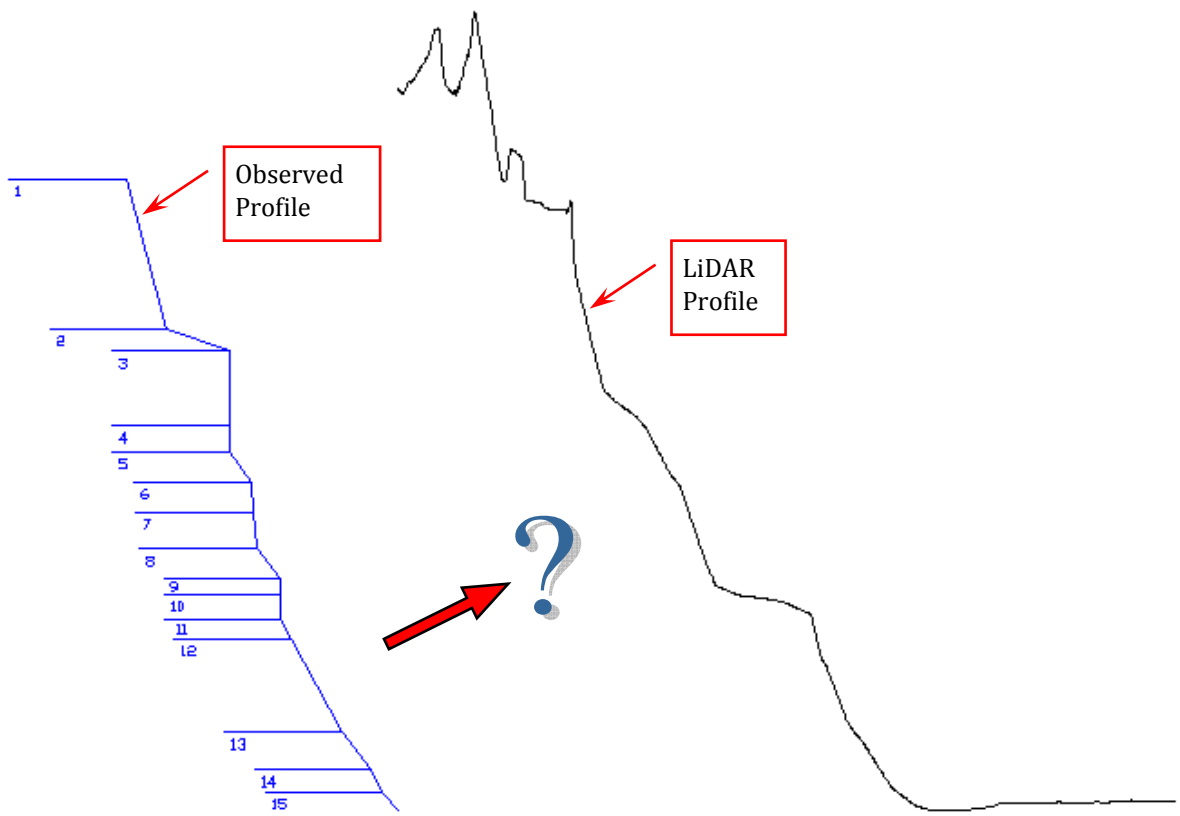


FIGURE 3-1. FIELD RECORDED PROFILE AND LIDAR PROFILE COMPARISON FOR SLOPE 3.

For this example, the field recorded profile is translated into following profile on the right. Unless a detailed field survey is carried out, the use of the fieldwork photographs is fundamental in achieving a good correlation.

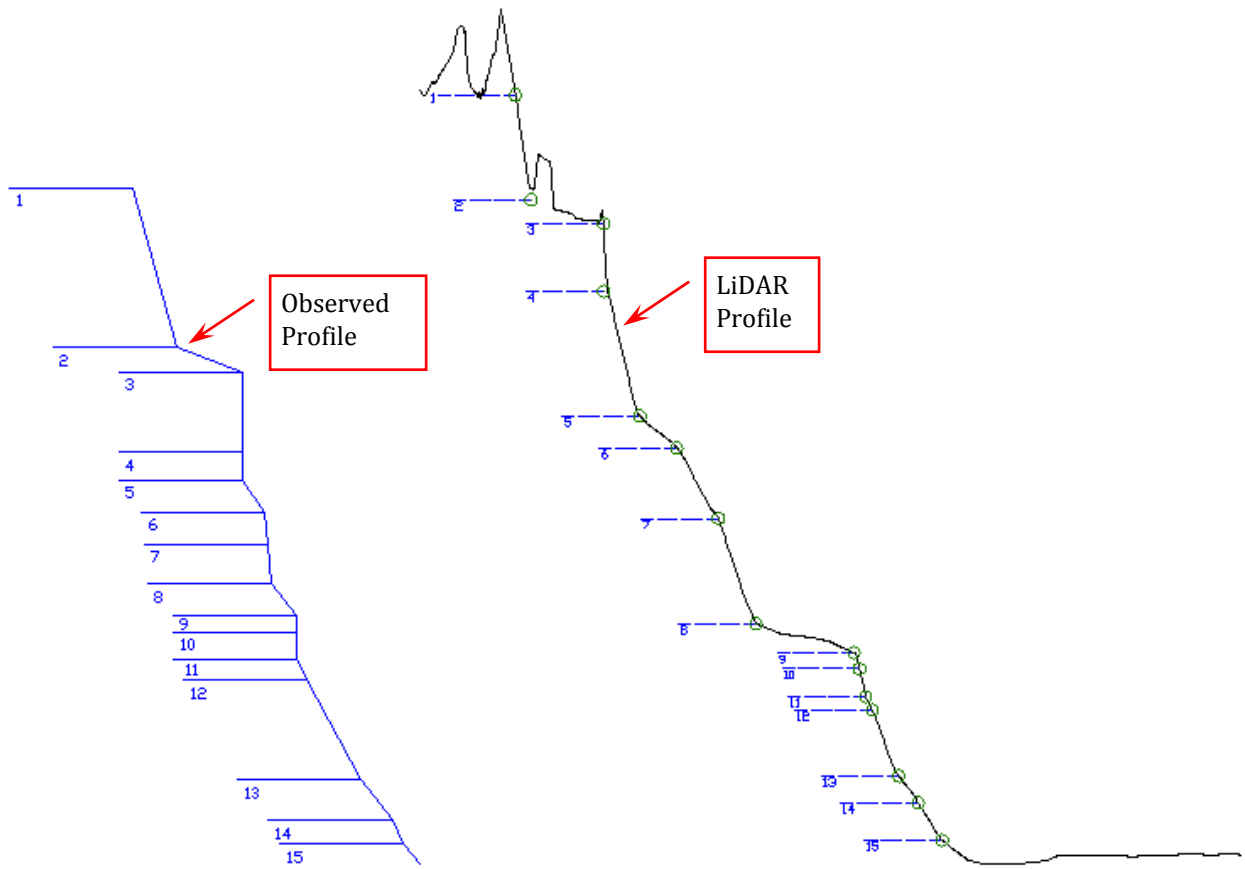


FIGURE 3-2. FIELD PROFILE AND LIDAR PROFILE CORRELATION FOR SLOPE 3.

After cleaning up the suspected vegetation causing undulation on the profile, a design profile is obtained (Figure 10). Specific points that represent the change in slope angle or material are placed on the LiDAR profile in order to determine the Begin X,Y and End X,Y of the "cells" for the CRSP profile. Finally, the representative points are connected through straight line segments (in red), which become the cells of the slope profile. The Begin X,Y and End X,Y of the

cells are easily acquired from the drawing and gathered –to create the input file for CRSP– along with their material parameters, such as surface roughness, tangential coefficient of frictional resistance, normal coefficient of restitution.

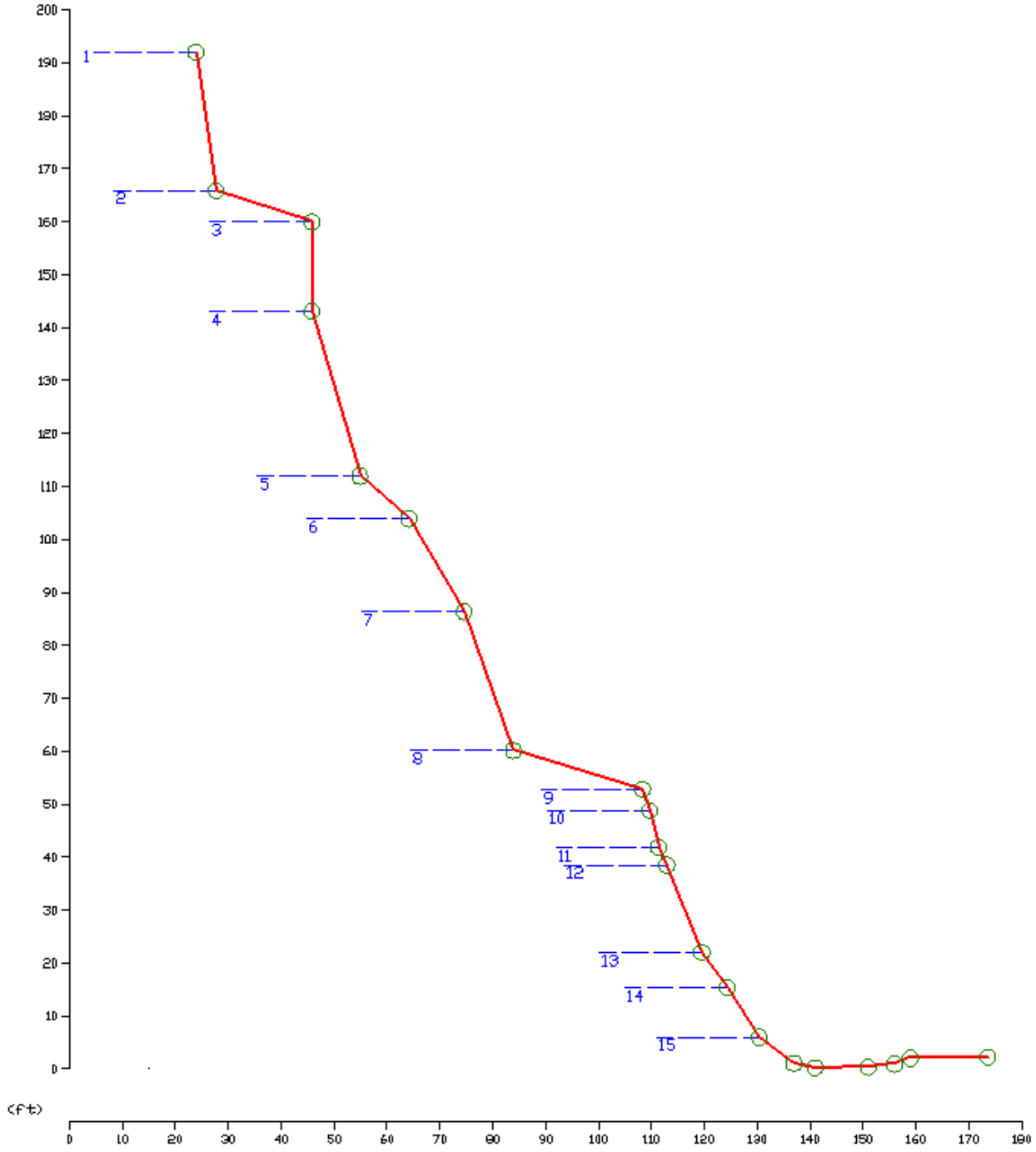


FIGURE 3-3. INPUT CROSS SECTION PROFILE FOR CRSP ANALYSIS ON SLOPE 3.

4. ANALYSIS

Besides the data mentioned above, the input data must include the following information:

- *Analysis point(s):* CRSP requires that at least one point of interest (analysis point) be entered for which the program will provide a detailed statistical analysis. The user may choose to include one, two, or three analysis points. Usually, an analysis point is a position where a mitigation strategy is to be evaluated. This point of interest can be the location of a fence in practice, or the edge of a trench. Only the x-coordinate of an analysis point will need to be entered into the data file (CRSP will calculate the corresponding y-coordinate).
- *Source zone*: CRSP will simulate rockfall from various source locations where rock slides are likely to initiate. The source zone is defined by upper and lower elevations only, which must be entered into the data file as upper and lower y-coordinates.
- *Total number of rocks to be simulated*,
- *Starting velocity*, and,
- Falling rock *density, shape and dimensions*.

The user is suggested to employ the input parameters we calibrated with our field work first.

It is important, however, for a user to run a sensitivity analysis by changing parameters to match the observation at a particular site. IT is possible that the variation of two parameters maybe sufficient for this purpose: They are the Tangential coefficient of frictional resistance, R_t, and the Normal restitution coefficient, R_n.

To match field observation data, one selects an analysis point and computes the percentage of rocks, from various locations of the slope, which would pass through. This is compared with the field observation. If the percentage is too high, one reduces the R_t and R_n, and vice versa. The report of Work Order No. 5 shows that the procedure generally requires the reduction of the values of R_n and R_t. It was observed that the normal coefficient is much more sensitive than the tangential coefficient. Thus, more attention should be paid to R_n than R_t in the coefficient selection process and site-specific calibration efforts. However, the tangential coefficient is observed to be important for hard slopes, presumably because the rock does not embed into hard slopes, while some degree of embedment is likely for softer slopes. Also, the tangential coefficient is known to be important for slopes where vegetation can impede a falling rock.

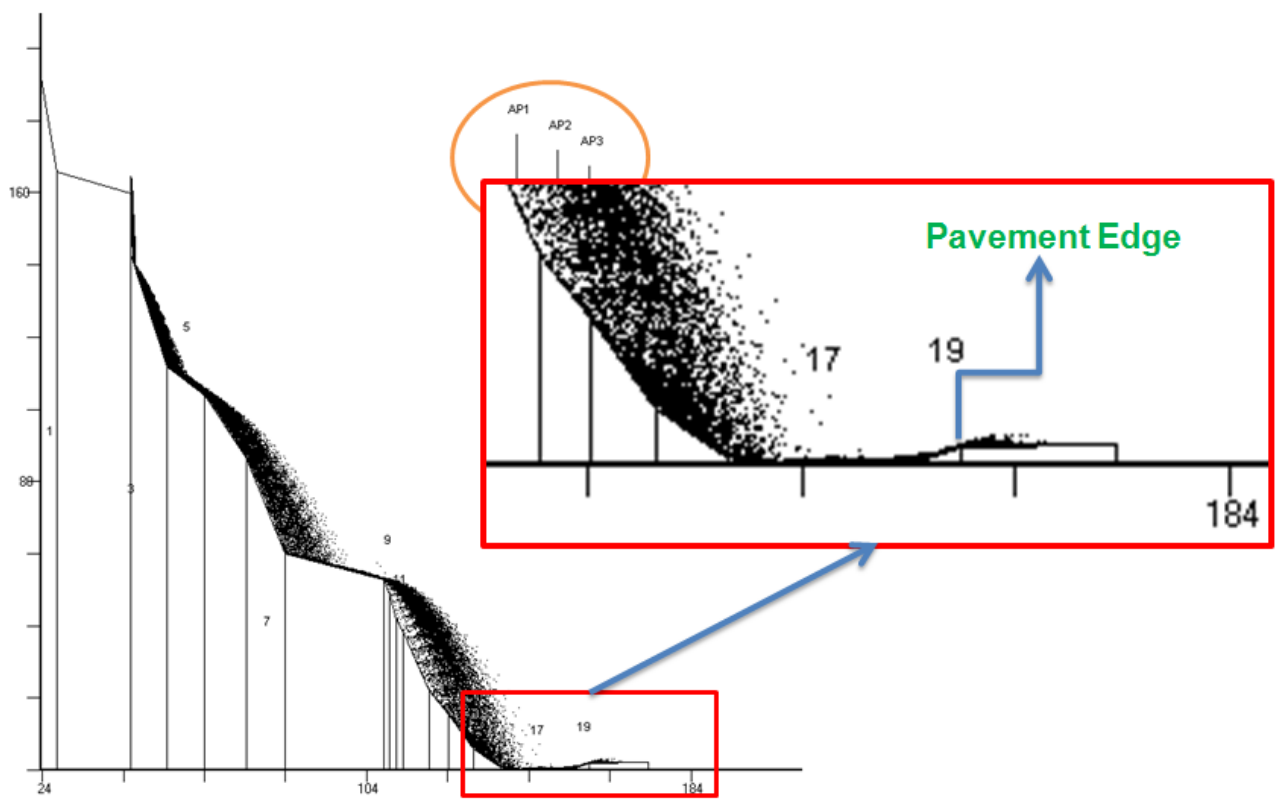


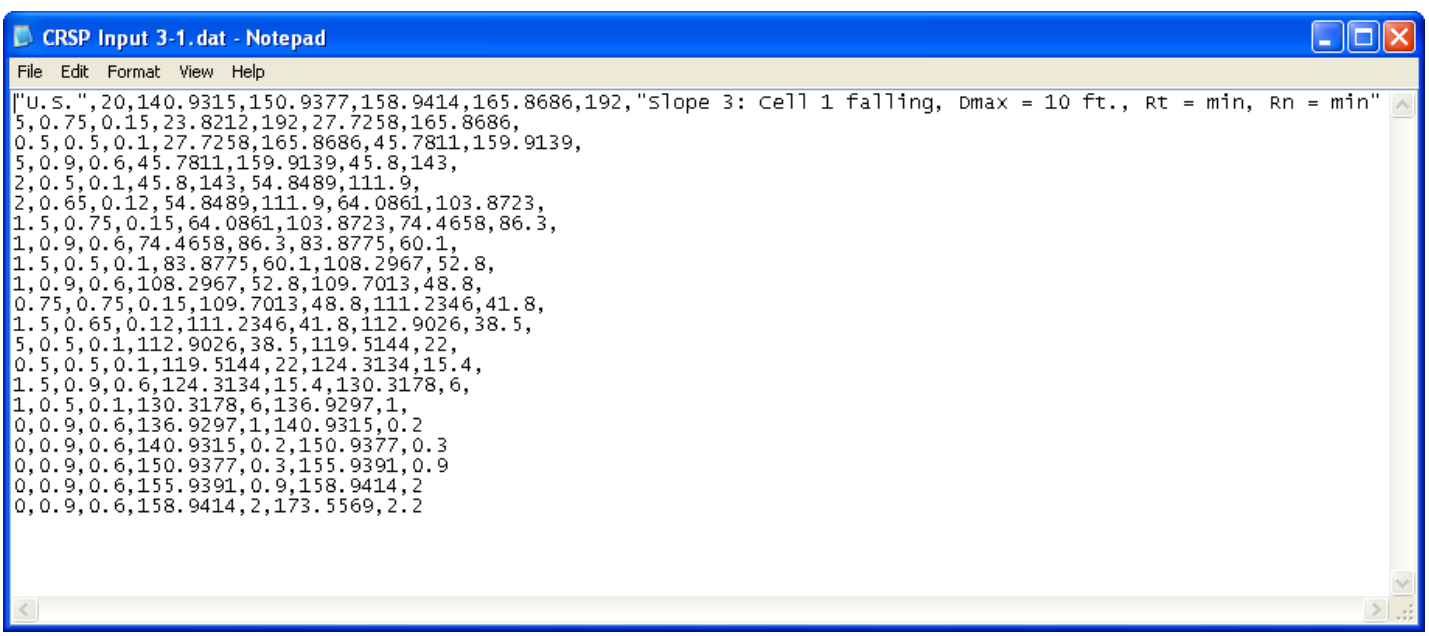
FIGURE 4-1. TUNING INPUT PARAMETERS TO MATCH FIELD OBSERVATIONS SLOPE 3.

Note that it is also important to change the density of the talus soils on and at the base of the slope to reflect conditions present during winter or frozen ground conditions between that of thawed or summer conditions.

Once this step is completed, one can start experimenting with different design scenarios.

- *Sample input file:*

To carry out an analysis, an input text file can be created beforehand containing all the information on slope profile, materials, and dimensions. Figure 12 is an example of the input text file created in order to simulate rocks falling from the first top layer (cell) of slope 3. R_t and R_n configured for this particular run correspond to the minimum values -suggested by CRSP manual- of each layer based on the type (hardness) of rock surface. CRSP manual includes the proper explanation for generating the input file, and is also shown in Figure 13.



CRSP Input 3-1.dat - Notepad

File Edit Format View Help

```
("U.S.",20,140.9315,150.9377,158.9414,165.8686,192,"Slope 3: Cell 1 falling, Dmax = 10 ft., Rt = min, Rn = min"
5,0.75,0.15,23.8212,192,27.7258,165.8686,
0.5,0.5,0.1,27.7258,165.8686,45.7811,159.9139,
5,0.9,0.6,45.7811,159.9139,45.8,143,
2,0.5,0.1,45.8,143,54.8489,111.9,
2,0.65,0.12,54.8489,111.9,64.0861,103.8723,
1.5,0.75,0.15,64.0861,103.8723,74.4658,86.3,
1,0.9,0.6,74.4658,86.3,83.8775,60.1,
1.5,0.5,0.1,83.8775,60.1,108.2967,52.8,
1,0.9,0.6,108.2967,52.8,109.7013,48.8,
0.75,0.75,0.15,109.7013,48.8,111.2346,41.8,
1.5,0.65,0.12,111.2346,41.8,112.9026,38.5,
5,0.5,0.1,112.9026,38.5,119.5144,22,
0.5,0.5,0.1,119.5144,22,124.3134,15.4,
1.5,0.9,0.6,124.3134,15.4,130.3178,6,
1,0.5,0.1,130.3178,6,136.9297,1,
0,0.9,0.6,136.9297,1,140.9315,0.2
0,0.9,0.6,140.9315,0.2,150.9377,0.3
0,0.9,0.6,150.9377,0.3,155.9391,0.9
0,0.9,0.6,155.9391,0.9,158.9414,2
0,0.9,0.6,158.9414,2,173.5569,2.2
```

FIGURE 4-2. EXAMPLE INPUT FILE FOR SLOPE 3

The input file format is shown below:

Line 1	→	"Units", C_n, X_{an1}, X_{an2}, X_{an3}, Y_2, Y_1, C
Lines 2 through $C_n + 1$	→	S, R_t, R_n, X_b, Y_b, X_e, Y_e

where:

"Units"	=	system of units (U.S. or metric)
C_n	=	total number of cells used for simulation
X_{an1}	=	x-coordinate of analysis point 1
X_{an2}	=	x-coordinate of analysis point 2 (optional)
X_{an3}	=	x-coordinate of analysis point 3 (optional)
Y_1	=	y-coordinate of the top of the source rock zone
Y_2	=	y-coordinate of the bottom of the source rock zone
C	=	remarks, comment, or descriptive statement (optional)
S	=	surface roughness
R_t	=	tangential coefficient of frictional resistance
R_n	=	normal coefficient of restitution
X_b	=	x-coordinate of the beginning of the cell
Y_b	=	y-coordinate of the beginning of the cell
X_e	=	x-coordinate of the end of the cell
Y_e	=	y-coordinate of the end of the cell

Although, creating an input file within CRSP 4.0 is simple, the user could create an input file using any ASCII text editor. To do so, simply follow the format presented above exactly as shown, with no spaces after the commas. Data for cell number 1 appears as the second line of the file and subsequent cells follow (each on a separate line). If less than three analysis points are desired, enter a zero (**0**) for X_{an2} and/or X_{an3}. If the user chooses not to enter any remarks, two quotation marks (**""**) should be entered at the end of the first line of the file, for C (as shown above).

FIGURE 4-3. CRSP INPUT FILE DESCRIPTION. SOURCE: CRSP MANUAL.

5. EXAMPLE PROCEDURE FOR SLOPE 5

A similar procedure for input preparation is given below for Slope 5 without annotation as the procedure is self-explanatory.

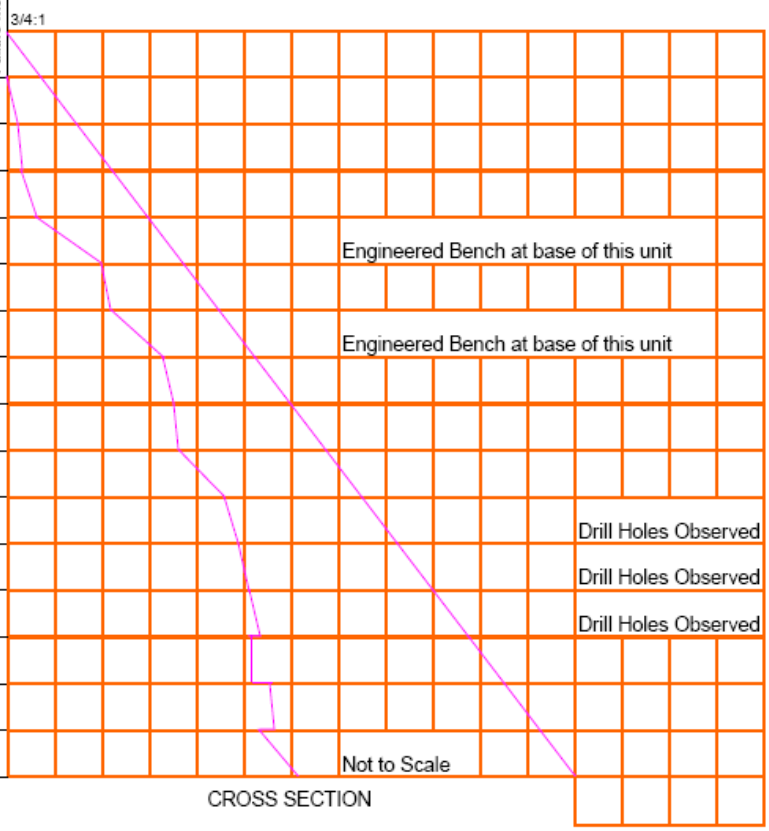
University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

Slope Cross Section Slope # 5 Sheet 1 of 1

Stratigraphic Sequence Initial Design Degree of cut slope: 65 degrees from Horizontal

Rock Type	Unit Thickness (1)	Degree of Weathering (2)	Weathering Rate (3)	Est. Largest Block Diameter (ft)	Face Angle (4)	Overhanging (5)	Fall Potential (6)	CRSP Cell #	Failure Mode(7)
Shale	5.0	C/H		0.7	75	N	Y	1	F/J
Limestone*	1.0	M		3.0	85	O	Y	2	J/U
Shale	10.0	H		0.7	70	N	Y	3	F/J
Talus	30.0	C		3.0	40	N	P	4	F
Shale	3.0	M		0.3	80	N	Y	5	F
Talus backed by shale	11.0	C		0.3	43	N	P	6	F
Shale	11.0	M/S		1.0	70	N	Y	7	J
Sandy Shale	15.0	M/S		8.0	80	O	Y	8	J/U
Talus	23.0	C		8.0	50	N	Y	9	F
Sandstone	5.0	S		1.0	70	N	Y	10	F/J
Sandstone (Massive)	8.0	S		5.0	70	N	Y	11	F/J
Shale	24.0	M/S		18.0	70	Y	Y	12	F/J
Shale with nodules	2.0	M/S		1.0	90	N	Y	13	F/J
Limestone	1.4	F		4.0	85	Y	Y	14	F/J
Talus Backed with Shale	3.5	C		2.0	50	N	N	15	F



*Unit observed on the ground

(1) Unit thickness based on vertical height in feet.
(2) Value based on visual inspection of unit (H=Highly, M=Moderately, S=Slightly,U=Unweathered, C=Completely)
(3) Weathering rate is based on extent of unit weathering as compared to the unit with least weathering within the same slope.
(4) Face Angle is existing outcrop slope angle.
(5) Indicates unit is overhanging other units, O=Overhanding other units, P=Protected by above overhanging unit, N=Not Overhanging, N/A=Not Applicable)
(6) Indicates whether material will reach the ground from this unit (Y=Yes, N=No, P=Partially Buried in Talus)
(7) How pieces detach from the slope (F=Flaking (Freeze/Thaw), J=Joint Intersections, U=Undercutting, W=Water Transported)

FIGURE 5-1. SLOPE CROSS SECTION DESCRIPTION FOR SLOPE 5.

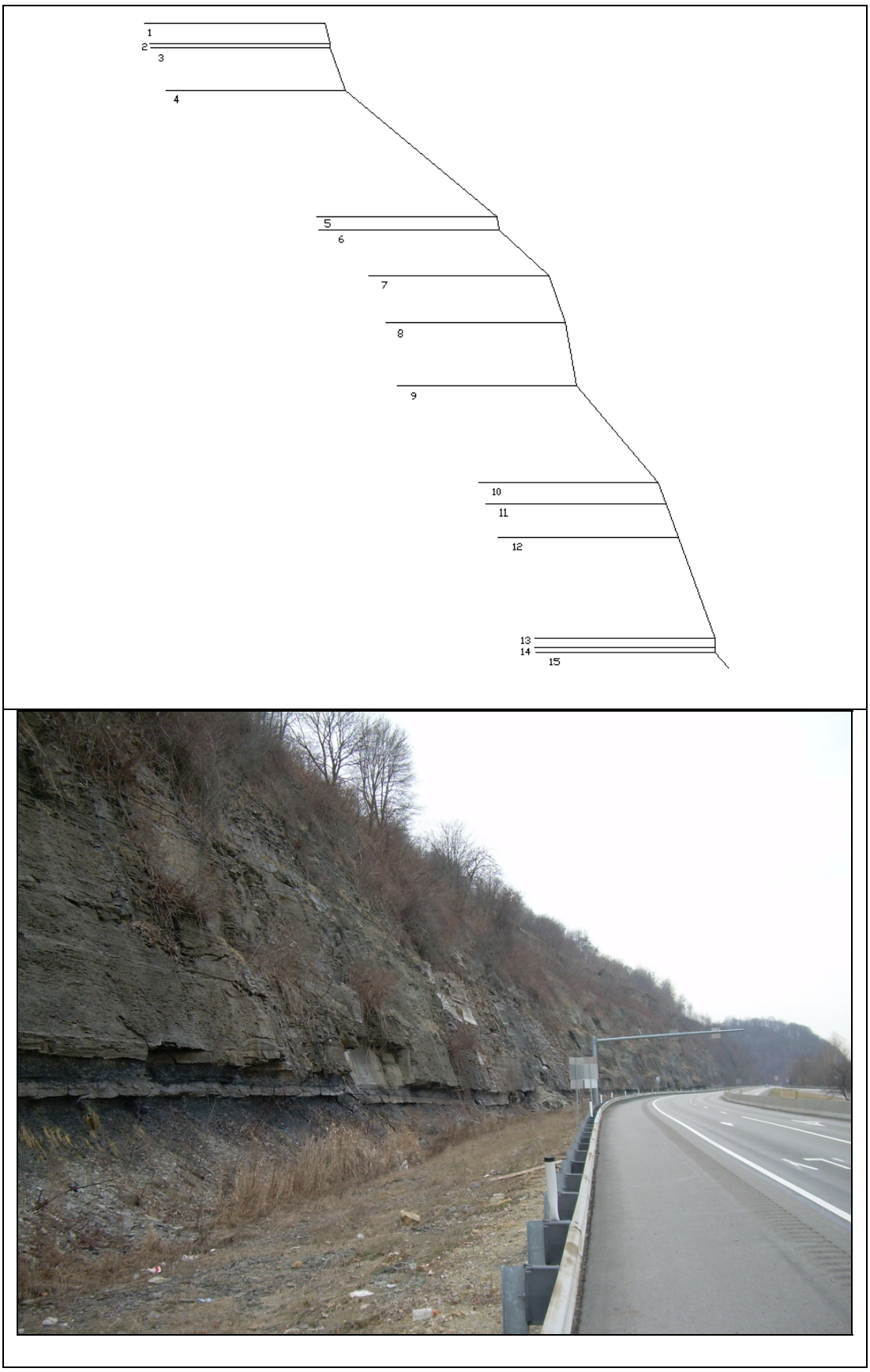


FIGURE 5-2. MAPPING IN THE FIELD, SLOPE 5.

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section Slope # 5 Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

38 ft

Barrier type and dimensions Guide Rail

Depth of ditch (ft) 2.5

Plot distribution of material within ditch. Use CRSP Cell # when possible

Failure Mode: ____ Shatters on impact

X Falls with subsequent weathering

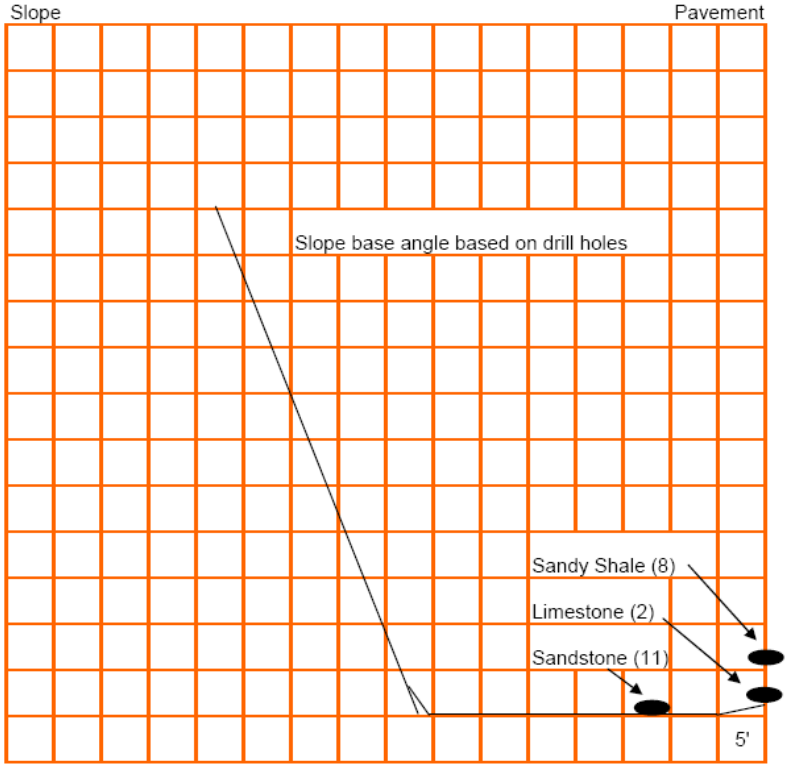
X Other (Describe)

Performance ____ Material contained with ditch

X Material on pavement or shoulder

Toppling

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

FIGURE 5-3. COLLECTION OF CATCHMENT DITCH & BARRIER INFORMATION FOR SLOPE 5.

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # 5 Sheet 1 of 1

CRSP Cell # _____

Existing Slope Angle (based off LiDAR) _____

Slope Strike 340

Slope Dip Various

Bedding Strike _____

Dip _____

Road Strike 340

Valley Strike N/A 340

Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	RMR Rating: Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?
1	290	90	2	210						No
2*	160	70E	Many	1-8	Dominate Joint system (Valley Stress Relief)					No
3	70	90	Many	3	Isolated to Limestone Cell # 14					Yes
4	335	45W	1							No

FIGURE 5-4. COLLECTION OF BEDDING, SLOPE, AND DISCONTINUITY ORIENTATION FOR SLOPE 5

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 5
Date: 3/27/2008

					Tangential Coefficient (Rt)				Normal Coefficient (Rn)								Rock Hardness (pcf)			
Cell #	Description	Rock Size (R) Radius (ft)	Surface Roughness (S) (ft) (in one Rock Radius)	Maximum Varation in Slope Angle θ=tan-1 (S/R)	Smooth Hard Surfaces (.9 to 1.0)	Most Bedrock and Boulder Fields (.75 to 0.95)	Talus and firm soil slopes (.65 to .95)	Soft soil slopes (.5 to .8)	Smooth Hard Surfaces (.6 to 1.0)	Most Bedrock and Boulder Fields (.15 to 0.35)	Talus and firm soil slopes (.12 to .2)	Soft soil slopes (.1 to .2)	Begin X	Begin Y	End X	End Y	Hard Sed (150 to 180)	Soft Sed (110 to 150)	Brush Covered Slopes Percent	Rock Shape Spherical (S), Disk (D), or Cylindrical (C)
1	Shale	0.3	0.5				X				X							X		D
2	Limestone"	1.5	0.1			X				X							X			S
3	Shale	0.3	0.5				X				X							X		D
4	Talus	1.5	1					X				X						X		S
5	Shale	0.125	0.1			X				X								X		D
6	Talus backed by shale	0.125	1					X				X						X		S
7	Shale	0.5	1			X				X								X		S
8	Sandy Shale	4	0.1		X				X									X		S
9	Talus	4	4					X				X						X		S
10	Sandstone	0.5	1			X				X								X		C
11	Sandstone	2.5	0.1		X				X								X			S
12	Shale	9	0.1			X				X								X		C
13	Shale with nodules	0.15	0.1				X				X							X		S
14	Limestone	2	0.1		X				X								X			C
15	Talus Backed with Shale	2	1.5					X				X						X		D

FIGURE 5-5. CRSP INPUT PARAMETER COLLECTION FOR SLOPE 5.

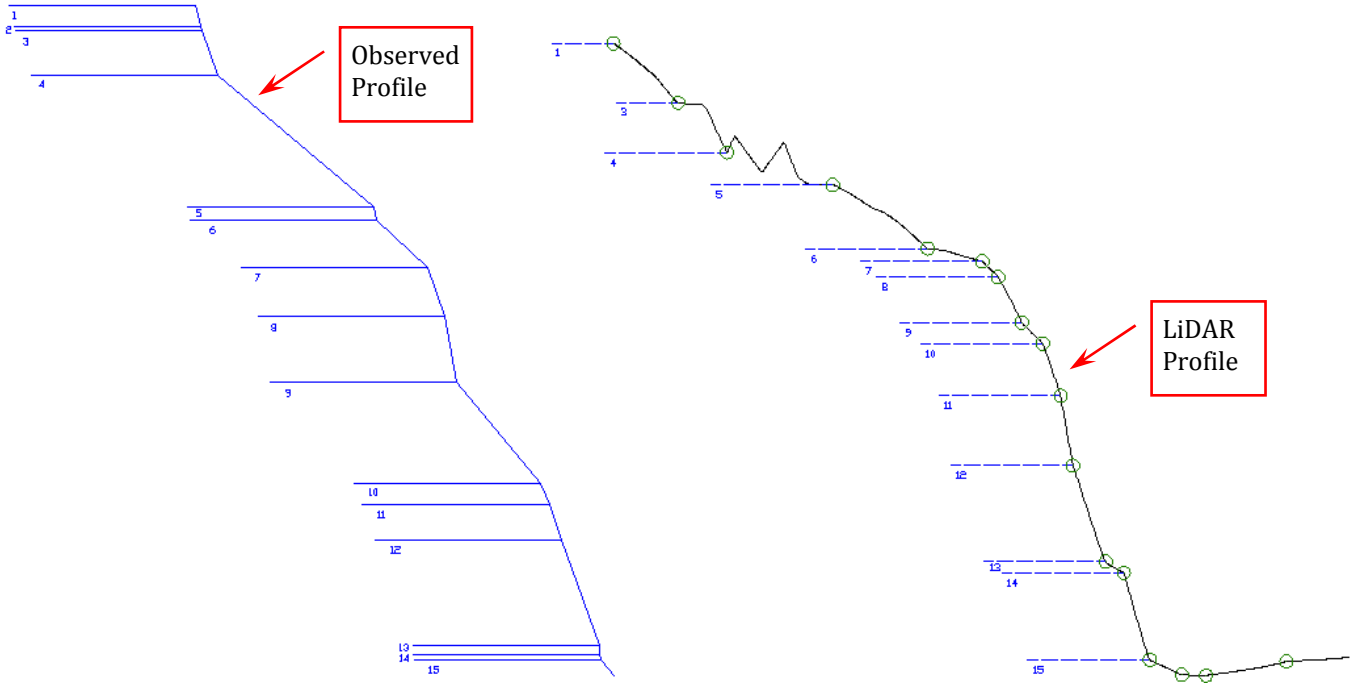


FIGURE 5-6. FIELD PROFILE AND LIDAR PROFILE CORRELATION FOR SLOPE 5.

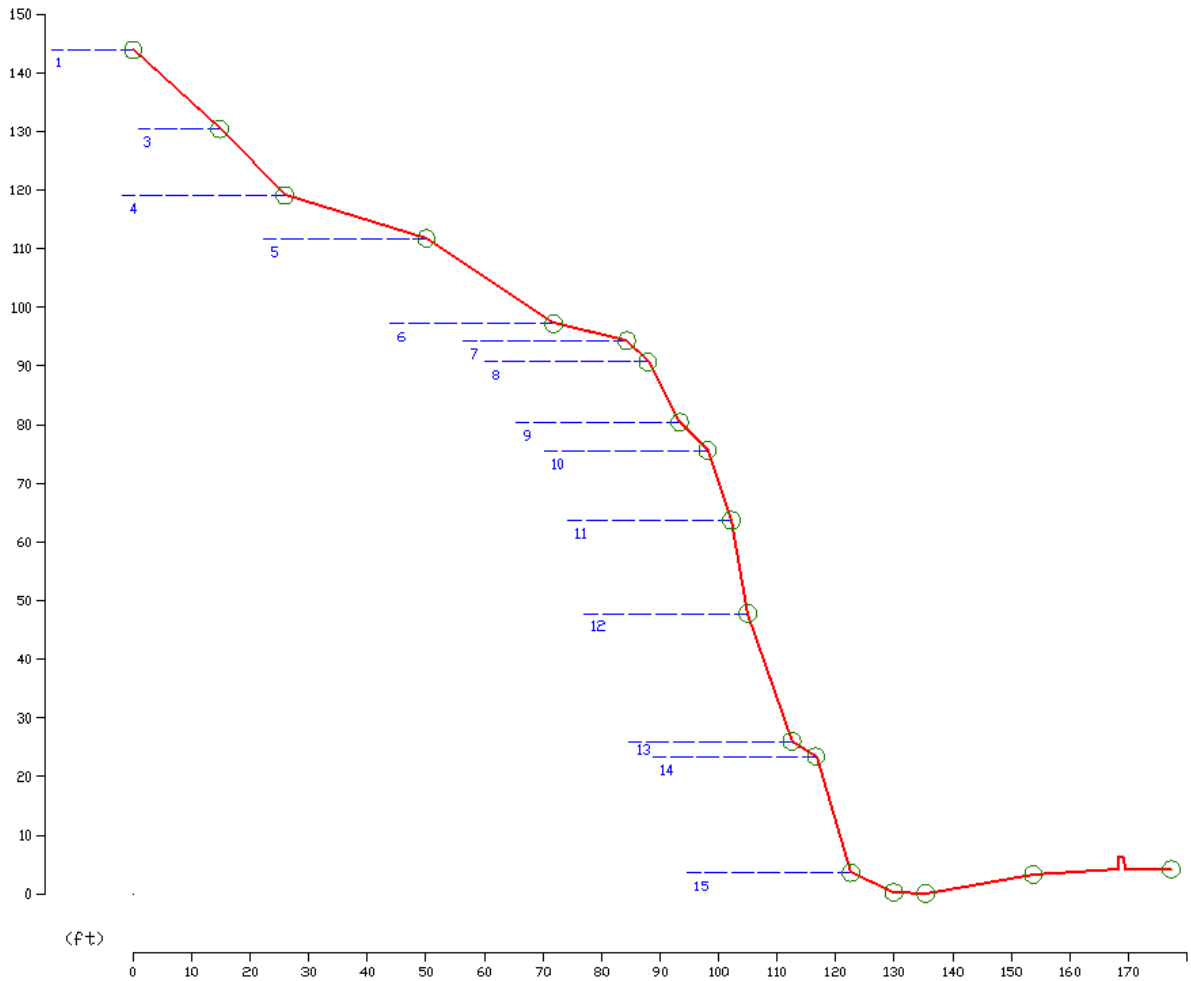


FIGURE 5-7. INPUT CROSS SECTION PROFILE FOR CRSP ANALYSIS ON SLOPE 5.

CRSP Input 5-9.dat - Notepad

File Edit Format View Help

```
["U.S.",21,129.908,153.7498,168.149,75.6,80.4,"Slope 5: Cell 9 falling, Dmax 8ft., Rt=min, Rn=min"
0.5,0.65,0.12,0,143.9,14.7825,130.4
0.5,0.75,0.15,14.7825,130.4,25.9507,119.1
1,0.65,0.12,25.9507,119.1,50.1019,111.7
0.1,0.5,0.1,50.1019,111.7,71.7864,97.2
1,0.75,0.15,71.7864,97.2,84.2726,94.3
1,0.5,0.1,84.2726,94.3,87.8869,90.7
0.1,0.75,0.15,87.8869,90.7,93.3007,80.4
4,0.9,0.6,93.3007,80.4,98.0702,75.6
1,0.5,0.1,98.0702,75.6,102.1736,63.7
0.1,0.75,0.15,102.1736,63.7,104.9656,47.8
0.044444444,0.9,0.6,104.9656,47.8,112.5196,26
0.1,0.75,0.15,112.5196,26,116.6297,23.4
0.1,0.65,0.12,116.6297,23.4,122.5402,3.6
1.5,0.9,0.6,122.5402,3.6,129.908,0.194
0,0.5,0.1,129.908,0.194,135.3786,0
0,0.9,0.6,135.3786,0,153.7498,3.241
0,0.9,0.6,153.7498,3.241,168.0991,4.1273
0,1,1,168.0991,4.1273,168.149,6.1304
0,1,1,168.149,6.1304,169.149,6.1304
0,1,1,169.149,6.1304,169.199,4.1801
0,1,1,169.199,4.1801,177.2901,4.1304
```

FIGURE 5-8. EXAMPLE INPUT FILE FOR SLOPE 5.

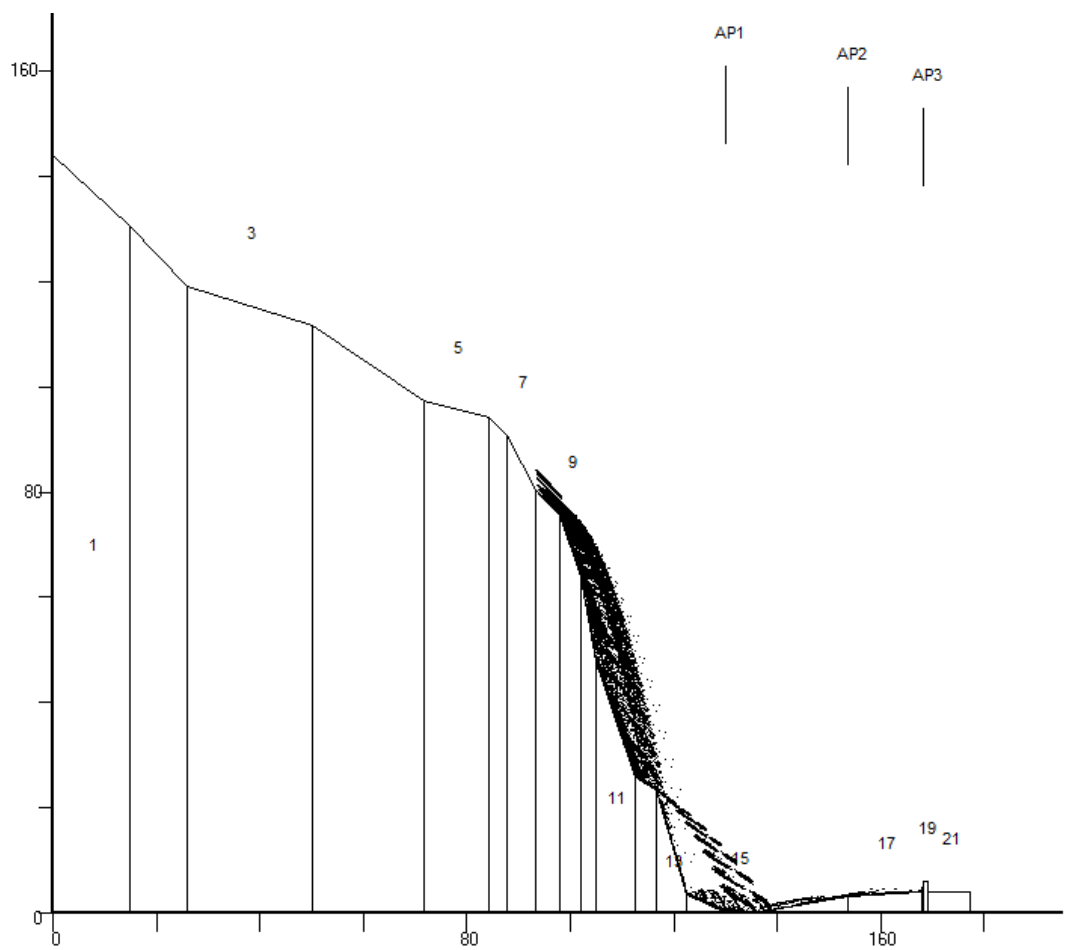


FIGURE 5-9. SAMPLE OF CRSP RESULTS FOR SLOPE 5.

Rocks falling from layer # 9, Sandy Shale covered with talus, D_{max} = 8 ft, with $R_{t\,min}$ *and* $R_{n\,min}$.

6. EXAMPLE PROCEDURE FOR SLOPE 7

Similar to that provided in the previous two sections, the input preparation for Slope 7 is given below.

University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

Slope Cross Section — Slope # 7 — Sheet 1 of 1

Stratigraphic Sequence — Initial Design Degree of cut slope: 70 degrees from Horizontal

Rock Type	Unit Thickness (1)	Degree of Weathering (2)	Weathering Rate (3)	Est. Largest Block Diameter (ft)	Face Angle (4)	Overhanging (5)	Fall Potential (6)	CRSP Cell #	Failure Mode(7)
Residual Soil	?	C	N/A	0.1	30	N/A	y	1	W
Shale	15.0	H		5.0	85	N	Y	2	F/J
Sandstone*	1.5	S		3.5	90	O	Y	3	U/J
Shale	8.0	M		0.5	63	N	Y	4	F
Limestone	1.5	M		1	90	O	Y	5	U/J
Shale	20.0	M		0.5	42	N	Y	6	F
Sandstone	1.5	S		1.5	82	O	Y	7	U/J
Sandy Shale	6.0	M		1.5	59	O	Y	8	U/F/J
Shale with sandstone interbeds	25.0	M		1.0	40	N	Y	9	F/J
Black Shale	6.0	M		0.5	65	N	Y	10	F
Sandstone with interbedded shale	10.0	S		1.0	70	N	Y	11	F/J
Sandstone	10.0	U		5.0	70	O	Y	12	U/J
Shale	10.0	S		4.5	72	N	Y	13	F/J
Sandstone	1.5	U		2.0	85	N	Y	14	J
Shale	5.5	S		1.0	71	N	Y	15	F/J
Talus	3+	C		1.0	30	N	N	16	F/W

*Unit observed on the ground

(1) Unit thickness based on vertical height in feet.
(2) Value based on visual inspection of unit (H=Highly, M=Moderately, S=Slightly,U=Unweathered, C=Completely)
(3) Weathering rate is based on extent of unit weathering as compared to the unit with least weathering within the same slope.
(4) Face Angle is existing outcrop slope angle.
(5) Indicates unit is overhanging other units (O=Overhanding other units, P=Protected by above overhanging unit, N=Not Overhanging, N/A= Not Applicable)
(6) Indicates whether material will reach the ground from this unit (Y=Yes, N=No, P=Partially Buried in Talus)
(7) How pieces detach from the slope (F=Flaking (Freeze/Thaw), J=Joint Intersections, U=Undercutting, W=Water Transported)

FIGURE 6-1. SLOPE CROSS SECTION DESCRIPTION FOR SLOPE 7.

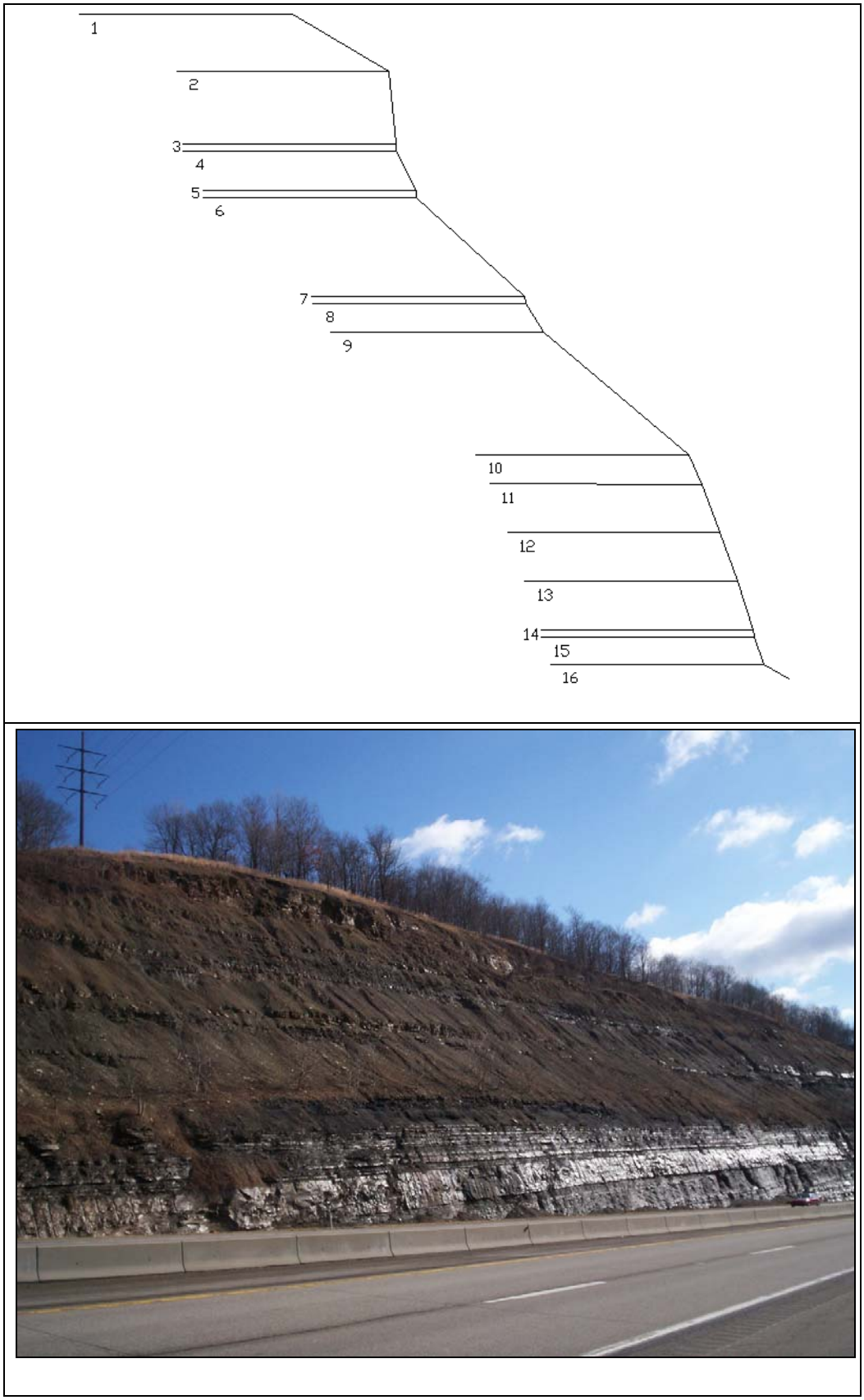


FIGURE 6-2. MAPPING IN THE FIELD, SLOPE 7.

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section Slope # 7 Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

51 ft

Barrier type and dimensions None

Depth of ditch Approximately 5 foot

Plot distribution of material within ditch. Use CRSP Cell # when possible

Failure Mode: ___ Shatters on impact

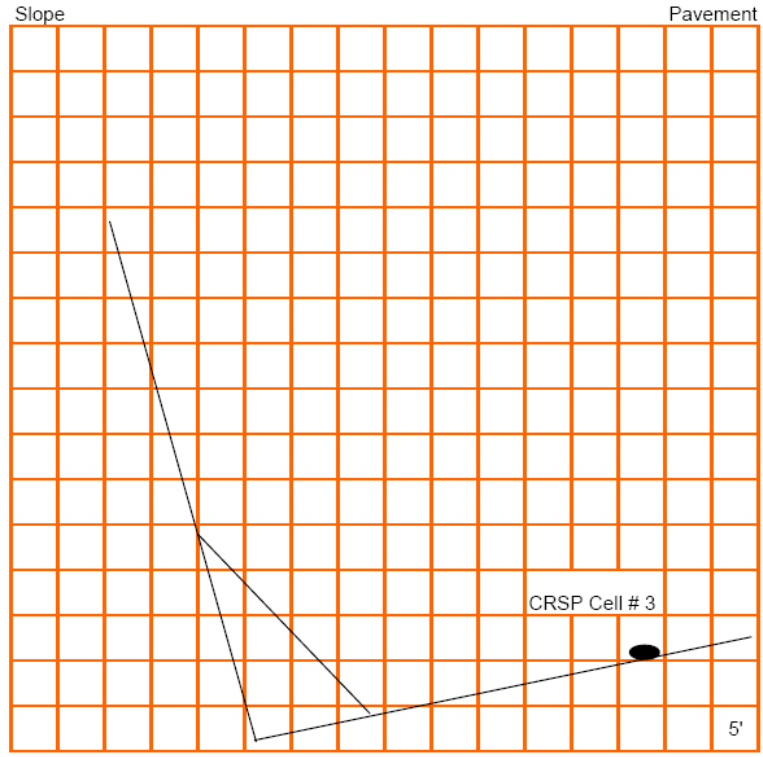
X Falls with subsequent weathering

___ Other (Describe)

Performance X Material contained with ditch

___ Material on pavement or shoulder

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

FIGURE 6-3. COLLECTION OF CATCHMENT DITCH & BARRIER INFORMATION FOR SLOPE 7.

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # 7 Sheet 1 of 1

CRSP Cell # N/A

Existing Slope Angle (based off LiDAR)

Slope Strike 60 degrees MN

Slope Dip 70 degrees to west Many visible blasting holes in lower slope

Bedding Strike

Dip

Road Strike 65 degrees MN

Valley Strike N/A

					RMR Rating					
Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?
1	88	79	W	10 to 15						
1	67	69	W							
1	92	70	W							
2	30	75	E	40						
2	20	85	E							

FIGURE 6-4. COLLECTION OF BEDDING, SLOPE, AND DISCONTINUITY ORIENTATION FOR SLOPE 7.

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 7
Date: 3/20/2008

					Tangential Coefficient (Rt)				Normal Coefficient (Rn)								Rock Hardness (pcf)			
Cell #	Description	Rock Size (R) Radius (ft)	Surface Roughness (S) (ft) (in one Rock Radius)	Maximum Varation in Slope Angle θ=tan-1 (S/R)	Smooth Hard Surfaces (.9 to 1.0)	Most Bedrock and Boulder Fields (.75 to 0.95)	Talus and firm soil slopes (.65 to .95)	Soft soil slopes (.5 to .8)	Smooth Hard Surfaces (.6 to 1.0)	Most Bedrock and Boulder Fields (.15 to 0.35)	Talus and firm soil slopes (.12 to .2)	Soft soil slopes (.1 to .2)	Begin X	Begin Y	End X	End Y	Hard Sed (150 to 180)	Soft Sed (110 to 150)	Brush Covered Slopes Percent	Rock Shape Spherical (S), Disk (D), or Cylindrical (C)
1	Residual Soil	0.01	0.01					X				X						X		D
2	Shale	2.5	1				X				X							X		D
3	Sandstone	1.75	0.3			X				X							X			C
4	Shale	0.3	0.7				X				X							X		D
5	Limestone	0.5	0.5			X				X							X			S
6	Shale	0.3	0.1				X				X							X		D
7	Sandstone	0.75	0.5		X				X								X			S
8	Sandy Shale	0.75	0.5		X				X									X		D
9	Shale with sandstone interbeds	1	1				X				X							X		D
10	Black Shale	0.3	0.5			X				X								X		D
11	Sandstone with shale interbeds	0.5	1		X				X								X	X		S
12	Sandstone	2.5	0.2		X				X								X			S
13	Shale	2.25	0.2		X				X									X		D
14	Sandstone	1	0.2		X				X								X			S
15	Shale	0.5	0.4		X				X									X		D
16	Talus	0.3	1					X				X						X		S

FIGURE 6-5. CRSP INPUT PARAMETER COLLECTION FOR SLOPE 7.

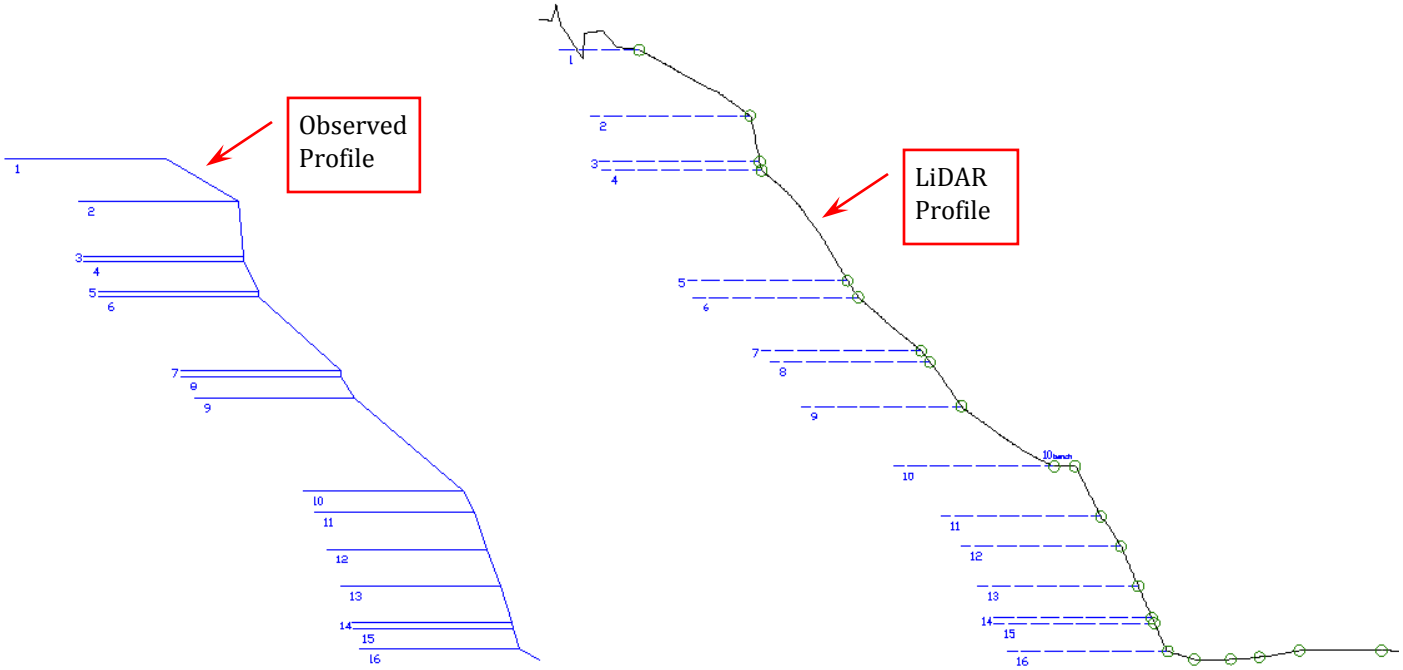


FIGURE 6-6. FIELD PROFILE AND LIDAR PROFILE CORRELATION FOR SLOPE 7.

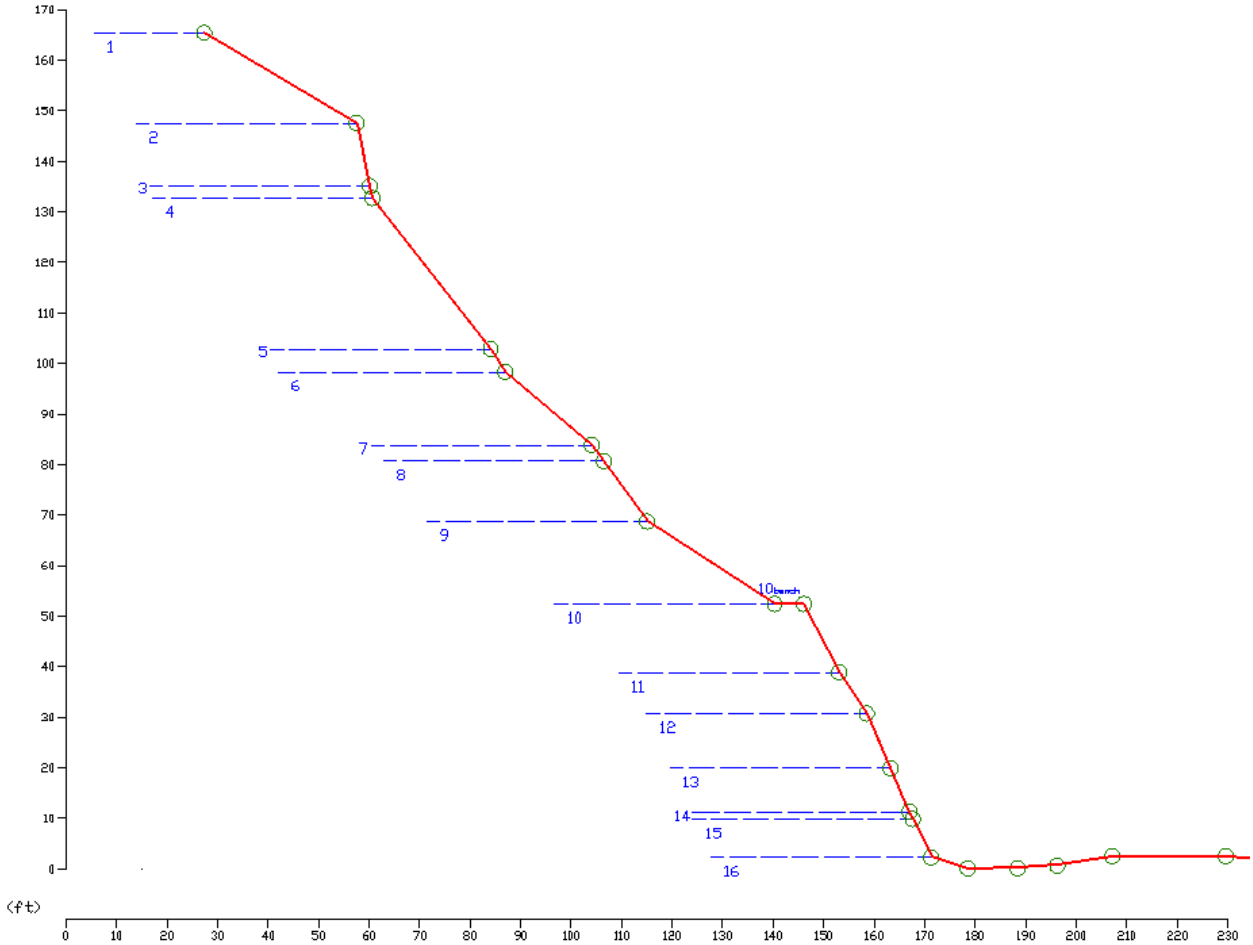


FIGURE 6-7. INPUT CROSS SECTION PROFILE FOR CRSP ANALYSIS ON SLOPE 7.

CRSP Input 7-3.dat - Notepad

File Edit Format View Help

```
"U.S.",22,178.5545,188.4448,207.1814,132.7,135.1,"Slope 7: Cell 3 falling, Dmax=1.75ft, L=3.5ft, Rt=min, Rn=min"
0.01,0.5,0.1,27.3298,165.4,57.5251,147.5
0.7,0.65,0.12,57.5251,147.5,60.1193,135.1
0.3,0.75,0.15,60.1193,135.1,60.647,132.7
0.7,0.65,0.12,60.647,132.7,84.074,102.8
0.5,0.75,0.15,84.074,102.8,86.9313,98.3
0.1,0.65,0.12,86.9313,98.3,104.1077,83.8
0.5,0.9,0.6,104.1077,83.8,106.4586,80.7
0.5,0.9,0.6,106.4586,80.7,115.0403,68.7
1,0.65,0.12,115.0403,68.7,140.2921,52.4
1,0.5,0.1,140.2921,52.4,146.0181,52.4
0.5,0.75,0.15,146.0181,52.4,153.0495,38.8
1,0.9,0.6,153.0495,38.8,158.5109,30.7
0.14,0.9,0.6,158.5109,30.7,163.193,19.9
0.155555556,0.9,0.6,163.193,19.9,166.9492,11.2943
0.2,0.9,0.6,166.9492,11.2943,167.6219,9.8
0.4,0.9,0.6,167.6219,9.8,171.2683,2.2
1,0.5,0.1,171.2683,2.2,178.5545,0
0,0.5,0.1,178.5545,0,188.4448,0.1
0,0.5,0.1,188.4448,0.1,196.2571,0.6
0,0.5,0.1,196.2571,0.6,207.1814,2.4
0,0.9,0.6,207.1814,2.4,229.5644,2.4
0,0.9,0.6,229.5644,2.4,266.2667,0.2
```

FIGURE 6-8. EXAMPLE INPUT FILE FOR SLOPE 7.

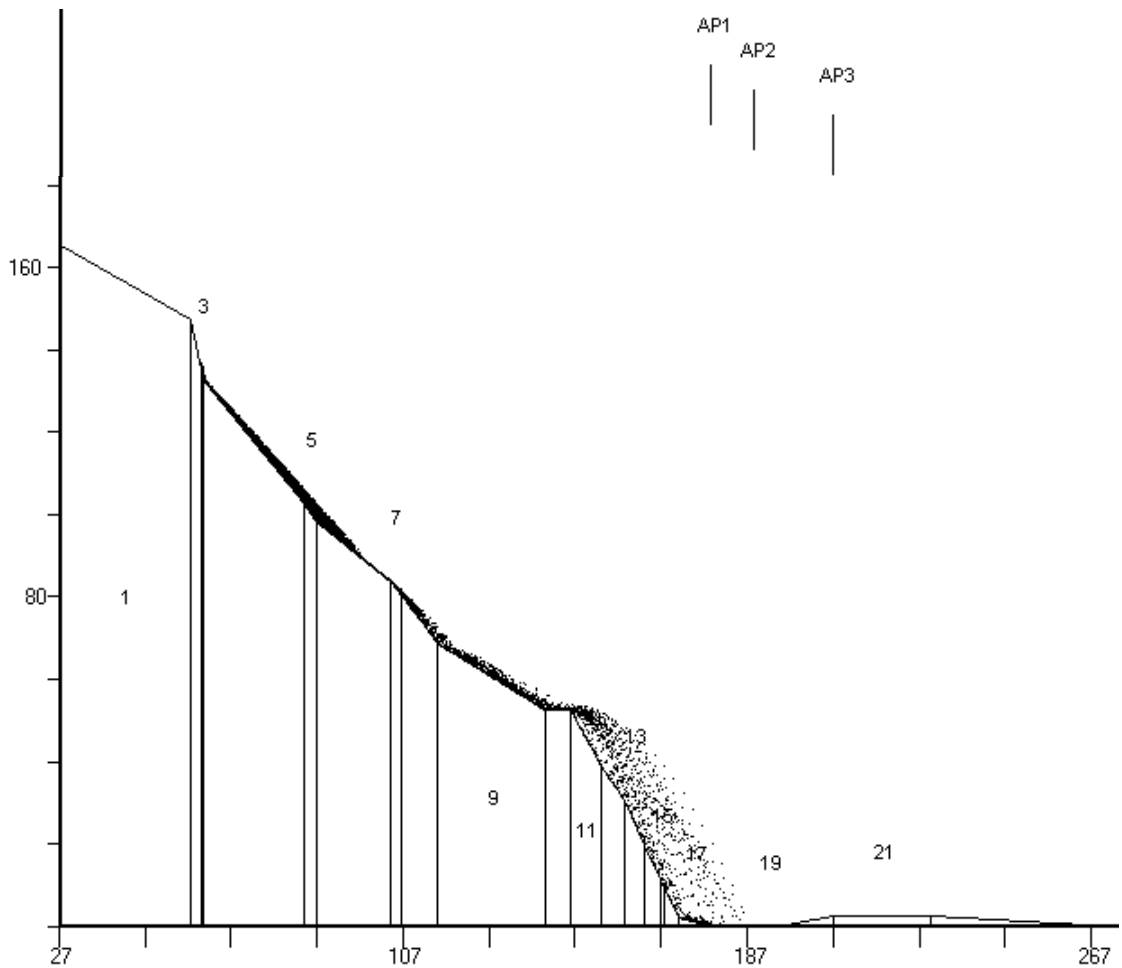


FIGURE 6-9. SAMPLE OF CRSP RESULTS FOR SLOPE 7.

Rocks falling from layer # 3, Sandstone, D_{max} = 3.5 ft, with $R_{t\,min}$ *and* $R_{n\,min}$.

7. USING CRSP AS A TOOL FOR DESIGN

CRSP analysis can be used as a tool to study the behavior of rockfall, determine the need for rockfall mitigation, and aid in the design of rockfall mitigation. As stated in the CRSP Manual, "The experience gained from using CRSP in many locations throughout the United States indicates that the program is useful in designing rock cuts and ditches. Various combinations of cut slope and ditch configurations can be tested until a configuration is found that is both aesthetically acceptable and safe with respect to rockfall."

It is important to remember that for a specific site, calibration of R_t and R_n with local experience is needed in order to obtain meaningful output. When possible, results from CRSP analysis should be compared with observed rockfall site-specific events.

A reasonable estimate of probable bounce height and velocity of rockfall events is desired in order to design rockfall fences and alternative catch ditches. Once the CRSP model is calibrated to the site, mitigation measures can be designed using the appropriate values for kinetic energy and bounce height. However, CRSP does not address every situation or every condition of all rockfall events. The designer should still use sound judgment based on extensive experience in engineering geology and erosional processes to verify the data and its validity.

CRSP uses the input data in a stochastic manner to produce statistics on probable rockfall velocity, kinetic energy, and bounce height based on a series of rock rolls under identical conditions. The following data is output by CRSP:

1. The slope profile showing cell locations and the position of each simulated rock every tenth of a second as it travels down slope (e.g. Figures 22, 31, and 33).

2. The maximum, average, minimum, and standard deviation of rock velocities at each of one to three selected points (analysis points) on the slope.
3. The maximum, average, and standard deviation of rock velocities at the end of each cell.
4. The maximum, average, geometric mean, and standard deviation of rock bounce heights at each analysis point.
5. The maximum and average bounce heights at the end of each cell.
6. The maximum, average, and standard deviation of kinetic energies at each analysis point.
7. Cumulative probability analyses of velocity, kinetic energy, and bounce height at each analysis point.
8. Graphs of the distribution of rock velocities and bounce heights at each analysis point.
9. Graphs of the maximum velocities and bounce heights along the slope.
10. The number of stopped rocks in each ten-foot or ten-meter slope interval.

"The cumulative probability analysis may be useful for design of rockfall mitigation, as a level of confidence may be chosen corresponding to values of velocity, kinetic energy, and bounce height that are likely not to be surpassed with the given level of confidence. However, many CRSP users choose not to use the cumulative probability analyses and instead work with the information provided at specific Analysis Points." (CRSP Manual)

In an attempt to illustrate the possibilities available from CRSP analyses, Figure 32 shows a scenario involving a vertical cut made to Slope 3. Figure 33 shows a corresponding rockfall output profile due to this alteration. By comparing this output with that from the original run,

one gets the picture of how a design may affect the future rockfall patterns. Details of the comparison are summarized in Figure 34.

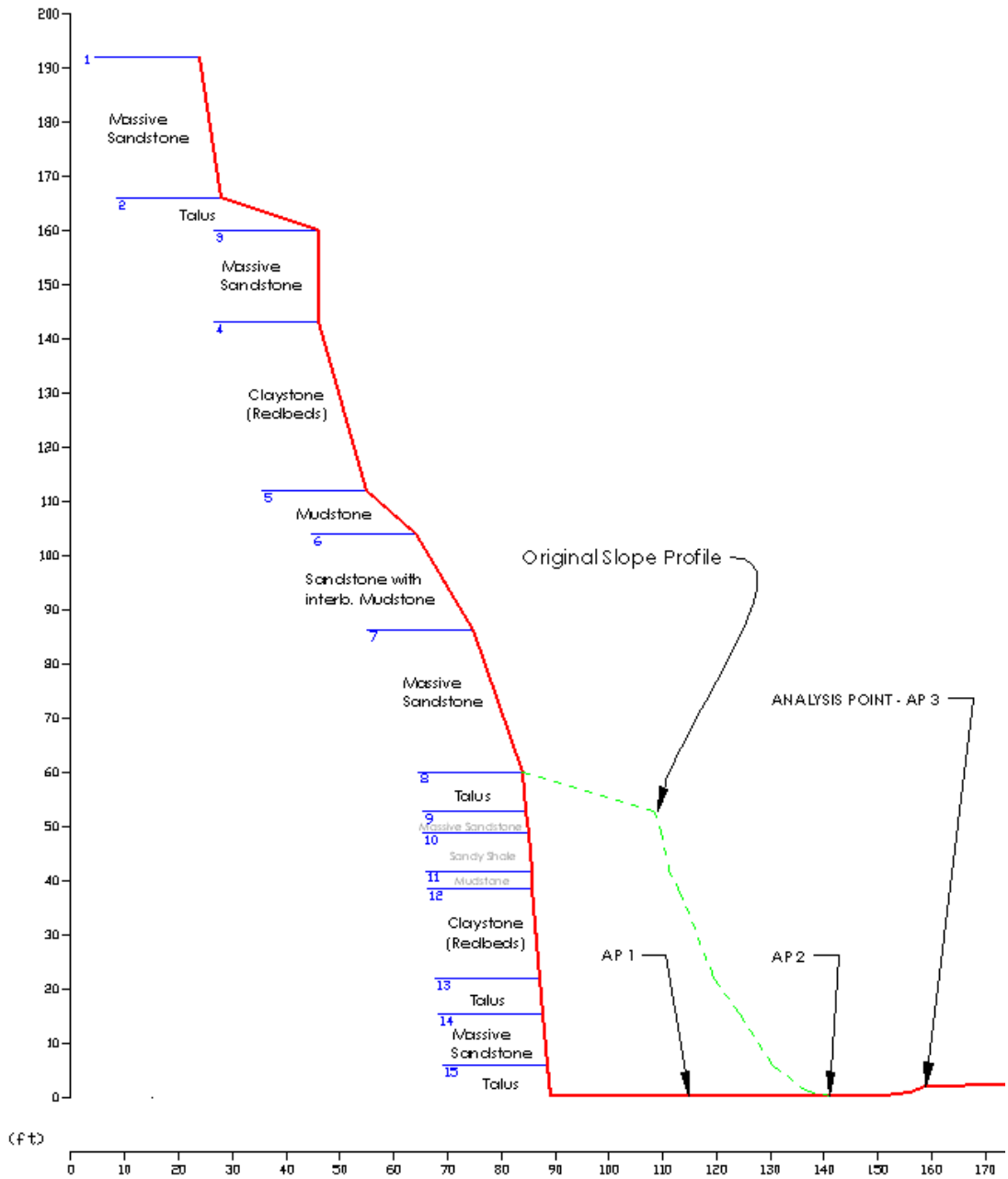


FIGURE 7-1. CUT SLOPE MODEL EXAMPLE IN SLOPE 3.

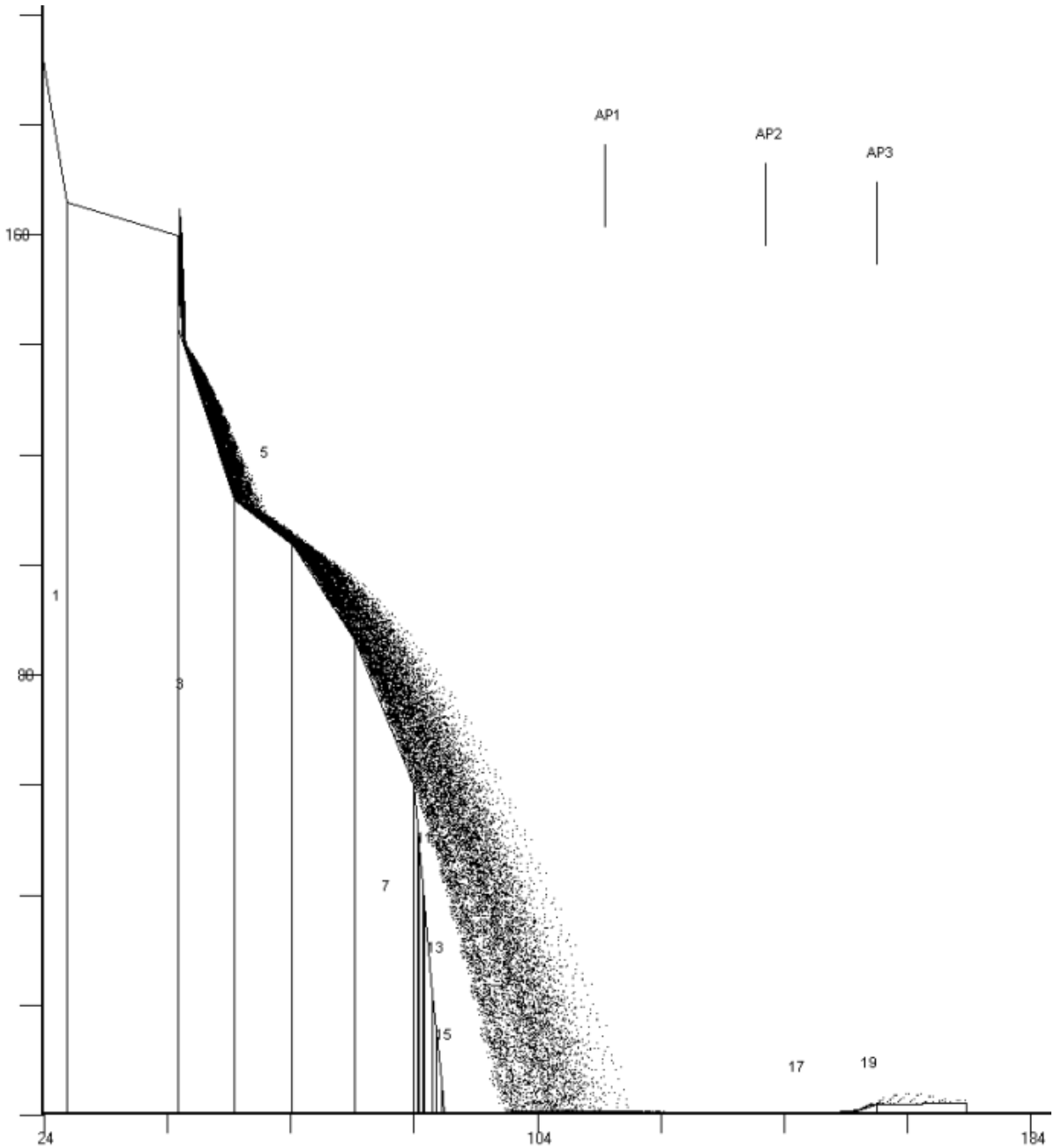


FIGURE 7-2. SAMPLE OF CRSP RESULTS FOR CUT SLOPE EXAMPLE.

Rocks falling from layer # 3, Massive Sandstone, D_{max} = 10 ft, with $\boldsymbol{R_{t\ min}}$ *and* $\boldsymbol{R_{n\ min}}$.

The configuration of the model example shown in Figure 32 and Figure 33 should be the starting point in designing rockfall mitigation protection. There are many details that one can zoom into, depending upon the objectives of a remedial measure. An iterative procedure should follow until a configuration is found that is both aesthetically acceptable and safe with respect to rockfall.

SUMMARY OF CRSP RESULTS - SLOPE 3 (Cut Slope Example)

Layer #	1000 rocks per simulation	Restitution Coefficients used: Rt_{min}, Rn_{min}			Sphere Diam.$_{MAX}$ (ft)
		Analysis Point 1	Analysis Point 2	Analysis Point 3	
1	% Rocks Passing	No rocks passed AP1	No rocks passed AP2	No rocks passed AP3	10
	Max Bounce height (ft)				
	Max K.Energy (ft-lb)				
	Max Vel. (ft/sec)				
3	% Rocks Passing	99.9%	24.8%	1.9%	10
	Max Bounce height (ft)	16.86	0.02	0.68	
	Max K.Energy (ft-lb)	10,485,930	1,618,721	922,740	
	Max Vel. (ft/sec)	86.68	29.38	21.74	
4	% Rocks Passing	74.0%	17.4%	13.8%	0.5
	Max Bounce height (ft)	37.16	0.73	0.73	
	Max K.Energy (ft-lb)	1,120	262	215	
	Max Vel. (ft/sec)	79.72	33.52	30.45	
6	% Rocks Passing	72.5%	32.3%	21.1%	2
	Max Bounce height (ft)	32.18	0.43	0.73	
	Max K.Energy (ft-lb)	65,214	12,275	8,847	
	Max Vel. (ft/sec)	75.92	28.68	23.88	
7	% Rocks Passing	16.9%	8.1%	2.9%	3
	Max Bounce height (ft)	21.53	0.02	0.35	
	Max K.Energy (ft-lb)	191,161	26,611	16,090	
	Max Vel. (ft/sec)	71.64	22.95	17.21	
9	% Rocks Passing	29.7%	1.2%	No rocks passed AP3	10
	Max Bounce height (ft)	0.29	0.02		
	Max K.Energy (ft-lb)	1,169,955	335,906		
	Max Vel. (ft/sec)	24.98	13.39		
10	% Rocks Passing	45.9%	0.1%	No rocks passed AP3	cylinder D=7' L=20'
	Max Bounce height (ft)	0.04	0.01		
	Max K.Energy (ft-lb)	1,257,467	55,587		
	Max Vel. (ft/sec)	21.63	4.60		
11	% Rocks Passing	39.1%	0.3%	No rocks passed AP3	6
	Max Bounce height (ft)	0.23	0.02		
	Max K.Energy (ft-lb)	237,855	26,244		
	Max Vel. (ft/sec)	24.23	8.07		
12	% Rocks Passing	59.1%	No rocks passed AP2	No rocks passed AP3	6
	Max Bounce height (ft)	0.13			
	Max K.Energy (ft-lb)	197,490			
	Max Vel. (ft/sec)	22.19			
13	% Rocks Passing	74.6%	No rocks passed AP2	No rocks passed AP3	2.5
	Max Bounce height (ft)	0.13			
	Max K.Energy (ft-lb)	7,845			
	Max Vel. (ft/sec)	16.46			
14	% Rocks Passing	5.9%	No rocks passed AP2	No rocks passed AP3	1.5
	Max Bounce height (ft)	0.00			
	Max K.Energy (ft-lb)	1,511			
	Max Vel. (ft/sec)	15.48			

FIGURE 7-3. SUMMARY OF SOME CRSP RESULTS FOR DESIGN.

APPENDIX A

FIELD DATA COLLECTION FORMS

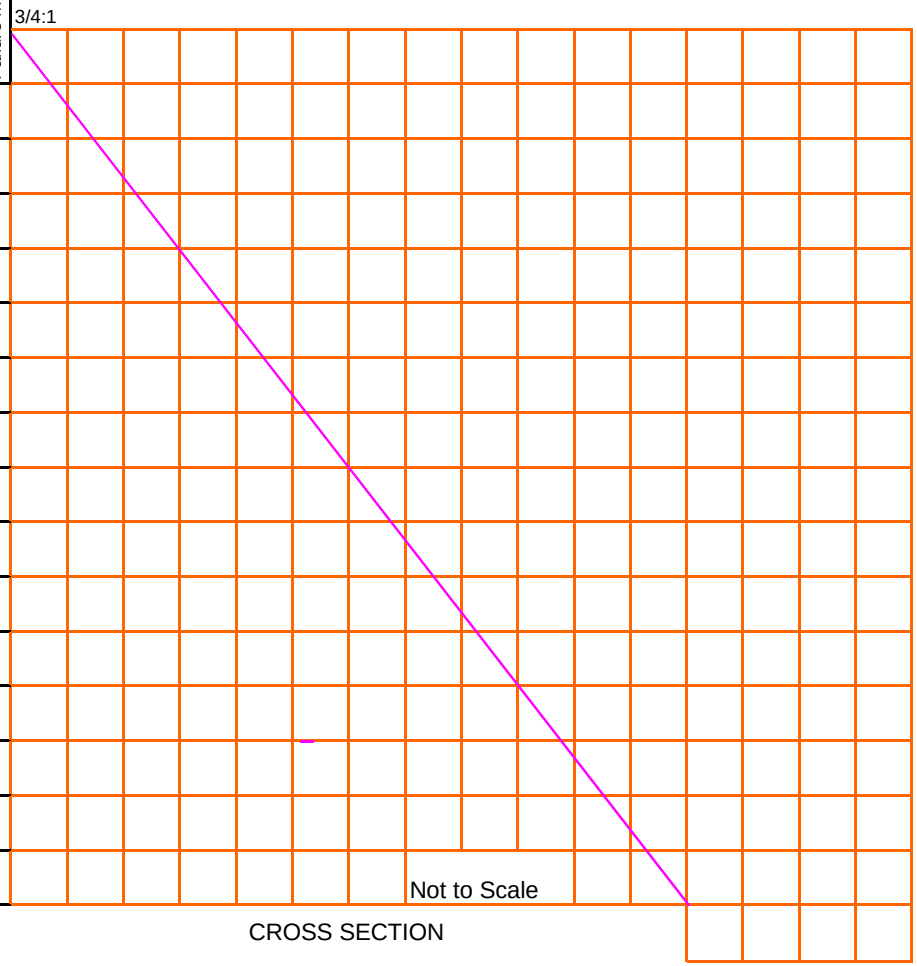
University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

Slope Cross Section Slope # Sheet of

Stratigraphic Sequence Initial Design Degree of cut slope: degrees from Horizontal

Rock Type	Unit Thickness (1)	Degree of Weathering (2)	Weathering Rate (3)	Est. Largest Block Diameter (ft)	Face Angle (4)	Overhanging (5)	Fall Potential (6)	CRSP Cell #	Failure Mode(7)



(1) Unit thickness based on vertical height in feet.
(2) Value based on visual inspection of unit (H=Highly, M=Moderately, S=Slightly,U=Unweathered, C=Completely)
(3) Weathering rate is based on extent of unit weathering as compared to the unit with least weathering within the same slope.
(4) Face Angle is existing outcrop slope angle.
(5) Indicates unit is overhanging other units, O=Overhanding other units, P=Protected by above overhanging unit, N=Not Overhanging, N/A=Not Applicable)
(6) Indicates whether material will reach the ground from this unit (Y=Yes, N=No, P=Partially Buried in Talus)
(7) How pieces detach from the slope (F=Flaking (Freeze/Thaw), J=Joint Intersections, U=Undercutting, W=Water Transported)

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section Slope # Sheet of

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement:

Barrier type and dimensions:

Depth of ditch (ft)

Plot distribution of material within ditch. Use CRSP Cell # when possible

Failure Mode: ____ Shatters on impact

____ Falls with subsequent weathering

____ Other (Describe)

Performance ____ Material contained with ditch

____ Material on pavement or shoulder

____ Toppling

● Rock encroachment to pavement

Slope Pavement

CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

Notes:

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # Sheet of

CRSP Cell # _____

Existing Slope Angle (based off LiDAR) _____

Slope Strike _____
Slope Dip _____

Bedding Strike _____
Dip _____

Road Strike _____
Valley Strike _____

					RMR Rating					
Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockfall Simulation Program Data Form Sheet of

Slope #
Date:

					Tangential Coefficient (Rt)				Normal Coefficient (Rn)								Rock Hardness (pcf)			
Cell #	Description	Rock Size (R) Radius (ft)	Surface Roughness (S) (ft) (in one Rock Radius)	Maximum Varation in Slope Angle θ=tan-1 (S/R)	Smooth Hard Surfaces (.9 to 1.0)	Most Bedrock and Boulder Fields (.75 to 0.95)	Talus and firm soil slopes (.65 to .95)	Soft soil slopes (.5 to .8)	Smooth Hard Surfaces (.6 to 1.0)	Most Bedrock and Boulder Fields (.15 to 0.35)	Talus and firm soil slopes (.12 to .2)	Soft soil slopes (.1 to .2)	Begin X	Begin Y	End X	End Y	Hard Sed (150 to 180)	Soft Sed (110 to 150)	Brush Covered Slopes Percent	Rock Shape Spherical (S), Disk (D), or Cylindrical (C)