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A RATIONAL PROCEDURE FOR ROCK SLOPE DESIGN FOR WESTERN PENNSYLVANIA

FINAL REPORT

December 31, 2008

Maria C. Jaime, Jeen-Shang Lin, Luis E. Vallejo

University of Pittsburgh

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16. Abstract

This report summarizes a research focusing on the application of Colorado Rockfall Simulation Program, CRSP, for rock slopes in Western Pennsylvania, with emphasis on the slopes representative of the geological conditions within the jurisdiction of the District 11-0 of the Pennsylvania Department of Transportation. Toward this goal, eight slopes were selected such that a complete spectrum of the geological profile in term of the rock stratigraphy of the area was covered. A procedure was developed to merge data collected in the field were with LiDAR data in creating analysis profiles for CRSP. Detailed simulation was carried out and the input parameters that gave results best matching field observations were obtained. These parameters are recommended as a reasonable starting point for applying CRSP for rock slope design in the studied area.

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Department of Civil and Environmental Engineering
University of Pittsburgh

A RATIONAL PROCEDURE FOR ROCK SLOPE DESIGN FOR WESTERN PENNSYLVANIA

PennDOT Work Order No. 5

Final Report

12/31/2008

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CHAPTER I:

REVIEW OF HIGHWAY ROCK SLOPE STABILITY DESIGN, GEOLOGY AND PRACTICE

I.1. BACKGROUND

Rockfall along highways that crisscross the rolling hills of Western Pennsylvania poses a serious challenge in terms of both the highway maintenance and the highway safety. Rockfall events are frequency occurrences in the region. These events are dictated not only by the engineering designs, but also by the local geological setting. One of the tools that have been widely employed by engineers to obtain an estimate of the path of a fallen rock fragment is the Colorado Rockfall Simulation Program, or, CRSP (Jones et al. 2000). Such estimates often form the basis for the design of protection fences, catchment trenches and cut slope geometry. Even though CRSP has been used in Pennsylvania, there is as yet no systematic validation; neither has there been a consistent procedure established for dealing with issues pertaining to local geological features. This research is aimed at addressing these two issues and, in the process, provides a starting point for a rational approach toward reliable designs.

This chapter encompasses three components: review of literature on the geology of the Pittsburgh area and the rock fall failures taken place in this area, a review of CRSP, as well as a summary of survey results on the practice involving rock slopes design for highways using CRSP. This survey includes interviews with PennDOT officials, consultants and contractors about the reliability of using existing software to analyze rock slope stability. The emphasis of the review was placed upon the relationship between the geology of the Pittsburgh area and the mode of rock failures taken place in this area, particularly in areas under the jurisdiction of PennDOT District 11-0.

I.2. GEOLOGICAL ASPECTS OF THE STUDY

I.2.1. GEOLOGY OF THE PITTSBURGH AREA

The Greater Pittsburgh region as dicussed in this report comprises Allegheny, Beaver, and Lawrence counties. Most of the area is within the Allegheny Plateau section of the Appalachian Plateaus province. Bedrock units exposed in the Greater Pittsburgh region range in age from Mississippian to Permian and include the Pocono Sandstone, Mauch Chunk Shale, and the Pottsville, Allegheny, Conemaugh, Monongahela, and Dunkard Groups (Figure I-1). Landslide problems on slopes underlain by the oldest rock units are uncommon and are relatively minor on slopes underlain by the Pottsville Group. The most severe slope stability problems are found on slopes underlain by the post-Pottsville cyclothemic units, especially in the Conemaugh and Dunkard Groups. The Conemaugh Group is not only the most widespread stratigraphic unit, but it also underlies the most populated area of the region (Pomeroy, 1982).

The vertical repetition of the sandstone, siltstone, shale, limestone, mudstone, claystone, and coal units in a cyclic pattern is characteristic throughout the region. Within each cycle sequence, most units commonly intertongue and grade laterally into other rock types. Coal and persistent limestone beds serve as marker beds. The rock units are generally horizontal in all but in the southeastern part of the region (Pomeroy, 1982).

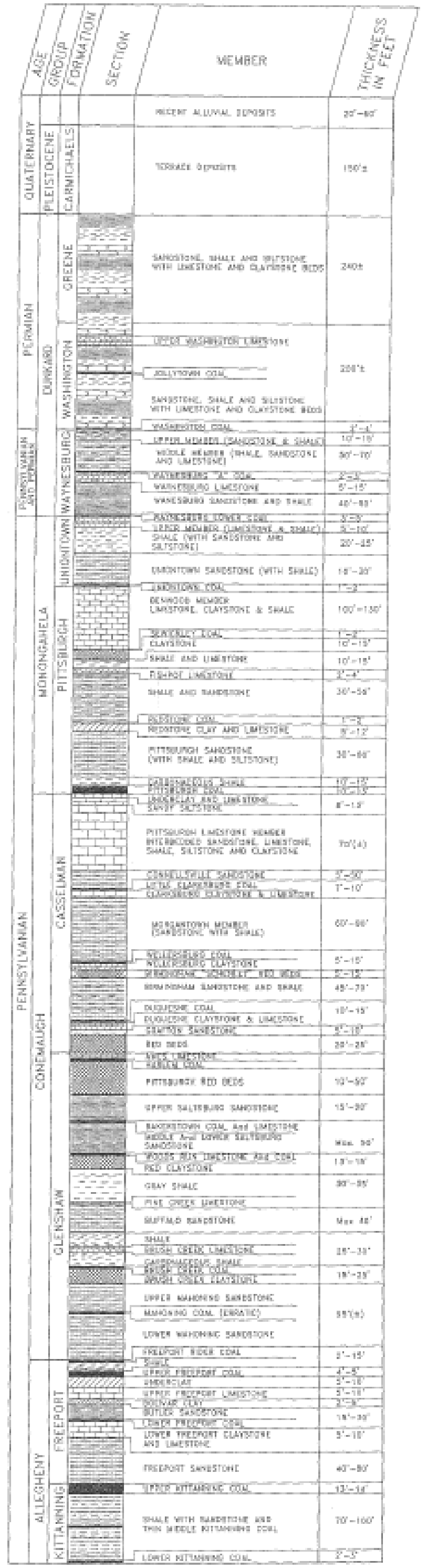
I.2.1.1. ROCKFALLS

A rockfall is a catastrophic movement of rocks from a slope that occurs as a direct result of gravity. The three principal types of landslide movements in the Pittsburgh area are rock falling, sliding, and flowing or a combination. This report will concentrate mainly on rock slope falls.

In an area underlain by cyclic sedimentary rocks, the widely different physical characteristics of the individual rock units are conducive to the production of rock falls.

Rock falls are produced by weathering and erosion that affect mudstone and shale more readily than sandstone, siltstone, and limestone. Differential weathering results in unsupported ledges, which eventually break away by falling. Fractures and bedding planes govern the geometry of rockfalls (Figure I-2). The joints in the more resistant lithologies also serve as detachment surfaces for rockfall (Figure I-2). Rockfalls are particularly common in cut slopes along the rivers in the region and along major highways (Ferguson, 1967; Ferguson and Hamel, 1981; Pomeroy, 1982).

FIGURE I-1. GEOLOGICAL STRATIGRAPHY OF ALLEGHENY COUNTY



I.2.1.2. GEOLOGIC FACTORS THAT AFFECT ROCK FALLS

The geologic factors that affect rock falls include: (1) lithology, (2) layering of the sedimentary beds, (3) position of critical beds on slopes, and (4) joints caused by stress relief (Pomeroy, 1982; Ferguson and Hamel, 1981).

Lithology, Layering, and Position of Sedimentary Beds

Because rocks in the Pittsburgh area are of heterogeneous character, made of many layers of competent and incompetent rocks, slope stability problems in the form of rockfalls are related largely to underlying layers of incompetent rock types in a section (Figure I-2). Rockfalls are caused by weathering and slaking of mudstone, claystone and shale underlying strong rock layers of sandstone, siltstone and limestone (Figure I-2). According to Pomeroy (1982), slaking of many red and non-red claystone and mudstone in the Pittsburgh area occur within an hour to a few hours after immersion in water. The process of freezing, thawing, drying and saturation also causes a loss in strength of the weaker beds that contribute to rockfalls (Kapur, 1960). Winters (1972) indicated that the position of the Pittsburgh red beds on a slope influences stability. He further established that the lower the position of the red beds on a slope, the greater the weight of the overburden, and the greater the volume of water available to the red beds. The availability of water would enhance slaking of the red beds and the overburden pressure would further advance the fragmentation of these water saturated red beds. The more fragmented a material is the easier its removal (erosion) from a slope.

Joints caused by stress relief

Joints in rock slopes contribute to rockfall susceptibility by providing planes of weakness along which rocks are prone to failure (Figures I-2 and I-3). The majority of the joints present in the sedimentary rocks in the Pittsburgh area are vertical and perpendicular to the bedding planes that are almost horizontal. The formation of these joints are the result of lateral stress relief accompanying valley erosion or rock cuts (for highway systems) in flat-lying interbedded strong and weak sedimentary strata (Wyrick and Borchers, 1981) (Figure I-3). Rockfalls are produced by the toppling of joint-bounded columns due to weathering of underlying weaker materials (Figure I-2). This type of rockfall occurs very often in the sedimentary rock slopes in the Pittsburgh area (Ferguson, 1967; Ferguson and Hamel, 1981; Delano and Wilshusen, 2001).

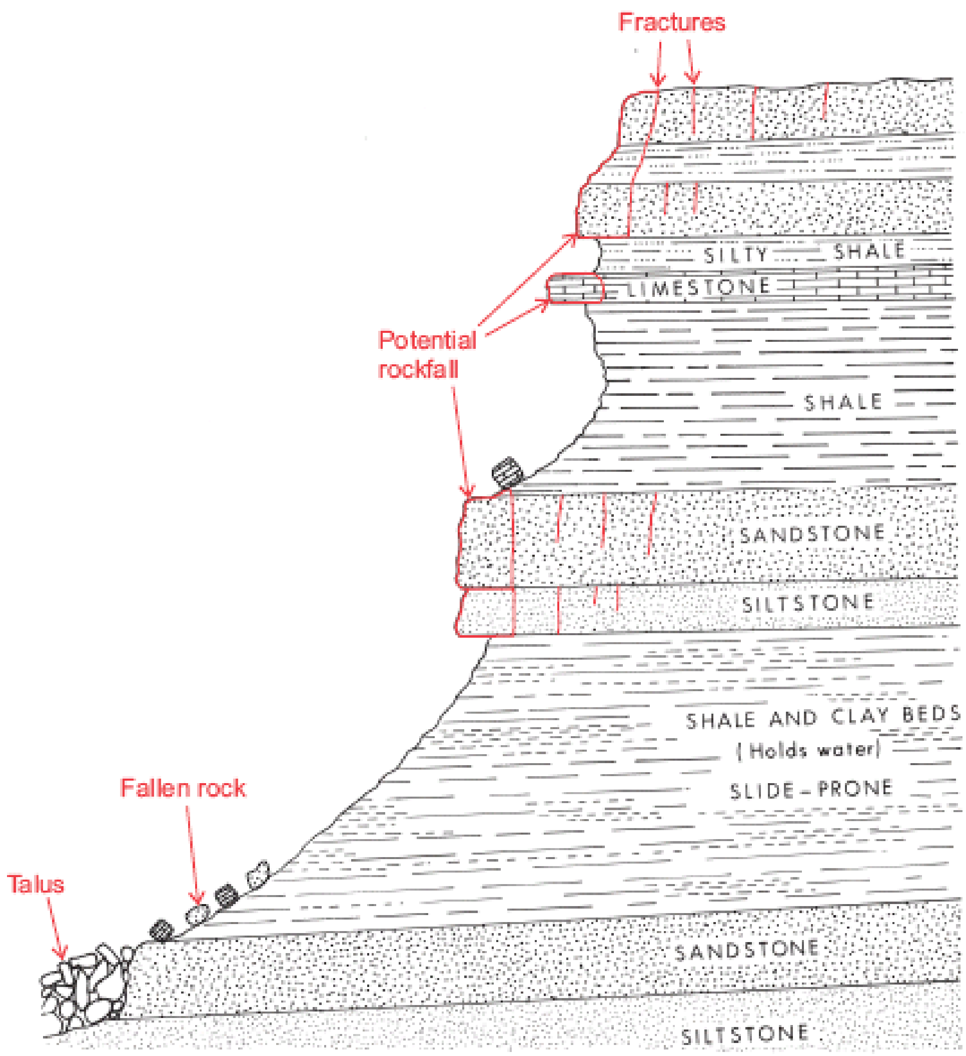


FIGURE I-2. ROCKFALLS AS A RESULT OF JOINTS AND WEATHERING IN SEDIMENTARY ROCK SLOPES IN THE PITTSBURGH AREA (DELANO AND WILHUSEN, 2001)

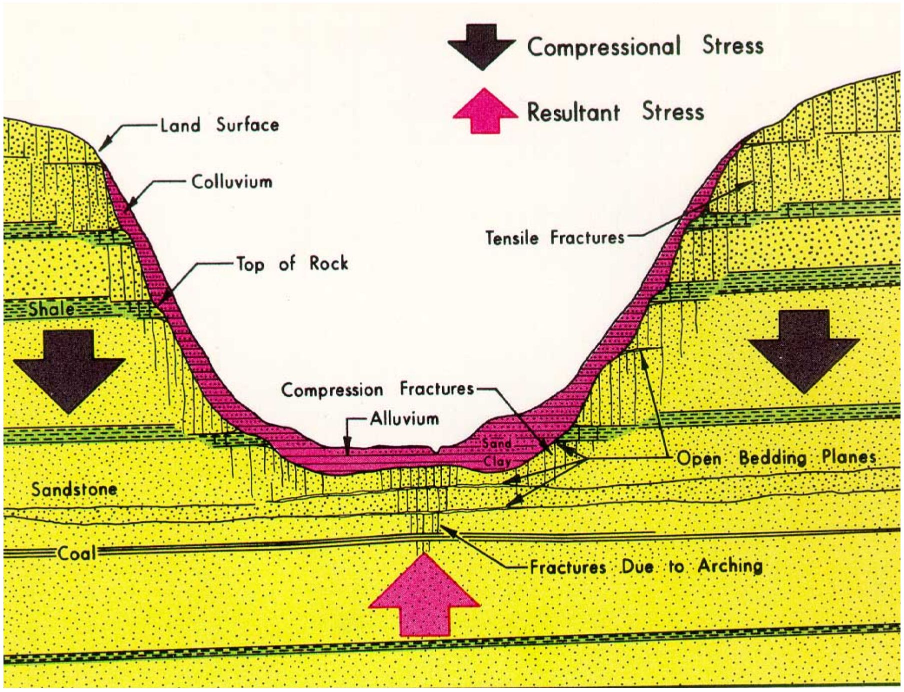


FIGURE I-3. ROCK JOINTS IN ROCK SLOPES RESULTING FROM LATERAL STRESS RELIEF (WYRICK, G.G., AND BORCHERS, J.W., 1981)

I.2.2. SELECTED ROCK SLOPES FOR A DETAILED STABILITY ANALYSIS

To establish the impact of local geological characteristics to rockfalls, this study also conducted field studies for a detailed collection of failure modes and stability analysis. Altogether eight rock slope locations represent existing cut slopes throughout PennDOT District 11-0 that were selected. The selections were made in an attempt to cover most of the geological formations of the area. These selected sites are listed below, while their stratigraphic profiles are shown in Appendix A.

1. SR 0079, Northbound - Segment 520. Offset 1,250 feet (South of Bridgeville Interchange);
2. SR 3048, Eastbound - Segment 190. (Near SR 0079 Carnegie Exit);
3. S.R. 0028, Southbound – Segment 251, Offset 3,100 feet (South of Harmarville Interchange);

4. SR 0279, Northbound - Segment 170, Offset 350 feet (south of Wexford);

5. SR 0051, Southbound – Segment 741, Offset 1,900 feet (North of Sewickley Bridge);

6. SR 0008, Northbound – Segment 270, Offset 1750 feet (North of Etna);

7. SR 0060, Northbound – Segment 180, Offset 1,1000 feet (North of Beaver Falls Interchange);

8. SR 0422 Westbound – Segment 311, Offset 0 feet (West of S.R. 168 Interchange);

I.2.3. ASSESSING ROCKFALL HAZARDS

To address the hazards posed by the rock slopes, several rock slope assessment systems have been developed for identification of problematic rock slopes including the Oregon Rockfall Hazard rating system (RHRS) (Pierson, 1991), the New York State Slope Rating Procedure (NYSDOT, 1996), The Oregon Catchment Area Design (Pierson et al, 2001), and the Ohio Rockfall Hazard Rating System (ORHRS) (Woodward and Woodward and Shakoor, 2006).

Of these evaluations systems, the Ohio Rockfall Hazard Rating System (Woodward and Shakoor, 2006) would be readily applicable for ranking the risk of rock slopes in the Pittsburgh area. The reason for this is that the geology in Ohio is characterized by the presence of gently dipping, harder, more competent strata (siltstones, sandstones, limestones) alternating with softer, less competent strata (claystones, mudstones, shales). This type of stratigraphy is very similar to the one present in the Pittsburgh area (Fig. 1 and 2). This type of stratigraphy is highly susceptible to differential weathering which results in undercutting of the competent layers (hard rocks) by erosion of the incompetent layers (shales, mudstones, and claystones). A description of the ORHRS is presented next.

I.2.4. THE OHIO ROCK HAZARD RATING SYSTEM (ORHRS)

The ORHRS system was developed after studying one hundred and eight sites along the Ohio highways. The information gathered at these sites included (a) the geology of the sites (stratigraphy, amount of undercutting, discontinuity characteristics, hydrologic conditions), (b) slope geometry (slope length, slope height, slope angle, width and depth of catchment ditches), and (c) traffic characteristics (average daily traffic, speed limit, decision site distance, pavement width. The data collected were statistically analyzed. Based on the results of statistical analyses and a review of the previously developed rating systems, a rating matrix was developed to assess the different parameters used (TABLE 1) (Woodward and Shakoor, 2006).

Computation of overall score

The overall score for a site can be determined by summing of the scores of different parameters following Table 1 or making use of the following equation (Woodward and Shakoor, 2006):

Overall Score = Geologic Parameters + Geometric Parameters + Traffic Parameters + Rock Fall History

With the overall scores, all sites with overall rating scores greater than 100 are considered as high hazard potential sites, those with total scores between 50 and 100 are considered as moderate hazard potential sites and those with total scores less than 50 are considered low hazard potential sites.

EVALUATION PARAMETERS			RATING SCORES FOR DIFFERENT CATEGORIES OF EVALUATION CRITERIA			
			3 Point/(1)	9 Points/(2)	27 Points/(3)	81 Points/(4)
GEOLOGIC PARAMETERS						
Geologic Character	Differential Weathering	Slake Durability Index	90-100%	75-90%	50-75%	<50%
Geologic Character	Differential Weathering	Max. Amount of Undercutting	0-1 ft	1-2 ft	2-4 ft	>4 ft
Geologic Character	Discontinuity Role	Discontinuity Extent/Orient.	Discontinuous joints, favorable orientation	Discontinuous joints, random orientation	Discontinuous joints, adverse orientation	Continuous joints, adverse orientation
Geologic Character	Discontinuity Role	Discontinuity Surface Features	Very rough JRC=20	Rough JRC=15	Undulating JRC=10	Smooth JRC=5
Block Size/Volume of Rock Fall			1 ft/ 3 yd^3	2 ft/ 6 yd^3	3 ft/ 9 yd^3	4 ft/ 12 yd^3
Hydrologic Conditions			No water seeps on slope	A few water seeps on slope	Many water seeps on slope	Numerous water seeps on slope
GEOMETRIC PARAMETERS						
Ritchie Score			<1	1-1.5	1.5-2.5	>2.5
TRAFFIC PARAMETERS						
$\frac{\text{ADT x Slope Length / 24 hrs}}{\text{Posted Speed Limit}}$ x100%			25% of time (very low)	50% of time (low)	75% of time (medium)	100% of time (high)
% Decision Sight Distance			Adequate sight distance, ≥100%	Moderate sight distance, 75%	Limited sight distance, 50%	Very limited sight distance, <50%
Pavement Width			50 feet	40 feet	30 feet	20 feet
ROCKFALL HISTORY			No falls	A few falls	Many falls	Numerous falls

TABLE I-1. THE OHIO ROCK HAZARD RATING SYSTEM (WOODWARD AND SHAKOOR, 2006)

I.3. AN OVERVIEW OF COLORADO ROCKFALL SIMULATION PROGRAM

To model the impact of rockfall on highway, it is imperative that one should be able to project the travel path of the falling rock blocks. By being able to track the block motion trajectory, it provides a rational method to assess potential damages of rockfalls and to effectively design the countermeasures. A comprehensive and theoretically correct approach would be to employ fundamental laws of physics and mechanics to solve a rockfall problem as a dynamic problem considering a 3D slope in its entirety and modeling falling blocks as 3D objects. This is not a difficult problem and can be readily formulated and implemented in a 3D discrete element framework. However, with a more precise methodology also comes a higher demand for more detailed input requirements. Otherwise, a better methodology may give a false sense of better or more accurate results. From a long term perspective, this is, however, the approach that has to be taken.

The Colorado Rockfall Simulation Program, CRSP, takes a different route: It is a simplified 2D version that has many limitations. Its successes derive from the effort in input parameter calibration with a large number of field tests results. Also, important in its construction is the introduction of statistical measures in recognition of variability and uncertainty in rockfall analysis. The simplicity of CSRP makes it easy to use and simple to implement.

In the sections that follow, we review and comment on the basic considerations of the formulation adopted in CRSP. Also discussed will be the input parameter selections and the meaning of the results obtained. The reference to CSRP in this study is the version 4 last updated in March of 2000.

I.3.1. BASIC ASSUMPTIONS

A number of assumptions form the basis of the CRSP:

(1) The slope profile should follow the most probable rockfall path as established during field investigations. Therefore, all calculations may be posed in two dimensions.

(2) Because the rock type does not change during a rockfall, coefficients assigned to the slope material can account for both the rock and slope properties.
(3) The worst case scenario is generally that of the largest rock that remains intact while traveling down a slope. Therefore, it is assumed that the rock does not break apart in its fall.
(4) Rock size and shape are assumed constant for analysis of rockfall from a given source.
(5) For determination of a rock's volume and inertia, a sphere may be used because it yields a maximum volume for a given radius, which will tend toward a worst case.

I.3.2. BASIC CONSIDERATIONS AND FORMULATION

The basic entities of a rockfall analysis in CSRP are a rock block and the slope that the block is falling off of. A rock block is given an initial position, and an initial velocity,both defined in a 2D setting.

A rockfall problem is defined in two sets of equations: the conservation of energy and the conservation of momentum. An additional equation, which is not explicitly presented in the CSRP manual, is the contact detection that determines if a block is in contact with the slope. To simplify the contact detection, currently CSRP assumes that a block is a circular disk, a cylinder, or a sphere. Here, we use a circular disk, depicted in Figure I-5, to illustrate the basic formulation.

Initial setup

Initially, a disk is given a set of initial velocities $\dot{x}(0)$, $\dot{y}(0)$, and $\dot{\theta}(0)$ and a starting location at x(0) and y(0), where 0 stands for time 0. The disk is also endowed with a mass moment of inertia of I, and a mass of M. The energy at time 0 consists of kinetic energy and potential energy as follows,

$$E(0) = \frac{1}{2}M(\dot{x}\,(0)^2 \; + \dot{y}(0)^2\,) + \frac{1}{2}I\dot{\theta}(0)^2 \; + Mgy \qquad \text{Eq. (1)}$$

Before the block collides with the slope

The energy conservation is maintained until the block hits the slope, upon which some energy will be lost due to the contact. Before hitting the slope, there is only one external force term caused by gravity, thus the equations of motion are as follows,

$$\ddot{x} = 0 \quad \text{Eq. (2)}$$

$$\ddot{y} = -g \quad \text{Eq. (3)}$$

$$\ddot{\theta} = 0 \quad \text{Eq. (4)}$$

A simple integration thus gives the velocities as

$$\dot{x}(t) = \dot{x}(0) \quad \text{Eq. (5)}$$

$$\dot{y}(t) = \dot{y}(0) - gt \quad \text{Eq. (6)}$$

$$\dot{\theta}(t) = \dot{\theta}(0) \quad \text{Eq. (7)}$$

If the block shape is not symmetric about the center, in contrast to what we have here, the angular velocity of the unsymmetrical mass distribution would have induced torque during motion, and angular acceleration would not be zero. A further integration of the velocity gives:

$$x(t) = x(0) + \dot{x}(0)t \quad \text{Eq. (8)}$$

$$y(t) = y(0) + \dot{y}(0)t - \frac{1}{2}gt^2 \quad \text{Eq. (9)}$$

With a disk, the angular displacement needs not be updated as it never enters an analysis.

Generally, the position update is computed by setting up a time increment, Δt, and repeating the computation until the rock block reaches a position beyond the interest of a study.

Contact detection

Given a typical slope profile, the contact detection as to when a disc hits the slope may be carried out through simple computation--at each time step, after the block, or disk, position is updated. A computation checks if the disk is in contact with the slope. A slope profile is defined by a sequence of line segments from the hill top downward. For each segment from the hill top, two conditions are checked:

(1) whether the distance from the center of the disk to the segment is smaller than the radius of the disk;
(2) whether the distance from the center of the disk to either of the end points is smaller than the radius of the disk;

If either of these two conditions is met, the disk has come into contact with the slope.

Formulating the bouncing

For the rockfall problem, explicit formulation is easy and sufficient. After satisfying that the overlap between block and slope due to contact is sufficiently small and has negligible effects on the block motion trajectory, the block bouncing is formulated through conservation of momentum. This formulation goes together with the energy loss due to plastic deformation and due to the frictional resistance against the block movement. The easiest approach is to use the restitution coefficient to model the energy loss on a rebound. A restitution coefficient, R, can be defined as

$$R = \frac{V_b}{V_i} \qquad \text{Eq. (10)}$$

where, V_b is the bouncing speed, and V_i the impact speed. In general, the coefficient of restitution is a function of both the impact speed and the material involved. The larger the impact speed, the more the energy loss occurs-- resulting in a smaller coefficient of restitution.

In physics, one would use a restitution coefficient and the conservation of momentum to solve for the bouncing velocities. In discrete elements, one would use spring and damping to model the process and compute the bouncing velocities from solving the block dynamics. CRSP uses a very unusual approach to model the block bouncing: the normal and tangential directions are assigned different coefficients of restitution but are implicitly coupled.

(1) CRSP formulation starts with a velocity dependent coefficient of restitution in the normal direction as,

$$R_n(V_n) = \frac{R_n}{1 + \left(\frac{V_n}{30}\right)^2} \quad \text{Eq. (11)}$$

After bouncing, the normal velocity, V_n, becomes

$$V_{n2} = \frac{V_{n1} \cdot R_n}{1 + \left(\frac{V_{n1}}{30}\right)^2} \quad \text{Eq. (12)}$$

(2) CRSP further assumes that after impact the tangential velocity is dictated by a disk's rotational velocity,

$$V_{t2} = \dot{\theta}_2 \cdot R = \omega_2 \cdot R \quad \text{Eq. (13)}$$

(3) Instead of solving the tangential velocity from conservation of momentum. CSRP modifies energy conservation to give v_{t2} in the following form,

$$\left[\frac{1}{2} \cdot \mathrm{I} \cdot \omega_1{}^2 + \frac{1}{2} \cdot \mathrm{M} \cdot \mathrm{V_{t1}}{}^2\right] \cdot f(F) \cdot SF = \frac{1}{2} \cdot \mathrm{I} \cdot \omega_2{}^2 + \frac{1}{2} \cdot \mathrm{M} \cdot \mathrm{V_{t2}}{}^2 \quad \text{Eq. (14)}$$

(4) By combining 2 and 3,

$$\mathrm{V_{t2}} = \sqrt{\frac{\mathrm{R}^2 \cdot \left(\mathrm{I} \cdot \omega_1{}^2 + \mathrm{M} \cdot \mathrm{V_{t1}}{}^2\right) \cdot f(F) \cdot SF}{\mathrm{I} + \mathrm{MR}^2}} \quad \text{Eq. (15)}$$

With the solution of V_{n2} and V_{t2}, the solution for the time step is completed.

In this formulation, *f(F),* reflecting the effects of frictional force, F, has the following form

$$f(F) = R_t + \frac{1 - R_t}{\left(\frac{V_{t1} - \omega_1 R}{20}\right)^2 + 1.2} \qquad \text{Eq. (16)}$$

SF, a scaling factor, is defined as

$$SF = \frac{R_t}{\left(\frac{V_{n1}}{250 \cdot R_n}\right)^2 + 1} \qquad \text{Eq. (17)}$$

This scale factor basically considers the coupling between the normal and shear restitution. Given R_t, R_n, and velocity before the contact, the bouncing velocity can readily be found.

Repeating computation

After the bouncing velocities are obtained, the new position of the block can be obtained Δt later. The computation repeats by checking if a contact is made in the next time. If not, the equations of motions readily give the new velocities. If yes, the equations from the coefficients of restitution give the new velocities. Position updates are straightforward and the computation continues until the preset limit position is reached.

If the distance the rock block travels between bounces is less than its radius, it is considered to be rolling and its new (x, y) position is set equal to a distance of one radius from its previous position. This models a rolling rock as a series of short bounces, much like an irregular rock rolls on an irregular surface.

I.3.3. VARIABILITY OF THE SLOPE PROFILE

CRSP employs a parameter to describe the roughness of a slope surface, S. It is defined as the perpendicular variation of the slope with a slope distance equals to the radius , R, of the rock block under consideration. From this, a maximum allowable variation in slope angle is obtained as,

$$\theta_{\max} = \tan^{-1}\left(\frac{S}{R}\right) \qquad \text{Eq. (18)}$$

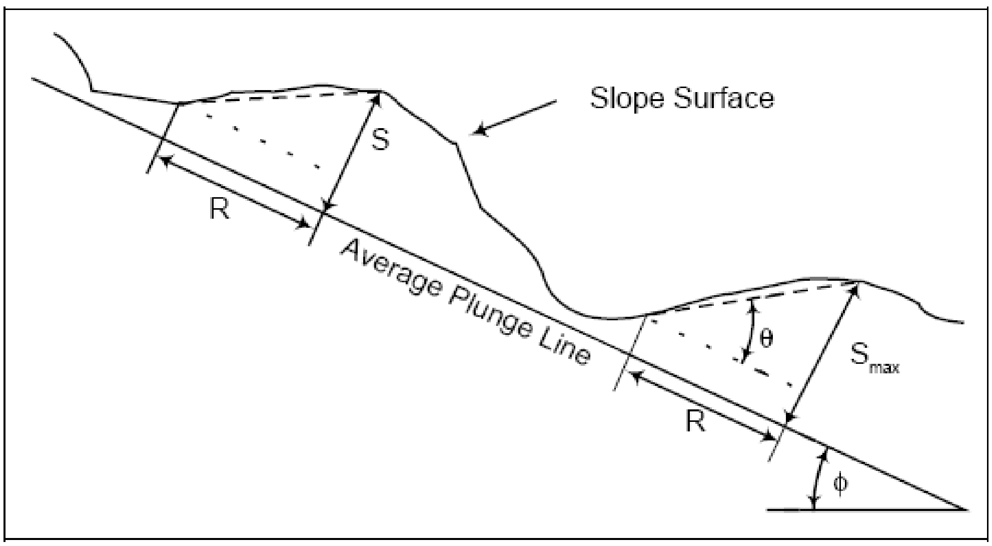


FIGURE I-4. SURFACE ROUGHNESS (S) ESTABLISHED AS THE PERPENDICULAR VARIATION FROM AN AVERAGE PLUNGE LINE (DEFINED BY SLOPE ANGLE (ϕ) OVER A DISTANCE EQUAL TO THE RADIUS OF THE ROCK (R). MAXIMUM SLOPE VARIATION (S_{MAX}) IS DEFINED BY S AND R. (PFEIFFER, 1989; PFEIFFER ET AL., 1991; 1995).

The slope angle used in the analysis is randomly selected but set to be less than θ_{max} during the impact. The way this is implemented is to introduce a random angle θ for each segment to create a slope profile for contact computation as depicted below.

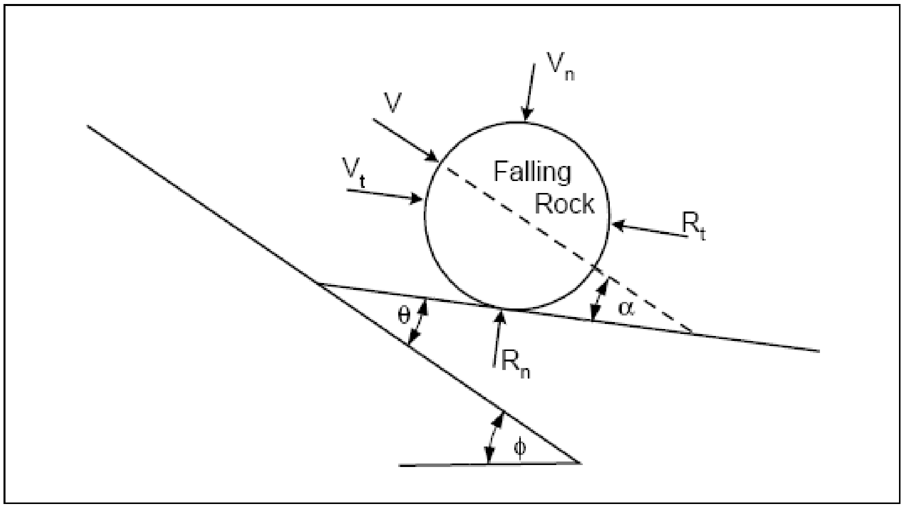


FIGURE I-5. IMPACT ANGLE (α) DEFINED AS A FUNCTION OF ROCK TRAJECTORY, SLOPE ANGLE (ϕ), AND SLOPE VARIATION (θ). ROCK VELOCITY (V) IS REDUCED INTO NORMAL (V_n) AND TANGENTIAL (V_t) COMPONENTS. (PFEIFFER, 1989; PFEIFFER ET AL., 1991; 1995).

I.3.4. REMARKS ON THE FORMULATION

The CRSP code has been extensively calibrated; however, it is not clear to what extent these equations remain valid. For instance, during the program calibration (Pfeiffer, 1989), it was observed that the normal restitution coefficient appeared to be somewhat dependent on slope length, with a longer slope corresponding to a greater value of R_n. This finding does not have physical justification and may be one indication of the deficiency of the semi-empirical formulation.

A better approach is to adopt the discrete element formulation, and let the energy loss be defined by velocity dependent normal and shear damping—represented as dashpots. One such example is depicted below. The left represents normal contact, the right the shear contact. This formulation is more fundamental and the resulting energy loss in the normal and shear directions will be automatically coupled even though the damping mechanisms are not.

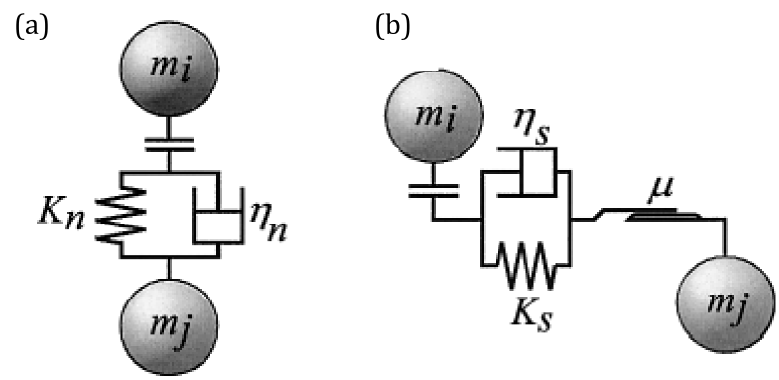


FIGURE I-6. THE CONVENTIONAL DISCRETE ELEMENT FORMULATION (a) FOR NORMAL SPRING (b) FOR SHEAR SPRING

The roughness term used in CRSP was design for 2D scenarios; it is conceivable that it may be calibrated in some fashion to indirectly reflect effects of 3D topography on where a rock block would land.

I.3.5. INPUT FOR CRSP

Each of the required input parameters and its selection is briefly summarized below taken from the CRSP user's manual.

Slope profile

If more than one potential rockfall pathes from the source area to the area that may require protection are present, then multiple analyses using multiple slope profiles may be required.

A slope profile of is input into CRSP as a series of straight-line segments called cells. Each cell is assigned a range of material properties that need to be defined (See CRSP Data Form).

Rock block size

Because a larger rock has greater momentum and is less likely to lodge among irregularities, it will travel farther down a slope than a smaller rock (Ritchie, 1963), thus rock block size is critical in determining the degree to which surface roughness will affect rockfall behavior.

The largest rocks found at the base of the rockfall path that can be identified as having fallen from the source area make a good choice for rock size determination. If no rocks are available at the base of the path, then a rock size can be determined from the source area by measuring joint spacing and orientation. It is possible to estimate the potential block size formed by the joints using computational geometry.

The rock block size or sizes selected will aid in the determination of surface roughness as they are related.

Cell boundaries

Cell, or line segment, boundaries are selected where changes in slope occur and/or where the slope material changes. Closely spaced cells may not be a good idea since each cell may be assigned a difference roughness, and smaller variations in the slope are further modeled by the surface roughness.

Cell configurations that require excessive precision may result in erroneous outputs because the variables in the program are coded in single precision.

Surface Roughness (S)

At the point of impact, CRSP selects a slope angle (θ) that is randomly varied up to the limit set by the maximum probable variation in the slope (S_{max}). This limit can be determined by field observation of the slope surface. Because the program selects an impact angle variation up to the value defined by the surface roughness, the largest probable surface roughness should be used. This is not always the value for the largest bump on the slope, or an average variation in the slope. Rather, it is the value of the largest variation that occurs with some frequency.

A range of probable surface roughness values should be selected for each cell, and if more than one rock size is being considered, separate surface roughness values are collected for each rock size.

Tangential Coefficient (R_t)

The tangential coefficient of frictional resistance determines how much the component of the rock's velocity parallel to the slope is slowed during impact. Vegetation and slope material both influence the tangential coefficient. A range of probable values should be selected for each cell, for use in a sensitivity analysis of the slope.

Normal Coefficient (R_n)

The normal coefficient of restitution is a measure of the change in the velocity normal to the slope after impact, compared to the normal velocity before the impact. The normal coefficient is determined by the rigidity of the slope surface.

Rock block shape

Rock block shape contributes to the randomness of rockfall behavior in a manner similar to that of slope surface roughness. Rock block shape also influences the apportionment of translational and rotational energy through the moment of inertia.

For determination of a rock block's volume and inertia, a sphere may be used because it yields a maximum volume for a given radius, which will tend toward a worst case. CRSP will also allow the use of discoidal or cylindrical rocks. Shown below is the recommended input data form by the authors of CRSP.

CRSP DATA FORM

LOCATION: ______________________________ DATE: ______________________________

STATION: ______________________________ FILENAME: ______________________________

SITE INVESTIGATOR: ______________________________

CELL #	DESCRIPTION	SURFACE ROUGHNESS			Rt	Rn	BEGIN X,Y	END X,Y

ANALYSIS POINT: ______________________________ STARTING ZONE: ______________________________

FIGURE I-7. CRSP DATA FORM PROVIDED BY CRSP MANUAL

I.4. SURVEY OF THE CURRENT PRACTICE IN WESTERN PA

A survey of over 30 geology and engineering professionals in the area was conducted to develop a baseline of information concerning both the historical and current state of the practice in rock slope analysis. Individuals interviewed were associated with PennDOT, the Pennsylvania Turnpike Commission, the Pennsylvania Department of Environmental Protection, other state highway departments, universities, and consulting firms.

I.4.1. SURVEY FORM DESIGN

The interview form developed (and provided here in Appendix B) addresses:

(1) The interviewee's past experience with rock slope stability analysis including general work locations, methods of analysis used, and typical modes of rock slope failures evaluated;

(2) Any correlations the interviewee has observed related to seasonal rock slope failures or falls, along with other conditions that influence rock falls or slope failures;

(3) Methods of rock slope analysis used by the interviewee other than CRSP including summary of input required for the method(s);

(4) The interviewee's experience with the CRSP program – both positive and negative;

(5) The interviewee's experience with other rock slope analysis methods – both positive and negative;

(6) Methods of data collection used by the interviewee for CRSP and other rock slope analysis methods; and

(7) The interviewee's use of sensitivity analyses for rock slope analysis methods used.

I.4.2. SUMMARY OF SURVEY RESULTS

Provided below are summaries of the interviewees responses, which amounted to only a very small sample of ten responses, to the questions provided above.

Past Experience

Those interviewed to date generally have rock slope analysis experience in Pennsylvania and West Virginia. Methods of analysis include empirical methods using published design guidance like Richie's "An Evaluation of Rockfall and its Control" and the West Virginia Department of Transportation "DD-403 Guide for Design in Cut Sections Through Rock," or personal experience; stereographic projections based on field measurements of strikes and dips; and software packages including CRSP, ROCKPACK III, and DIPS. Rock failure modes evaluated include block type failures because of strikes and dips in our region, toppling failures, wedge failures, and rockfalls resulting from weathering.

Seasonal Influences/Other Influences on Rock Slope Failures/Rock Falls

In general, most respondents identified the spring and fall rainy seasons as the times when most slope problems occur especially when slopes include red beds. Others have observed that for deep seated rock slides, the critical times were during February after early warming followed by heavy precipitation. And typically for more resistant type rocks, there is no specific time for failures/falls. Instead, over time, as a result of freezing and thawing and erosion of the weaker rock units, the rocks start to come down. One interviewee remarked that he was involved in a SR 19 shale slope stability problem in late summer, which is counterintuitive to what one would expect.

Rock Slope Analyses Methods other than CRSP

Other methods used include programs like STABL with typical strength failures where the slip plane is forced to occur in the red bed units. For this type of analysis, the respondents look at the material in the joints and use published values of soil on rock. CRSP is appropriate for rockfall, but, in addition, the Europeans have developed valuable methods based on energy transfer principals like CRSP. Another approach identified is the use of stereographic projections based on measurements of strikes and dips in the field to select appropriate slope angles. By measuring rock characteristics like slope height, joint measurements, and bedding plane details, ROCKPACK III evaluates the type of failure mode that might occur, i.e., planer, toppling, or wedge, from which slopes and benches can be selected. Following the use of ROCKPACK III, CRSP can be used to test slope configurations to determine the need for additional benches, fall zones, or rock fall fences. An empirical method developed and used in the late 1980s and early 1990s was geared around the point load test evaluating quality of rock coupled with the slope geometry and stratigraphy of rock.

CRSP Experience

In general, the consensus from those interviewed is that the CRSP model, while valuable, is not a standalone program. For example, CRSP cannot evaluate translational type failure in the red beds. The evaluator needs to make the distinction of where CRSP applies and where it does not apply and why. Of the ten individuals interviewed, five have used CRSP for rock slope stability analysis. Four of five have been very satisfied with the CRSP results. One interviewee stated that he had used the CRSP program from 1990 through 1995 and did not find the program to be useful. He had tried to field verify his program output and was not pleased with the results.

Other Methods Experience

For the other rock slope analysis methods provided above, the interviewees unanimously agreed that the slopes designed with those methods have performed acceptably. But they cautioned that experience plays a huge role in the final result. One interviewee who uses the software program DIPS noted that he did an independent analysis of a slope that had failed, and his results were within one degree of the failed slope angle. A disadvantage to DIPs, in his opinion, is that it concludes only that the design is “safe” or “not safe.” He is interested in the ROCKPACK III program because it provides factors of safety, but he understands that it is not user-friendly. ROCKPACK IV, due out soon, is expected to be a significant improvement over the existing version.

Data Collection Methods

CRSP requires a significant amount of field work data collection including joints, bedding planes, surface roughness, estimated sizes of rocks that might fall, and other parameters. In addition, drilling and logging of the boreholes needs to be performed. And the drilling program needs to be designed so that geological cross sections can be drawn. In many cases, the CRSP parameters have to be estimated which can lead to poor results if the evaluator does not have the appropriate experience to select these parameters. If dealing with a new slope, the evaluator needs to find rock outcrops or cut slopes nearby to estimate data input to CRSP. Need to evaluate groundwater conditions and potential global slope movements. A few of the interviewees noted that they are considering the use of a downhole camera to collect more accurate discontinuity information. And environmental documents should be reviewed to find other impacts. Most interviewees focus on the slope areas that they deem are the potential significant problem areas when collecting data.

Sensitivity Analyses

Sensitivity analyses, to varying degrees, have been performed by most of the interviewees. Most of the respondents felt that sensitivity analyses are critical in rock slope analyses, but sometimes the client's budget does not support this work. Many felt that the level of sensitivity analysis effort depends on the specific project based on vehicle safety, location, rock units involved, and past history of instability for the rock units being cut. Others felt that an observational method and years of experience lead to the most appropriate conclusions rather than a computer model with numerous input parameters that have to be estimated followed by sensitivity analyses. In some cases, as part of a sensitivity analysis, interviewees will determine Factor of Safety = 1.0 parameters, then compare to the parameters they have chosen and adjust and reanalyze as appropriate.

CHAPTER II:

FIELD DATA COLLECTION AND SETUP FOR CRSP RUNS

II.1. AN OVERVIEW OF THE FIELD INVESTIGATION

This chapter summarizes the field effort performed for this project. At each slope location shown in Figures II-1, II-2, and II-3, representative and relevant data were collected. The field investigation conducted consisted of the following elements:

Final selection of field sites: The inventory of slopes included in the study changed slightly since the inception of the project. The final selection of sites is shown in the stratigraphic columns in Appendix A. This selection was presented to the District Geotechnical Engineer for concurrence prior to commencement of the field work. The final slope inventory was selected to provide coverage of the entire stratigraphic sequence in District 11-0, concentrating on those intervals commonly exposed along the Department cut slopes.

Compilation of base mapping: The project team gathered base mapping data for each site to be used in the field. The base mapping was derived from LiDAR data obtained from the DCNR website. This data is draft at this time as per the DCNR's caution to end users. However, it was deemed of sufficient quality for use in this study. The LiDAR data provided elevation contours which were overlain on aerial photographs. The base mapping is shown on Figures II-4 through II-11.

Development of Field Data Forms: The field data forms included in Appendix C were developed by the project team to ensure the following information was collected at each site:

- Slope Cross Section Information
- Catchment Ditch & Barrier Information
- Bedding, Slope, and Discontinuity Orientation
- The information that is relevant to CRSP Input Parameters.

Collection of Field Data: Each site was visited and the field data forms mentioned above were completed. The data sheets for each site are shown in Appendix D-1 through D-8. In addition to the field forms, photographs of each site are included in Appendix F-1 through F-8.

A Further Note on Restitution Coefficients: Restitution coefficients are critical CRSP input parameters. Because of the built-in empirical nature of these parameters, they are taken from the CRSP manual and their use in this study can be found through Appendix D-1 through D-8.

(a) Tangential Coefficients

Description of Slope	Tangential Co-efficient (R_t)	Remarks
Smooth hard surfaces and paving	0.90 – 1.0	-R_t is not very sensitive compared to R_n, but may be important for hard or significantly vegetated slopes -Use lower R_t as the density of vegetation on the slope increases.
Most bedrock and boulder fields	0.75 – 0.95	
Talus and firm soil slopes	0.65 - 0.95	
Soft soil slopes*	0.50 - 0.80	

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

(b) Normal coefficients

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

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

TABLE II-1. CRSP SUGGESTED RESTITUTION COEFFICIENTS

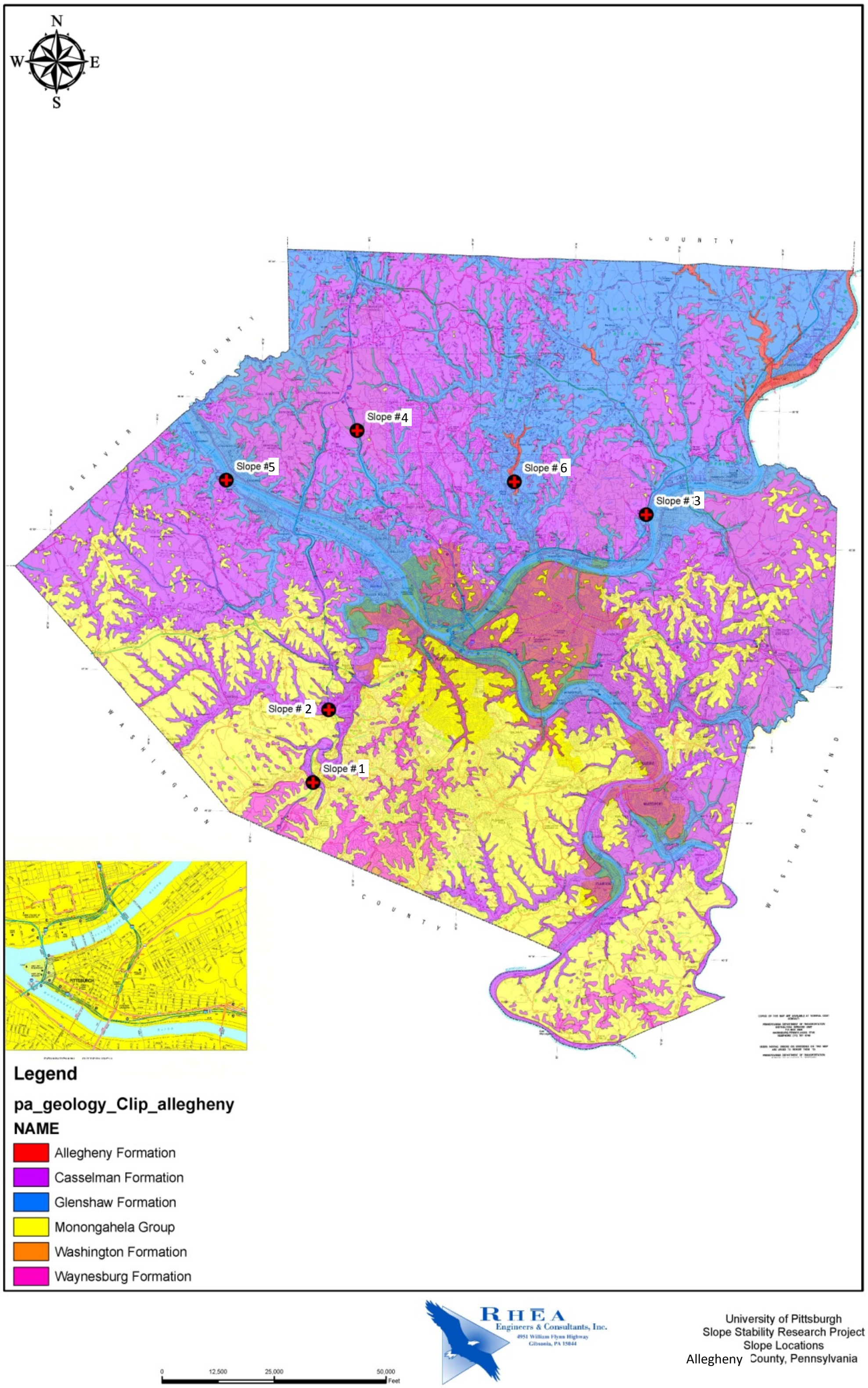


FIGURE II–1. SLOPE LOCATIONS IN ALLEGHENY COUNTY

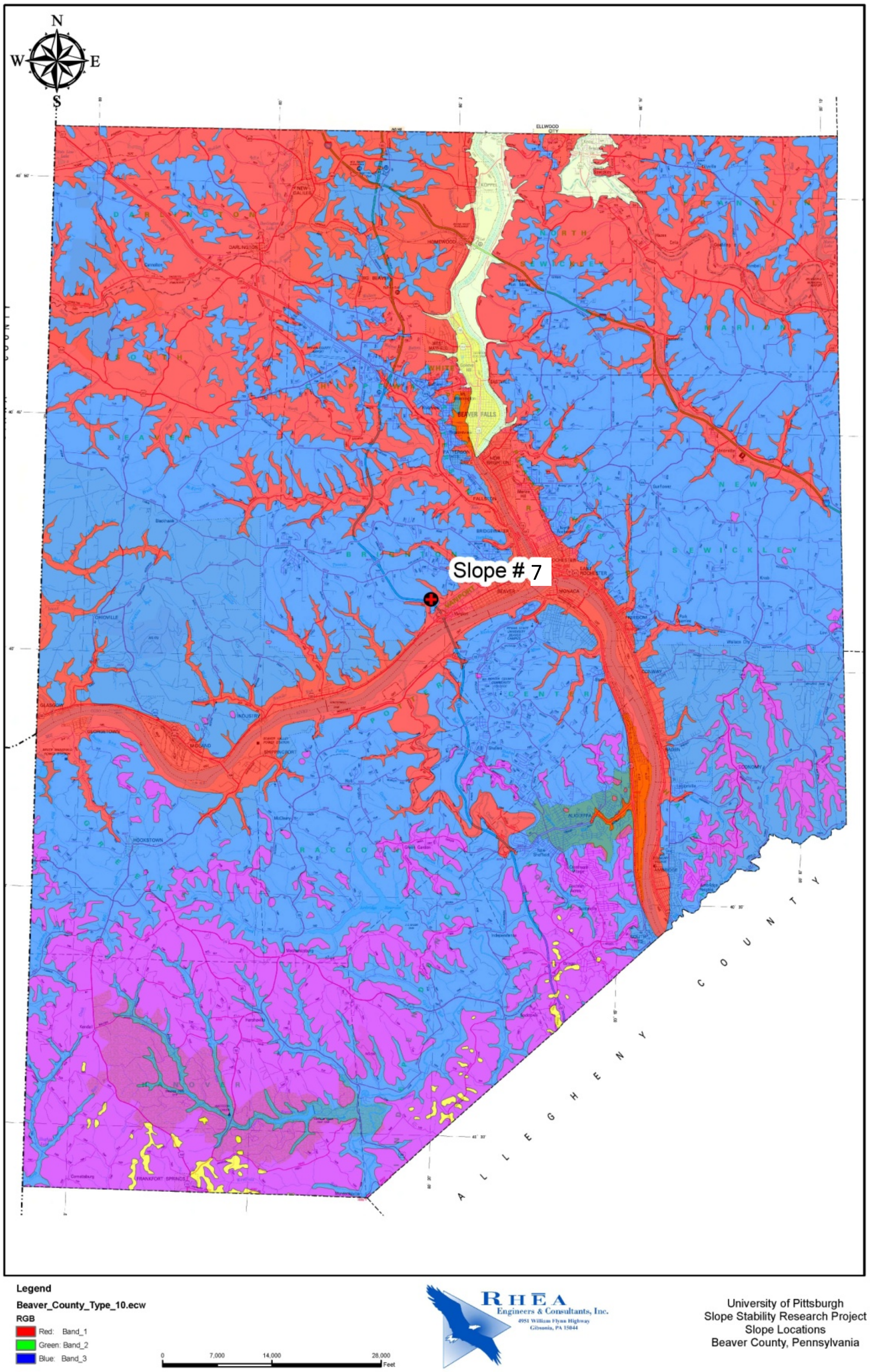


FIGURE II-2. SLOPE LOCATION IN BEAVER COUNTY

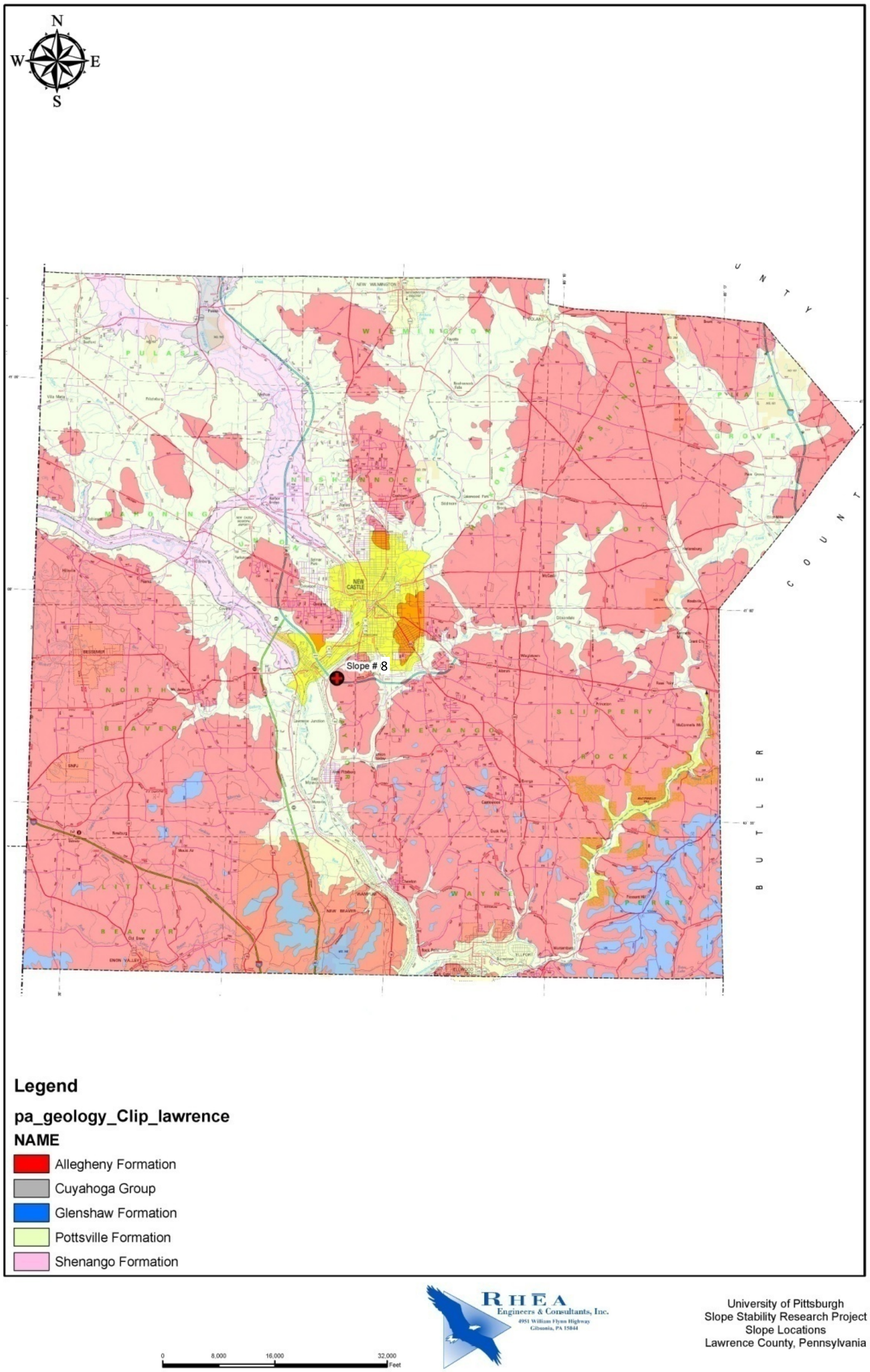


FIGURE II-3. SLOPE LOCATION IN LAWRENCE COUNTY

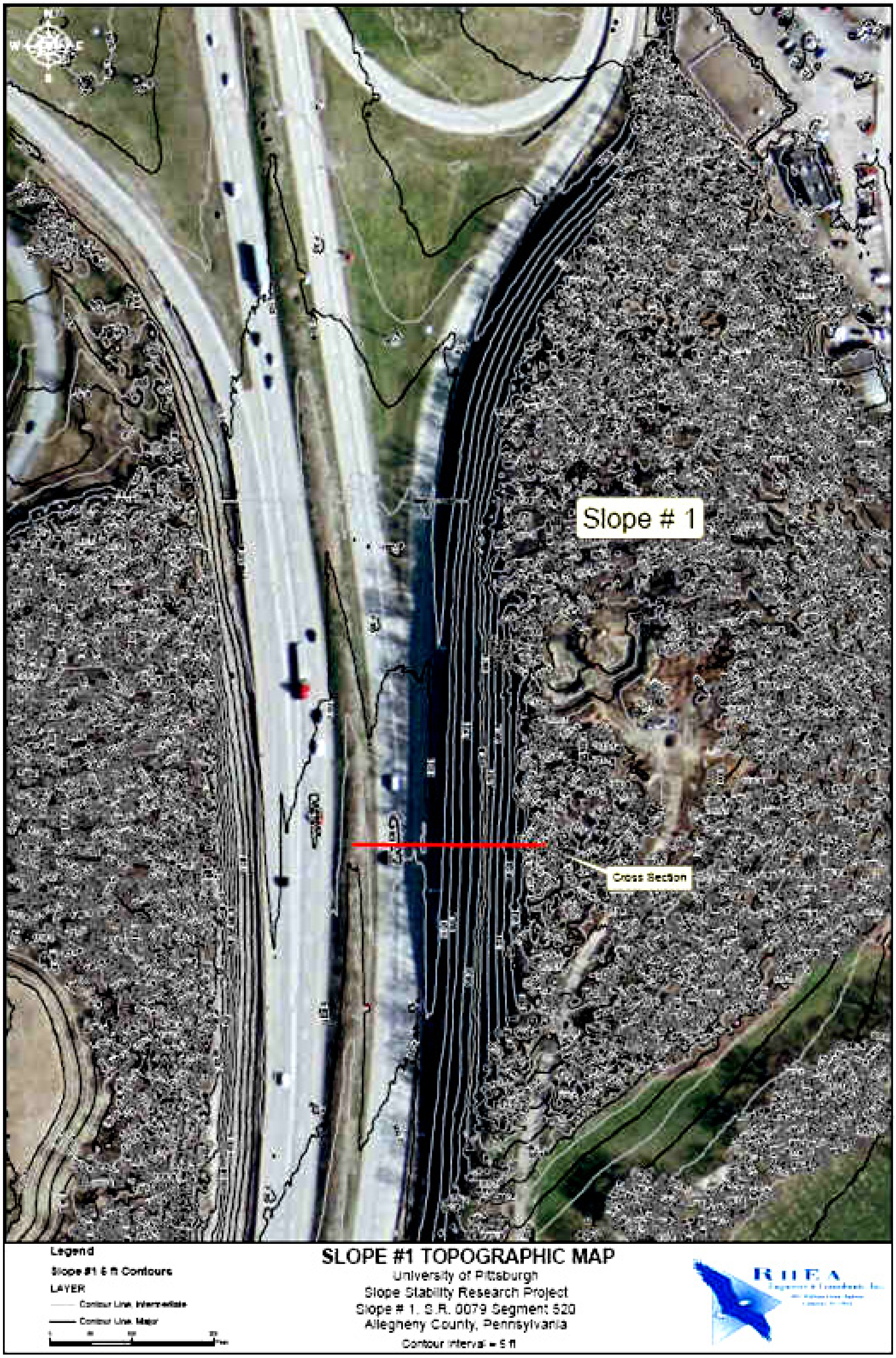


FIGURE II-4. BASE MAPPING FOR SLOPE 1

FIGURE II-5. BASE MAPPING FOR SLOPE 2

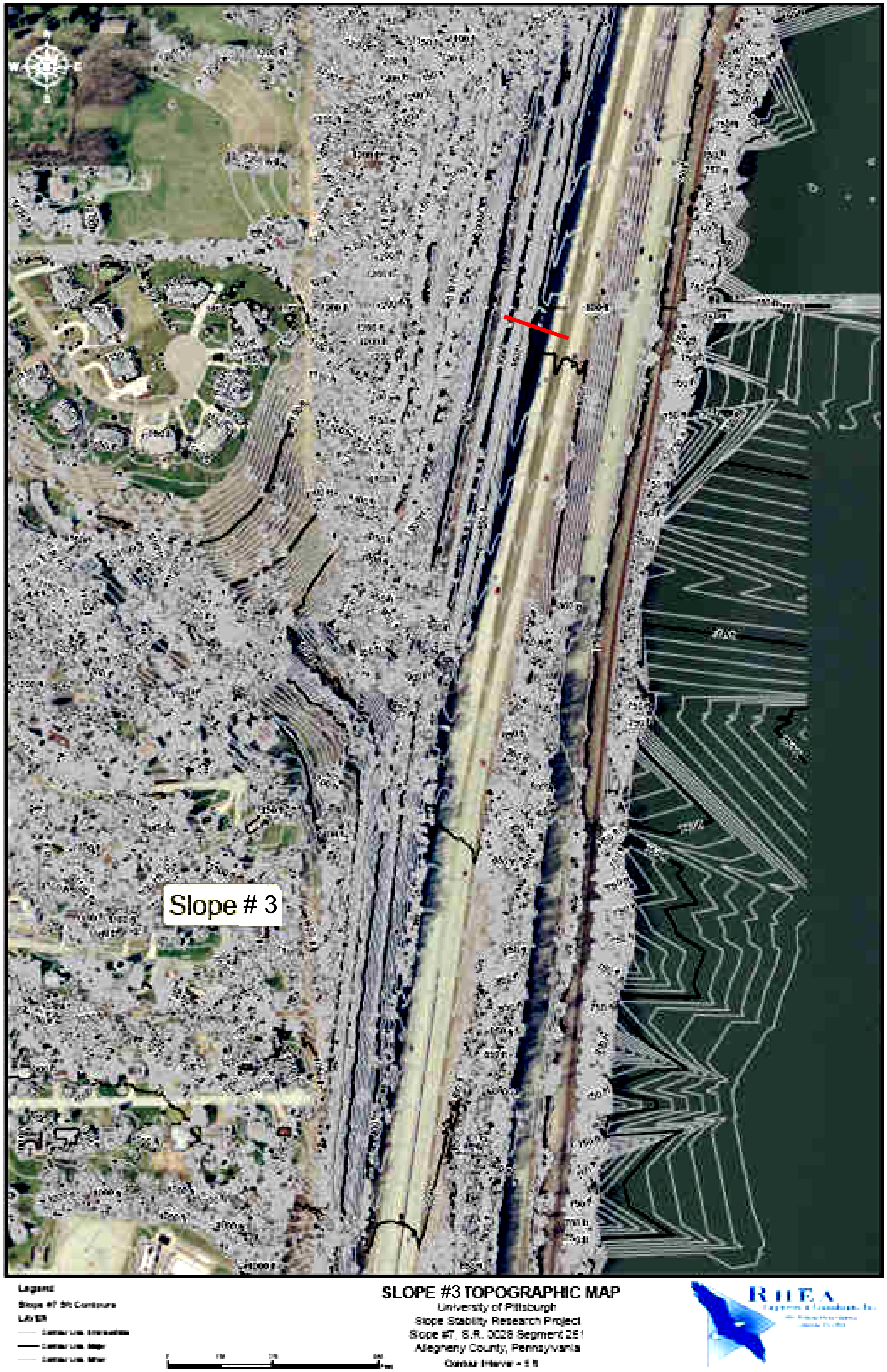


FIGURE II-6. BASE MAPPING FOR SLOPE 3

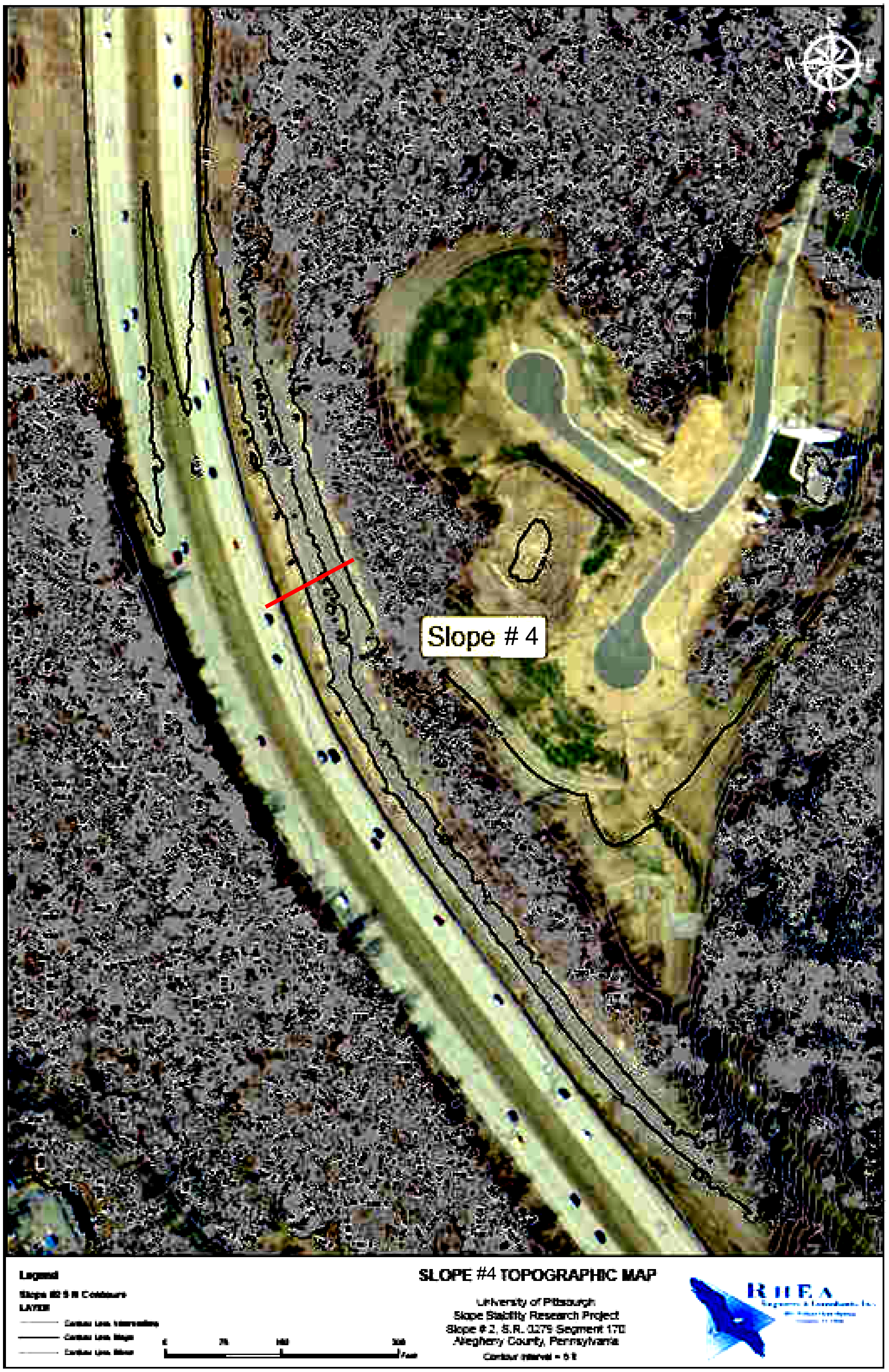


FIGURE II-7. BASE MAPPING FOR SLOPE 4

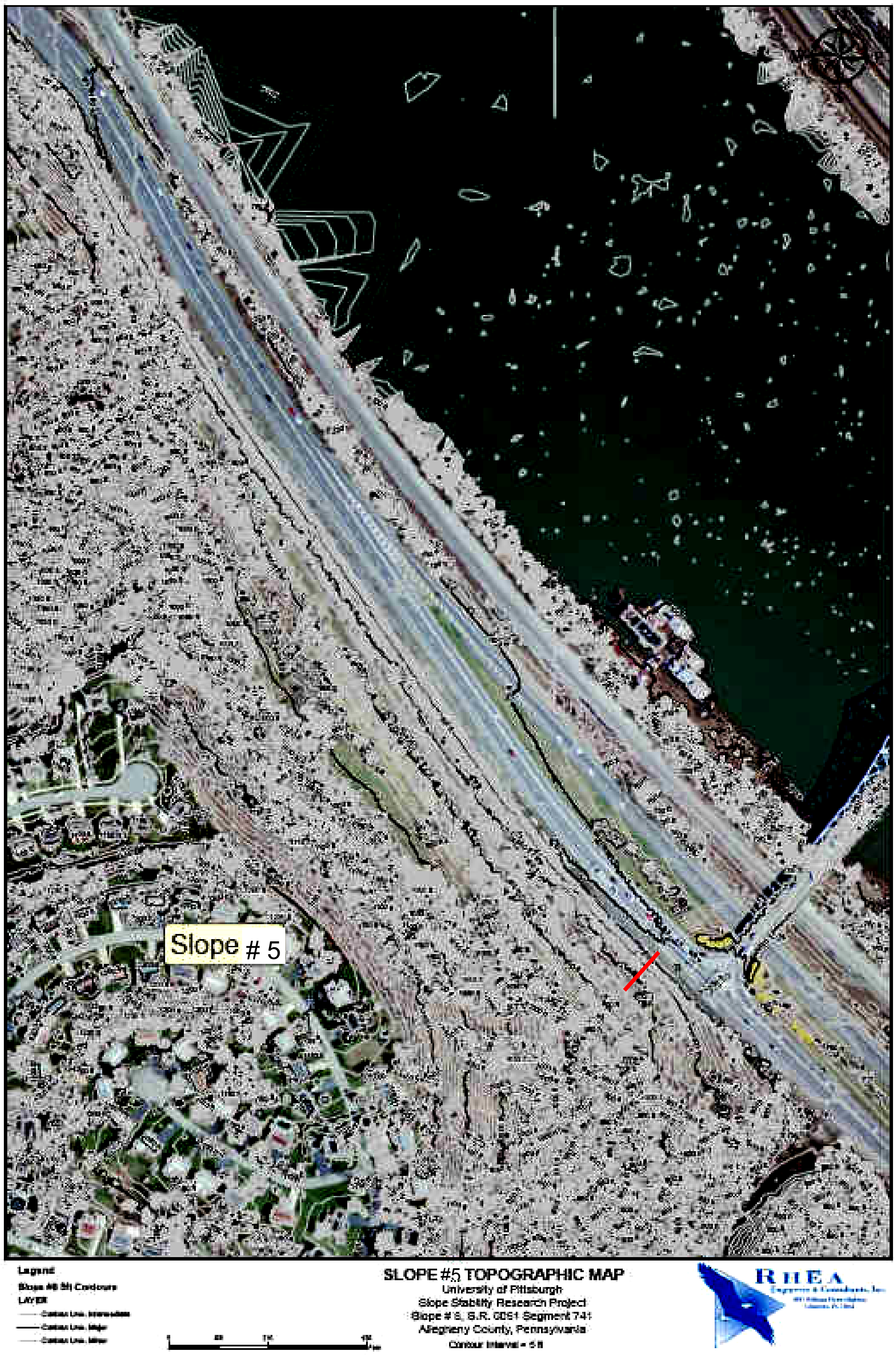


FIGURE II-8. BASE MAPPING FOR SLOPE 5

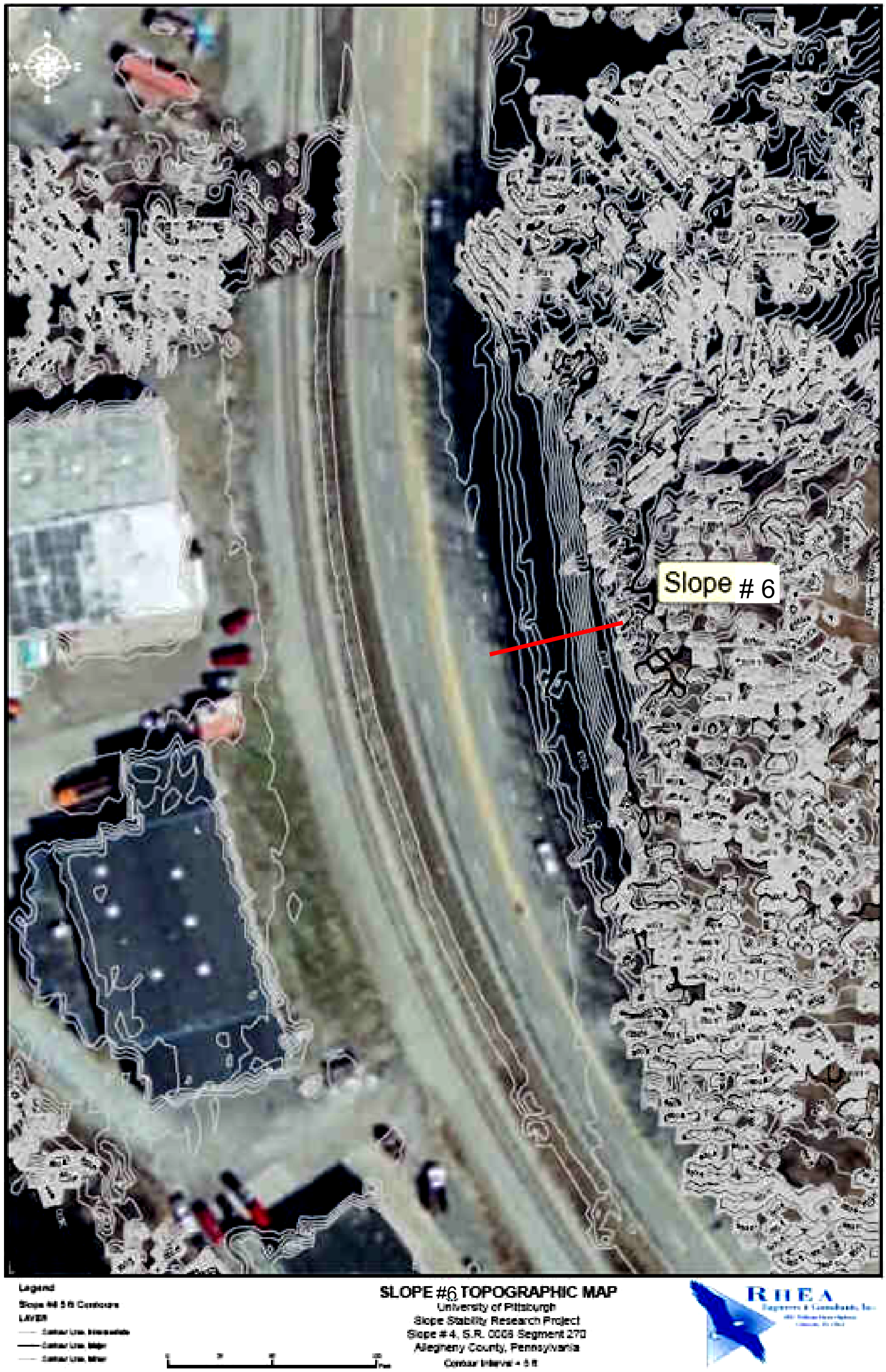


FIGURE II-9. BASE MAPPING FOR SLOPE 6

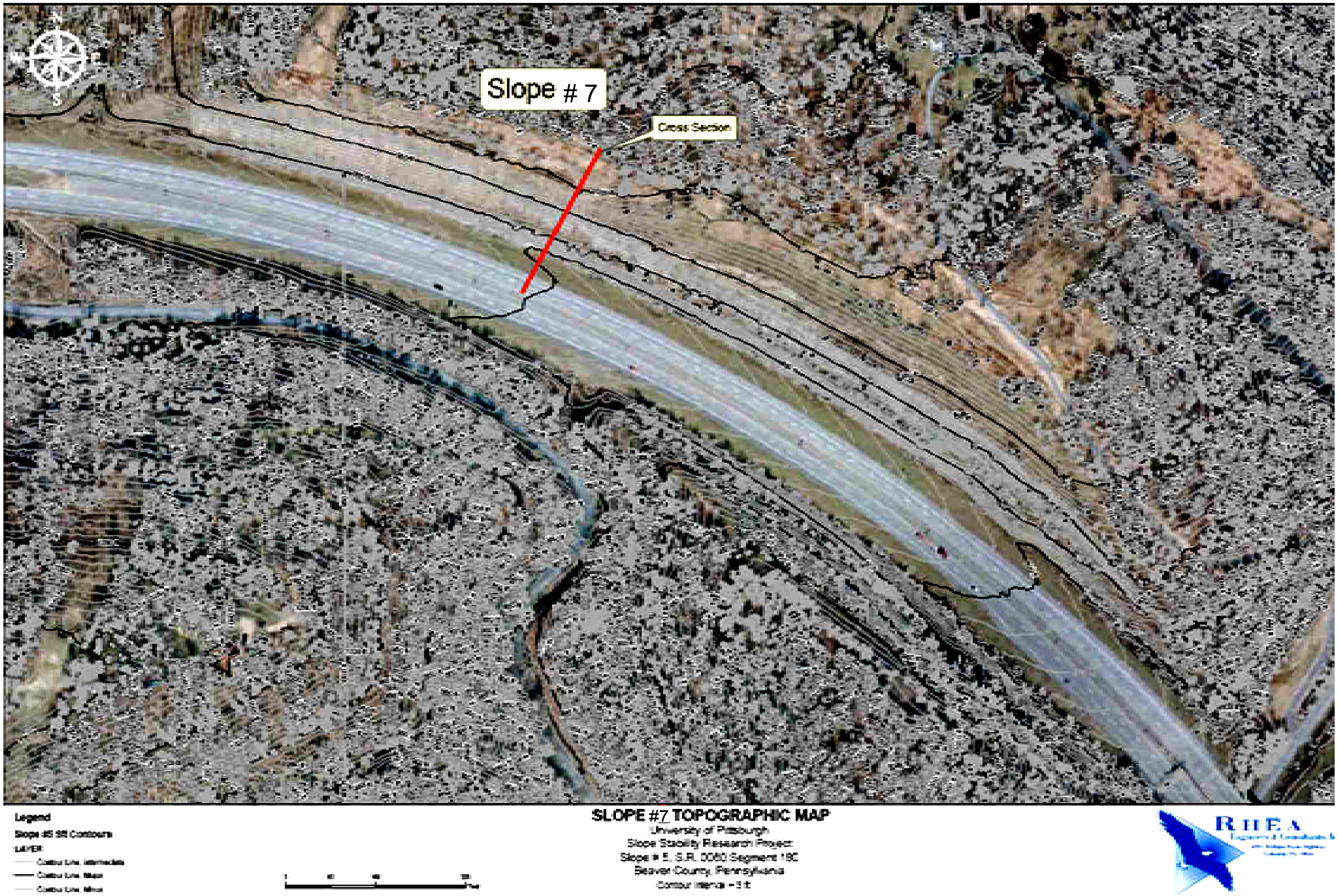


FIGURE II-10. BASE MAPPING FOR SLOPE 7

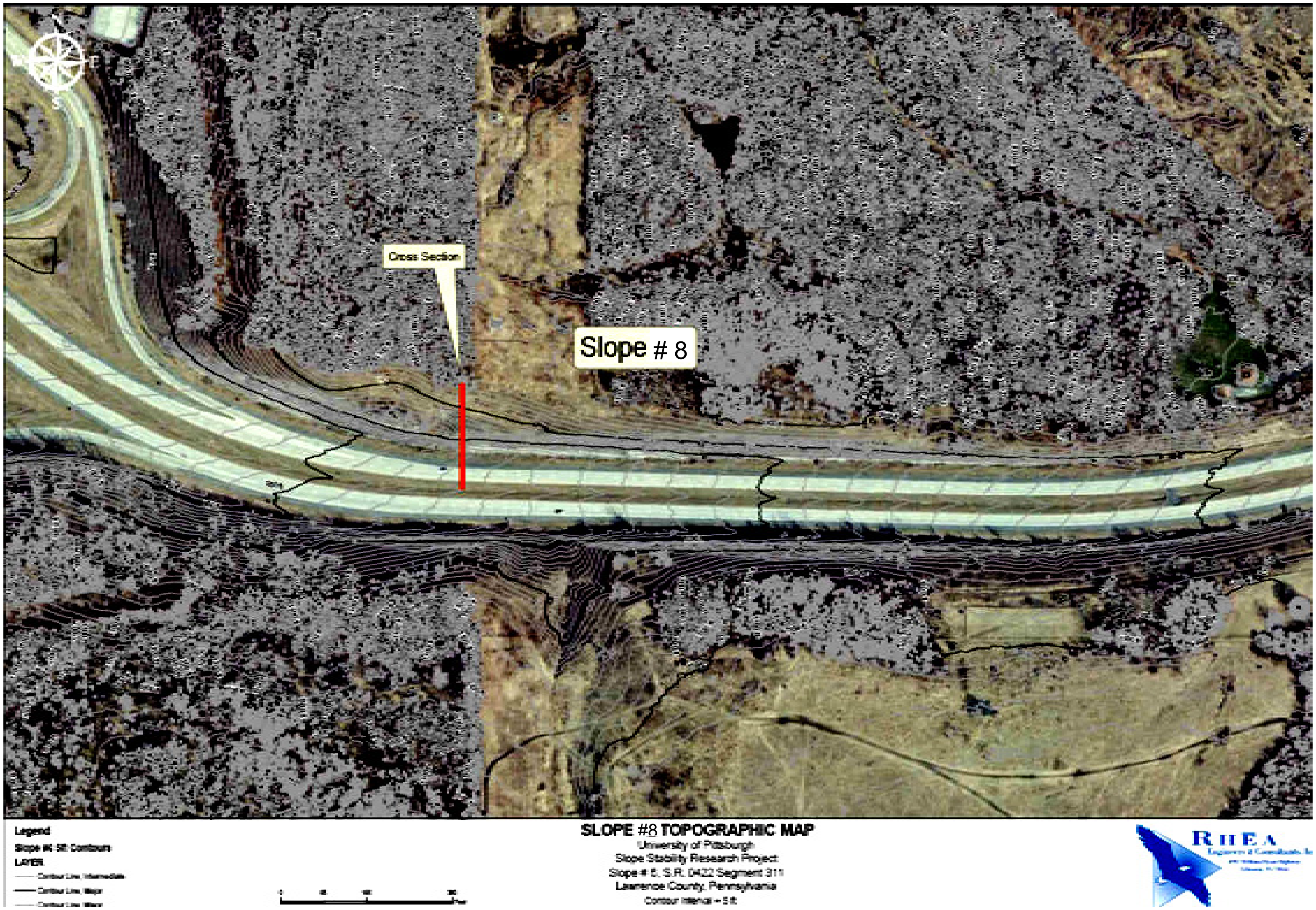


FIGURE II-11. BASE MAPPING FOR SLOPE 8

II.2. SUMMARY OF SITE SPECIFIC DATA

This section presents summarized site specific data collected during the field phase of the study. Tables and graphs are used where applicable to facilitate comparison of site characteristics.

II.2.1. SLOPE CROSS SECTION INFORMATION

Slope Number	Height (ft)	Block Size (ft)		Failure Mode			Comment
		Smallest	Largest	Spalling	Joint bound	Undercutting	
1	113	0.3	2.0	SH	LS		
2	97	0.5	15.0		LS, SS, coal		Drill holes observed in sandstone and shale
3	169	0.5	20.0	CS,	SS, SH, CS	SS	Drill holes; SS undercut by SH and CS
4	90	0.1	8.0	SH	SS	SS	SS undercut by carbonaceous SH
5	153	0.7	18.0	SH	SS, LS, SH	LS, SS	LS & SS undercut by SH
6	126	0.4	4.0	SH, SS, coal	SS, coal	SS, SH	SS & SH undercut by SH and coal
7	125	0.5	5.0	SH	SS, SH, LS	SS, LS	LS & SS undercut by SH
8	142	0.3	3.0	SH, CS	SS, LS, coal	SS, LS, coal	SS, LS, coal undercut by SH and CS

Note: Rock units present in slope: LS[limestone], SS[sandstone], SH[shale], CS[claystone]

TABLE II-2. SUMMARY OF CROSS SECTION CHARACTERISTICS

As shown in the table above, the majority of the slopes in the study exhibit a mix of weathering processes where the weaker fine grained materials (e.g. shale, claystone) degrade through spalling, resulting in undercutting of stronger materials (sandstone, limestone), which eventually fail along existing discontinuities.

II.2.2. CATCHMENT DITCH AND BARRIER PARAMETERS

Slope Number	Runout Distance* & Vertical Depth (ft)	Catchment Material		Performance		Barrier Type	
		Shatter	Intact	Contained	Material on Pavement	Concrete	Guiderail
1	22 / 5		x	x		x	
2	20 / 0		x		x		x
3	26 / 2.5		x		x	None present	
4	27 / 4		x		x		x
5	38 / 2.5		x		x		x
6	4.5 / >5		x		x	x	
7	51 / 5		x	x		None present	
8	20 / 1		X	X		None present	

*Distance from slope face to barrier.

TABLE II-3. SUMMARY OF CATCHMENT AREA CHARACTERISTICS

From the data above, the following may be concluded:

- The existing catchment areas are not sufficient to protect the roadway from encroachment by rockfall.
- Concrete barrier may be more protective than guiderail in preventing encroachment, if sufficient runout distance is provided.

II.2.3. BEDDING, FRACTURE, AND JOINT ORIENTATION

Slope Number	Range of Spacing between vertical joint sets		Range of observed block sizes	
	Min	Max	Min	Max
1	5	50	0.3	2.0
2	10	100	0.5	15.0
3	3	100	0.5	20.0
4	10	30	0.1	8.0
5	1	10	0.7	18.0
6	8	8	0.4	4.0
7	10	40	0.5	5.0
8	3	5	0.3	3.0

TABLE II-4. SUMMARY OF JOINTING CHARACTERISTICS

The comparison above shows that in general, the maximum block size is bound by the joint spacing in the more resistant units. A stereographic analysis would be helpful in determining the influence of slope alignment, bedding, and joint orientation and spacing on potential rock block sizes.

II.3. SETUP FOR SIMULATION IN CRSP

II.3.1. CRSP INPUT DATA PREPARATION

The CRSP input data was collected as shown in Appendix D-1 through D-8. This information was input for CRSP analyses and is discussed in Section II.4.

Cross section determination procedure

STEP 1:

As part of the field investigation, several parameters were determined throughout the observation process, including the face angle and the thickness of the different layers within one particular slope. The observed preliminary data are plotted and a first draft of the cross section profile is created (Figure II-12 left).

STEP 2:

LiDAR data was collected for the study slopes. The designated cross section (line) is located on the contour map of the specific slope site (Figures II-4 through II-11) and subsequently, the actual X,Y,Z coordinates of the cross section are obtained. The interval of the points comprising the profile is approximately ¼ inch. The cross section is outlined in three dimensions, and after manipulation of the front view of the profile, a two-dimensional model is drafted (Figure II-12 right).

STEP 3:

Once both profiles from step 1 and 2 are on the same plane, the rock layer definition is done. With the aid of the observed data and the photographs from the slope, the location of the strata's levels is matched from the observed profile onto the LiDAR profile. Then, 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.

STEP 4:

Finally, the representative points are joined through straight line segments, 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.

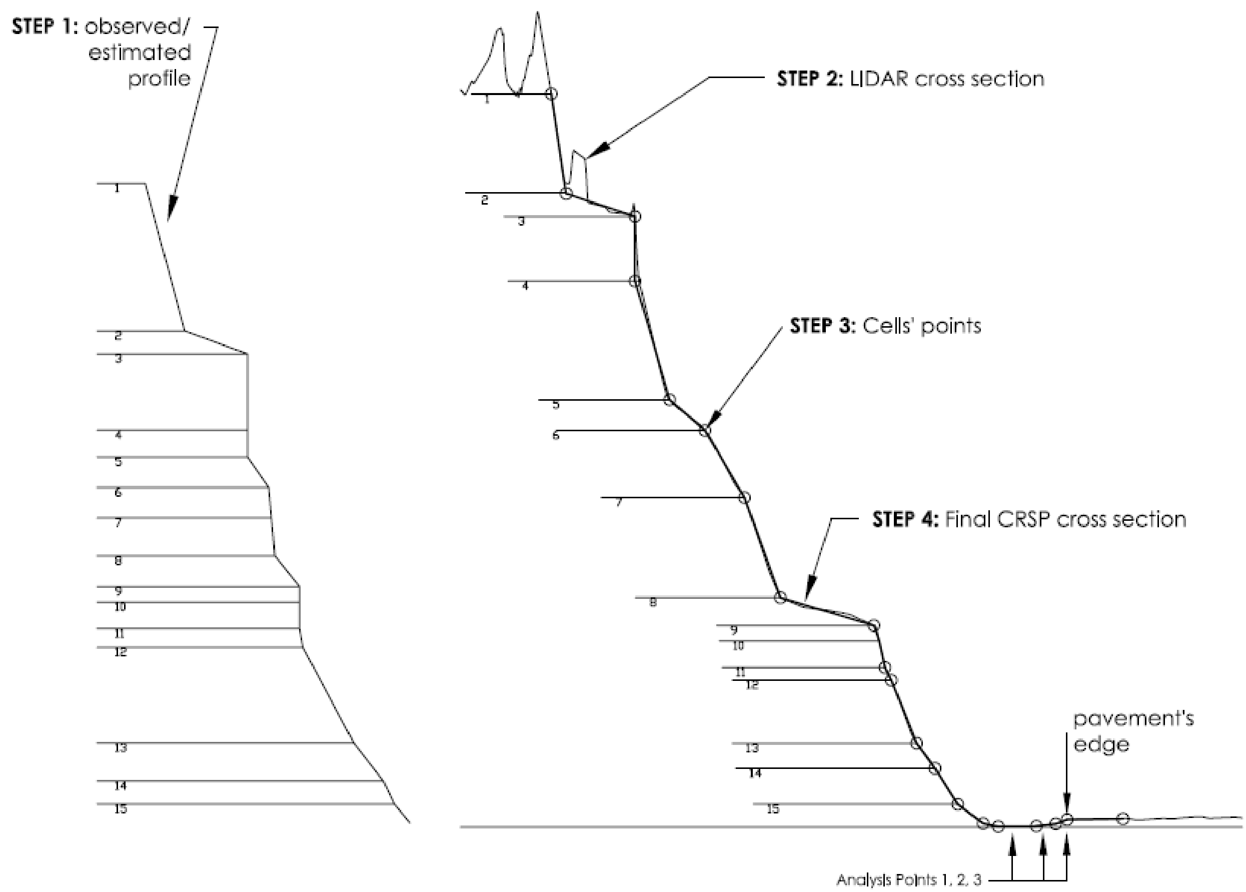


FIGURE II-12. MAPPING AND SYNTHESIS OF THE FIELD OBSERVATION

II.3.2. PRELIMINARY CRSP RUNS

Beside 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 mitigation is being considered. This point of interest can be the location of a proposed or existing fence. Only the x-coordinate of an analysis point needs 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
- Falling rock density, shape and dimensions.

CRSP uses this input data in a stochastic model 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 (Figure II-13).
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 output file with the results of one analyzed case is presented in Appendix E. The case scenario analyzed for Slope No. 3 considers spherical rocks of 10 ft in diameter falling from cell No. 3. All cells' tangential coefficient of frictional resistance and normal coefficient of restitution have their minimum possible value. Analysis point 3 is located right on the pavement's edge and Analysis points 1 and 2 are within the catchment ditch (Figure II-12 right and II-13).

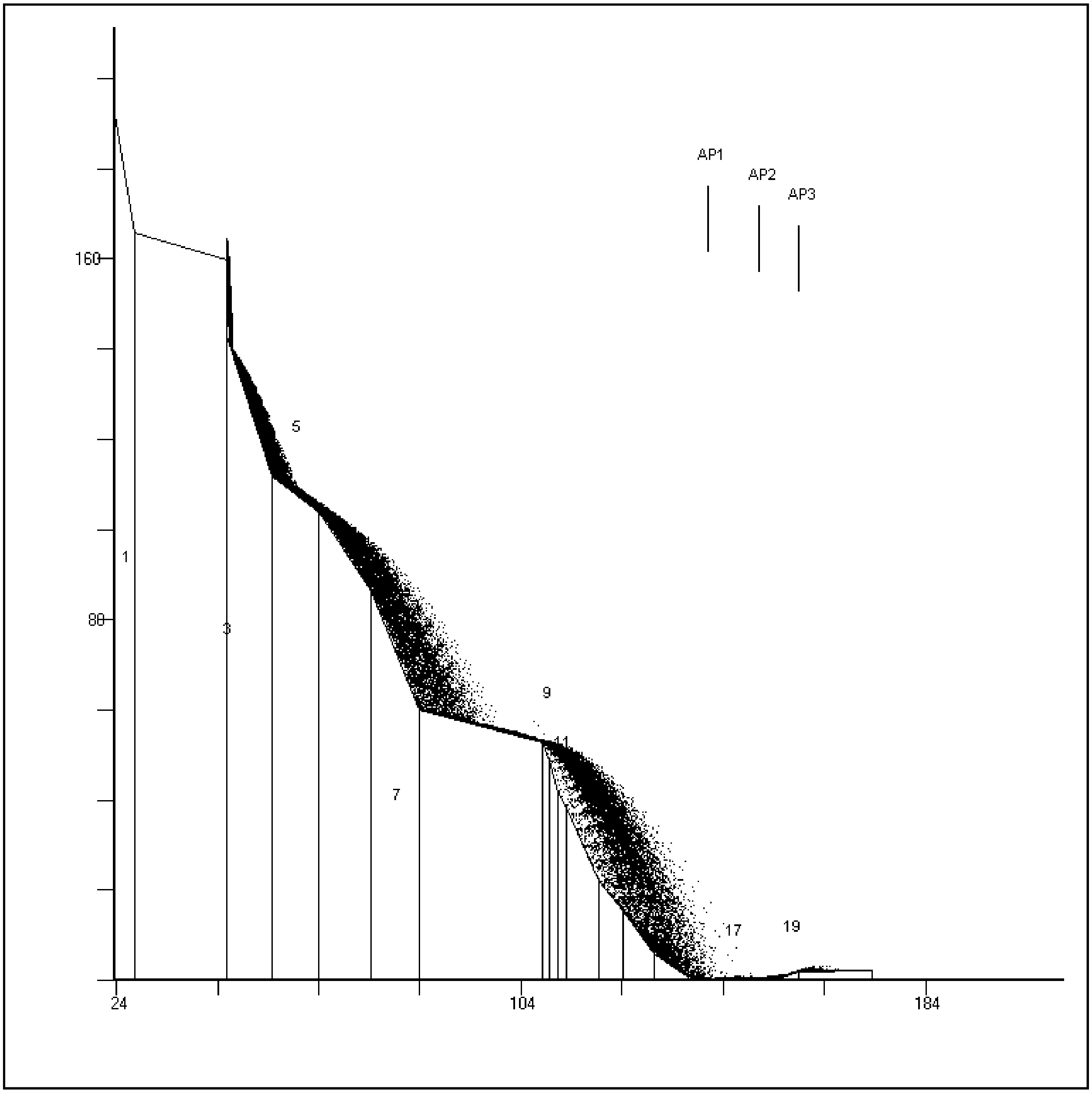


FIGURE II-13. SLOPE PROFILE SHOWING CELL LOCATIONS AND THE POSITION OF EACH SIMULATED ROCK EVERY TENTH OF A SECOND AS IT TRAVELS DOWNSLOPE

II.4. CONCLUSIONS

The results obtained herein include not only quantified data but also drawings that will be useful for future research. The advantage of having LiDAR data was immeasurable. Its value exceeded our expectations as laid out in the original plan. The manner in which this study combined LiDAR data, aerial photos, field photos, and field observations can serve as a model for future Department's field investigations.

The next Chapter describes the CRSP simulation conducted for this study. The main objectives are to tune the input parameters such that the field observed failures can be duplicated, if possible. For each of the eight sites under study, there were numerous cases to be analyzed. These include the variation in the source zones of slides and the variation in the input parameters.

CHAPTER III:

DEVELOPMENT OF A RATIONAL PROCEDURE CAPABLE OF PREDICTING FIELD OBSERVED FAILURE EVENTS

III.1. SIMULATION AND PROCEDURE DESIGN

The objectives of the simulation runs were to determine how to select the appropriate input parameters so that the program CRSP can be used with confidence for the design of highway rock slopes in Western Pennsylvania. Toward these goals, we have investigated in great details the 8 slopes selected for the study making use of the information gathered during the field work.

For a given slope, with data gathered from field work, local geology map, and high resolution surveying data from LiDAR, we were able to generate analysis profiles with the rock layers clearly marked. A sample of such a profile for Slope 3 is depicted below,

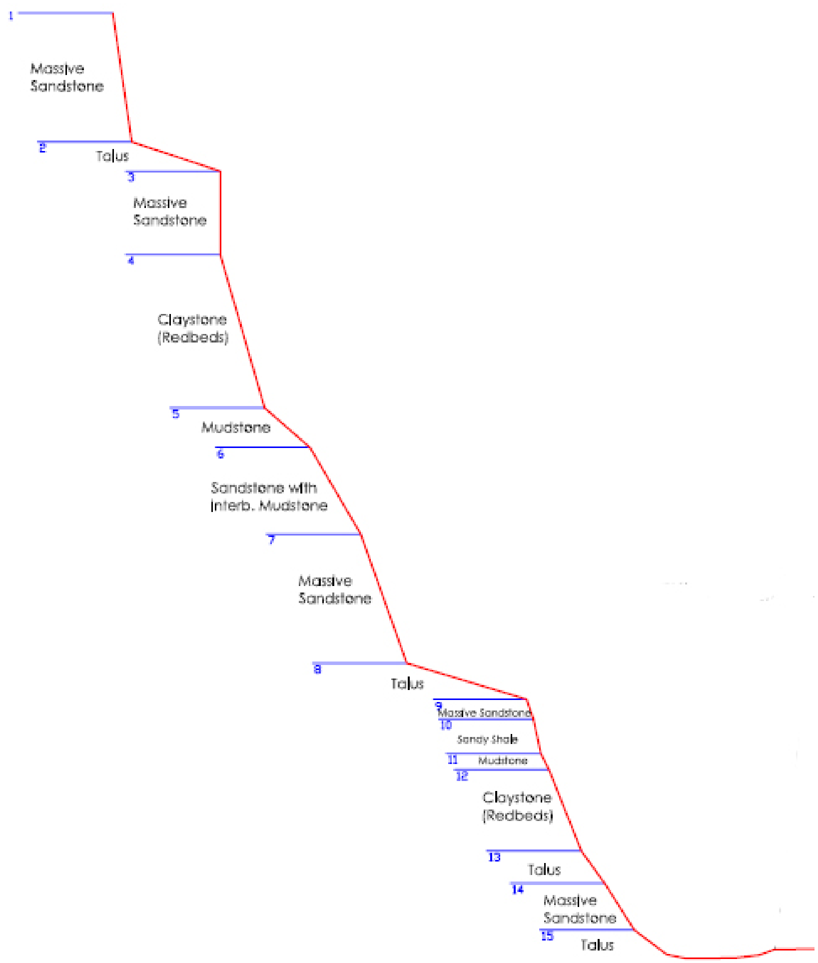
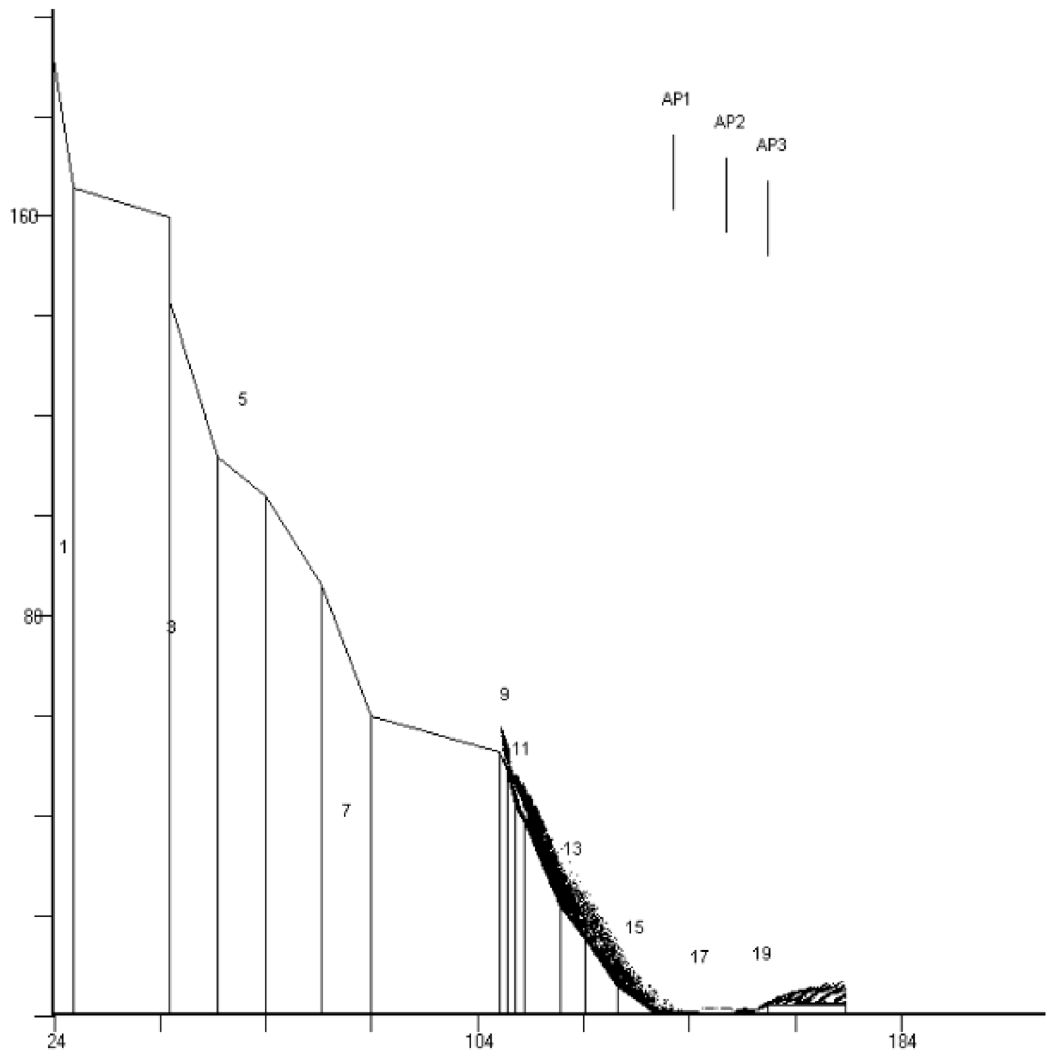


FIGURE III.1. SLOPE BASE PROFILE FOR CRSP ANALYSIS (SLOPE 3)

This base profile was further translated into an input profile by drawing vertical lines through the layer boundaries. These vertical intervals, in terms of CRSP terminology, are referred to as cells.



Sample of CRSP results

Rocks falling from layer # 9, Massive Sandstone D_{max} = 10 ft, with ***Rt min*** *and* ***Rn min.***

FIGURE III-2. SLOPE OUTPUT PROFILE AFTER ANALYSIS, SHOWING FALLING ROCKS EVERY TENTH OF A SECOND (SLOPE 3)

In addition to the geometry, for each cell or layer the following input parameters to CRSP are required,

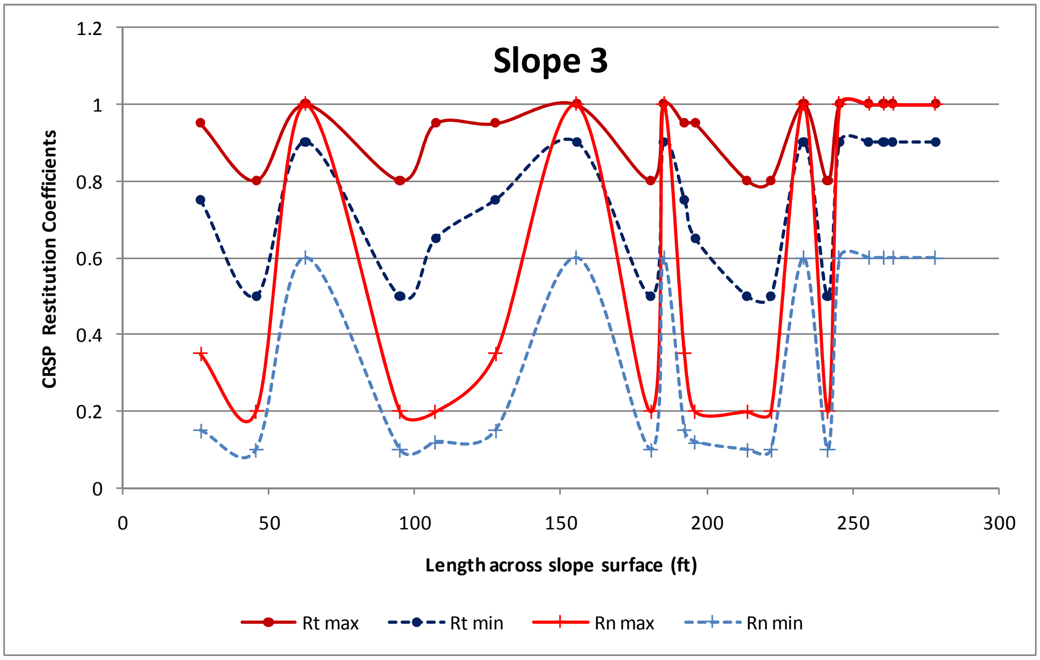
- *Rock block size:* The likely size of a fragment or block falls from each stratum, or cell.
- *Rock block shape:* CRSP limits the choices between discoidal or cylindrical shapes.
- *Surface Roughness (S):* This reflects the possible slope angle variation within a cell.
- *Tangential Coefficient of frictional resistance (R_t):* This coefficient determines how much the component of the rock's velocity parallel to the slope is slowed by impact.
- *Normal Coefficient of restitution (R_n):* This coefficient is determined by the hardness of the rock, and gives the change in the velocity normal to the slope after impact.

After a number of sensitivity analyses, we have concluded that the last two parameters, the tangential coefficient of frictional resistance and the normal coefficient of restitution play the key role as to where a rock block would land. Because "where a rock block would land" is the critical information regarding a highway rock slope design, this study thus focused the parameter selection on the determination of these two parameters, R_t and R_n. Even with this narrow focus, the combinatorial possibilities are prohibitive. This study eventually set a strategy as follows:

1) For each layer, the upper and lower bounds of R_t and R_n are taken from the CRSP users manual based upon the rock type. A sample of these values for Slope 3 is presented in Figure III-3.

2) Since R_t and R_n are coupled in energy loss computation in CRSP, we further decided that we will group the upper bound of R_t with that of R_n, and vice versa.

3) Furthermore, we choose three additional values for each parameter that divide the range into three equal intervals. These numbers from small to large are referred to as *mid1*, *mid*, *mid2.* Thus for each layer we have 5 values for R_t and R_n, respectively. They are denoted as *min*, *mid1*, *mid*, *mid2*, and *max*. Again, in the runs, R_t and R_n are paired *min* to *min*, *mid1* to *mid1* and so on.



Tangential frictional resistence and Normal restitution coefficients **recommended by CRSP authors**

FIGURE III-3. THE MAXIMUM AND MINIMUM R_T AND R_N FOR EACH LAYER BASED UPON CSRP MANUAL ALONG THE SLOPE FOR SLOPE 3

As stated, the focus of analysis for this study is where rock blocks fallen from the slope would end up. Thus, we select three target points, referred to as analysis points or AP, for each slope, with AP 1 closer to the slope, and AP 3 farthest—generally close to the curb edge of a highway. By examining the statistics of the percentage of blocks fallen beyond a particular target point, and comparing that with what was observed in the field, the credence of the parameters were judged.

A partial sample input data table for Slope 3 and the resulting statistics are shown as Figure III-4. Depending upon what were observed in the field, we may track a particular AP point for evaluation. For instance, in our field work we observed that rocks on the ground are of a particlular rock type, thus came from certain layers, and that all of them scatter within a particular area. This allowed us to zoom in on the percentage of rocks passing a particular AP point from those layers. The results are summarized in Figure III-4.

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)					Sphere Diam.$_{MAX}$ (ft)
		min	mid1	mid	mid2	max	
1	**% Rocks Passing AP3**	**0.0%**	**0.1%**	**1.1%**	**10.3%**	**34.7%**	10
	Max Bounce height (ft)	0.00	0.48	6.58	14.63	23.59	
	Max K.Energy (ft-lb)	0	744,455	6,766,235	7,107,504	7,974,044	
	Max Vel. (ft/sec)	0.00	19.52	66.99	69.27	72.40	
3	**% Rocks Passing AP3**	**99.2%**	**99.6%**	**99.7%**	**99.6%**	**94.7%**	10
	Max Bounce height (ft)	0.81	1.04	1.47	9.95	4.40	
	Max K.Energy (ft-lb)	2,423,850	2,731,303	3,228,281	7,067,841	7,587,547	
	Max Vel. (ft/sec)	36.11	38.37	41.26	61.83	64.94	
4	**% Rocks Passing AP3**	**7.2%**	**9.1%**	**12.3%**	**14.8%**	**4.2%**	0.5
	Max Bounce height (ft)	0.77	1.20	3.47	20.63	15.06	
	Max K.Energy (ft-lb)	257	308	742	869	962	
	Max Vel. (ft/sec)	32.96	36.47	63.83	68.58	71.49	

FIGURE III-4. PARTIAL SAMPLE INPUT TABLE AND THE RESULTS OBTAINED

For our simulation run, a complete statistical analysis was performed at the location of each analysis point (AP) that included the following:

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

III.2. REVIEW OF THE SIMULATION RESULTS

III.2.1. GENERAL OBSERVATION

Rockfall from each layer behaved differently due to factors such as the slope inclination, the slope length, the surface roughness, the lateral variability, the slope coefficients, the rock size, and the rock shape. However, there are general trends that can be concluded from the results of the group of slopes.

As the dominating parameters R_t and R_n reflect the degree to which energy is conserved after impact, the larger these numbers are, the higher the bounce a rock block makes after impact and the farther it lands away from the slope.

In general, as the normal and tangential coefficients were increased, not only the percentage of rocks passing the analysis points increased, but also increased were their maximum bounce height, maximum velocity, and maximum kinetic energy. This pattern is expected as the lower values of the coefficients would represent surfaces such as vegetated areas and soft soils while the larger values would represent harder and smoother surfaces such as hard rocks or concrete.

Another significant trend we observed was the important effects of the size of the falling rocks: the smaller the rock, the slower it moves and therefore fewer rocks pass a certain analysis point. In addition, the shape of the rock accounted for the percentage of rocks passing the analysis points. Spherical rocks roll faster than cylindrical and disc shaped rocks. As this percentage increased, so did the maximum kinetic energy, maximum bounce height, and maximum velocity. Unfortunately, the code does not allow for other shapes of rocks. This, we have no doubt, was an important factor that was left out.

After the initial simulation was completed for each of the 8 slopes, only slope 7 and 8 were found to be modeled properly using the lower range of the input parameters. It was evident that the manual suggested values were giving unreasonable results in terms of the amount of rocks passing the analysis points in slopes 1 through 6. This can clearly be seen from the results for Slope 3 that a large percentage of the rock blocks would pass AP3 and land on the highway. This is contrary to what we have observed during our site visits. A cautious note, however, is that our findings regarding the parameter values should not be interpreted in isolation. The parameters should be regarded as an integral part of how the input files are prepared, that include the configuration of profile geometry and rock layers definition.

A question thus aroused: "How do we proceed from this point?" We came up with a strategy that would be the easiest for applications. We would reduce the values of R_t and R_n **until a good match with the field observation was obtained**. We adopted the following new 3 combinations of coefficients for each layer of each slope:

- ½ R_t min and R_n min
- R_t min and ½ R_n min
- ½ R_t min and ½ R_n min

The tables below indicated that additional 213 simulations were carried out for a total of 753 simulations.

Stage 1

Slope #	# of layers	variable cases	# of simulations	slope height (ft)	slope horizontal length (ft)
1	11	5	55	112	113
2	15	5	75	143	92
3	14	5	70	192	141
4	4	5	20	69	95
5	14	5	70	144	130
6	13	5	65	111	58
7	16	5	80	166	179
8	21	5	105	122	122
Total # of simulations performed			540		

Stage 2

Slope #	# of layers	variable cases	# of simulations	slope height (ft)	slope horizontal length (ft)
1	11	3	33	112	113
2	15	3	45	143	92
3	14	3	42	192	141
4	4	3	12	69	95
5	14	3	42	144	130
6	13	3	39	111	58
7	16	0	0	166	179
8	21	0	0	122	122
Total # of simulations performed			213		

TABLE III-1. COUNT OF SIMULATIONS CARRIED OUT FOR THE STUDY

A comprehensive illustration of the results for each one of the 8 slopes of the study is presented in Appendix F-1 through F-8. Appendix F compiles the following information for each slope:

- The maximum and minimum R_t and R_n for each layer based upon CSRP manual along the slope.
- Slope output profile after analysis, showing falling rocks every tenth of a second, analyzed with coefficients BEFORE calibration.
- R_t and R_n coefficients along the slope, **which best fit field observations (result of calibration process).**
- Slope output profile after analysis, showing falling rocks every tenth of a second, analyzed with coefficients AFTER calibration.
- Photographs
- Summary of CRSP results (e.g. Max bounce height, Max kinetic energy, Max. velocity) at strategic analysis points. Comparison of the influence of different R_t and R_n coefficients.

The next section contains a compilation of the main findings.

III.2.2. SPECIFIC DISCUSSIONS REGARDING EACH SLOPE

III.2.2.1. SLOPE 1

- Field Observations:

Horizontal Distance from rock slope to barrier/road	22 ft
Barrier type and dimensions	Cast in place concrete. 3-ft high, 1-ft wide
Ditch design	Trapezoidal trench, 5-ft deep. Partially grass covered. Concrete barrier placed 2-ft away of trench end.
Failure mode	Mostly Freeze/Thaw
Ditch performance	Fallen rocks contained within the ditch. Rocks from layers 4, 5, and 7 found closest

	to the barrier.

- CRSP analysis:
    - No rocks passed analysis point AP2, located at the upper end of the trench, close to the barrier.
    - Rocks from all layers passed analysis point AP1, located at the toe (talus base).
    - By using the smallest values of R_t and R_n, the program reflects that only rocks from layers 4, 5, and 7 may reach the furthest point of the ditch, as seen in the field.

- *RECOMMENDATION*: Use of the minimum value of R_t suggested by CRSP manual, and only half of R_n suggested by CRSP manual: *½ R_t min* and *R_n min*.

III.2.2.2. SLOPE 2

- Field Observations:

Upper bench

Horizontal Distance from rock slope to barrier/road	20 ft
Barrier type and dimensions	Steel guardrail, 3-ft high
Ditch design	Flat surface, highly populated with rockfall material
Failure mode	Coal mine subsidence-related fracturing
Ditch performance	Rocks from all units encounter the guardrail, in some cases producing damage to it.

Slope toe

Horizontal Distance from rock slope to barrier/road	12 ft
Barrier type and dimensions	Partial steel guardrail, 3-ft high
Ditch design	Flat surface, highly populated with rockfall material

Failure mode	Mostly freeze/thaw
Ditch performance	Rocks from the two units below the upper bench, and even from above it, were found past the bottom guardrail

- CRSP analysis:
  - The program is limited to simulating properly the failure mode of the lower layers of rock above the bench (above the coal seam). The actual failure mechanism taking place is a pronounced undercutting of a large shale layer lying on a brittle coal seam. Rocks from this shale unit don't roll, but rather slide down. Once the shale fractures in a vertical manner, it induces fracturing of the units above.
  - Large pieces of shale from layer # 10, in form of disc and cylinder, resulted in no encroachment of the bench, which does not validate the field observations (see photographs of slope 2).
  - The results of the simulations using the minimum coefficients were fairly close to the field observations. Further reduction of the values of R_t and R_n, did not show much difference in the results.

- *RECOMMENDATION*: Use of the minimum value of R_t and R_n suggested by CRSP manual: R_t *min* and R_n *min*.

III.2.2.3. SLOPE 3

- Field Observations:

Horizontal Distance from rock slope to barrier/road	26 ft, after closure of 3 lanes of highway
Barrier type and dimensions	none
Ditch design	2.5-ft deep, 20-ft wide horizontal trench, recently excavated
Failure mode	Rocks fall with subsequent weathering
Ditch performance	Poor. Rocks from the upper units were

	able to reach the highway in events prior to the beginning of this study.

- CRSP analysis:
  - The program indeed validated the field events by projecting a high number of rocks from the larger size units passing analysis point AP3, located 20 ft away from the slope toe.
  - The results of the simulations using the minimum coefficients were fairly close to the field observations. Greater values of R_t and R_n could work fine as well. Lower values of R_t and R_n may eliminate the possibility for rocks from some units to reach the highway, which does not match the reality.

- *RECOMMENDATION*: Use of the minimum value of R_t and R_n suggested by CRSP manual: R_t *min* and R_n *min*.

III.2.2.4. SLOPE 4

- Field Observations:

Horizontal Distance from rock slope to barrier/road	27 ft
Barrier type and dimensions	Steel guardrail, 2-ft high
Ditch design	4-ft deep, grass covered trapezoidal trench.
Failure mode	Mainly jointing
Ditch performance	Although most of rockfall material from layers 1 and 2 remains within the trench, some rocks from layer 1 were observed past the guardrail.

- CRSP analysis:

The results of the simulations using the smallest coefficients were very close to the field observations. By using the smallest values of R_t and R_n, the program reflects that only rocks from layers 1, 2, and 4 may reach the furthest point of the ditch, as seen in the field.

- *RECOMMENDATION*: Use of only half of the minimum values of R_t and R_n suggested by CRSP manual: ½ R_t *min* and ½ R_n *min*.

III.2.2.5. SLOPE 5

- Field Observations:

Horizontal Distance from rock slope to barrier/road	38 ft
Barrier type and dimensions	Steel guardrail, 2-ft high
Ditch design	Flat surface, 2.5-ft deep trench
Failure mode	Rocks fall with subsequent weathering. Lower units exhibit pronounced toppling of large pieces due to jointing.
Ditch performance	The area of ditch is large enough to hold rockfall events, however, rocks from layers 8 and 11 were observed below the guardrail.

- CRSP analysis:
  - The program is limited to simulating properly the failure mode of the lower jointed shale layers. Rocks from these shale units don't roll, but rather slide down. Once the shale fractures in a vertical manner, it induces fracturing of the units above.
  - Large pieces of shale from layer # 12 and 14, in form of cylinder, resulted in no rocks passing AP1, located right at the toe, which does not validate the field observations (see photographs of slope 5).

- The results of the simulations using the minimum coefficients were fairly close to the field observations. Normal coefficient of restitution, R_n, presented a greater influence in the results.

- *RECOMMENDATION*: Use of the minimum value of R_t suggested by CRSP manual, and only half of R_n suggested by CRSP manual: R_t *min* and ½ R_n *min*.

III.2.2.6. SLOPE 6

- Field Observations:

Horizontal Distance from rock slope to barrier/road	4.5 ft
Barrier type and dimensions	Jersey concrete barrier
Ditch design	None.
Failure mode	Rocks fall with subsequent weathering. Storm water transport
Ditch performance	Poor. Rocks from the upper units were able to reach the highway. Rocks from layers 2, 4 and 6 were observed on the median of the road.

- CRSP analysis:
  - Often times the program stopped working while running this particular configuration of slope, with a barrier so close to the slope face. It is suspected that with large values of R_t and R_n, the energy of the rocks when reaching the bottom and getting in contact with the barrier is such that they hit back and the calculation of the motion crashes.
  - With low values of R_t and R_n, the program indeed validated the field events by projecting a number of rocks from the larger size units passing analysis point AP3, located 16 ft away from the slope barrier, into the road.
  - The results of the simulations using the smallest coefficients were fairly close to the field observations. Normal coefficient of restitution, R_n, presented a greater influence in the results.

- *RECOMMENDATION*: Use of only half of the minimum values of R_t and R_n suggested by CRSP manual: ½ R_t *min* and ½ R_n *min*.

III.2.2.7. SLOPE 7

- Field Observations:

Horizontal Distance from rock slope to barrier/road	51 ft
Barrier type and dimensions	None
Ditch design	Inclined flat surface towards toe, about 5-ft deep. Grass covered.
Failure mode	Rocks fall with subsequent weathering
Ditch performance	Good. All the material is contained within the ditch.

- CRSP analysis:

The results of the simulations using low coefficients were very close to the field observations. **No reduction of the original CRSP suggested values was necessary**. By using the minimum or *mid1* values of R_t and R_n, the program reflects that only rocks from layers 3 may reach the furthest point of the ditch, as seen in the field.

- *RECOMMENDATION*: Use of the minimum values of R_t and R_n suggested by CRSP manual: R_t *min* and R_n *min*.

III.2.2.8. SLOPE 8

- Field Observations:

Horizontal Distance from rock slope to barrier/road	25 ft approx.
Barrier type and dimensions	None

Ditch design	Inclined flat surface towards toe, about 1-ft deep. Grass covered.
Failure mode	Rocks fall with subsequent weathering
Ditch performance	Good. All the material is contained within the ditch.

- CRSP analysis:

  The results of the simulations using low coefficients were very close to the field observations. **No reduction of the original CRSP suggested values was necessary**. By using the minimum or *mid1* values of R_t and R_n, the program reflects that only rocks from layers 3 may reach the furthest point of the ditch, as seen in the field.

- *RECOMMENDATION*: Use of the minimum values of R_t and R_n suggested by CRSP manual: R_t *min* and R_n *min*.

III.3. CONCLUSIONS

The study clearly demonstrates that either the lower ends of the manual suggested input parameters be used, or a further reduction of these values be used for CRSP. This may be the best way at this time for effectively applying CRSP in rock slope design in Western Pennsylvanian provided that the input are prepared as laid out in this report. The reduction varies as suggested in the summary below.

Slope	Suggested values of R_t and R_n
1	½ R_t *min* and R_n *min*
2	R_t *min* and R_n *min*
3	R_t *min* and R_n *min*
4	½ R_t *min* and ½ R_n *min*
5	R_t *min* and ½ R_n *min*
6	½ R_t *min* and ½ R_n *min*
7	R_t *min* and R_n *min*
8	R_t *min* and R_n *min*

The reasons behind this conclusion are many. First, the program employs some empirical relationships that were established based upon observation in Colorado and have been calibrated as such. These relationships may not work well for the low highway slopes of Western Pennsylvania. Thus it is difficult to obtain a consistent trend. One proposed future work is to modify the code by removing these relationships and replace them with physics based computation using established mechanics principles that were widely used in discrete elements. Also, the impact of the shape of the rock block might be important but could not be addressed. This obstacle could also be removed by implementing a general contact detection scheme considering irregular rock block shapes in the revised code. We believe our recommendations of using low values for R_t and R_n at this point represents the best current practice until the code is modified.

The study provides a clear procedure on how to map a rock slope into an input profile, and how to conduct field reconnaissance work to acquire the information necessary for a detailed analysis. We believe this work represents a first comprehensive effort of its kind in this respect. Further follow-up studies on the code improvement, on the numerical evaluation of existing practice would be of great value in that it would further remove the remaining uncertainties and make the design of highway rock slope a much more reliable process.

CHAPTER IV:

CONCLUDING REMARKS

This research focuses on the application of CRSP for rock slopes in Western Pennsylvania, with emphasis on the slopes representative of the geological conditions within the jurisdiction of the District 11-0 of the Pennsylvania Department of Transportation. Toward this goal, eight slopes were selected such that a complete spectrum of the geological profile in term of the rock stratigraphy of the area was covered.

The computer program CRSP, Colorado Rockfall Simulation Program, was originally developed for Colorado in which the slopes are higher and the rocks are harder, in general. The assumptions that were adopted in the CRSP and the subsequent calibration in its input parameter determination might not work well for the highway slopes of the area studied. In terms of the order of magnitude, heights of slopes of the studied area generally lie below 200’ and mostly lies around 100’. The geological characteristics of the slopes are also very different from those the CRSP was developed for. Thus a systematic way to acquire input parameters was initiated.

We have carried out field work in collecting the data, and conducted extensive analysis to calibrate the CRSP input parameters such that the field conditions as observed could be best matched by the analysis. It is to be noted that the actual field conditions may have been different from the condition as observed since fallen rocks fragments or blocks might have been removed, and that slope profile as observed might be subjected to alteration since the surveyed data was acquired. Albeit such potential discrepancies, we believe the recommendations of the study could serve as a reasonable starting point for an analysis using CRSP in the studied area. The results of such analysis should, however, be verified by practitioners on a case by case basis using all the available site information. Conservatism should be introduced should the information for verification be limited. In such cases, it is suggested that an observation plan be devised so that a design or an assessment be properly updated as new information comes in.

A computational tool, such as CRSP, with easy interactive input, sometimes gets abused. It cannot be overemphasized that the objectives of running a CRSP analysis is to determine the consequences of a rock block falling from any part of a slope, and to evaluate the various designs or countermeasures such that the consequences of a rock fall become acceptable. The stochastic nature of the problem dictates that a proper interpretation of the results should be a critical and integral part of an analysis—this interpretation requires experience and judgment. The design guidance manual, which is provided as part of the project product, should be viewed in this light.

Finally, a workshop will be conducted to disseminate the finding of the project.

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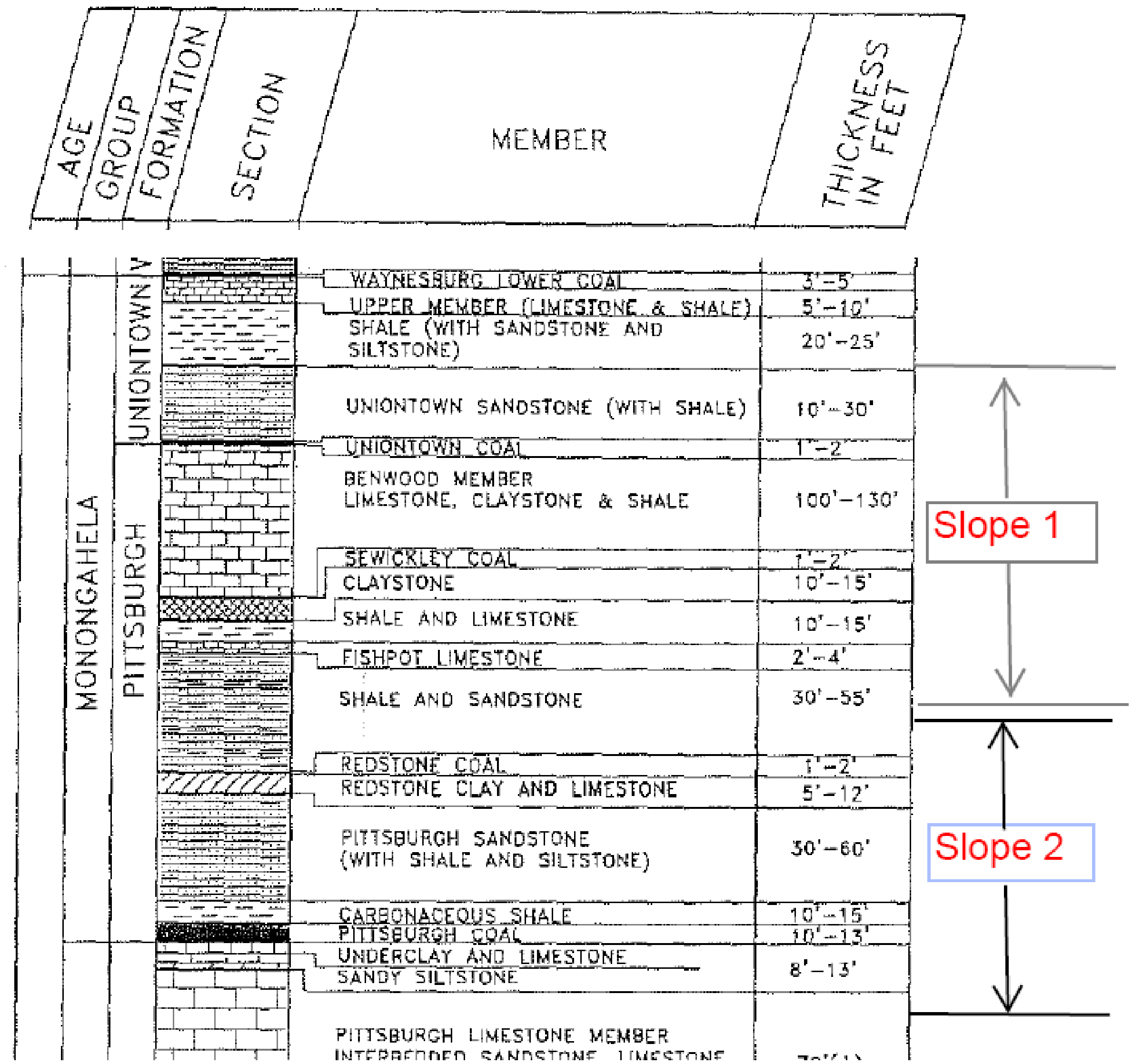
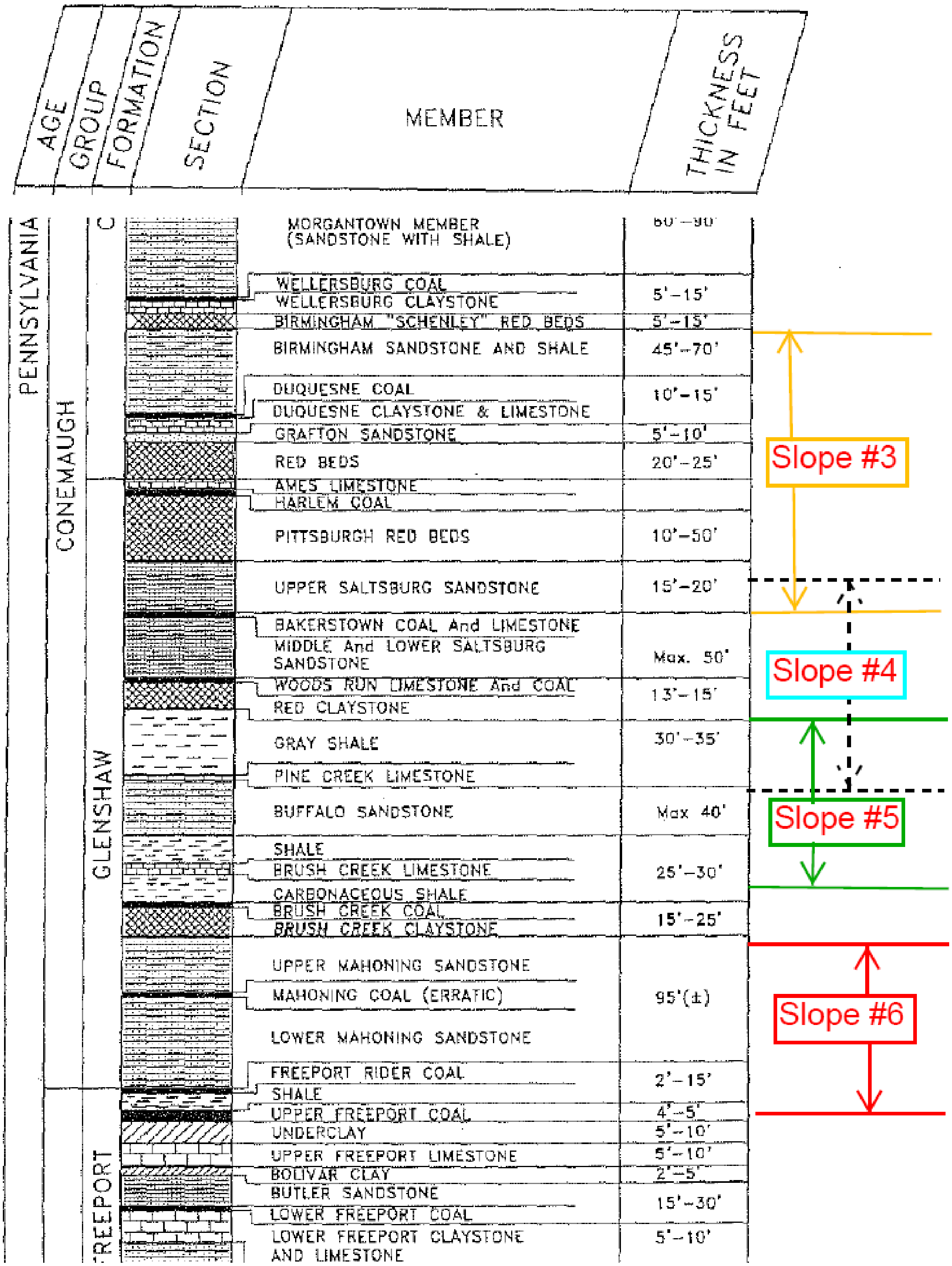
Appendix A:

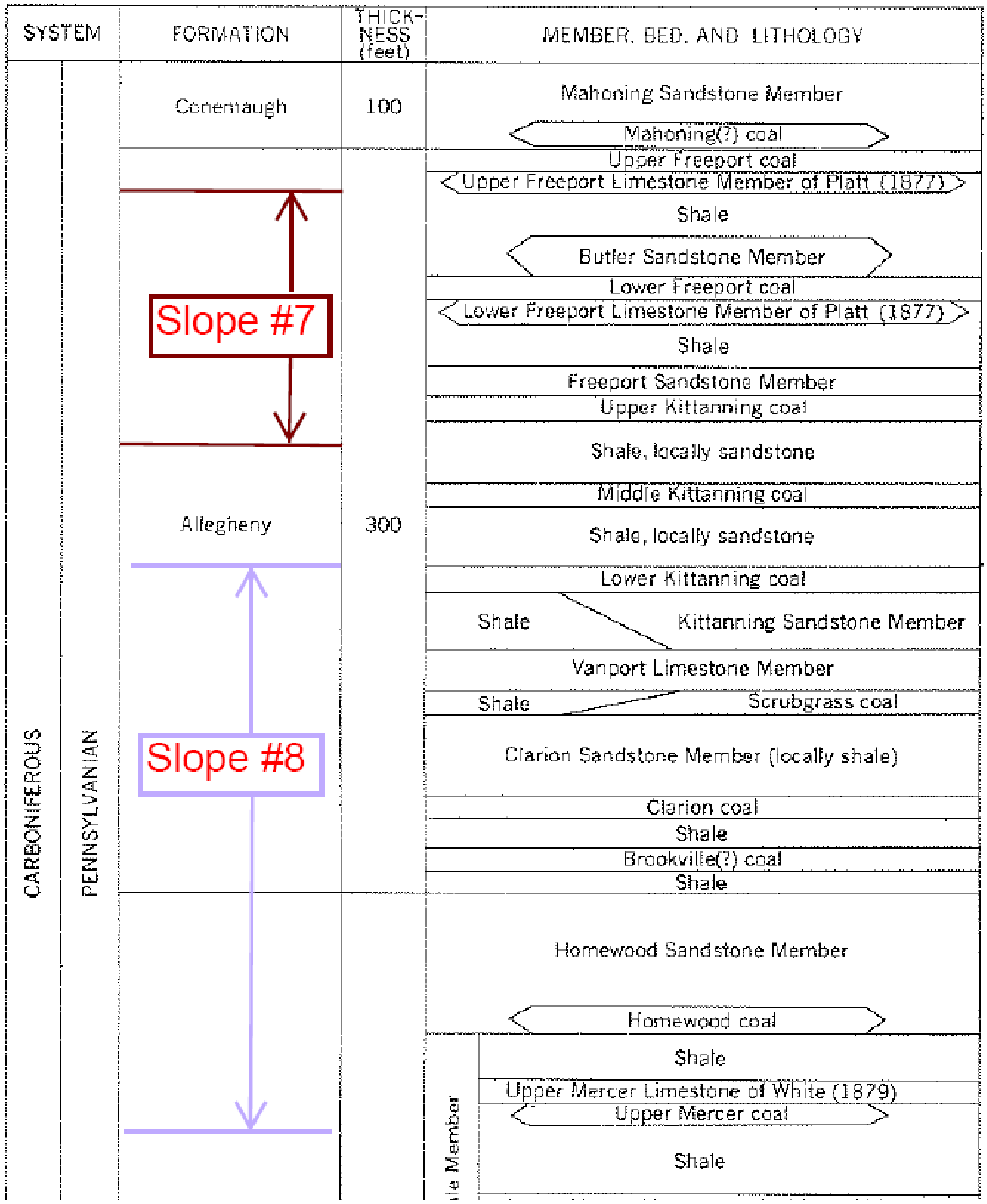
Stratigraphic Profiles of the Eight Study Slopes



Slope Sites 1 and 2 on the Stratigraphic Profile of Allegheny County



Slope Sites 3 to 6 on the Stratigraphic Profile of Allegheny County



Slope Sites 7 and 8 on the Stratigraphic Profile of Lawrence County

Appendix B:

Interview Form for Current-State-of-the-Practice-in-Rock-Slope-Analysis Survey

University of Pittsburgh

A Rational Procedure for Rock Slope Designs for Western Pennsylvania

Interview Form

Interviewer

Interviewee

Interviewee Title/Organization:

Interview Date

Background: The University of Pittsburgh is performing a study for the Pennsylvania Department of Transportation (PennDOT) District 11-0 aimed at building a coherent framework that is easily implemented for consistent and reliable designs of rock slopes located in District 11-0. During rock slope analysis, western Pennsylvania geologists/engineers frequently use the Colorado Rockfall Simulation Program (CRSP) to develop design input parameters. At times, the model results have led to unsuccessful designs. Through literature reviews; interviews with PennDOT, PA Turnpike, PADEP, and other state highway officials, University professors, and consultants; collection and review of existing analysis and design documents; field data collection at existing rock cut slopes; and modeling; this study aims to develop a CRSP application manual that will provide clear program input guidance to the western Pennsylvania rock slope investigator, with the goal being improved rock slope design alternatives.

1. Please briefly summarize your experiences with rock slope stability analysis and design, including general locations of the slopes and methods of analysis, e.g., computer models used, and typical modes of rock slope failure evaluated.

2. Have you noticed if there is a specific time of year when significant rock slope failures occur? Any other significant conditions to evaluate prior to analyzing rock slopes?

3. If you are or have in the past used an analysis method for rock slopes other than the CRSP computer model (or your consultants have), please provide a short summary of the required input parameters to the analysis method and the situations where this analysis method would be used. If more than one additional method of analysis, please discuss each method.

4. Do you or have you (or have your consultants) used the CRSP for rock cut slope analysis? Do you feel that the CRSP provides accurate and reliable rock slope design input parameters? If yes, please provide examples. If not, please elaborate.

5. For the other rock slope analyses methods you or your consultants have used, do you feel that they provide accurate and reliable rock slope design input parameters? If yes, please provide examples. If not, please elaborate.

6. The information ultimately used as input parameters for CRSP, or other analysis methods used, is collected by what means. Is information collected for all lithologic units in a proposed cut slope?

7. For the rock slope analysis method(s) you or your consultants use, are sensitivity analyses an integral part of the effort? If yes, please elaborate.

Appendix C:

Blank Field Data Collection Forms

University of Pittsburgh Rock Slope Study

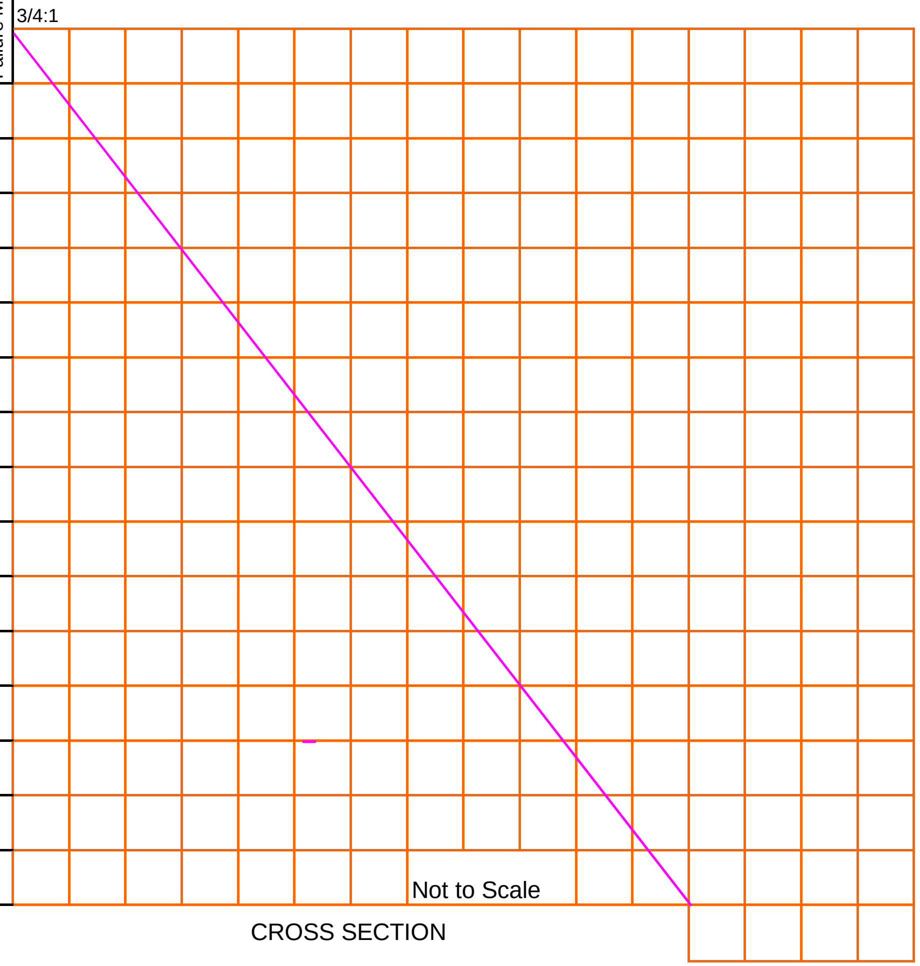
Step 1 Slope Cross Section

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)



CROSS SECTION

(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

Notes:

Slope   Pavement

CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

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)

Appendix D:

Site-Specific Field Data Forms

APPENDIX D-1

SLOPE 1 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

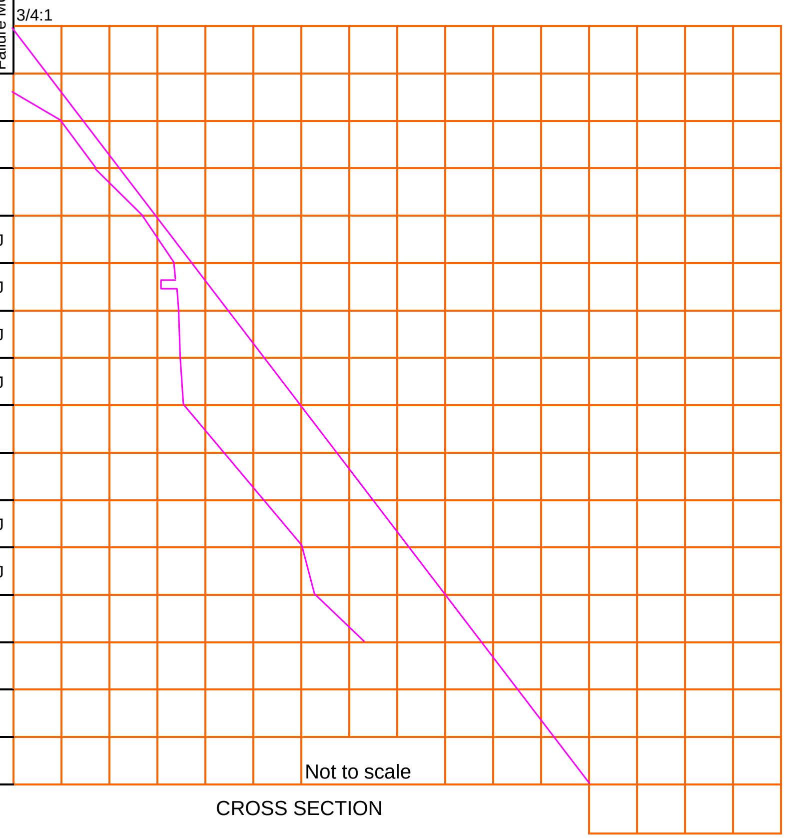
Step 1 Slope Cross Section

Slope Cross Section Slope # 1 Sheet 1 of 1

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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)
Soil	5.0	C		0.2	30	N	N	1	F
Shale	5.0	H		0.5	50	N	Y	2	F
Shaly Sandstone	20.0	M		1.5	45	N	Y	3	F
Limestone	20.0	M		2.0	50	N	Y	4	F/J
Limestone	5.0	S		2	85	O	Y	5	F/J
Calcareous Shale	4.0	S		0.5	85	N	Y	6	F/J
Limestone	10.0	S		2.0	85	N	Y	7	F/J
Talus	3.0	C		0.3	55	N	Y	8	F
Shale	25.0	M		0.3	55	N	Y	9	F
Limestone	5.0	S		1.0	55	N	Y	10	F/J
Limestone With Interbedded Shale	3.0	M		1.0	75	N	Y	11	F/J
Talus	8.0	C		0.5	45	N	Y	12	F



CROSS SECTION

*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)

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section   Slope # 1   Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

22 ft

Barrier type and dimensions   None

Cast in Place Concrete

Depth of ditch

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

Failure Mode: ___ Shatters on impact

___ Falls with subsequent weathering

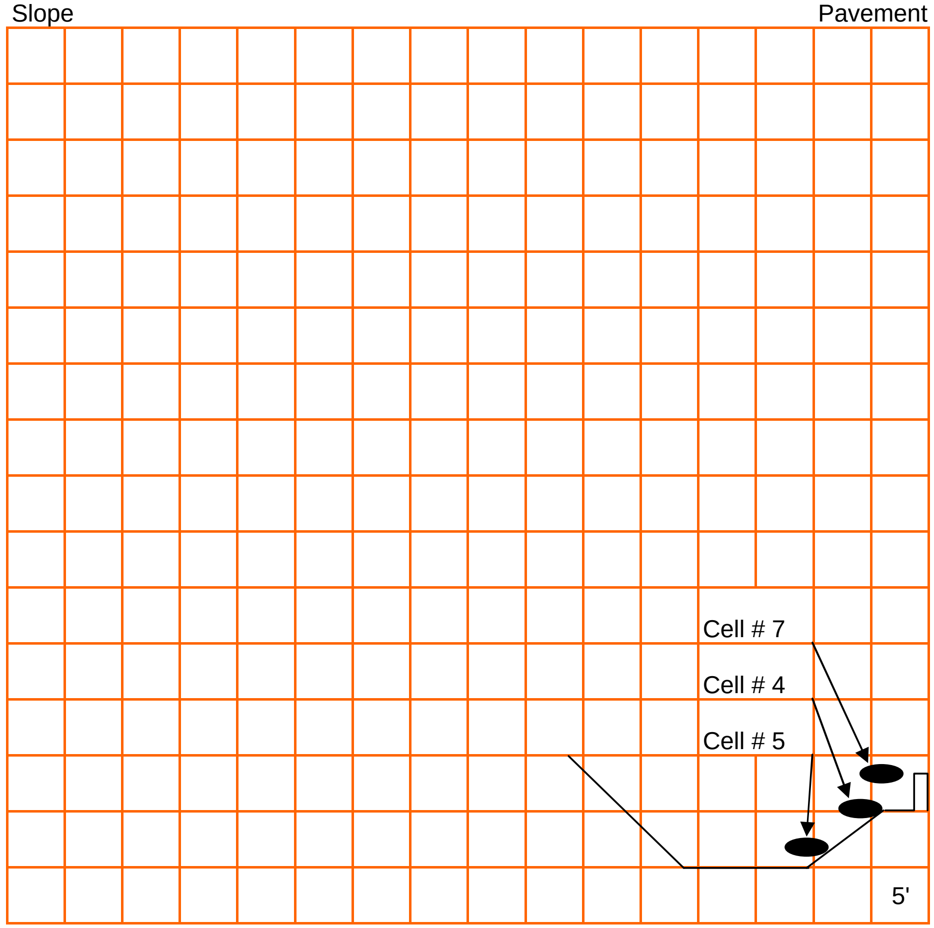
X__ Other (Describe)

Freeze/thaw

Performance X__ Material contained with ditch

___ Material on pavement or shoulder

● Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 1
Date: 4/3/2008

					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	Soil	0.1	0.2					X				X						X		S
2	Shale	0.25	0.2				X				X							X		D
3	Shaly Sandstone	0.75	1.5				X				X							X		D
4	Limestone	1	1		X				X								X			S
5	Limestone	1	2		X				X								X			S
6	Calcareous Shale	0.25	1.5			X				X								X		D
7	Limestone	1	1.5		X				X								X			S
8	Talus	0.25	0.3					X				X						X		S
9	Shale	0.15	0.5					X				X						X		D
10	Limestone	0.5	0.5			X				X							X			S
11	Limestone With Interbedded Shale	0.5	1			X				X								X		S
12	Talus	0.25	0.2					X				X						X		S

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

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

CRSP Cell # ______________________   Existing Slope Angle (based off LiDAR) ______________________

Slope Strike ______ 5 ______
Slope Dip ______ 55 ______

Bedding   Strike ______
          Dip ______

Road Strike ______ 5 ______
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	250	87	N	10-30						
2	320	87	S	5-50						

APPENDIX D-2

SLOPE 2 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

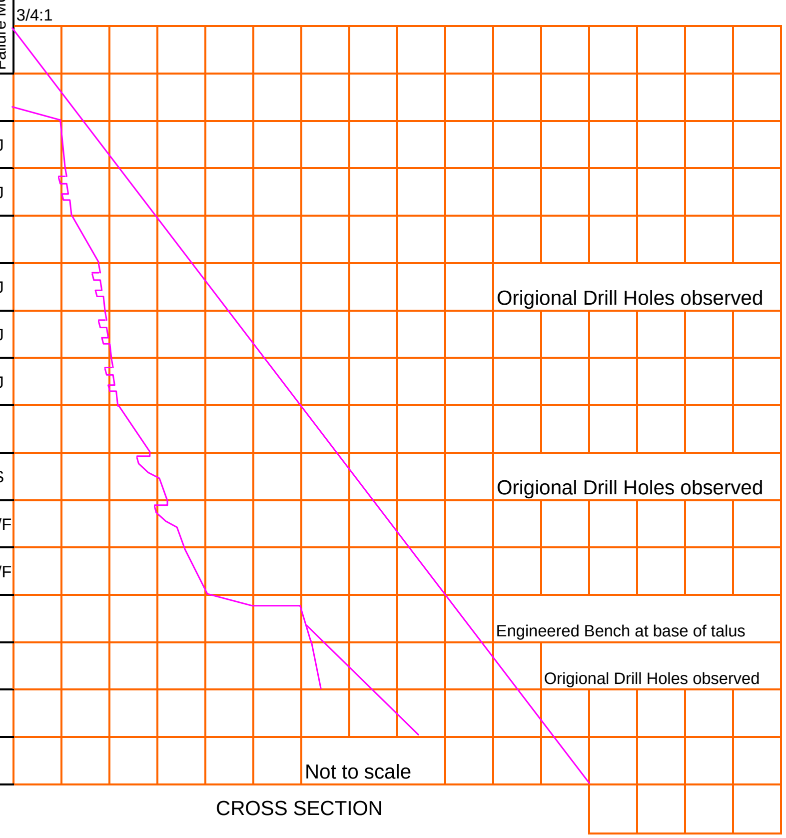
Step 1 Slope Cross Section

Slope Cross Section   Slope #   2   Sheet 1 of 1

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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)
Soil	5.0	C		0.2	20	N	N	1	F
Shale	6.0	M		1.0	86	N	Y	2	F/J
Claystone with Interbedded Limestone	5.0	M		2.0	86	O	Y	3	F/J
Shale	15.0	M		2.0	60	N	Y	4	F
Sandstone w/ Interbedded Shale	3.0	M/S		2	85	O	Y	5	F/J
Shale	5.0	M		0.8	85	O	Y	6	F/J
Shaly Sandstone	2.0	M		2.0	85	O	Y	7	F/J
Shale	4.0	M		0.5	55	N	Y	8	F
Sandstone	1.5	S		3.0	73	O	Y	9	J/S
Shale w/minor Interbedded Sandstone	16.0	M/S		15.0	73	O	Y	10	J/S/F
Coal (Pittsburgh)	4.0	M		0.6	65	N	Y	11	J/S/F
Talus	3.6	C		0.6	25	N	N	12	F
Shale	8.0	M		0.5	73	N	Y	13	F
Limestone	7.0	S		1.5	75	N	P	14	J
Talus	12.0	C		0.5	45	N	N	15	F



CROSS SECTION

*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, S=Subsidence)

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section Slope # 2 Sheet 1 of 2

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

20 feet

Barrier type and dimensions Guiderail

Depth of ditch 0 ft

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

Failure Mode: ___ Shatters on impact

___ Falls with subsequent weathering

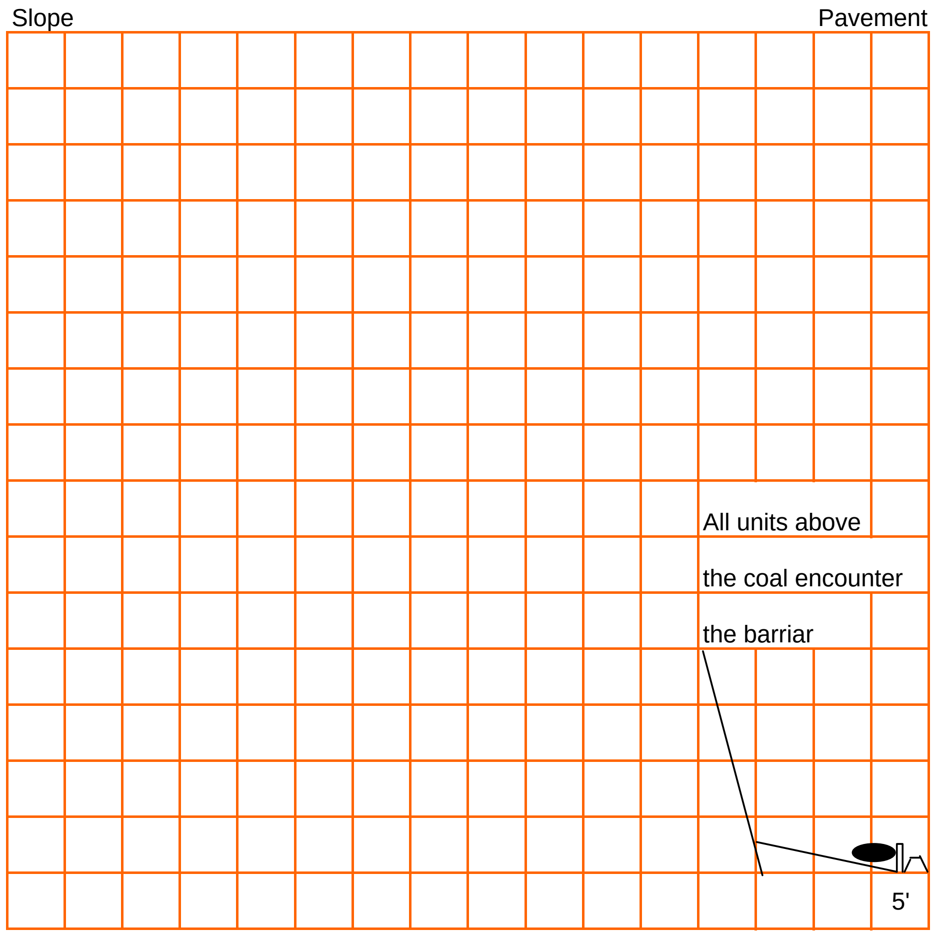
X__ Other (Describe)

Sudsidence related fracturing

Performance ___ Material contained with ditch

X__ Material on pavement or shoulder

⬬ Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section   Slope # 2   Sheet 2 of 2

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

12 feet

Barrier type and dimensions   Guiderail (part)

Depth of ditch   0 ft

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

Failure Mode: ___ Shatters on impact

___ Falls with subsequent weathering

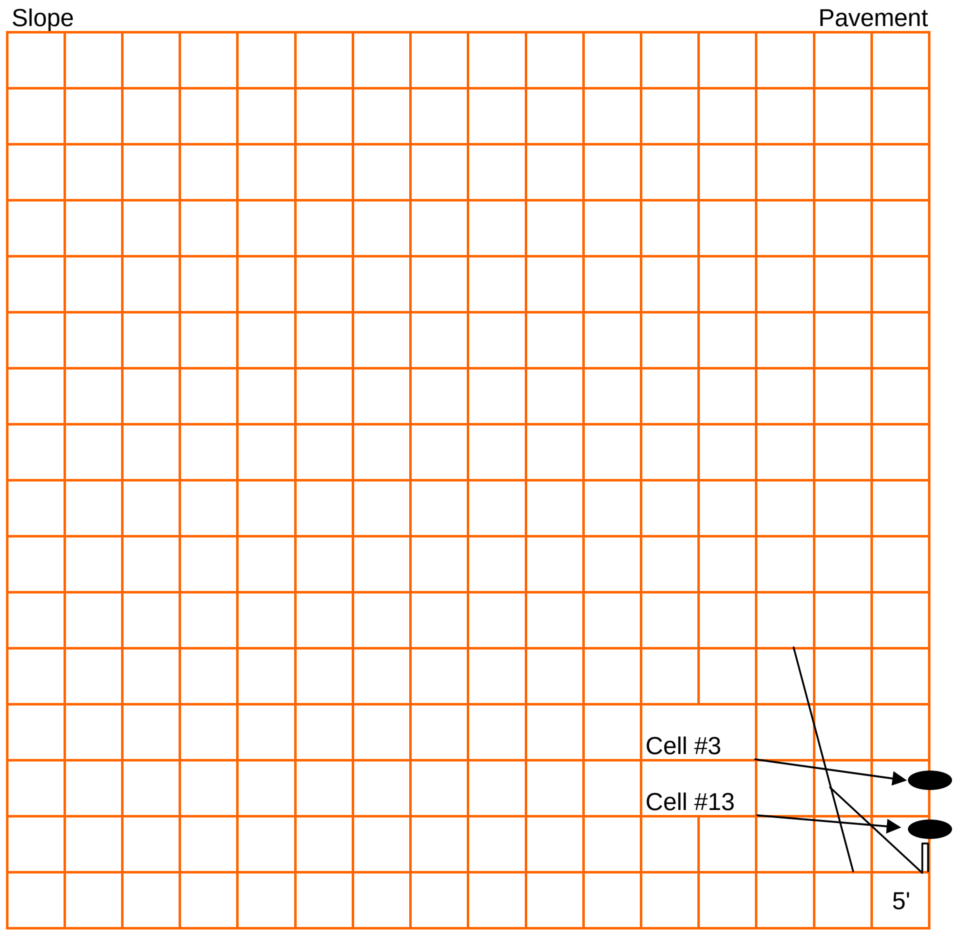
X___ Other (Describe)

Freeze/thaw

Performance ___ Material contained with ditch

X___ Material on pavement or shoulder

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation   Slope # 2   Sheet 1 of 1

CRSP Cell # ____________

Existing Slope Angle (based off LiDAR) ____________

Slope Strike 60

Slope Dip 63

Bedding Strike ____________

Dip ____________

Road Strike 60

Valley Strike N/A

Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	RMR Rating: Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?
1	280	61	N	10						
1	260	64	N							
2	314	84	E	Various	Subsidence Joints					
2	355	80	E		Subsidence Joints					
3	215	80	W	100						

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 2
Date: 4/3/2008

					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	Soil	0.1	0.1					X				X						X		S
2	Shale	0.5	0.5				X				X							X		D
3	Claystone with Interbedded Limestone	1	1.5			X				X							X			S
4	Shale	0.25	0.5				X				X							X		D
5	Sandstone w/ Interbedded Shale	1	1			X				X							X			S
6	Shale	0.4	0.5				X				X							X		D
7	Shaly Sandstone	1	1.5			X				X							X			S
8	Shale	0.25	0.5				X				X							X		D
9	Sandstone	1.5	1			X				X							X			S
10	Shale w/minor Interbedded Sandstone	7.5	2		X				X								X			D
11	Coal (Pittsburgh)	0.3	0.5					X				X						X		S
12	Talus	0.3	0.5					X				X						X		S
13	Shale	0.25	0.3				X				X							X		D
14	Limestone	0.75	0.3		X				X								X			S
15	Talus	0.25	0.3					X				X						X		S

APPENDIX D-3

SLOPE 3 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

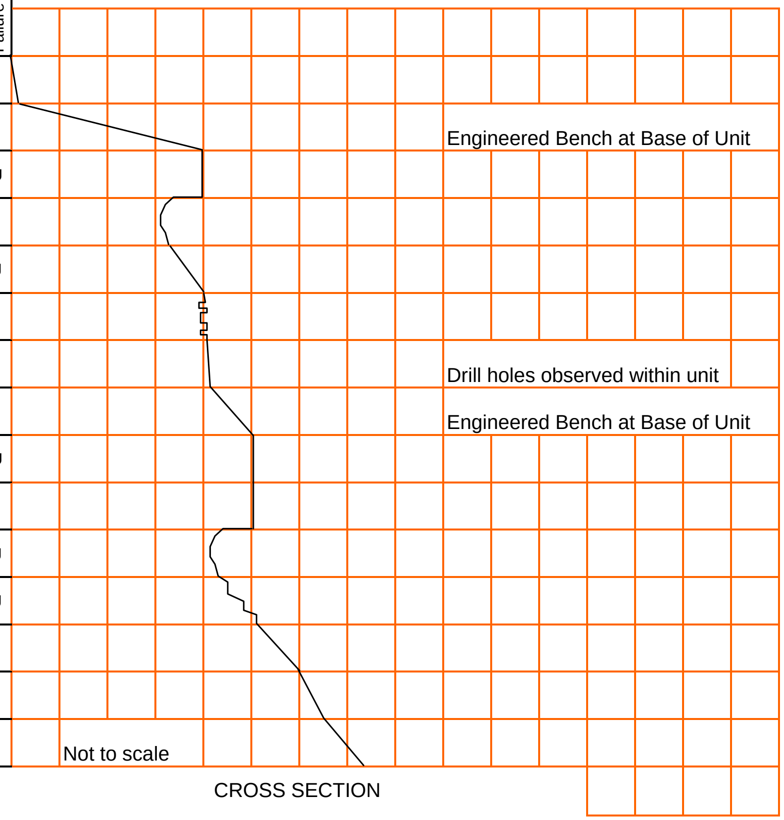
Step 1 Slope Cross Section

Slope Cross Section Slope # 3 Sheet 1 of 1

Initial Design Degree of cut slope:

Stratigraphic Sequence

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

CROSS SECTION

(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 # 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

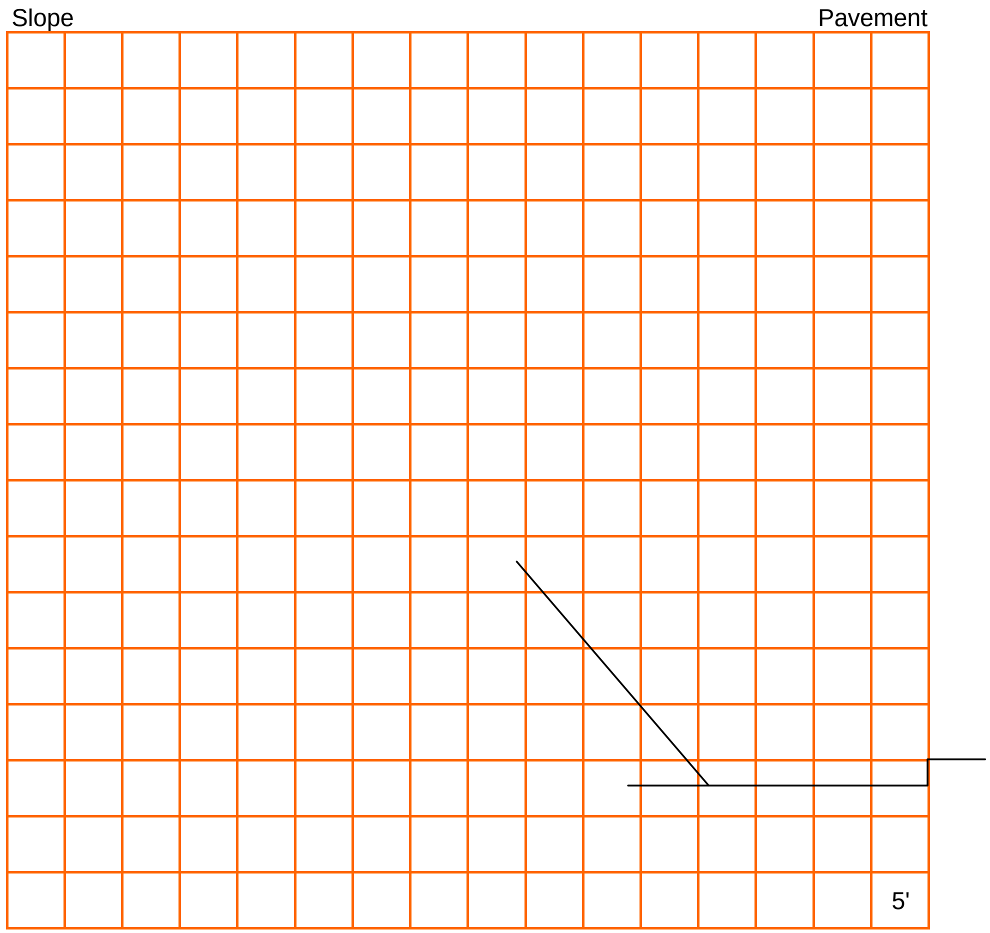
X__ Falls with subsequent weathering

___ Other (Describe)

Performance ___ Material contained with ditch

X__ Material on pavement or shoulder

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

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

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

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

APPENDIX D-4

SLOPE 4 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

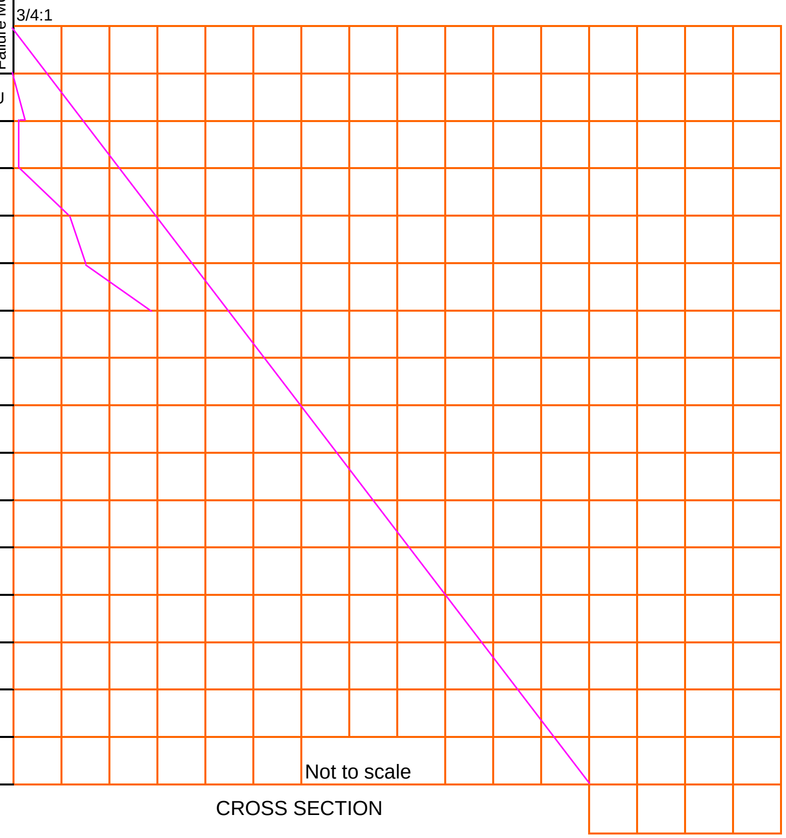
Step 1 Slope Cross Section

Slope Cross Section   Slope # 4   Sheet 1 of 1

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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	60.0	H-M		8.0	76	Y	Y	1	J/U
Carbonaceous Shale int w/ Coal	2.0	M		0.1	90	P	Y	2	F
Talus	1.0	C		0.1	45	N	Y	3	F
Sandstone (Massive)	20.0	M		4.0	66	Y	Y	4	J
Talus	7.0	C		1	40	N	N	5	F



CROSS SECTION

*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)

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section   Slope # 4   Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

27 Feet

Barrier type and dimensions None

Guiderail

Depth of ditch

4.0 feet

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

Failure Mode: ___ Shatters on impact

___ Falls with subsequent weathering

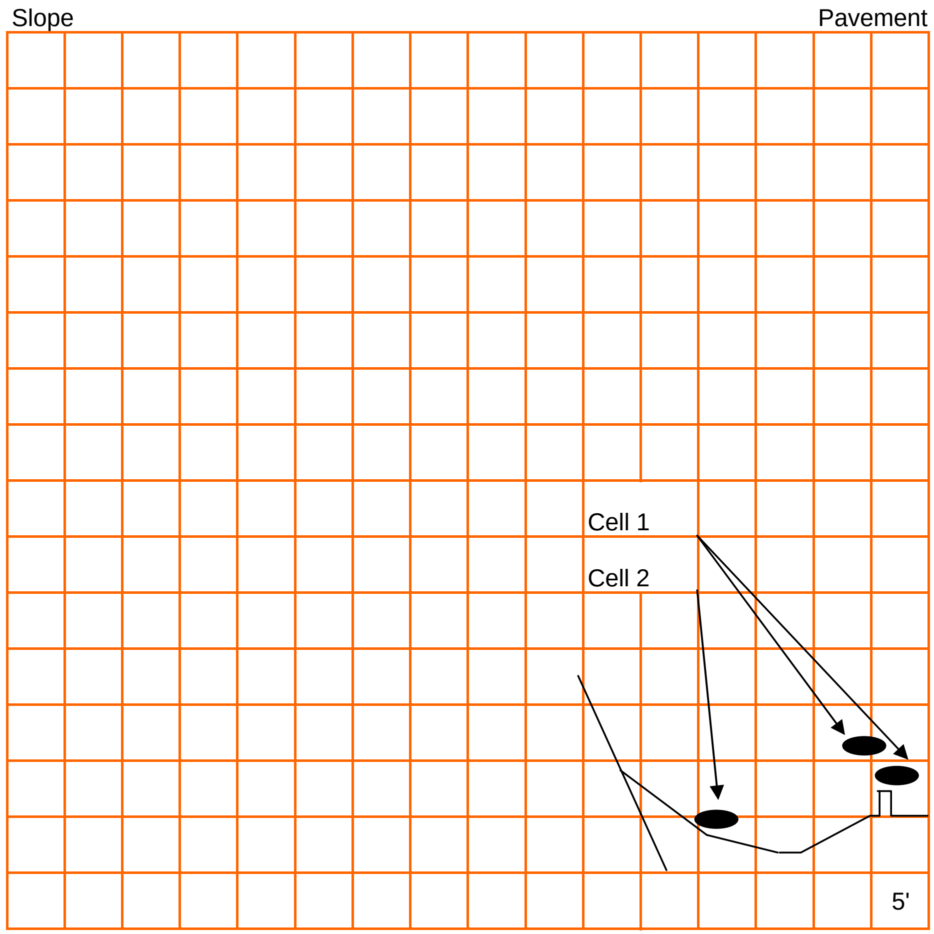
X Other (Describe)

Jointing

Performance ___ Material contained with ditch

X Material on pavement or shoulder

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # 4 Sheet 1 of 1

CRSP Cell # ______

Existing Slope Angle (based off LiDAR) ______

Slope Strike Concentric

Slope Dip ______

Bedding Strike ______

Dip ______

Road Strike Concentric

Valley Strike N/A

Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	RMR Rating: Spacing of Discontinuities	Separation	Roughness	Infilling	Weathering	Water seepage?
1	30	90		10 to 20						
2	112	87	S	10 to 20						
3	Spherical joints within the pillow structures of the massive sandstone									
4	80	76	N	10 to ?						
5	85	54	S	30						
6	30	65	E	30						

University of Pittsburgh

Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 4
Date: 4/9/2008

					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	4	4			X				X							X			S
2	Carbonaceous Shale int w/ Coal	0.15	0.1				X				X							X		D
3	Talus	0.15	0.1					X				X						X		D
4	Sandstone (Massive)	2	4			X				X							X			S
5	Talus	0.25	1					X				X						X		S

APPENDIX D-5

SLOPE 5 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

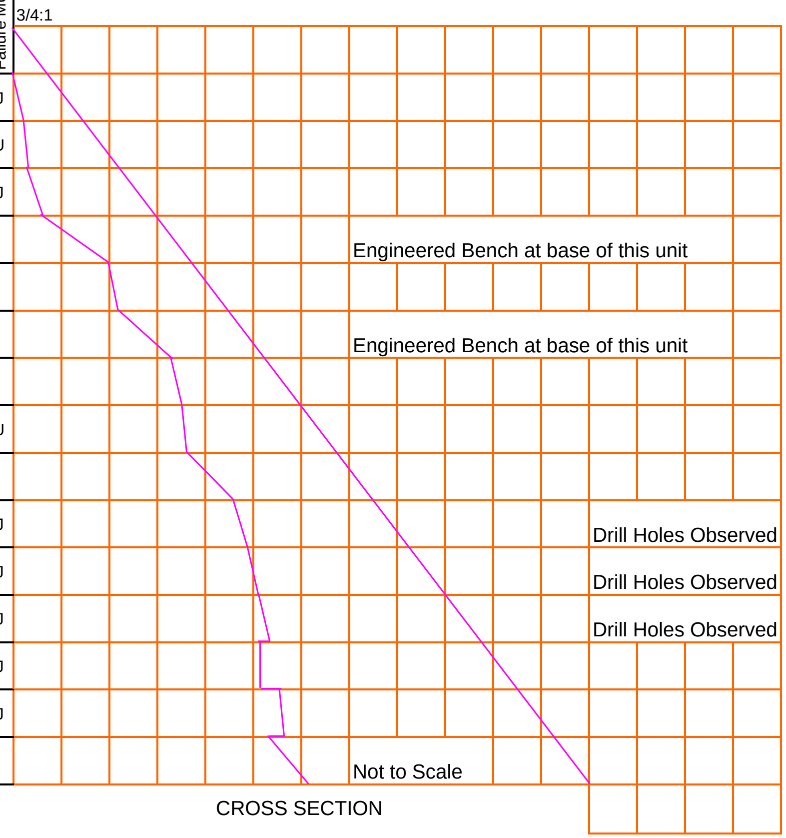
Slope Cross Section　　Slope # 5　　Sheet 1 of 1

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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



CROSS SECTION

(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 # 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

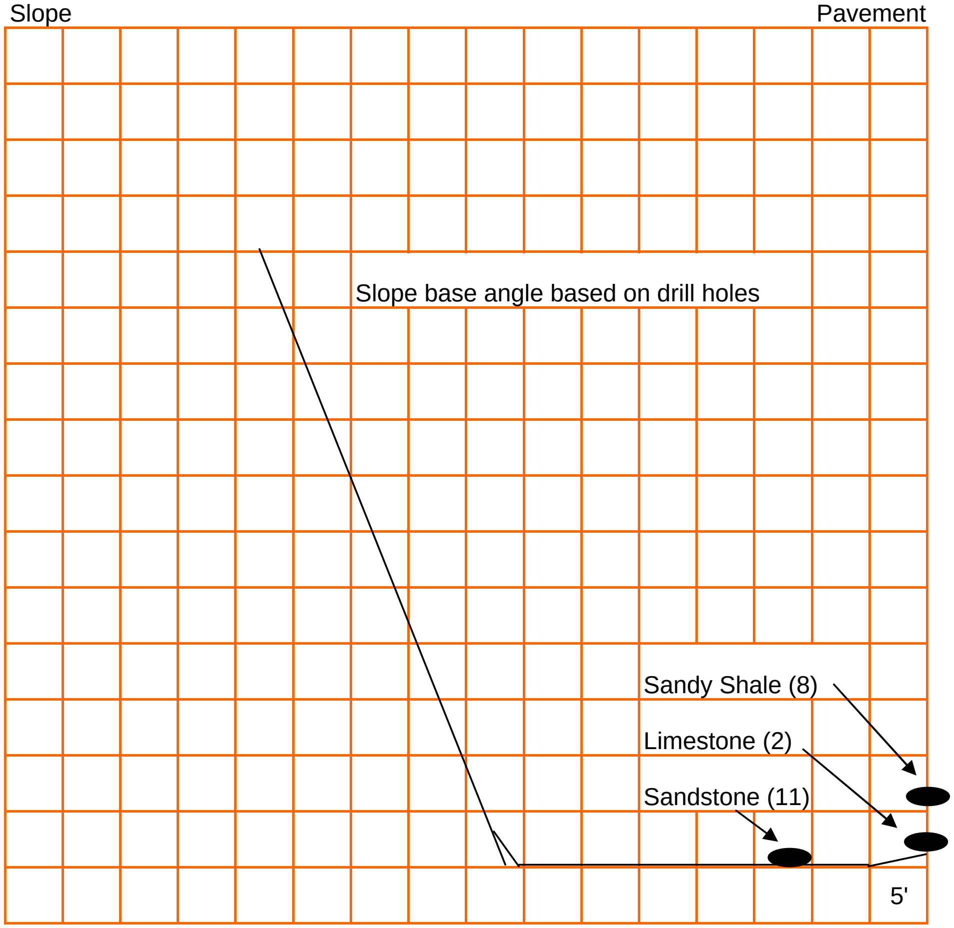
X__ Other (Describe)

Performance ___ Material contained with ditch

X__ Material on pavement or shoulder

Toppling

⬬ Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

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

					RMR Rating					
Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	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

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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

APPENDIX D-6

SLOPE 6 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

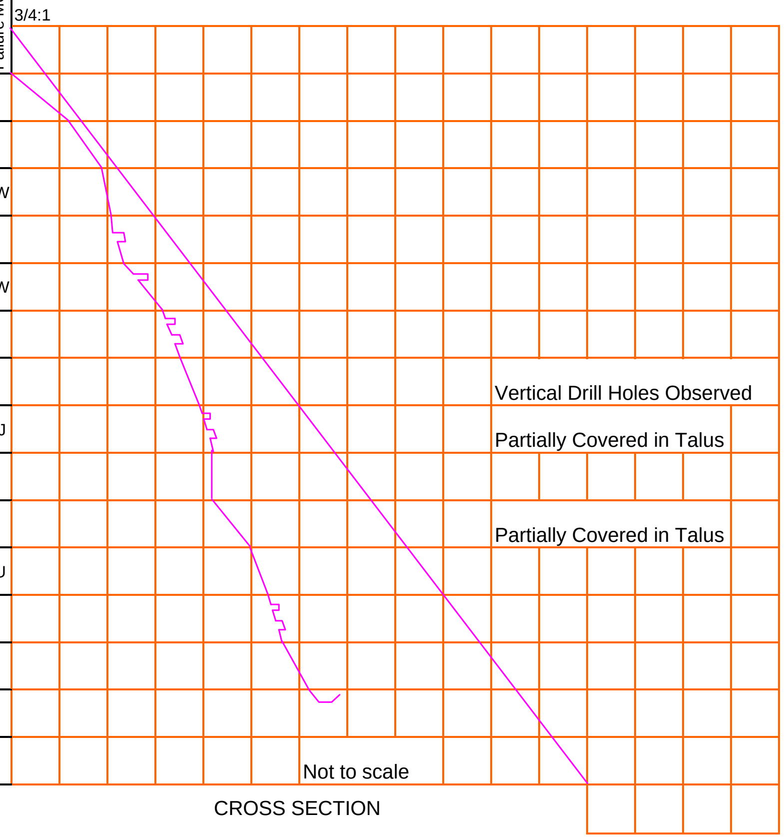
Slope Cross Section

Slope # 6 Sheet 1 of 1

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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	1.0	C		0.2	40	N	N	1	F
Sandstone	28.0	M		4.0	55	N	Y	2	J/U
Carbonaceous Shale	6.0	H		0.3	85	N	Y	3	F/U/W
Sandstone	5.0	H		2.0	85	Y	Y	4	F/U
Shale	30.0	H		1	55	Y	Y	5	F/U/W
Sandstone	8.0	M		3.0	76	Y	Y	6	J/U
Sandstone (Massive)	6.0	S		4.0	76	N	Y	7	J/F
Shale with sandstone interbeds	13.0	M		2.0	80	Y	P	8	U/F/J
Coal	0.5	S		0.5	90	N	Y	9	J/F
Shale with sandstone interbeds	12.0	M		1.5	55	N	P	10	J/F
Sandstone	4.0	M		2.5	70	Y	Y	11	J/F/U
Shale with Nodules	4.0	M		0.4	77	N	Y	12	F/U
Sandstone	5.5	S		1.5	65	N	Y	13	F/J
Talus	3.0	C		1.5	Concave	N	N	14	F



CROSS SECTION

*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)

University of Pittsburgh Rock Slope Study

Step 2 Containment Ditch and Barrier Cross Section

Containment Ditch Cross Section   Slope # 6   Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

4.5 ft

Barrier type and dimensions   Jersey Barriar

Depth of ditch   Unknown

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

Failure Mode: ___ Shatters on impact

_X_ Falls with subsequent weathering

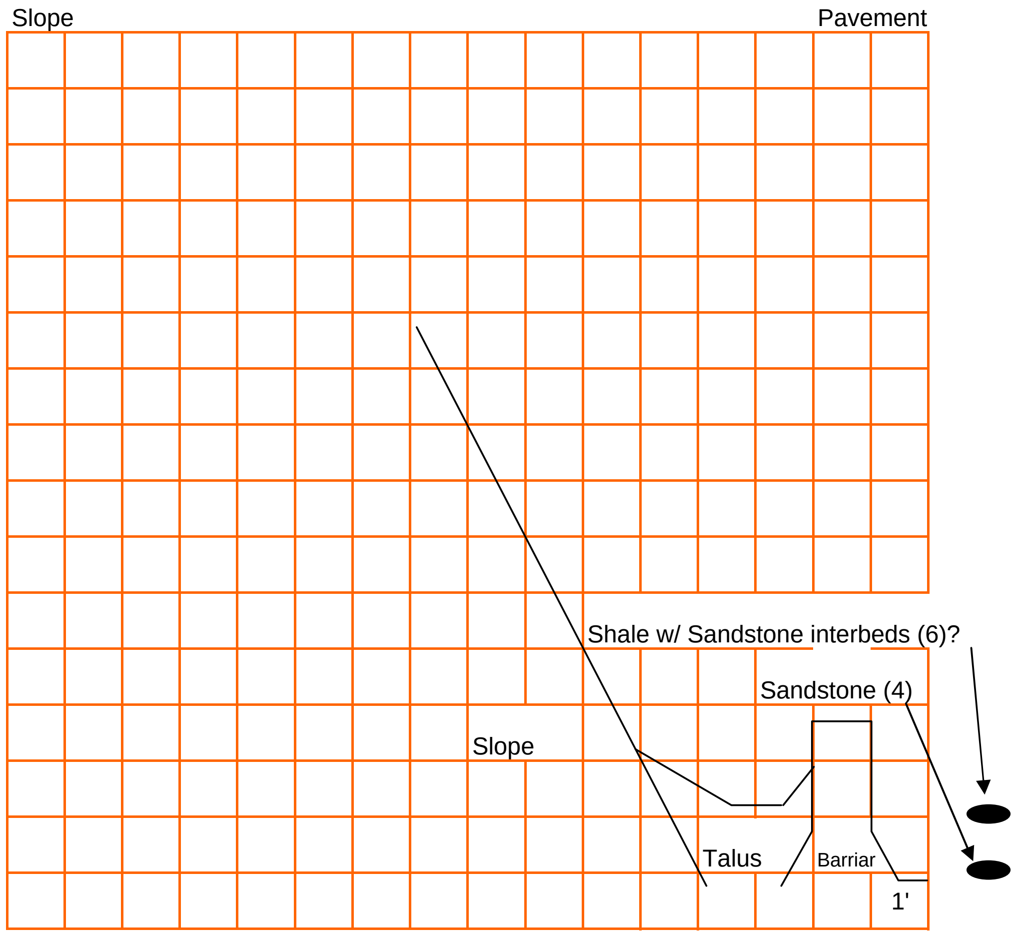
_X_ Other (Describe)

Storm water Transport

Performance ___ Material contained with ditch

_X_ Material on pavement or shoulder

Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation — Slope # 6 — Sheet 1 of 1

CRSP Cell # ______

Existing Slope Angle (based off LiDAR) ______

Slope Strike: 1
Slope Dip: 62

Bedding Strike: ______
Bedding Dip: ______

Road Strike: 1
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	25	90								No
2	320	75	West							No
3	115	90		8						No
4	30	75	West							No
5	30	90								No

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Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 6

Date: 3/28/2008

					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	0.1	0.05					X				X						X		D
2	Sandstone	2	2			X				X							X			S
3	Carbonaceous Shale	0.15	0.125				X				X							X		D
4	Sandstone	1	2				X				X							X		D
5	Shale	0.5	0.5				X				X							X		D
6	Sandstone	1.5	1				X				X						X			D
7	Sandstone (Massive)	2	1			X				X							X			S
8	Shale with sandstone interbeds	1	1			X				X							X			D
9	Coal	0.25	0.2				X				X							X		S
10	Shale with sandstone interbeds	0.75	0.8			X				X							X			D
11	Sandstone	1.25	0.5			X				X							X			S
12	Shale with Nodules	0.2	0.2				X				X						X			S
13	Sandstone	0.75	0.8		X				X								X			S
14	Talus	1	0.5					X				X						X		S

APPENDIX D-7

SLOPE 7 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

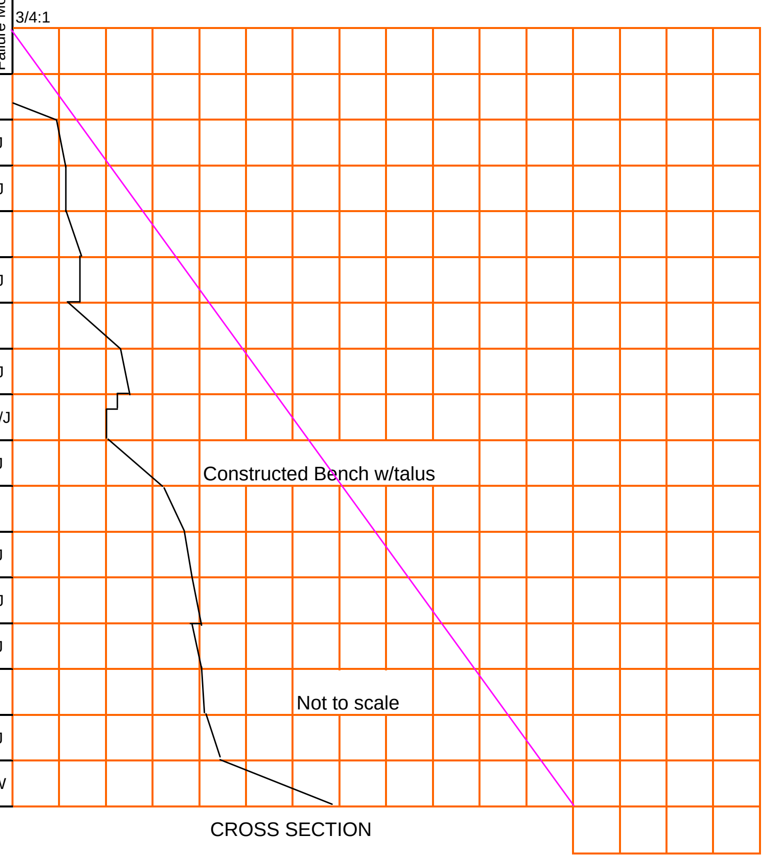
Step 1 Slope Cross Section

Slope Cross Section   Slope # 7   Sheet 1 of 1

Initial Design Degree of cut slope: 70 degrees from Horizontal

Stratigraphic Sequence

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)

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

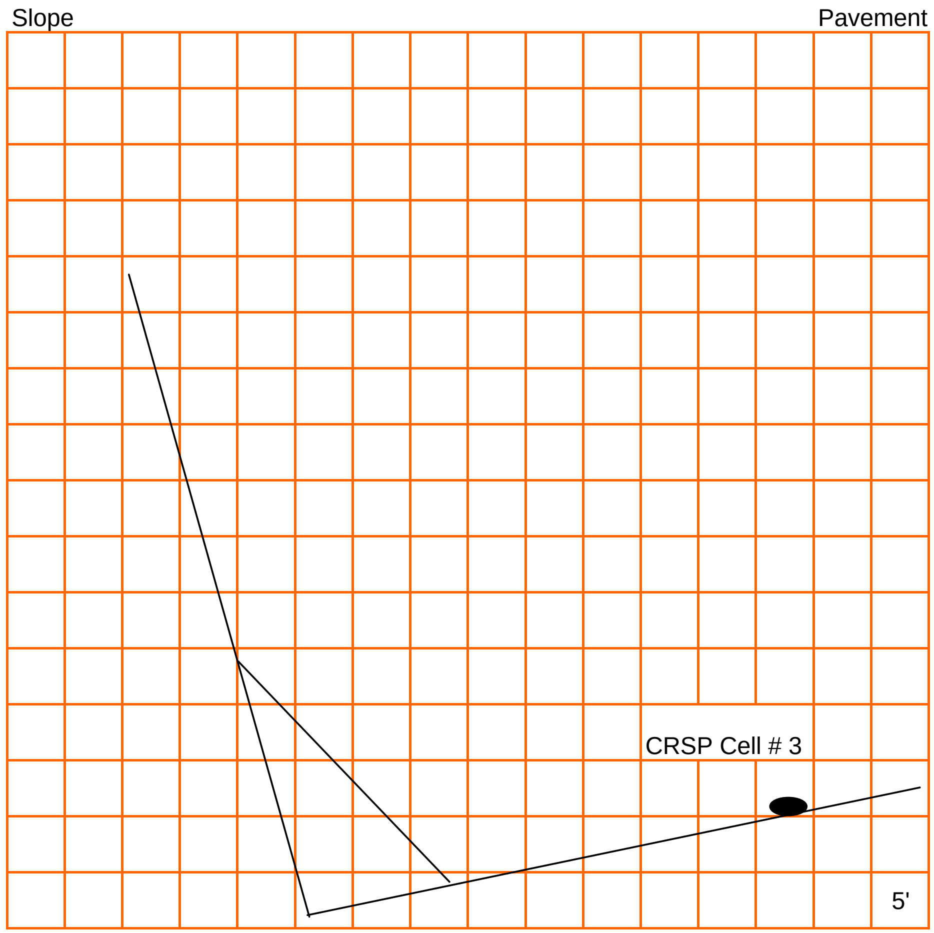
_X_ Falls with subsequent weathering

___ Other (Describe)

Performance _X_ Material contained with ditch

___ Material on pavement or shoulder

⬬ Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

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

Joint Set	Strike	Dip	Dip Directions	Perpendicular distance between joints (ft - range)	RMR Rating: 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							

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Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 7
Date: 3/20/2008

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)	Tangential Coefficient (Rt) Smooth Hard Surfaces (.9 to 1.0)	Tangential Coefficient (Rt) Most Bedrock and Boulder Fields (.75 to 0.95)	Tangential Coefficient (Rt) Talus and firm soil slopes (.65 to .95)	Tangential Coefficient (Rt) Soft soil slopes (.5 to .8)	Normal Coefficient (Rn) Smooth Hard Surfaces (.6 to 1.0)	Normal Coefficient (Rn) Most Bedrock and Boulder Fields (.15 to 0.35)	Normal Coefficient (Rn) Talus and firm soil slopes (.12 to .2)	Normal Coefficient (Rn) Soft soil slopes (.1 to .2)	Begin X	Begin Y	End X	End Y	Rock Hardness (pcf) Hard Sed (150 to 180)	Rock Hardness (pcf) 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

APPENDIX D-8

SLOPE 8 FIELD DATA FORMS

University of Pittsburgh Rock Slope Study

Step 1 Slope Cross Section

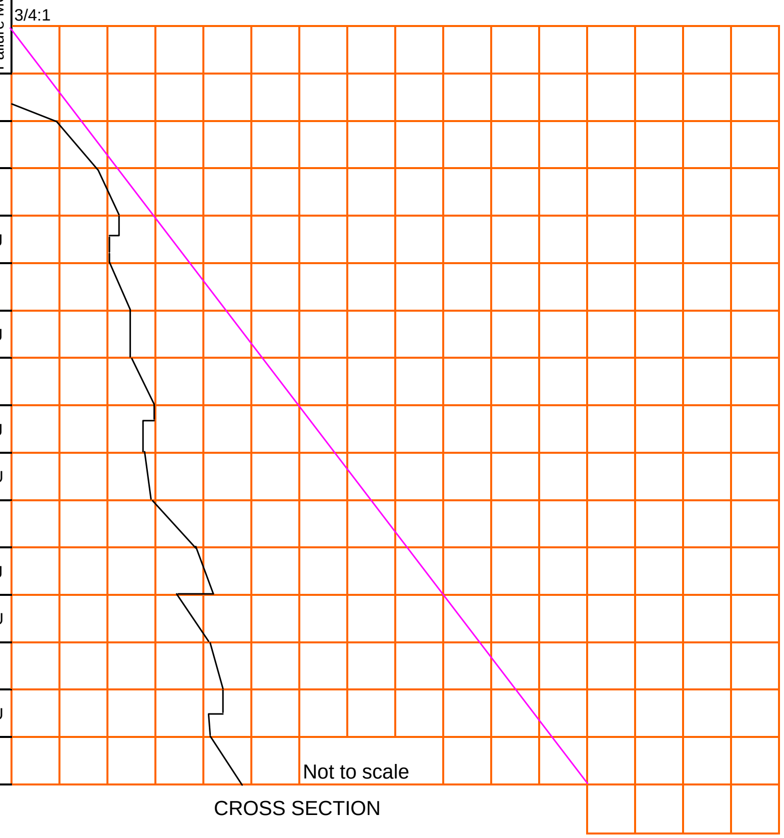
Slope Cross Section — Slope # 8 — Sheet 1 of 2

Initial Design Degree of cut slope: 65 degrees from Horizontal

Stratigraphic Sequence

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)
Glacial Outwash	?	S	N/A	0.8	30	N/A	Y	1	W
Shale	5+	H		0.3	42	N	Y	2	F
Sandstone*	5.0	S		3.0	64	N	Y	3	J
Sandstone with Shale interbeds	29.0	S		3.0	90	O	Y	4	U/J
Shale	4.0	M		0.3	60	N	Y	5	F
Coal	1.5	S		1.5	90	O/P	Y	6	U/J
Claystone	9.0	H		0.1	61	P	Y	7	F
Sandstone	1.0	S		1.0	90	O	Y	8	U/J
Shale with Nodules	5.0	M		0.7	85	N	Y	9	F/U
Shale	5.0	M		0.3	45	N	Y	10	F
Limestone (Black)	2.0	U		2.0	60	O	Y	11	U/J
Calcareous Shale w/ Limestone Nodules	5.0	M		0.3	52	P	Y	12	F/U
Shale	5.0	M		0.3	68	N	Y	13	F
Iron Carbonate Nodules	0.4	S		0.7	90	O	Y	14	F/U
Shale	14.0	M		0.3	56	N	Y	15	F

*Unit observed on the ground



CROSS SECTION

(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

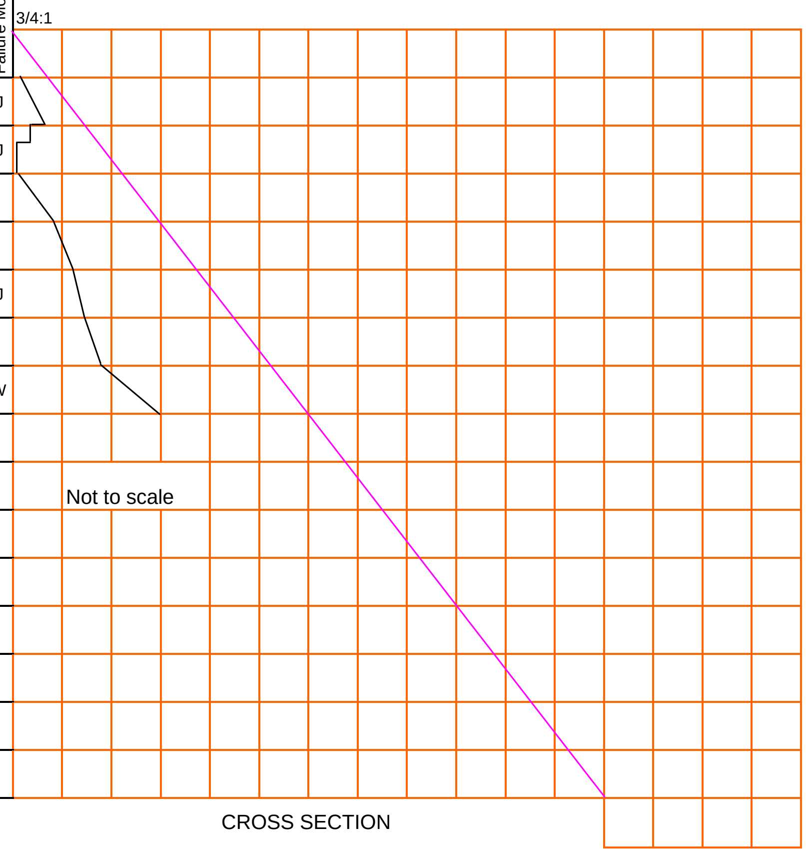
Step 1 Slope Cross Section

Slope Cross Section Slope # 8 Sheet 2 of 2

Initial Design Degree of cut slope: 65 from Horizontal

Stratigraphic Sequence

Rock Type	Unit Thickness (1)	Degree of Weathering (2)	Weathering Rate (3)	Est. Largest Block Size (ft)	Face Angle (4)	Overhanging (5)	Fall Potential (6)	CRSP Cell #	Failure Mode(7)
Limestone	1.0	U		2.0	65	O	Y	16	U/J
Coal	1.5	M		1.5	90	O/P	Y	17	U/J
Claystone	4.0	H		0.1	50	P	Y	18	F
Shale	6.0	M		0.3	65	N	Y	19	F
Sandstone	3.0	S		3.0	75	N	Y	20	U/J
Shale with claystone layer	23.0	M		0.3	68	N	P	21	F
Shale Talus	13.0	C	N/A	0.3	40	N	N	22	F/W



CROSS SECTION

(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 # 8   Sheet 1 of 1

Containment Ditch Parameters

Horizontal distance from rock slope to Barrier / Pavement

Barrier type and dimensions   None

Depth of ditch   Approximately 1 foot

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

Failure Mode: ___ Shatters on impact

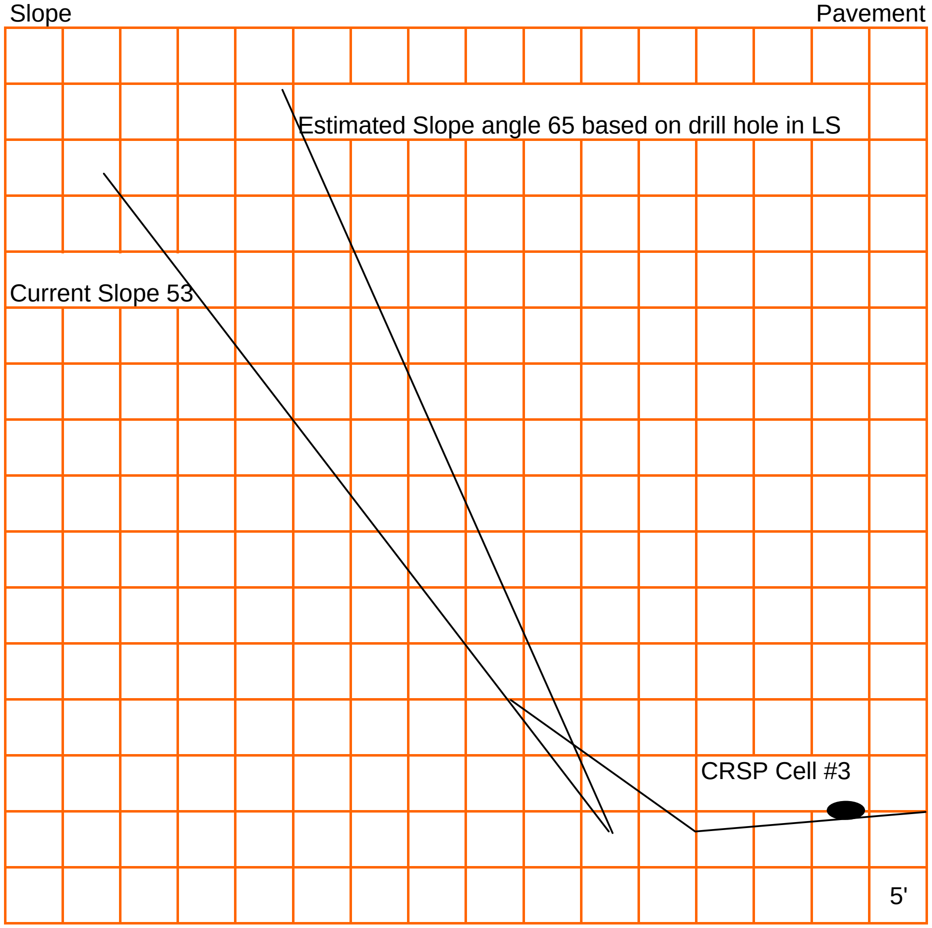
___ Falls with subsequent weathering

___ Other (Describe)

Performance _X_ Material contained with ditch

___ Material on pavement or shoulder

⬬ Rock encroachment to pavement



CROSS SECTION OF CONTAINMENT DITCH AND BARRIER

University of Pittsburgh Rock Slope Study

Step 3 Bedding, Fracture, and Joint Investigation

Bedding, Slope, and Joint Orientation Slope # 8 Sheet 1 of 1

CRSP Cell # N/A

Existing Slope Angle (based off LiDAR)

Slope Strike

Slope Dip

Bedding Strike

Dip

Road Strike

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	55	79								
1	70	72								
1	58	90								
1	35	90								
2	310	85								
2	335	87								

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Step 4 CRSP Parameter Collection

Colorado Rockmass Rating System Data Form Sheet 1 of 1

Slope # 8
Date: 3/18/2008

					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	Glacial Outwash	0.5	0.01					X				X					X			S
2	Shale	0.125	0.5				X				X							X		D
3	Sandstone	3	1		X				X								X			S
4	Sandstone w/ interbedded shale	1.5	1		X				X								X			C
5	Coal	0.75	0.4		X				X									X		S
6	Claystone	0.01	0.01				X				X							X		D
7	Thin Sandstone	1.5	0.5		X	X			X	X							X			D
8	Shale w/ Nodules	0.33	0.33			X	X			X	X							X		D
9	Shale	0.125	0.5				X				X							X		D
10	Black Limestone	1	0.4		X				X								X			S
11	Calcareous Shale w/ Limestone Nodules	0.125	0.5				X				X							X		D
12	Shale	0.125	0.5				X				X							X		D
13	Nodules	0.33	0.33			X				X							X			S
14	Shale	0.125	0.5				X				X							X		D
15	Limestone	1	0.4		X				X								X			S
16	Coal	0.75	0.4		X				X									X		S
17	Claystone	0.01	0.01				X				X							X		D
18	Shale	0.125	0.5				X				X							X		D
19	Sandstone	1.5	1		X				X								X			S
20	Silty Shale w/ claystone layer	0.125	0.125				X				X							X		D
21	Shale Talus	0.125	0.125					X				X						X		D

Appendix E:

Sample CRSP Output File (Slope 3)

CRSP Input File -C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Input File Specifications

Units of Measure: U.S.
Total Number of Cells: 20
Analysis Point 1 X-Coordinate: 140.9315
Analysis Point 2 X-Coordinate: 150.9377
Analysis Point 3 X-Coordinate: 158.9414
Initial Y-Top Starting Zone Coordinate: 159.9139
Initial Y-Base Starting Zone Coordinate: 143

Remarks: Slope 3: Cell 3 falling, Dmax = 10 ft., Rt = min, Rn = min

Cell Data

Cell No.	S.R.	Tang. C.	Norm. C.	Begin X	Begin Y	End X	End Y
1	5	0.75	0.15	23.8212	192	27.7258	165.8686
2	0.5	0.5	0.1	27.7258	165.8686	45.7811	159.9139
3	5	0.9	0.6	45.7811	159.9139	45.80	143
4	2	0.5	0.1	45.80	143	54.8489	111.9
5	2	0.65	0.12	54.8489	111.9	64.0861	103.8723
6	1.5	0.75	0.15	64.0861	103.8723	74.4658	86.3
7	1	0.9	0.6	74.4658	86.3	83.8775	60.1
8	1.5	0.5	0.1	83.8775	60.1	108.2967	52.8
9	1	0.9	0.6	108.2967	52.8	109.7013	48.8
10	0.75	0.75	0.15	109.7013	48.8	111.2346	41.8
11	1.5	0.65	0.12	111.2346	41.8	112.9026	38.5
12	5	0.5	0.1	112.9026	38.5	119.5144	22
13	0.5	0.5	0.1	119.5144	22	124.3134	15.4
14	1.5	0.9	0.6	124.3134	15.4	130.3178	6
15	1	0.5	0.1	130.3178	6	136.9297	1
16	1	0.5	0.1	136.9297	1	140.9315	0.2
17	1	0.5	0.1	140.9315	0.2	150.9377	0.3
18	1	0.5	0.1	150.9377	0.3	155.9391	0.9
19	1	0.5	0.1	155.9391	0.9	158.9414	2
20	1	0.5	0.1	158.9414	2	173.5569	2.2

CRSP Simulation Specifications: Used with C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Total Number of Rocks Simulated: 1000
Starting Velocity in X-Direction: 1 ft/sec
Starting Velocity in Y-Direction: -1 ft/sec
Starting Cell Number: 1

Ending Cell Number: 20
Rock Density: 165.4 lb/ft^3
Rock Shape: Spherical
Diameter: 10 ft

CRSP Analysis Point 1 Data - C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Analysis Point 1: X = 140.9315, Y = 0

Total Rocks Passing Analysis Point: 985

Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Bounce Ht. (ft)
50%	23.62	1158570	0.03
75%	30.98	1918131	7.43
90%	37.59	2601309	14.08
95%	41.56	3011463	18.07
98%	46.01	3471789	22.55

Velocity (ft/sec)	Bounce Height (ft)	Kinetic Energy (ft-lb)
Maximum: 62.8	Maximum: 18.34	Maximum: 5561210
Average: 23.62	Average: .34	Average: 1158570
Minimum: 11.69	G. Mean: .03	Std. Dev.: 1124942
Std. Dev.: 10.89	Std. Dev.: 10.95	

Remarks: Slope 3: Cell 3 falling, Dmax = 10 ft., Rt = min, Rn = min

CRSP Analysis Point 2 Data - C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Analysis Point 2: X = 150.9377, Y = 0

Total Rocks Passing Analysis Point: 908

Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Bounce Ht. (ft)
50%	13.56	427158	0.01
75%	17.94	698232	5.26
90%	21.88	942045	9.97
95%	24.25	1088422	12.81

98%	26.9	1252704	15.99

Velocity (ft/sec)	Bounce Height (ft)	Kinetic Energy (ft-lb)
Maximum: 29.04	Maximum: .51	Maximum: 1589325
Average: 13.56	Average: .04	Average: 427158
Minimum: 3.02	G. Mean: .01	Std. Dev.: 401471
Std. Dev.: 6.49	Std. Dev.: 7.77	

Remarks: Slope 3: Cell 3 falling, Dmax = 10 ft., Rt = min, Rn = min

CRSP Analysis Point 3 Data - C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Analysis Point 3: X = 158.9414, Y = 2

Total Rocks Passing Analysis Point: 263

Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Bounce Ht. (ft)
50%	12.04	328381	0.02
75%	14.97	458488	5.66
90%	17.6	575512	10.72
95%	19.18	645769	13.77
98%	20.95	724620	17.18

Velocity (ft/sec)	Bounce Height (ft)	Kinetic Energy (ft-lb)
Maximum: 19.18	Maximum: .38	Maximum: 722894
Average: 12.04	Average: .07	Average: 328381
Minimum: 2.29	G. Mean: .02	Std. Dev.: 192695
Std. Dev.: 4.33	Std. Dev.: 8.35	

Remarks: Slope 3: Cell 3 falling, Dmax = 10 ft., Rt = min, Rn = min

CRSP Data Collected at End of Each Cell - C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

Velocity Units: ft/sec   Bounce Height Units: ft

Cell #	Max. Vel.	Avg. Vel.	S.D. Vel.	Max. Bounce Ht.	Avg. Bounce Ht.
1	No rocks	past end of cell			
2	No rocks	past end of cell			
3	2	2	.14	22	13
4	47	38	5	11	4
5	34	27	2.62	2	0
6	46	39	3.79	11	4
7	61	52	4.83	26	11
8	27	16	3.44	1	0
9	27	18	2.98	4	3
10	31	20	2.49	11	9
11	37	22	2.18	14	11
12	45	33	3.47	26	17
13	51	40	5.5	27	13
14	58	47	6.33	29	8
15	62	36	14.17	25	2
16	63	24	10.89	18	0
17	29	14	6.49	1	0
18	24	14	6.83	0	0
19	19	12	4.33	0	0
20	14	8	2.24	0	-1

CRSP Rocks Stopped Data - C:\Documents and Settings\Maria C\My Documents\PITT PhD\Rock fall Penndot Project\SLOPES INFORMATION\CRSP input data\Slope 3\2-Slope 3 Cell 3 falling Dmax 10ft. Rt min Rn min\CRSP Input 3-2.dat

X Interval	Rocks Stopped
0 To 10 ft	1
10 To 20 ft	0
20 To 30 ft	0
30 To 40 ft	0
40 To 50 ft	0
50 To 60 ft	0
60 To 70 ft	0
70 To 80 ft	0
80 To 90 ft	0
90 To 100 ft	0
100 To 110 ft	14
110 To 120 ft	0
120 To 130 ft	0
130 To 140 ft	0
140 To 150 ft	48
150 To 160 ft	699
160 To 170 ft	117

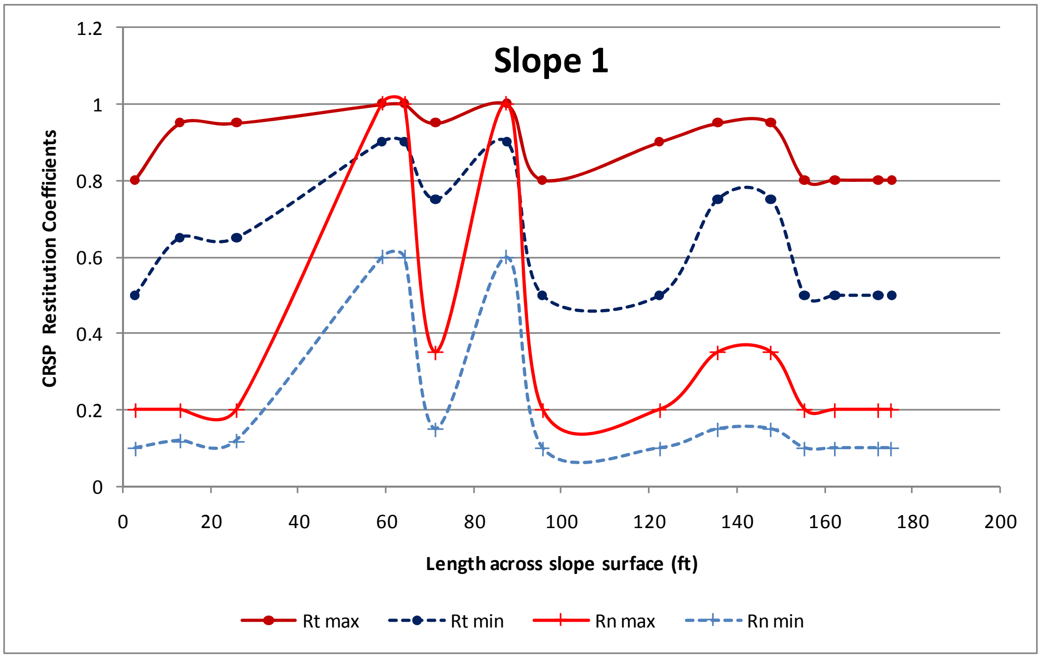
Appendix F:

Site-Specific Compilation of Results and Photographs

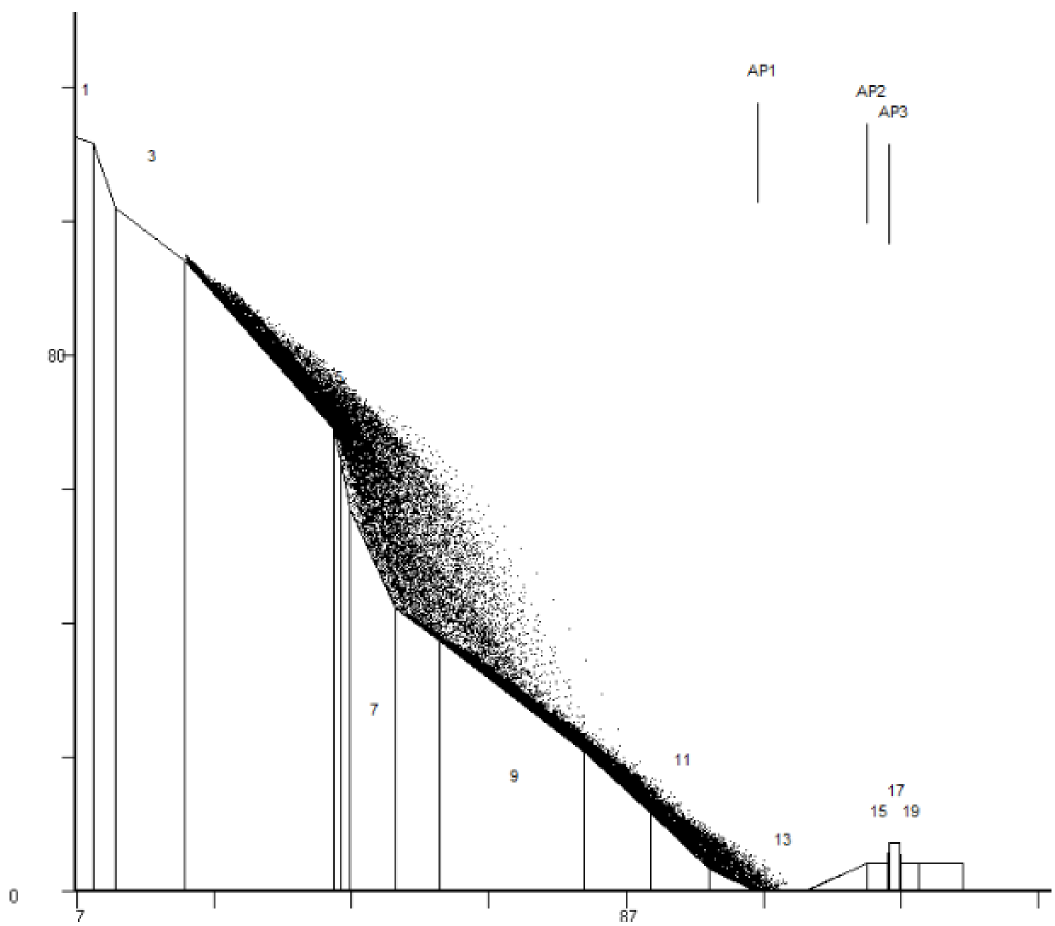
APPENDIX F-1

SLOPE 1 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 1: S.R. 0079 Northbound, Segment 520, Allegheny Co.



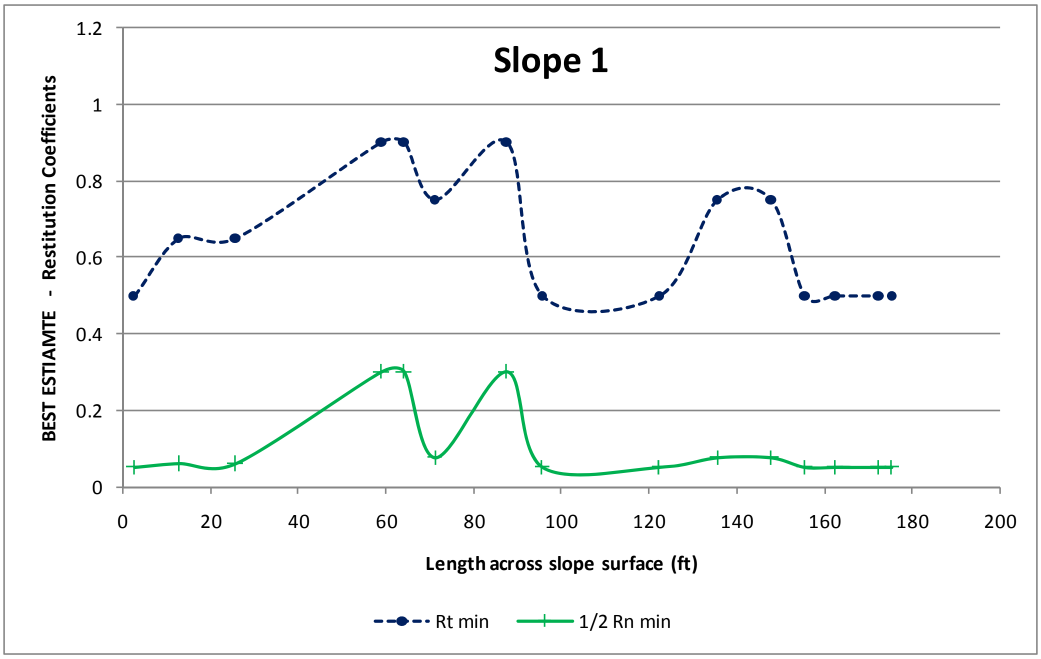
Tangential and Normal restitution coefficients **recommended by CRSP authors**



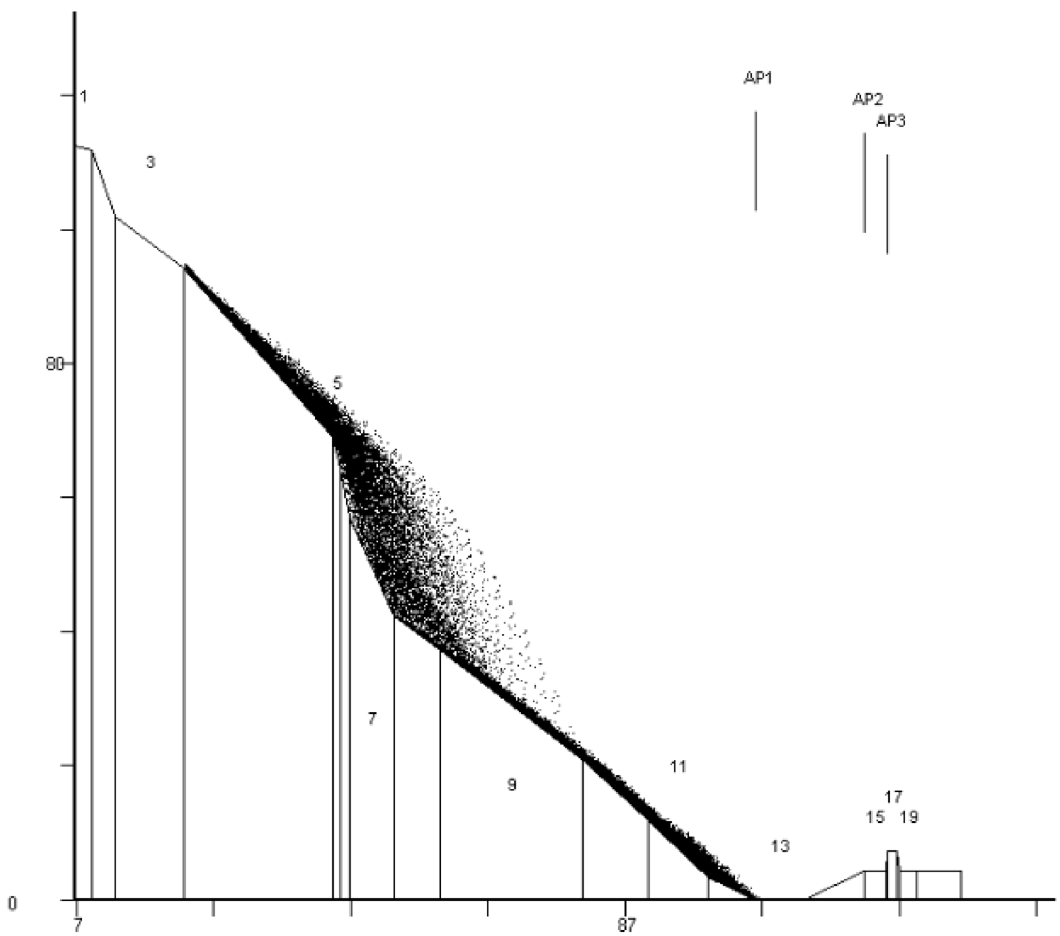
Sample of CRSP results

Rocks falling from layer # 4, Limestone D_{max} = 2ft, with ***Rt min*** *and* ***Rn min****.*

SLOPE # 1: S.R. 0079 Northbound, Segment 520, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 4, Limestone D_{max} = 2ft, with ***Rt min** and **½ Rn min**.*

SLOPE # 1: S.R. 0079 Northbound, Segment 520, Allegheny Co.

Good performance of rock-fall mitigation design: All rocks from slope within the ditch

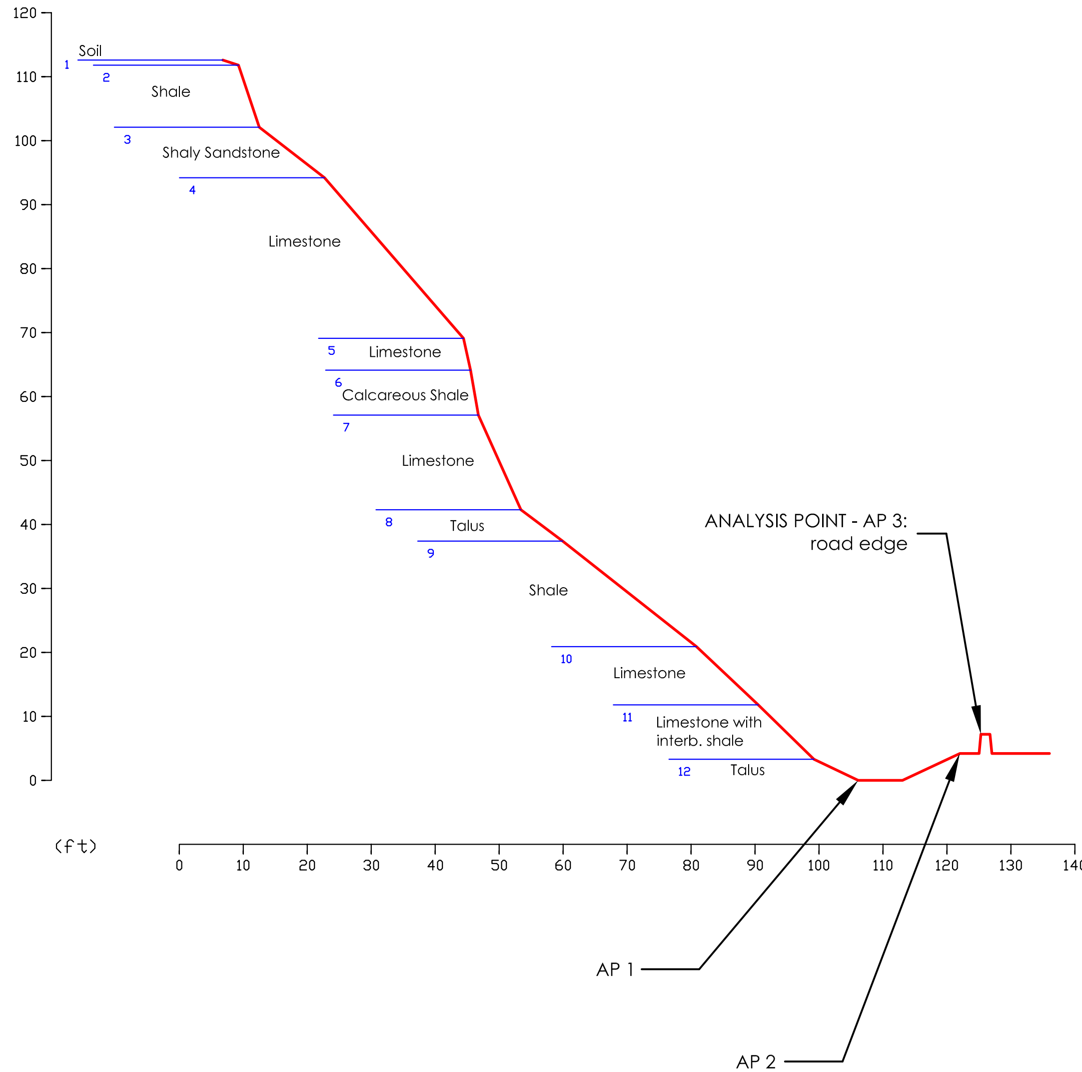
SLOPE # 1: S.R. 0079 Northbound, Segment 520, Allegheny Co.

Height = 112.6 ft. Avg. Slope angle = 45°

SUMMARY OF CRSP RESULTS - SLOPE 1 (Phase 2 w/barrier)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)				Sphere Diam.$_{MAX}$ (ft)
		Rt min Rn min	1/2 Rt min	1/2 Rn min	1/2 Rt min 1/2 Rn min	
2	% Rocks Passing AP1*	58.6%	50.4%	28.6%	32.9%	disk D=0.5 T=0.167'
	Max Bounce height (ft)	8.35	5.09	1.21	2.06	
	Max K.Energy (ft-lb)	180	151	52	94	
	Max Vel. (ft/sec)	42.73	38.88	21.23	29.97	
3	% Rocks Passing AP1	25.5%	18.6%	15.5%	12.5%	disk D=1.5 T=0.167'
	Max Bounce height (ft)	7.38	3.58	0.36	1.12	
	Max K.Energy (ft-lb)	1,592	1,727	593	705	
	Max Vel. (ft/sec)	39.75	44.42	25.60	27.07	
4	% Rocks Passing AP1	99.9%	99.9%	96.5%	99.2%	2
	Max Bounce height (ft)	5.17	4.52	1.01	1.44	
	Max K.Energy (ft-lb)	31,642	25,598	10,349	13,533	
	Max Vel. (ft/sec)	49.92	45.31	28.42	32.69	
5	% Rocks Passing AP1	99.9%	99.9%	96.2%	98.6%	2
	Max Bounce height (ft)	5.25	4.29	1.00	1.33	
	Max K.Energy (ft-lb)	25,398	20,304	12,409	13,796	
	Max Vel. (ft/sec)	45.10	40.42	31.36	33.32	
6	% Rocks Passing AP1	81.6%	77.5%	37.0%	51.8%	disk D=0.5' T=0.167'
	Max Bounce height (ft)	3.91	3.30	0.81	1.54	
	Max K.Energy (ft-lb)	141	116	41	69	
	Max Vel. (ft/sec)	37.19	34.49	19.50	26.38	
7	% Rocks Passing AP1	95.9%	94.3%	87.9%	83.3%	2
	Max Bounce height (ft)	4.41	3.43	0.83	0.75	
	Max K.Energy (ft-lb)	21,235	18,004	10,804	9,562	
	Max Vel. (ft/sec)	40.39	38.06	29.60	27.72	
8	% Rocks Passing AP1	5.0%	1.3%	0.2%	0.1%	0.5
	Max Bounce height (ft)	1.48	0.81	0.49	0.45	
	Max K.Energy (ft-lb)	185	73	24	32	
	Max Vel. (ft/sec)	31.22	18.14	10.72	11.64	
9	% Rocks Passing AP1	1.0%	0.8%	0.3%	0.3%	disk D=0.3' T=0.167'
	Max Bounce height (ft)	0.95	0.64	0.11	0.11	
	Max K.Energy (ft-lb)	8	10	1	7	
	Max Vel. (ft/sec)	13.99	15.64	6.92	13.00	
10	% Rocks Passing AP1	85.0%	76.5%	71.3%	50.8%	1
	Max Bounce height (ft)	0.85	0.62	0.31	0.36	
	Max K.Energy (ft-lb)	818	670	495	429	
	Max Vel. (ft/sec)	21.90	20.17	16.90	15.84	
11	% Rocks Passing AP1	48.3%	33.5%	36.4%	14.6%	1
	Max Bounce height (ft)	0.43	0.31	0.23	0.19	
	Max K.Energy (ft-lb)	402	312	340	236	
	Max Vel. (ft/sec)	15.34	13.60	14.19	12.04	

*** No rocks from any layer passed AP2 nor AP3**



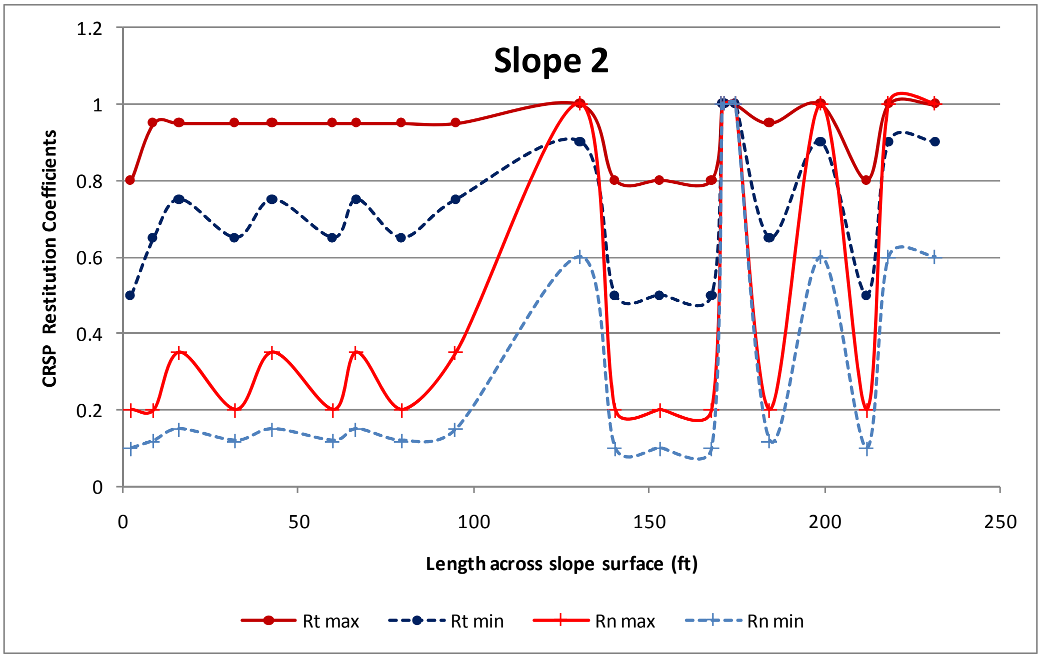
SLOPE # 1: S.R. 0079 Northbound, Segment 520, Allegheny Co.

Scale 1 : 30

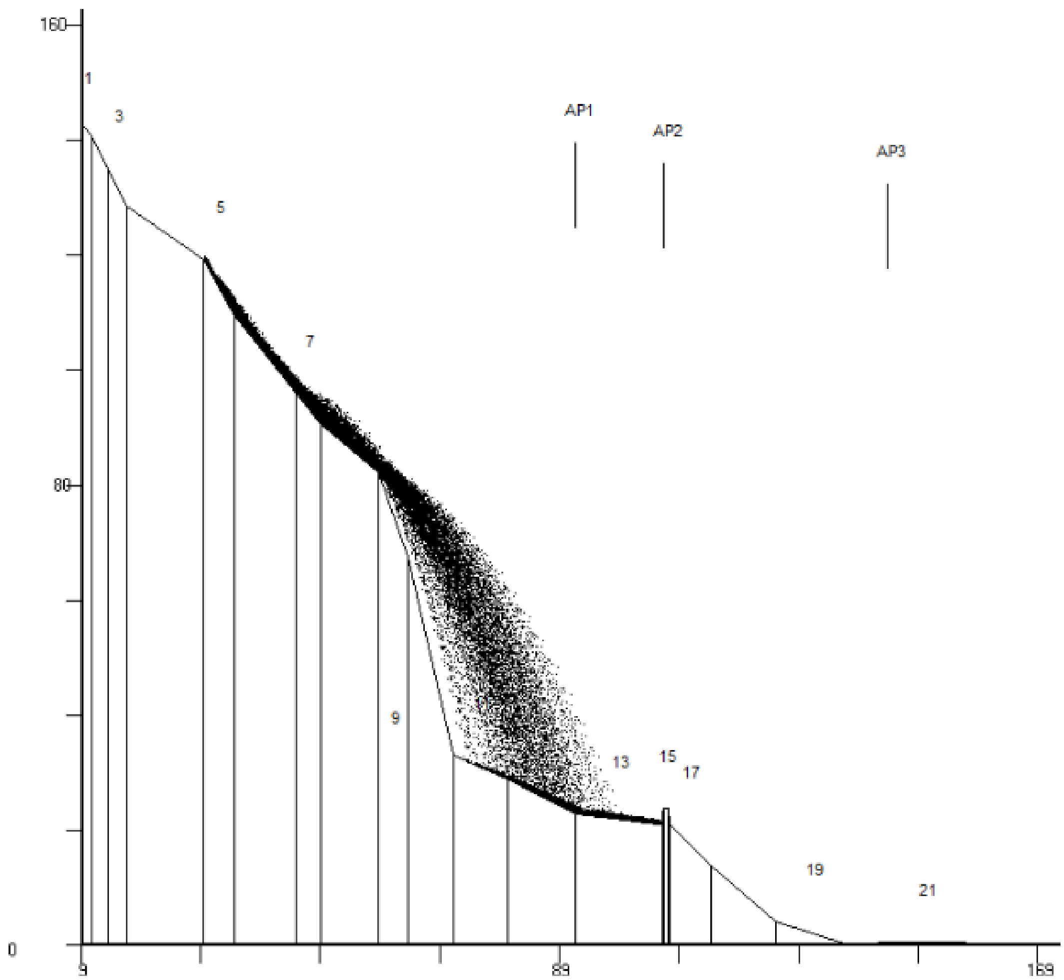
APPENDIX F-2

SLOPE 2 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 2: S.R. 3048 Eastbound, Segment 190, Allegheny Co.



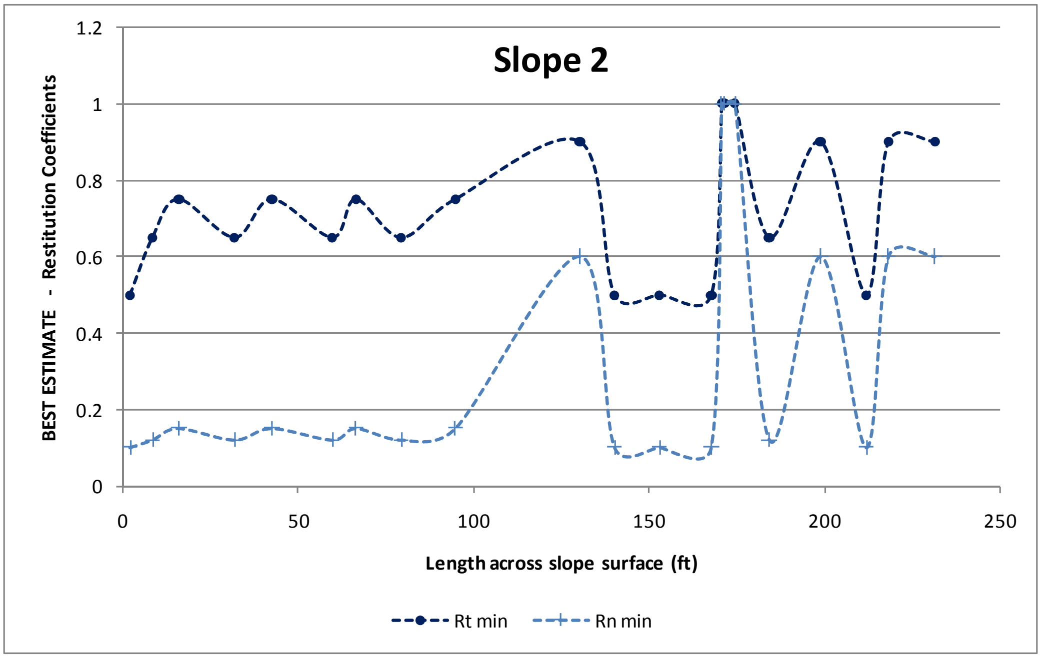
Tangential and Normal restitution coefficients **recommended by CRSP authors**



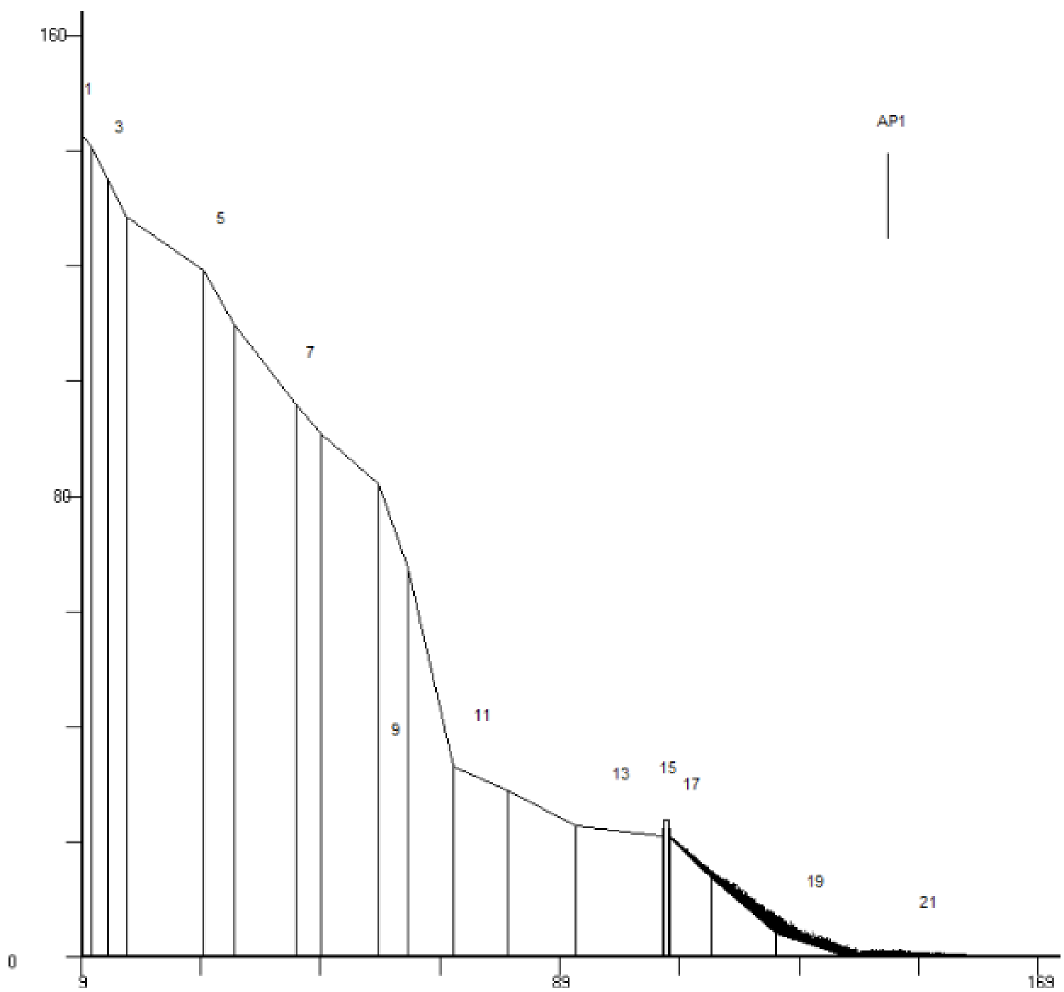
Sample of CRSP results

Rocks falling from layer # 5, Claystone with Sandstone interb., D_{max} = 2ft, with ***Rt min*** *and* ***Rn min.***

SLOPE # 2: S.R. 3048 Eastbound, Segment 190, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 14 (17 in figure), Shale D_{max} = 0.5 ft, with ***Rt min*** *and* ***Rn min****.*

SLOPE # 2: S.R. 3048 Eastbound, Segment 190, Allegheny Co.

Bench at 20-ft slope height: lower layers of shale experience undercutting due to coal mine collapse

Slope toe

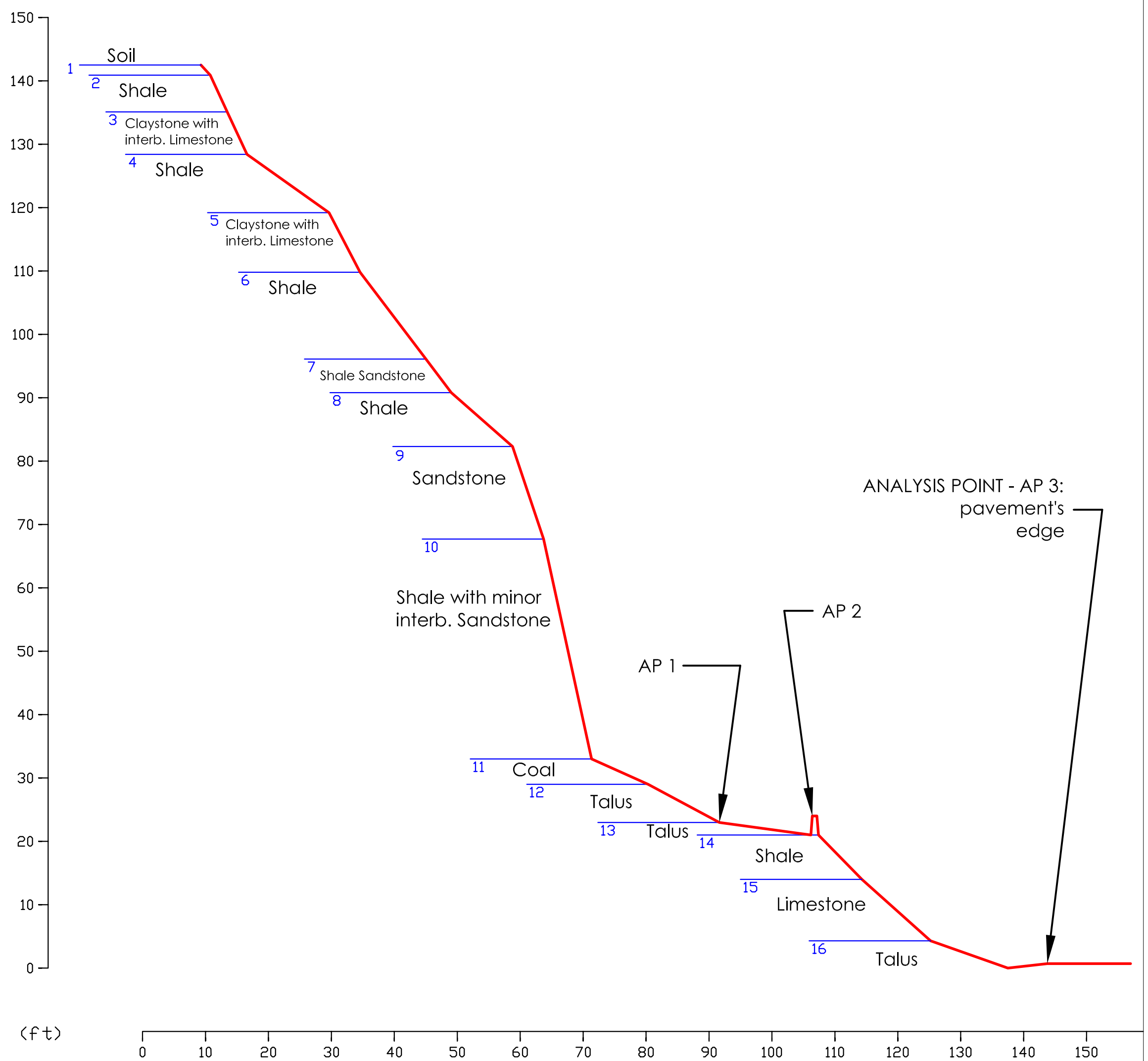
SLOPE # 2: S.R. 3048 Eastbound, Segment 190, Allegheny Co.

Height = 142.5 ft. Avg. Slope angle = 55° Bench height = 21 ft.

SUMMARY OF CRSP RESULTS - SLOPE 2 (Phase 2 w/barrier)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)				Sphere Diam.$_{MAX}$ (ft)
		Rt min Rn min	1/2 Rt min	1/2 Rn min	1/2 Rt min 1/2 Rn min	
2	% Rocks Passing AP1*	91.5%	91.9%	99.9%	70.7%	disk D=1 T=0.167'
	Max Bounce height (ft)	26.76	18.66	4.03	2.10	
	Max K.Energy (ft-lb)	1,811	1,656	49,174	309	
	Max Vel. (ft/sec)	70.34	68.44	66.06	26.48	
3	% Rocks Passing AP1	99.9%	99.7%	99.0%	97.7%	2
	Max Bounce height (ft)	26.81	20.94	0.93	5.08	
	Max K.Energy (ft-lb)	58,777	54,458	7,815	49,658	
	Max Vel. (ft/sec)	71.50	69.28	24.16	66.65	
4	% Rocks Passing AP1	2.1%	1.5%	0.2%	0.3%	disk D=.5 T=0.167'
	Max Bounce height (ft)	8.75	2.45	1.26	0.77	
	Max K.Energy (ft-lb)	366	78	14	12	
	Max Vel. (ft/sec)	64.25	25.73	10.73	11.02	
5	% Rocks Passing AP1	99.9%	99.9%	99.9%	99.9%	2
	Max Bounce height (ft)	19.13	13.98	0.91	1.39	
	Max K.Energy (ft-lb)	54,102	51,717	7,130	9,717	
	Max Vel. (ft/sec)	69.38	67.90	22.73	26.71	
6	% Rocks Passing AP1	51.7%	50.6%	20.8%	30.6%	disk D=0.8 T=0.267'
	Max Bounce height (ft)	3.36	3.67	1.14	1.64	
	Max K.Energy (ft-lb)	1,515	446	233	291	
	Max Vel. (ft/sec)	64.80	31.49	23.11	26.51	
7	% Rocks Passing AP1	97.4%	95.5%	90.9%	86.5%	2
	Max Bounce height (ft)	1.40	1.32	0.80	0.85	
	Max K.Energy (ft-lb)	7,718	7,853	5,440	5,807	
	Max Vel. (ft/sec)	24.23	24.50	19.19	20.05	
8	% Rocks Passing AP1	11.4%	7.9%	2.0%	2.1%	disk D=0.5 T=0.167'
	Max Bounce height (ft)	2.27	3.62	0.52	1.36	
	Max K.Energy (ft-lb)	99	88	55	47	
	Max Vel. (ft/sec)	30.74	27.35	21.76	21.03	
9	% Rocks Passing AP1	99.7%	97.9%	98.3%	95.9%	3
	Max Bounce height (ft)	1.46	1.33	0.68	67.00	
	Max K.Energy (ft-lb)	55,153	48,335	28,086	28,272	
	Max Vel. (ft/sec)	35.00	32.93	24.31	24.63	
10a	% Rocks Passing AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	a.disk D=15' T=6'
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
10b	% Rocks Passing AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	b.cylinder D=10' L=15'
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
14	% Rocks Passing AP3**	43.5%	33.7%	7.5%	5.6%	0.5
	Max Bounce height (ft)	0.73	0.29	0.21	0.03	
	Max K.Energy (ft-lb)	73	55	44	26	
	Max Vel. (ft/sec)	17.61	15.45	13.83	10.57	
15	% Rocks Passing AP3**	56.5%	43.3%	25.0%	9.2%	1.5
	Max Bounce height (ft)	0.22	0.23	0.05	0.02	
	Max K.Energy (ft-lb)	1,583	1,136	683	422	
	Max Vel. (ft/sec)	15.77	13.27	10.31	8.15	

* No rocks from layers 2 thru 10 passed AP2 nor AP3
** Only rocks from layer 14 and 15 passed AP3



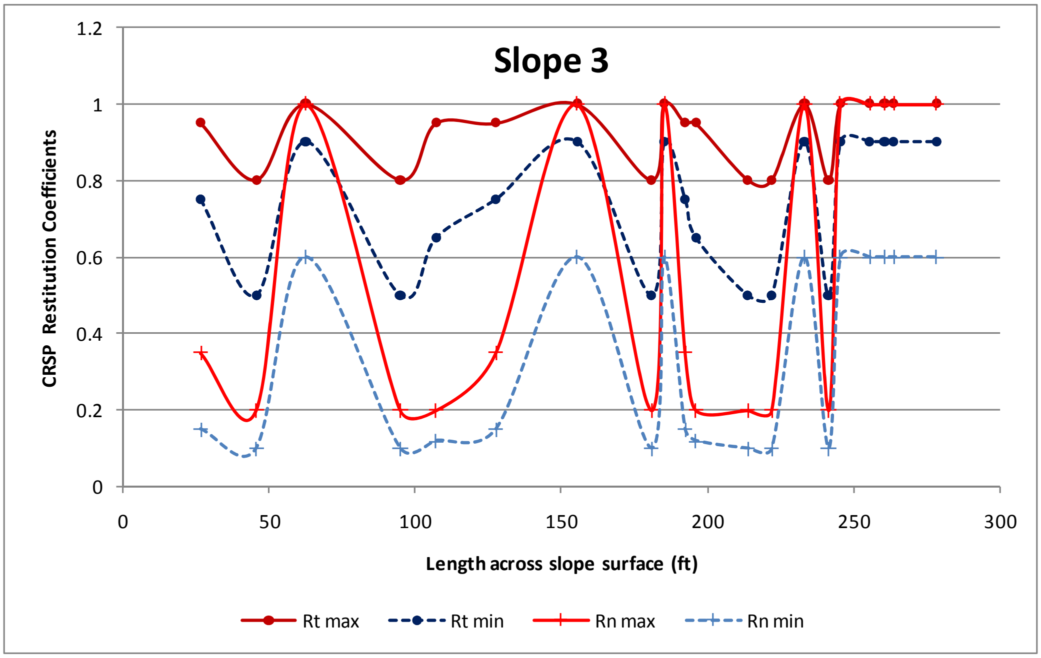
SLOPE # 2: S.R. 3048 NorthEastbound Segment 190, Allegheny Co.

Scale 1 : 30

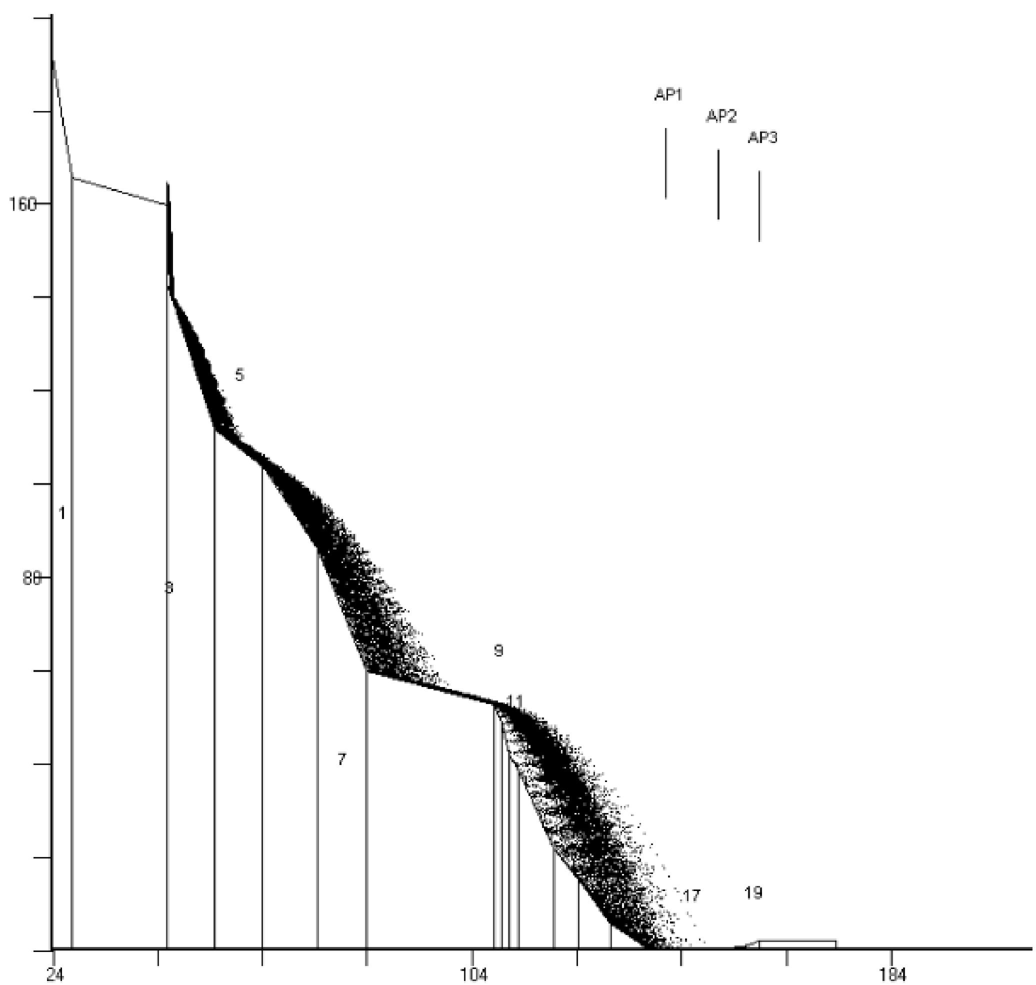
APPENDIX F-3

SLOPE 3 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 3: S.R. 0028 Southbound, Segment 251, Allegheny Co.



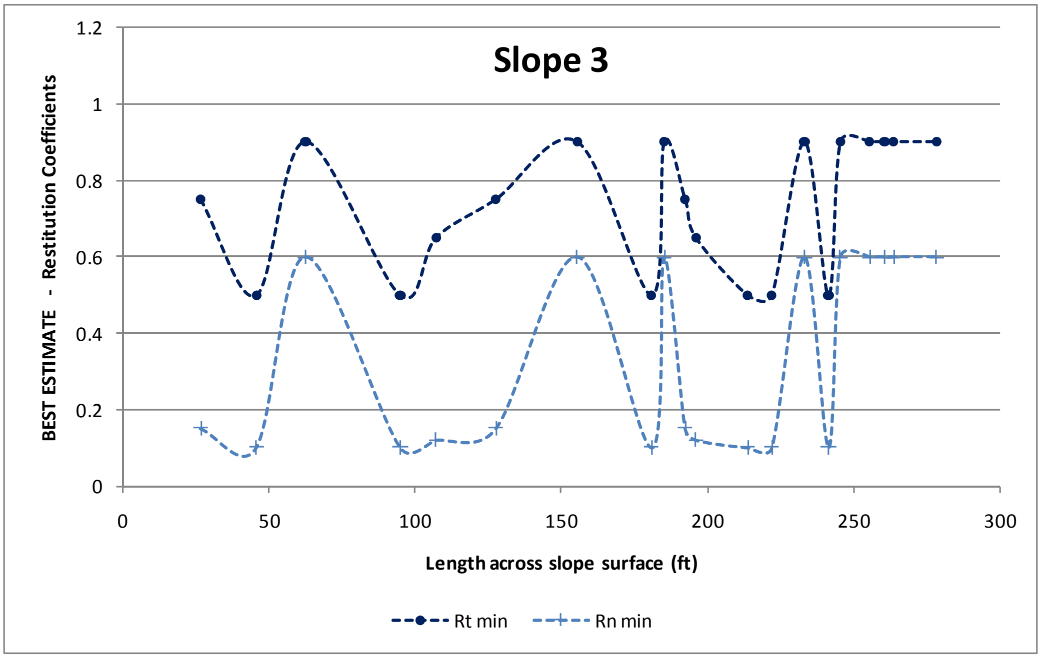
Tangential and Normal restitution coefficients **recommended by CRSP authors**



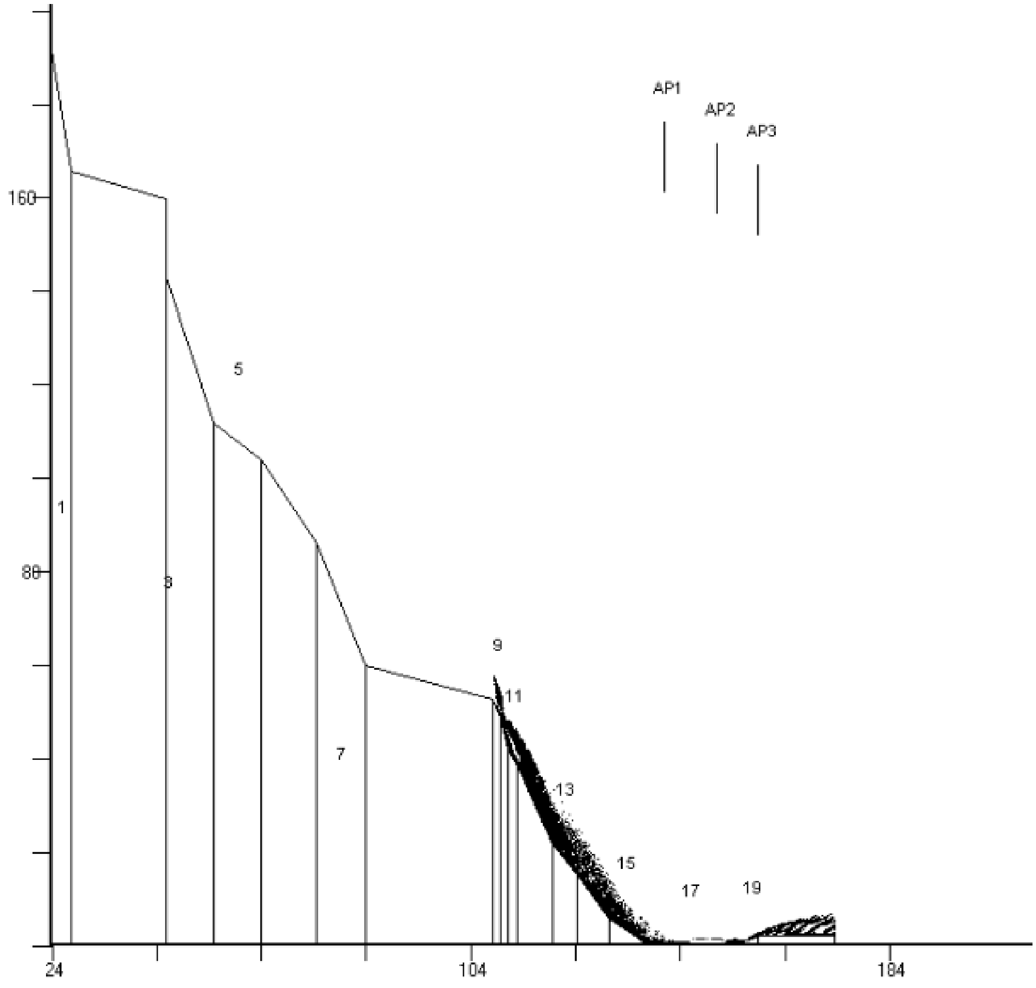
Sample of CRSP results

Rocks falling from layer # 3, Massive Sandstone D_{max} = 10 ft, with ***Rt min*** *and* ***Rn min****.*

SLOPE # 3: S.R. 0028 Southbound, Segment 251, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 9, Massive Sandstone D_{max} = 10 ft, with ***Rt min*** *and* ***Rn min.***

SLOPE # 3: S.R. 0028 Southbound, Segment 251, Allegheny Co.

3 Lanes of S.R. 28 were closed after large pieces of rock reached the road and affected the traffic.

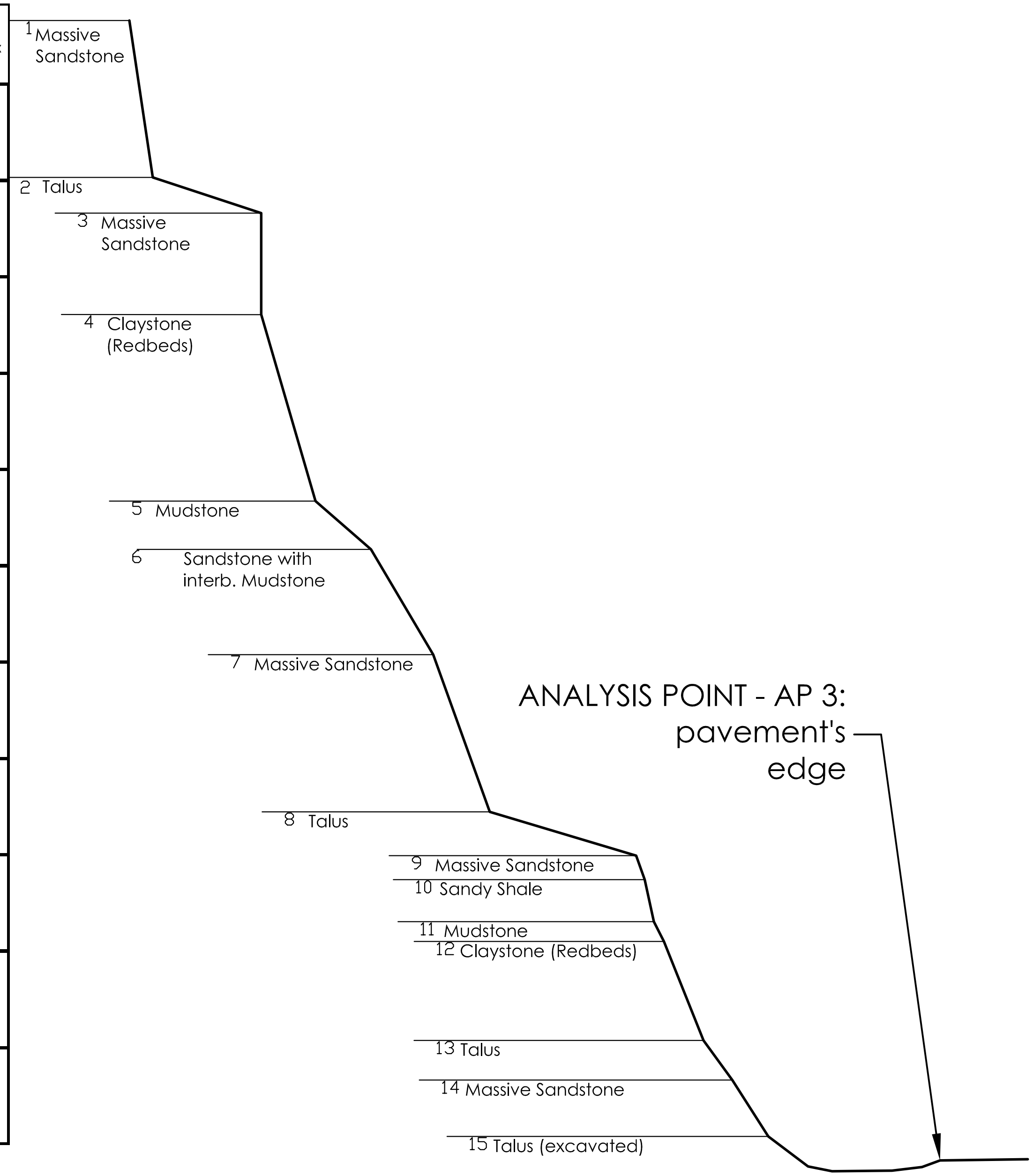
Fallen rocks were removed from pavement. It is assumed they reached further than AP3.

SLOPE # 3: S.R. 0028 Southbound, Segment 251, Allegheny Co.

Height = 192 ft Avg. Slope angle = 57°

SUMMARY OF CRSP RESULTS - SLOPE 3

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)					Sphere Diam.$_{MAX}$ (ft)
		min	mid1	mid	mid2	max	
1	**% Rocks Passing AP3**	**0.0%**	**0.1%**	**1.1%**	**10.3%**	**34.7%**	10
	Max Bounce height (ft)	0.00	0.48	6.58	14.63	23.59	
	Max K.Energy (ft-lb)	0	744,455	6,766,235	7,107,504	7,974,044	
	Max Vel. (ft/sec)	0.00	19.52	66.99	69.27	72.40	
3	**% Rocks Passing AP3**	**99.2%**	**99.6%**	**99.7%**	**99.6%**	**94.7%**	10
	Max Bounce height (ft)	0.81	1.04	1.47	9.95	4.40	
	Max K.Energy (ft-lb)	2,423,850	2,731,303	3,228,281	7,067,841	7,587,547	
	Max Vel. (ft/sec)	36.11	38.37	41.26	61.83	64.94	
4	**% Rocks Passing AP3**	**7.2%**	**9.1%**	**12.3%**	**14.8%**	**4.2%**	0.5
	Max Bounce height (ft)	0.77	1.20	3.47	20.63	15.06	
	Max K.Energy (ft-lb)	257	308	742	869	962	
	Max Vel. (ft/sec)	32.96	36.47	63.83	68.58	71.49	
6	**% Rocks Passing AP3**	**14.0%**	**20.4%**	**25.1%**	**31.3%**	**12.6%**	2
	Max Bounce height (ft)	0.86	0.99	1.53	7.71	14.20	
	Max K.Energy (ft-lb)	17,666	21,254	25,961	50,107	51,076	
	Max Vel. (ft/sec)	34.42	37.82	41.91	65.53	65.69	
7	**% Rocks Passing AP3**	**4.4%**	**6.8%**	**7.8%**	**11.7%**	**9.7%**	3
	Max Bounce height (ft)	0.82	1.11	1.51	2.41	9.21	
	Max K.Energy (ft-lb)	59,573	64,500	72,653	93,422	83,728	
	Max Vel. (ft/sec)	34.44	35.97	38.27	42.84	40.71	
9	**% Rocks Passing AP3**	**99.8%**	**99.9%**	**99.9%**	**99.9%**	**99.9%**	10
	Max Bounce height (ft)	0.85	0.97	1.21	1.37	5.22	
	Max K.Energy (ft-lb)	2,044,190	2,400,624	3,088,339	3,477,032	3,594,571	
	Max Vel. (ft/sec)	33.04	36.03	40.35	43.01	43.84	
10	**% Rocks Passing AP3**	**72.1%**	**91.4%**	**98.9%**	**99.9%**	**99.9%**	cylinder D=7' L=20'
	Max Bounce height (ft)	0.70	1.02	1.22	1.22	2.83	
	Max K.Energy (ft-lb)	3,118,181	3,293,039	4,399,983	4,828,219	5,083,605	
	Max Vel. (ft/sec)	34.18	34.96	40.25	42.20	43.90	
11	**% Rocks Passing AP3**	**99.9%**	**99.9%**	**99.9%**	**99.9%**	**35.5%**	6
	Max Bounce height (ft)	0.89	1.22	1.39	1.45	8.01	
	Max K.Energy (ft-lb)	323,653	396,416	484,648	553,421	16,672	
	Max Vel. (ft/sec)	28.00	31.47	34.30	36.75	33.88	
12	**% Rocks Passing AP3**	**99.5%**	**99.8%**	**99.9%**	**99.9%**	**96.6%**	6
	Max Bounce height (ft)	0.74	1.23	1.72	2.31	6.30	
	Max K.Energy (ft-lb)	306,740	365,055	406,179	473,040	466,776	
	Max Vel. (ft/sec)	27.63	30.17	31.43	33.92	33.87	
13	**% Rocks Passing AP3**	**86.6%**	**95.8%**	**99.3%**	**99.7%**	**21.8%**	2.5
	Max Bounce height (ft)	0.67	0.84	1.69	2.37	6.07	
	Max K.Energy (ft-lb)	12,446	13,872	17,282	17,514	17,591	
	Max Vel. (ft/sec)	20.11	21.43	24.49	24.63	24.23	
14	**% Rocks Passing AP3**	**23.7%**	**4.6%**	**54.8%**	**64.3%**	**0.6%**	1.5
	Max Bounce height (ft)	0.33	0.69	0.95	2.19	3.40	
	Max K.Energy (ft-lb)	1,597	1,512	2,304	3,007	1,184	
	Max Vel. (ft/sec)	15.29	14.82	18.87	21.67	13.42	

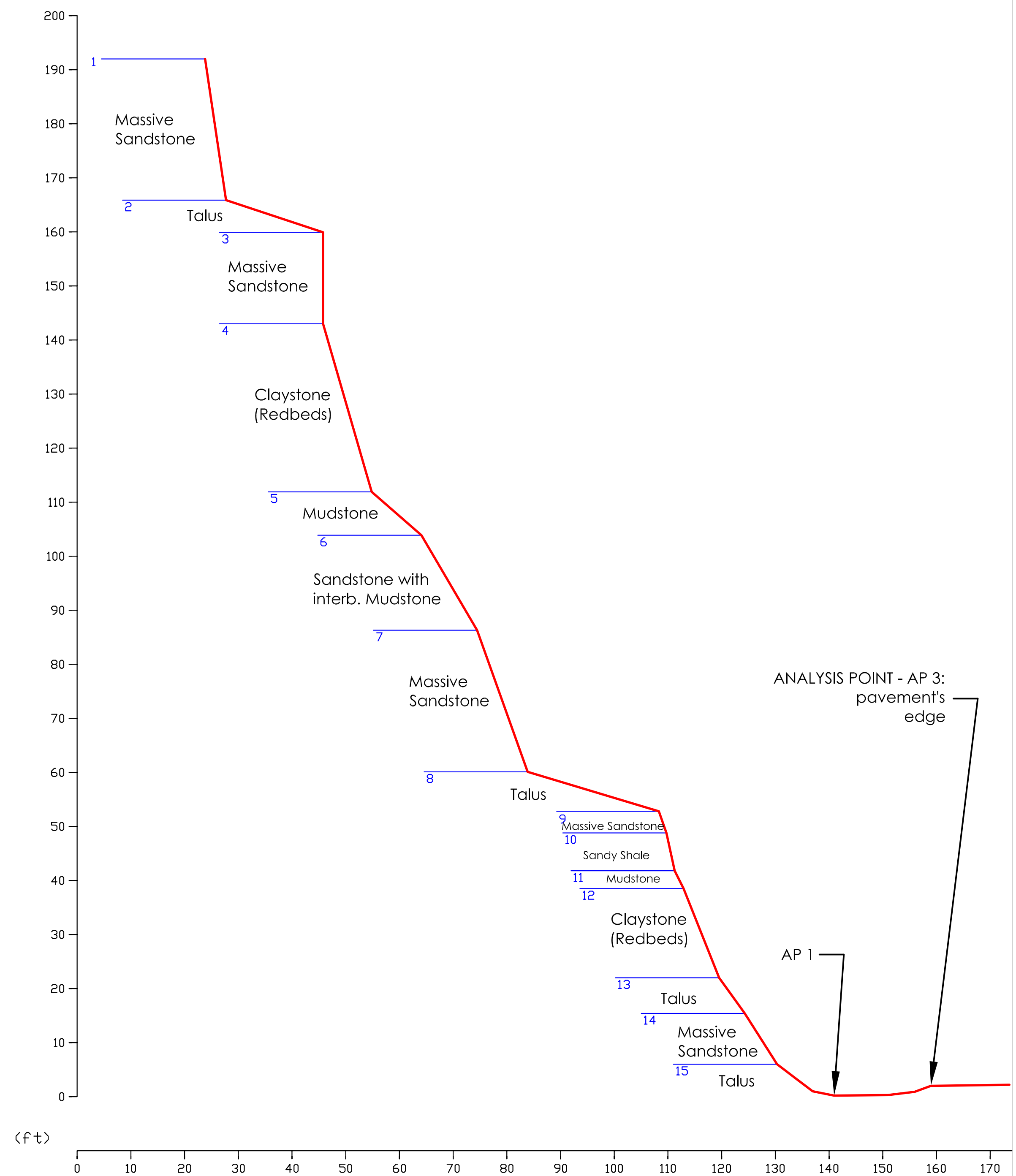


SLOPE # 3, S.R. 0028 Southbound, Segment 251, Allegheny Co.

Scale 1 : 30

SUMMARY OF CRSP RESULTS - SLOPE 3 (Phase 2)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn): Rt min Rn min	1/2 Rt min Rn min	Rt min 1/2 Rn min	1/2 Rt min 1/2 Rn min	Sphere Diam.$_{MAX}$ (ft)
1	% Rocks Passing AP3	0.0%	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	10
	Max Bounce height (ft)	0.00				
	Max K.Energy (ft-lb)	0				
	Max Vel. (ft/sec)	0.00				
3	% Rocks Passing AP3	99.2%	94.6%	39.7%	No rocks passed AP1	10
	Max Bounce height (ft)	0.81	0.70	0.27		
	Max K.Energy (ft-lb)	2,423,850	1,129,134	1,303,130		
	Max Vel. (ft/sec)	36.11	24.37	25.98		
4	% Rocks Passing AP3	7.2%	5.3%	0.1%	No rocks passed AP1	0.5
	Max Bounce height (ft)	0.77	0.86	0.07		
	Max K.Energy (ft-lb)	257	127	35		
	Max Vel. (ft/sec)	32.96	22.94	11.95		
6	% Rocks Passing AP3	14.0%	8.2%	0.9%	0.1%	2
	Max Bounce height (ft)	0.86	0.83	0.09	0.00	
	Max K.Energy (ft-lb)	17,666	9,281	4,833	296	
	Max Vel. (ft/sec)	34.42	24.52	17.45	4.31	
7	% Rocks Passing AP3	4.4%	4.8%	0.1%	No rocks passed AP1	3
	Max Bounce height (ft)	0.82	0.87	0.02		
	Max K.Energy (ft-lb)	59,573	28,554	5,031		
	Max Vel. (ft/sec)	34.44	23.34	9.96		
9	% Rocks Passing AP3	99.8%	98.7%	90.3%	No rocks passed AP1	10
	Max Bounce height (ft)	0.85	0.71	0.21		
	Max K.Energy (ft-lb)	2,044,190	1,042,009	1,141,207		
	Max Vel. (ft/sec)	33.04	23.18	24.25		
10	% Rocks Passing AP3	72.1%	57.9%	31.2%	No rocks passed AP1	cylinder D=7' L=20'
	Max Bounce height (ft)	0.70	0.69	0.19		
	Max K.Energy (ft-lb)	3,118,181	1,455,758	1,217,507		
	Max Vel. (ft/sec)	34.18	23.37	20.85		
11	% Rocks Passing AP3	99.9%	98.0%	91.8%	No rocks passed AP1	6
	Max Bounce height (ft)	0.89	0.71	0.16		
	Max K.Energy (ft-lb)	323,653	186,567	176,961		
	Max Vel. (ft/sec)	28.00	21.03	20.44		
12	% Rocks Passing AP3	99.5%	89.1%	72.0%	No rocks passed AP1	6
	Max Bounce height (ft)	0.74	0.64	0.11		
	Max K.Energy (ft-lb)	306,740	150,008	139,742		
	Max Vel. (ft/sec)	27.63	18.65	18.02		
13	% Rocks Passing AP3	86.6%	36.3%	9.6%	No rocks passed AP1	2.5
	Max Bounce height (ft)	0.67	0.44	0.06		
	Max K.Energy (ft-lb)	12,446	5,482	3,942		
	Max Vel. (ft/sec)	20.11	13.04	11.26		
14	% Rocks Passing AP3	23.7%	0.7%	No rocks passed AP1	No rocks passed AP1	1.5
	Max Bounce height (ft)	0.33	0.04			
	Max K.Energy (ft-lb)	1,597	221			
	Max Vel. (ft/sec)	15.29	5.66			



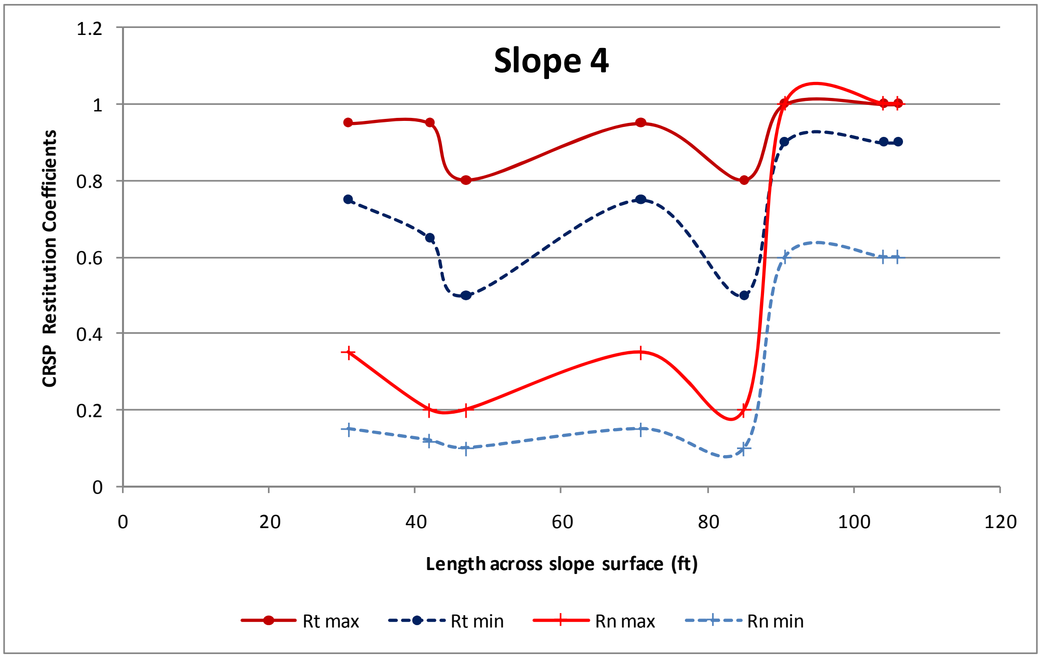
SLOPE # 3: S.R. 0028 Southbound, Segment 251, Allegheny Co.

Scale 1 : 30

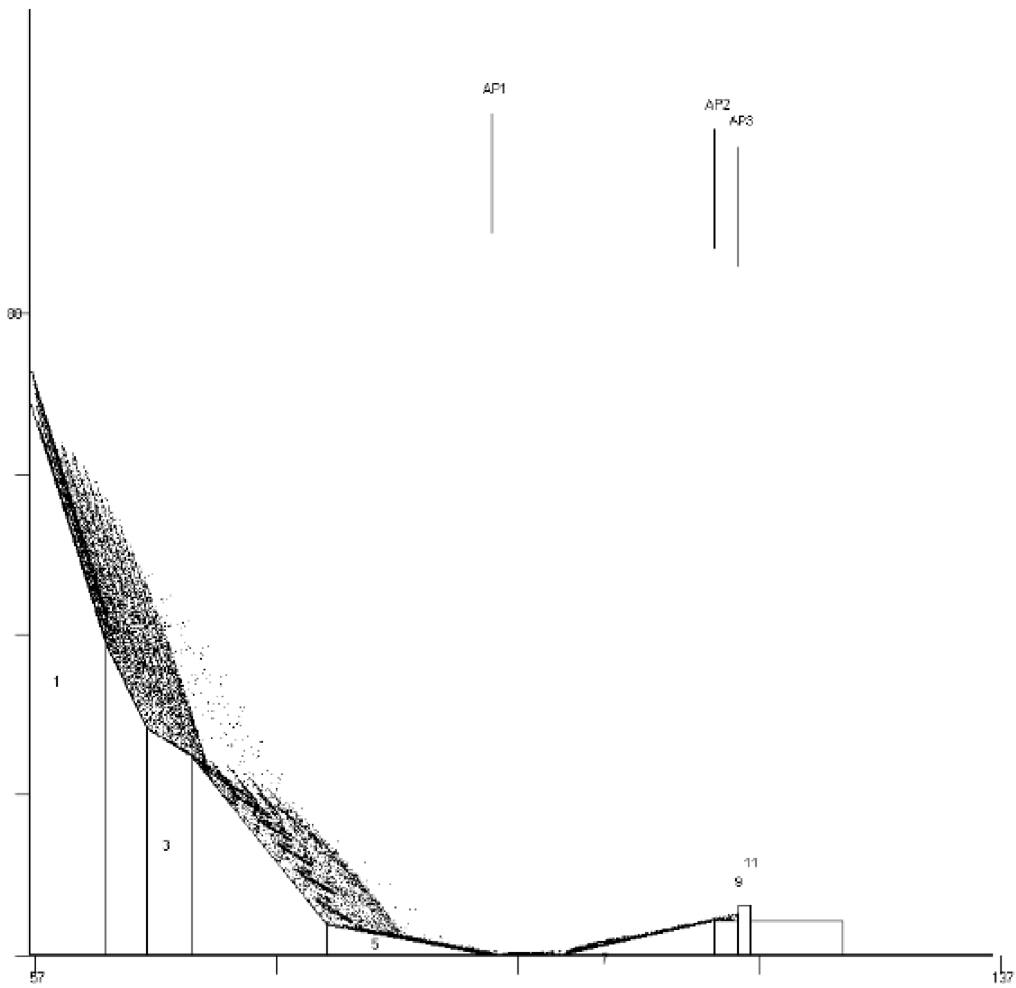
APPENDIX F-4

SLOPE 4 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 4: S.R. 0279 Northbound Segment 170, Allegheny Co.



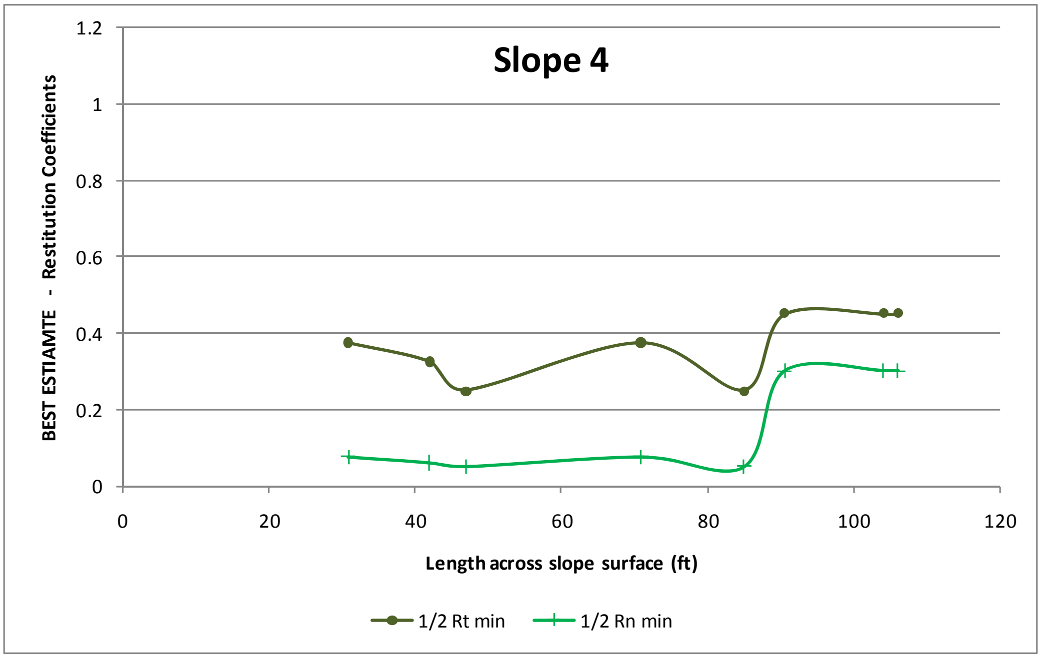
Tangential and Normal restitution coefficients **recommended by CRSP authors**



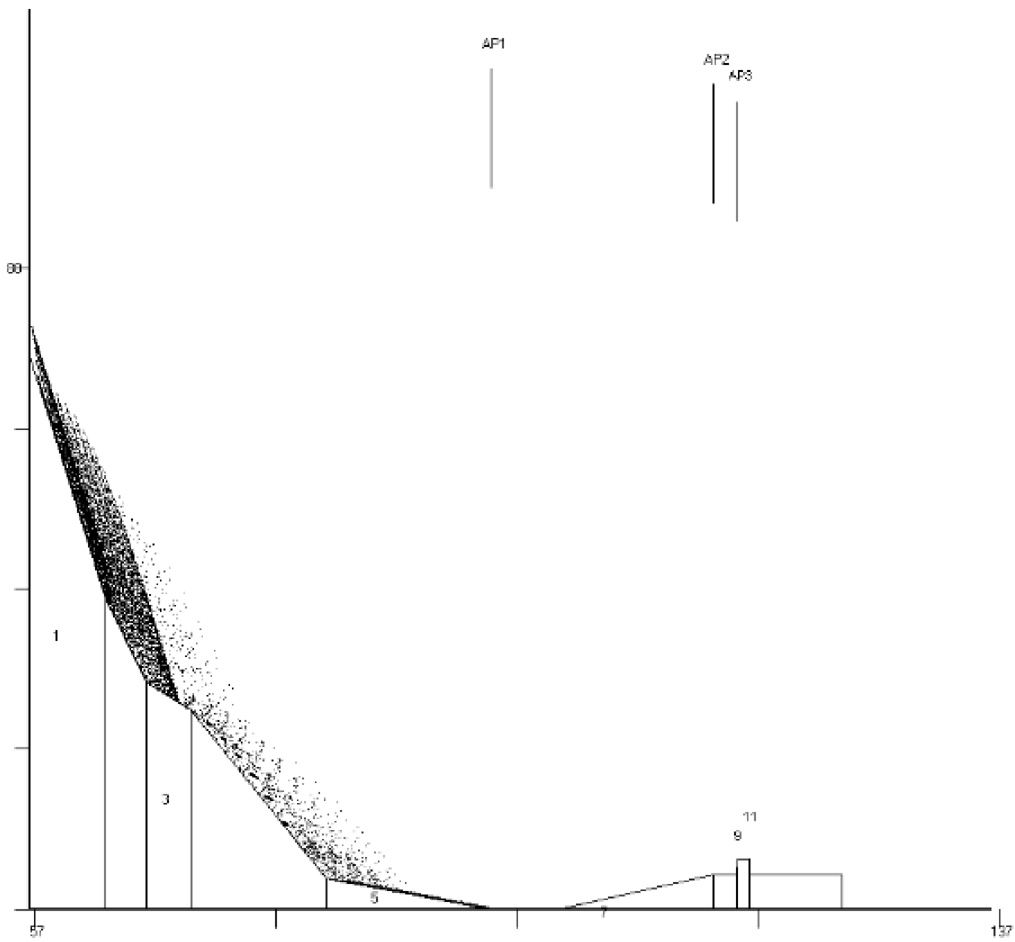
Sample of CRSP results

Rocks falling from layer # 1, Sandstone D_{max} = 8 ft, with ***Rt min*** *and* ***Rn min***.

SLOPE # 4: S.R. 0279 Northbound Segment 170, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 1, Sandstone D_{max} = 8 ft, with **½ *Rt min*** *and* **½ *Rn min***.

SLOPE # 4: S.R. 0279 Northbound Segment 170, Allegheny Co.

Good performance of rock-fall mitigation design: All rocks from slope within the ditch

SLOPE # 4: S.R. 0279 Northbound Segment 170, Allegheny Co.

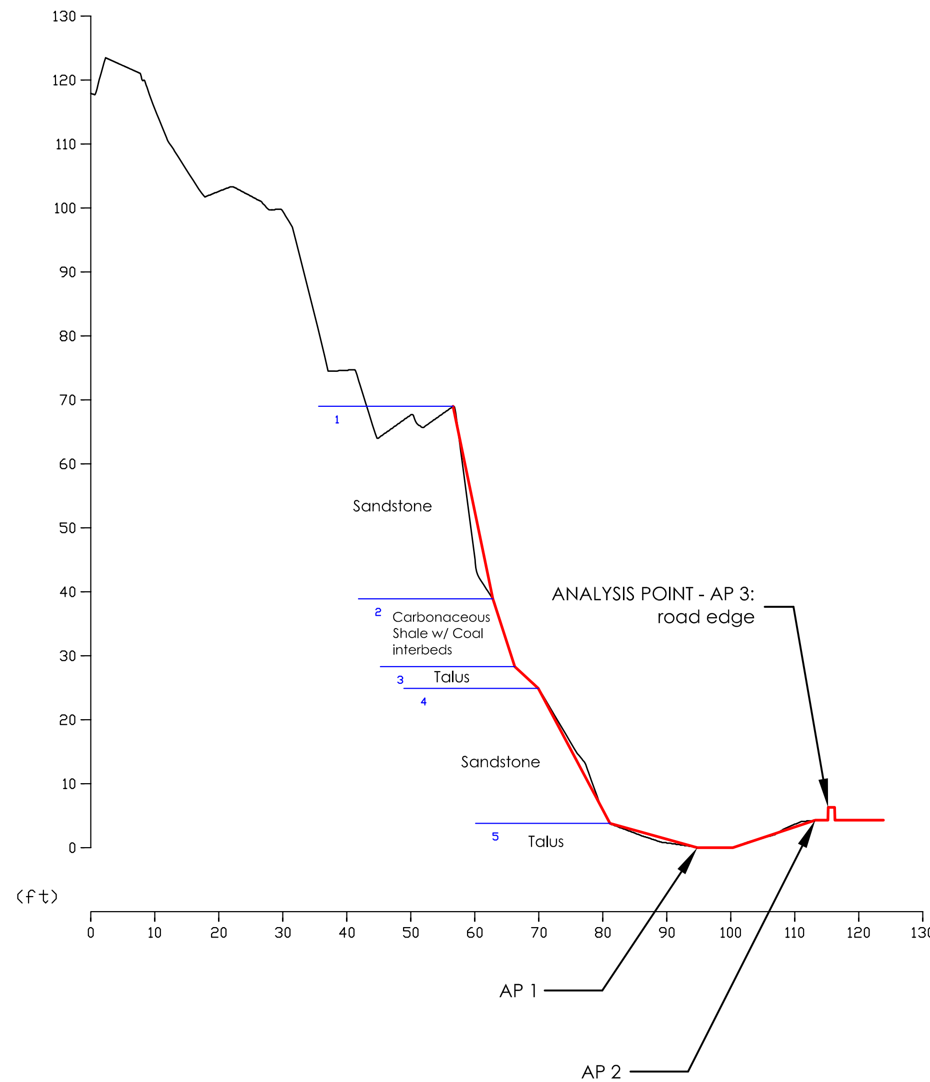
Height = 69 ft.   Avg. Slope angle = 69°

SUMMARY OF CRSP RESULTS - SLOPE 4 (Phase 2 w/barrier)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)				Sphere Diam.$_{MAX}$ (ft)
		Rt min Rn min	1/2 Rt min	1/2 Rn min	1/2 Rt min 1/2 Rn min	
1	**% Rocks Passing AP1***	**75.4%**	**67.8%**	**23.6%**	**18.0%**	8
	Max Bounce height (ft)	0.68	0.56	0.13	0.22	
	Max K.Energy (ft-lb)	682,737	574,492	226,735	287,789	
	Max Vel. (ft/sec)	27.14	25.04	15.75	17.75	
2	**% Rocks Passing AP1****	**7.9%**	**8.5%**	**0.2%**	**0.5%**	Disc D=0.3' T=0.167'
	Max Bounce height (ft)	1.37	1.12	0.16	0.21	
	Max K.Energy (ft-lb)	19	11	2	3	
	Max Vel. (ft/sec)	21.85	17.03	8.25	9.54	
3	**% Rocks Passing AP1**	**2.5%**	**1.0%**	No rocks passed AP1	No rocks passed AP1	Disc D=0.3' T=0.167'
	Max Bounce height (ft)	0.97	0.51			
	Max K.Energy (ft-lb)	8	8			
	Max Vel. (ft/sec)	14.31	13.50			
4	**% Rocks Passing AP1**	**61.4%**	**42.5%**	**16.1%**	**13.6%**	4
	Max Bounce height (ft)	0.59	0.63	0.20	0.19	
	Max K.Energy (ft-lb)	34,330	36,301	13,621	18,395	
	Max Vel. (ft/sec)	17.84	18.40	11.12	12.64	

*** No rocks from any layer passed AP3**

**** Only rocks from layer 1, 1st and 2nd cases, passed AP2 with 20.5% and 3.9% respectively.**



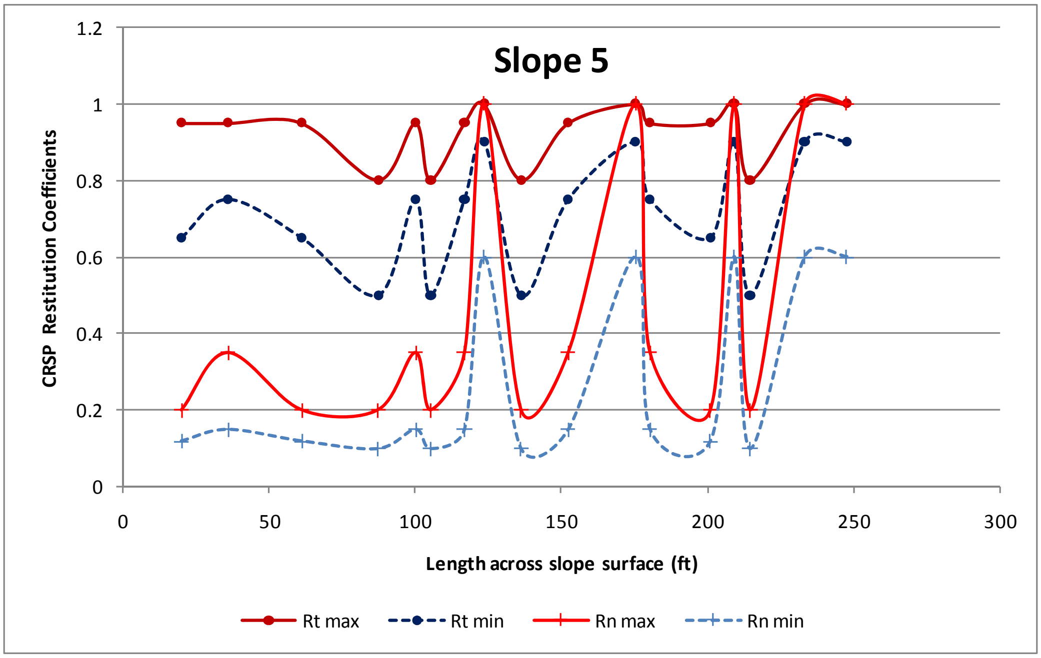
SLOPE # 4: S.R. 0279 Northbound, Segment 170, Allegheny Co.

Scale 1 : 30

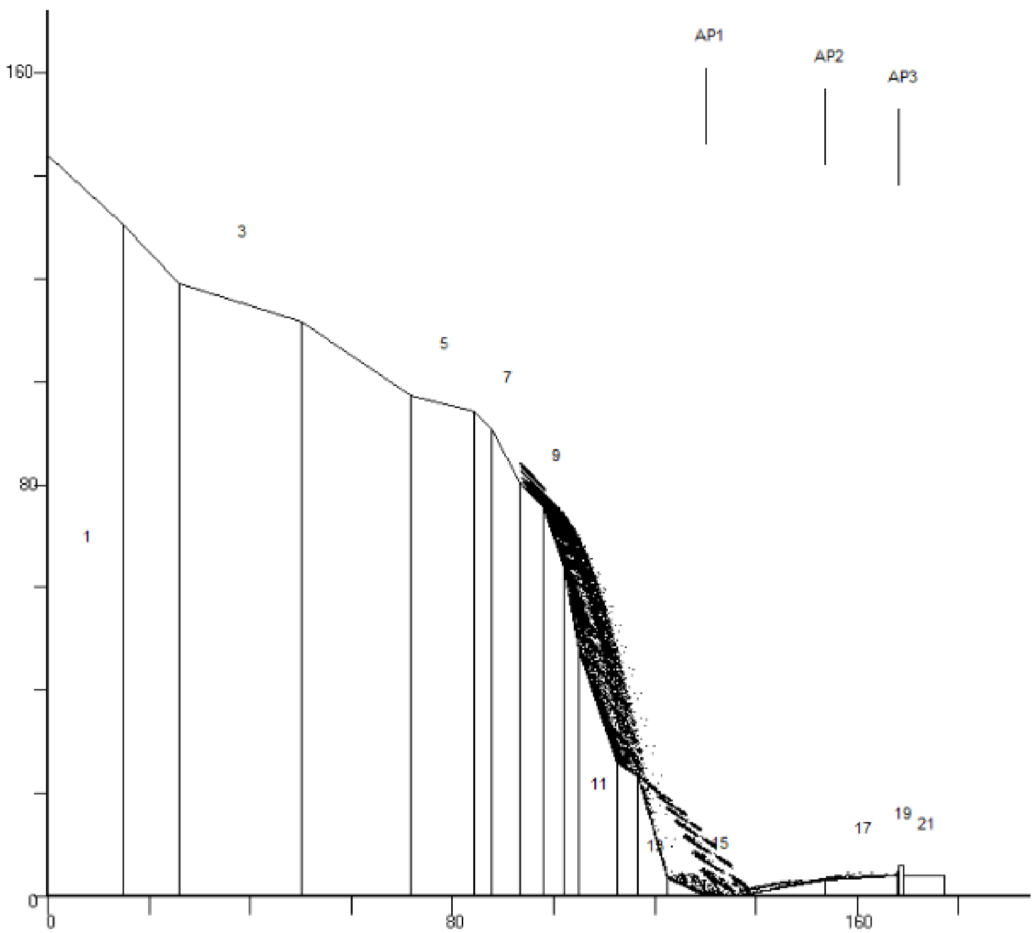
APPENDIX F-5

SLOPE 5 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 5: S.R. 0051 Southbound Segment 741, Allegheny Co.



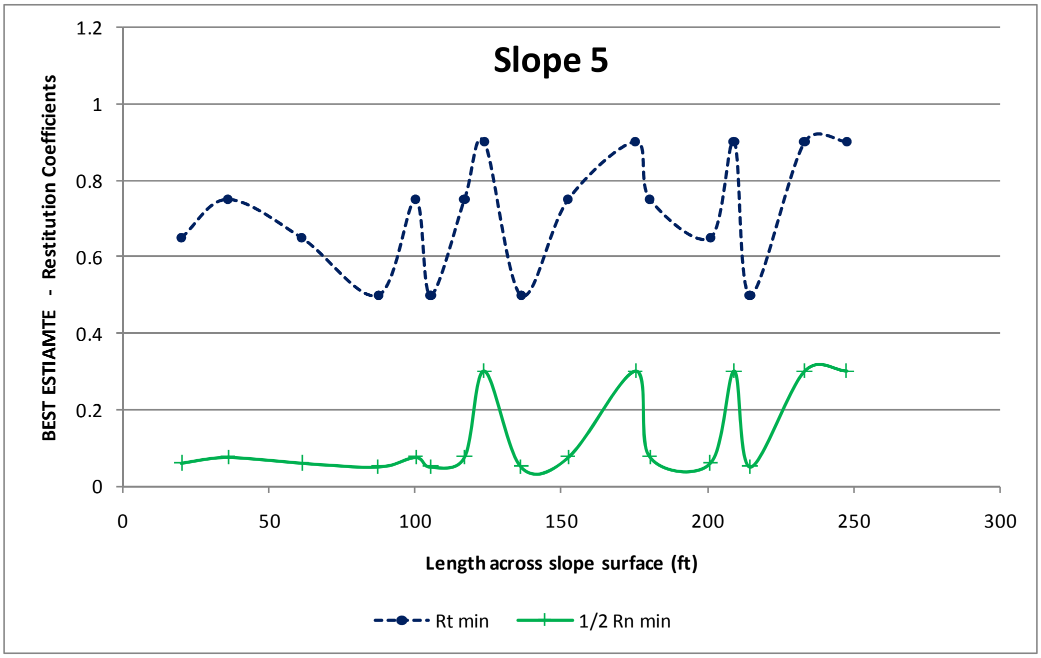
Tangential and Normal restitution coefficients **recommended by CRSP authors**



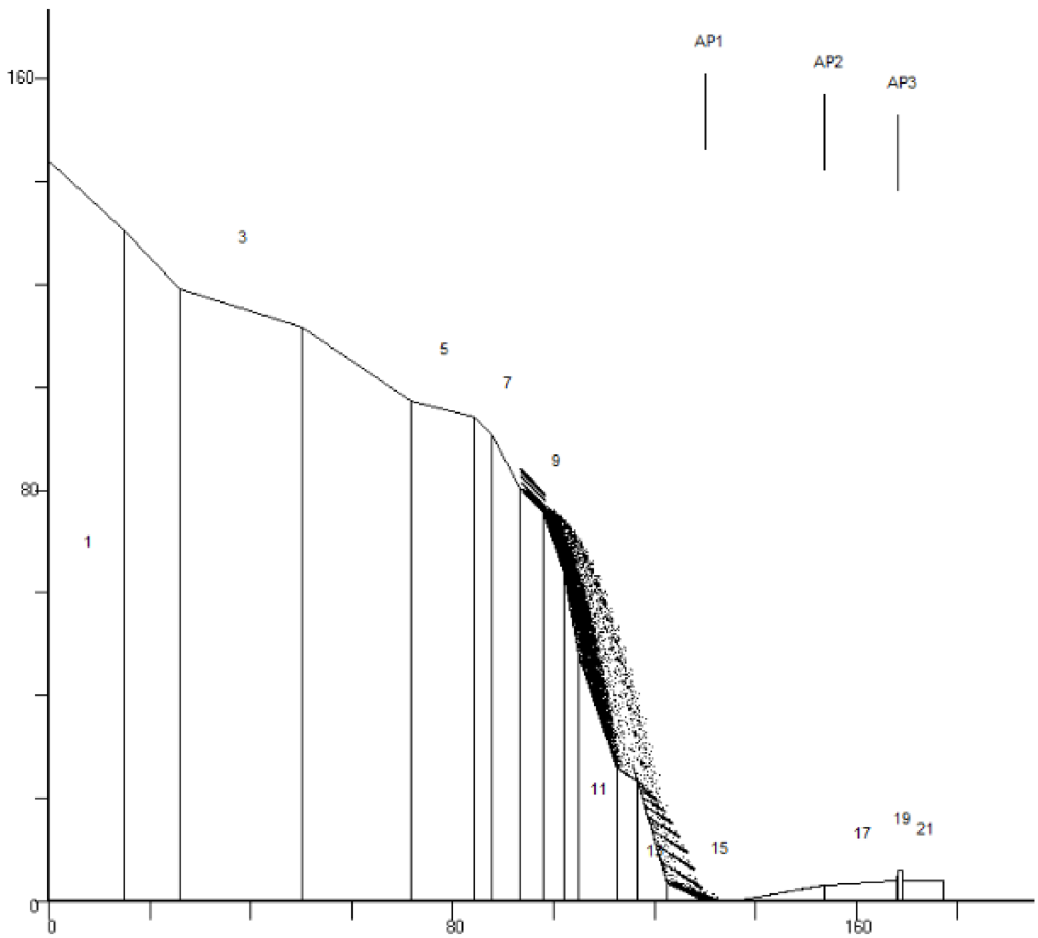
Sample of CRSP results

Rocks falling from layer # 9, Sandy Shale covered with talus, D_{max} = 8 ft, with ***Rt min*** *and* ***Rn min****.*

SLOPE # 5: S.R. 0051 Southbound Segment 741, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 9, Sandy Shale covered with talus, D_{max} = 8 ft, with ***Rt min*** *and* ***½ Rn min****.*

SLOPE # 5: S.R. 0051 Southbound Segment 741, Allegheny Co.

Rocks from the lower layers of shale fall due to jointing parallel to the slope surface and remain close to the slope toe

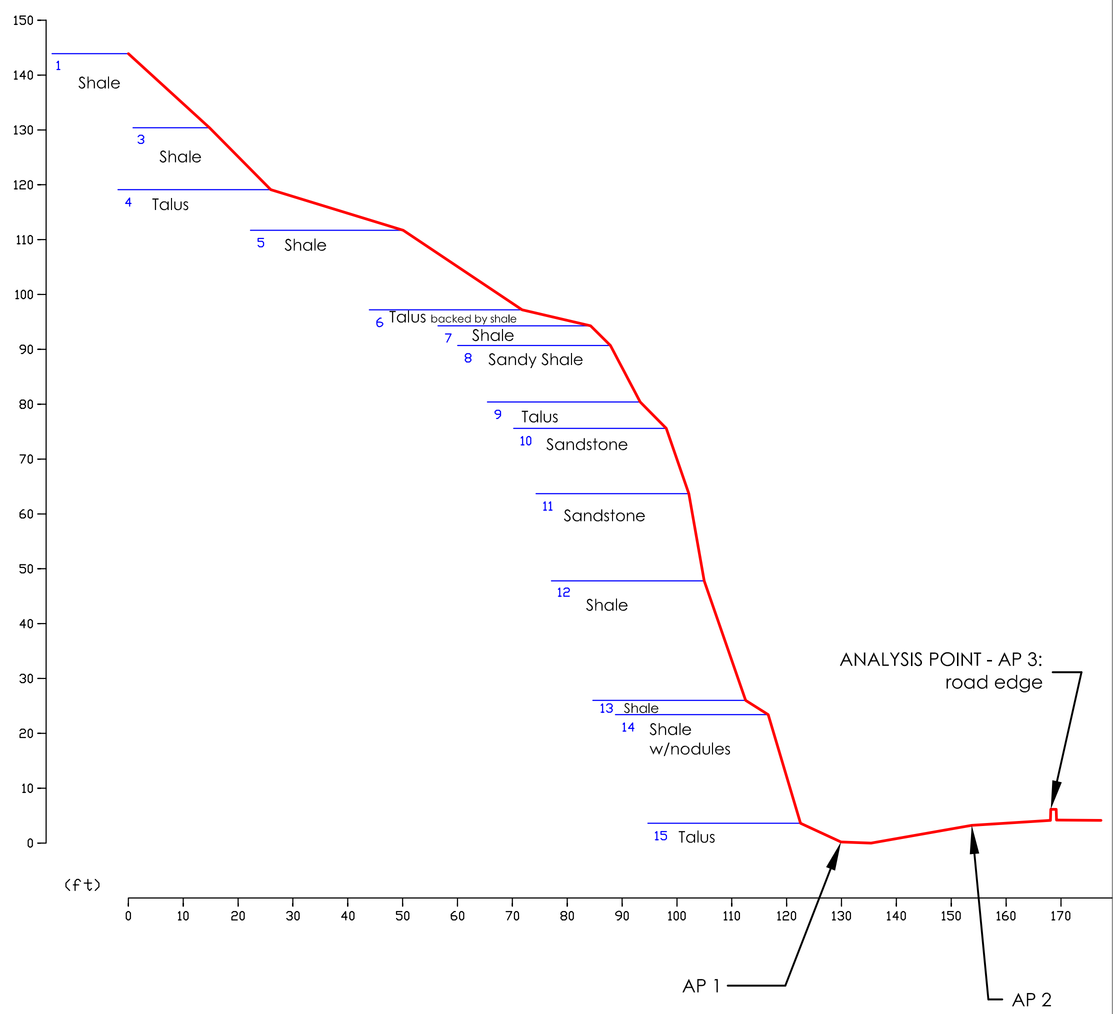
Rocks from upper layers (above # 12) fall and reach the guard-rail

SLOPE # 5: S.R. 0051 Southbound Segment 741, Allegheny Co.

Height = 143.9 ft Avg. Slope angle = 68°

SUMMARY OF CRSP RESULTS - SLOPE 5 (Phase 2 w/barrier)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn): Rt min Rn min	1/2 Rt min	1/2 Rn min	1/2 Rt min 1/2 Rn min	Sphere Diam.$_{MAX}$ (ft)
1	% Rocks Passing AP1*	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	Disc D=0.6' T=0.167'
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
3	% Rocks Passing AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	Disc D=0.6' T=0.167'
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
5	% Rocks Passing AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	Disc D=0.25' T=0.167'
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
7	% Rocks Passing AP2**	32.8%	AP1: 0.4%	0.9%	No rocks passed AP1	1
	Max Bounce height (ft)	0.38	1.54	0.01		
	Max K.Energy (ft-lb)	1,176	630	140		
	Max Vel. (ft/sec)	25.05	18.51	8.60		
8	% Rocks Passing AP2	70.5%	13.6%	0.6%	AP1: 8.6%	8
	Max Bounce height (ft)	0.37	0.13	0.00	9.47	
	Max K.Energy (ft-lb)	854,064	266,735	7,711	1,324,190	
	Max Vel. (ft/sec)	29.91	16.46	8.87	42.64	
9	% Rocks Passing AP2	71.8%	54.2%	AP1: 99.9%	AP1: 7.1%	8
	Max Bounce height (ft)	0.38	0.09	2.13	9.31	
	Max K.Energy (ft-lb)	754,702	200,791	1,289,805	1,323,309	
	Max Vel. (ft/sec)	27.83	14.29	42.08	42.64	
10	% Rocks Passing AP2	78.9%	42.5%	0.2%	AP1: 50.1%	Cylind. D=0.5' L=1'
	Max Bounce height (ft)	0.36	0.06	0.00	12.28	
	Max K.Energy (ft-lb)	422	145	16	1,016	
	Max Vel. (ft/sec)	24.42	14.30	4.86	43.23	
11	% Rocks Passing AP2	74.0%	2.0%	AP1: 99.7	No rocks passed AP1	5
	Max Bounce height (ft)	0.11	0.02	1.33		
	Max K.Energy (ft-lb)	65,414	10,042	105,089		
	Max Vel. (ft/sec)	16.48	6.48	22.57		
12	% Rocks Passing AP2	65.9%	AP1: 77.0%	AP1: 99.9%	No rocks passed AP1	Cylind. D=3' L=18'
	Max Bounce height (ft)	0.03	5.87	0.40		
	Max K.Energy (ft-lb)	71,401	630,563	225,551		
	Max Vel. (ft/sec)	12.78	42.56	23.58		
13	% Rocks Passing AP2	0.1%	No rocks passed AP1	AP1: 4.4%	No rocks passed AP1	0.3
	Max Bounce height (ft)	0.02		0.56		
	Max K.Energy (ft-lb)	2		4		
	Max Vel. (ft/sec)	7.63		10.09		
14	% Rocks Passing AP2	1.2%	AP1: 17.5%	AP1: 91.6%	AP1: 5.0%	Cylind. D=2' L=4'
	Max Bounce height (ft)	0.02	2.08	1.37	1.15	
	Max K.Energy (ft-lb)	2,884	16,999	21,426	8,738	
	Max Vel. (ft/sec)	7.93	21.05	23.14	14.76	



* No rocks from layers 1 thru 5 reached the bottom of the ditch

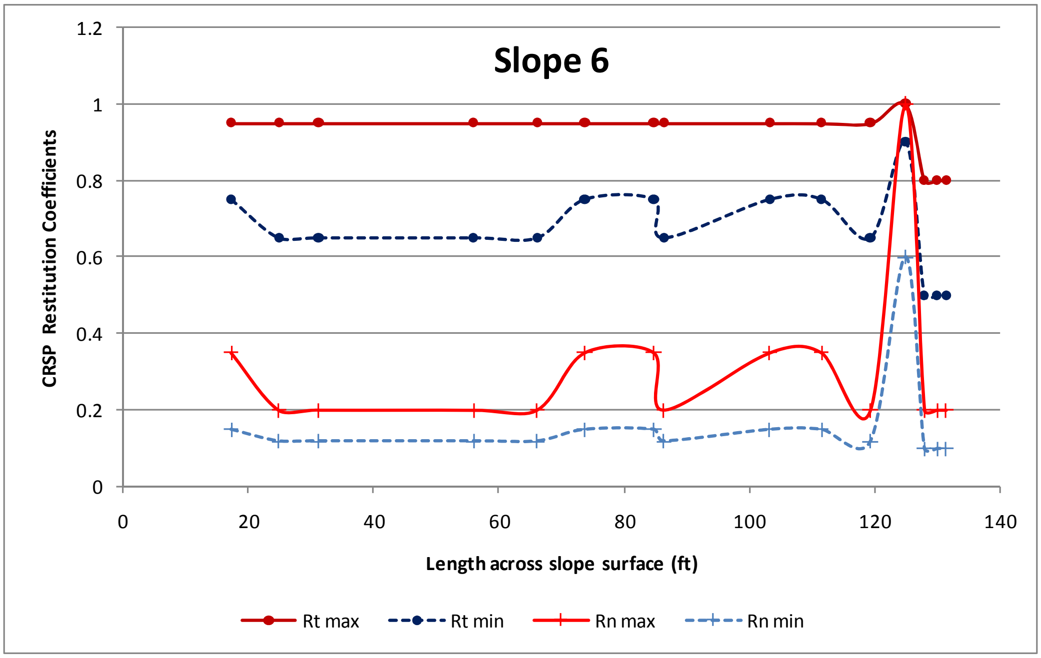
** No rocks from any layer passed AP3

SLOPE # 5: S.R. 0051 Southbound Segment 741, Allegheny Co. | Scale 1 : 35

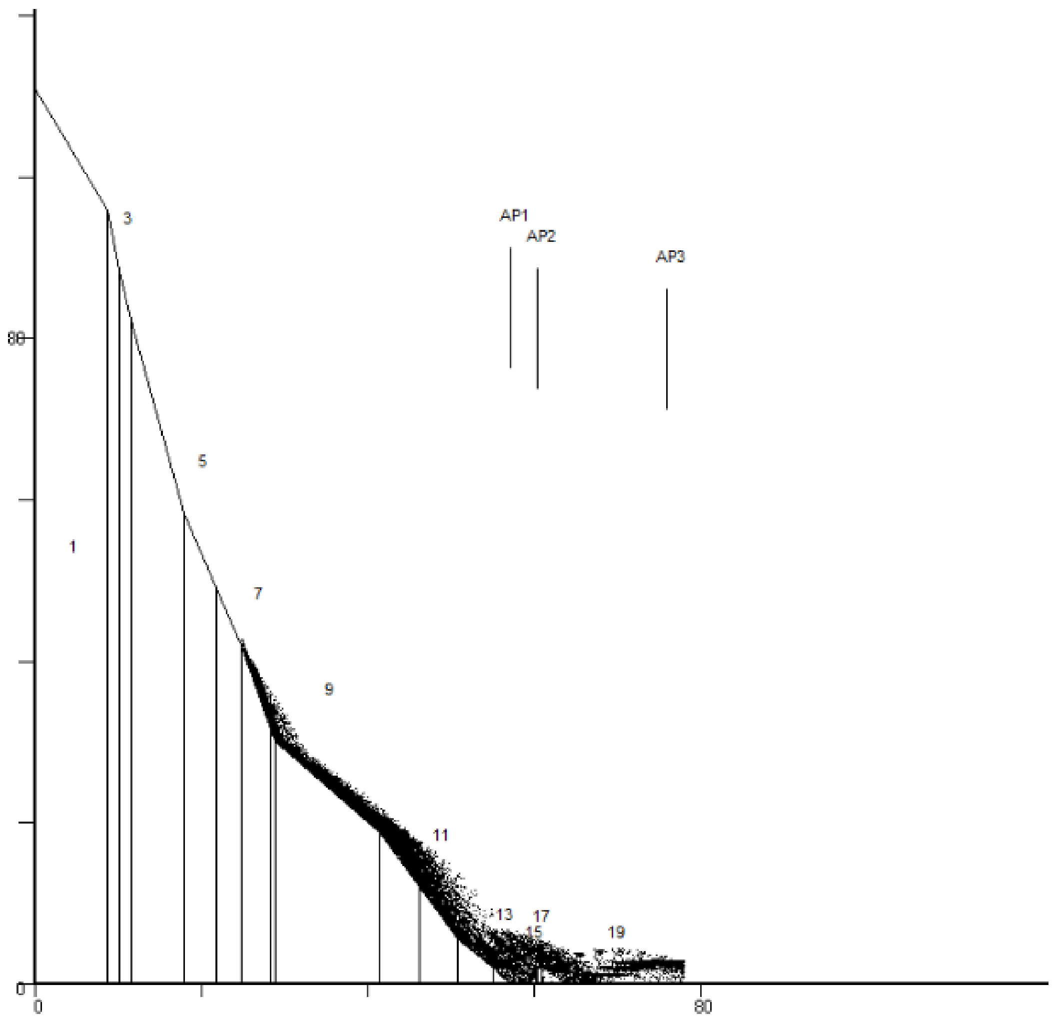
APPENDIX F-6

SLOPE 6 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 6: S.R. 0008 Northbound, Segment 270, Allegheny Co.



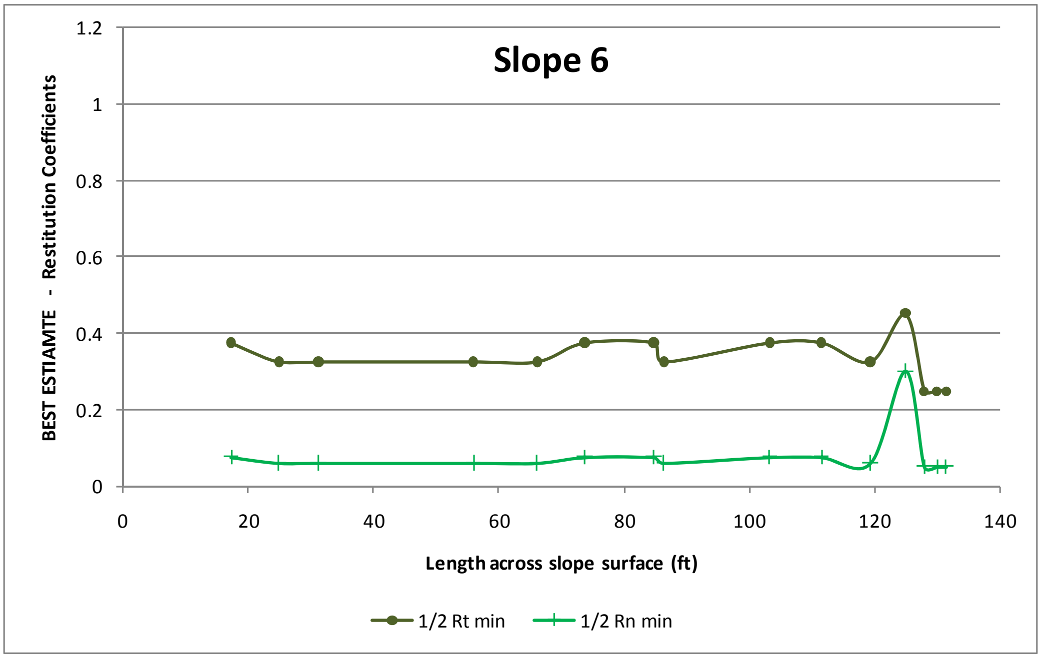
Tangential and Normal restitution coefficients **recommended by CRSP authors**



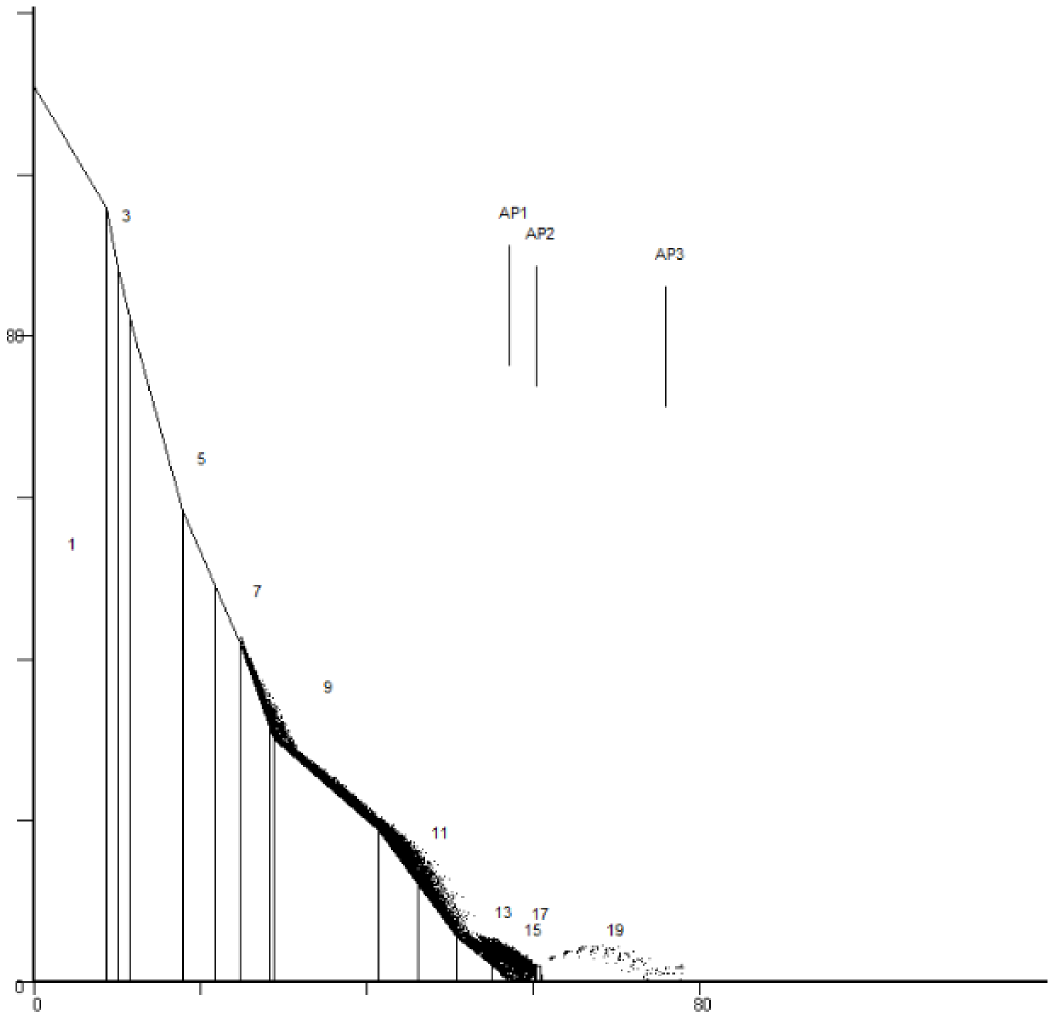
Sample of CRSP results

Rocks falling from layer # 8 (#7 in figure), Shale with Sandstone interb., D_{max} = 2 ft, with ***Rt min*** *and* ***Rn min.***

SLOPE # 6: S.R. 0008 Northbound, Segment 270, Allegheny Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 8 (#7 in figure), Shale with Sandstone interb., D_{max} = 2 ft, with **½ *Rt min*** *and* ***½ Rn min.***

SLOPE # 6: S.R. 0008 Northbound, Segment 270, Allegheny Co.

Rock-fall mitigation design is not sufficient for Slope 6.

SLOPE # 6: S.R. 0008 Northbound, Segment 270, Allegheny Co.

Rocks from upper layers (above # 12) fall and pass the Jersey barrier reaching the median.

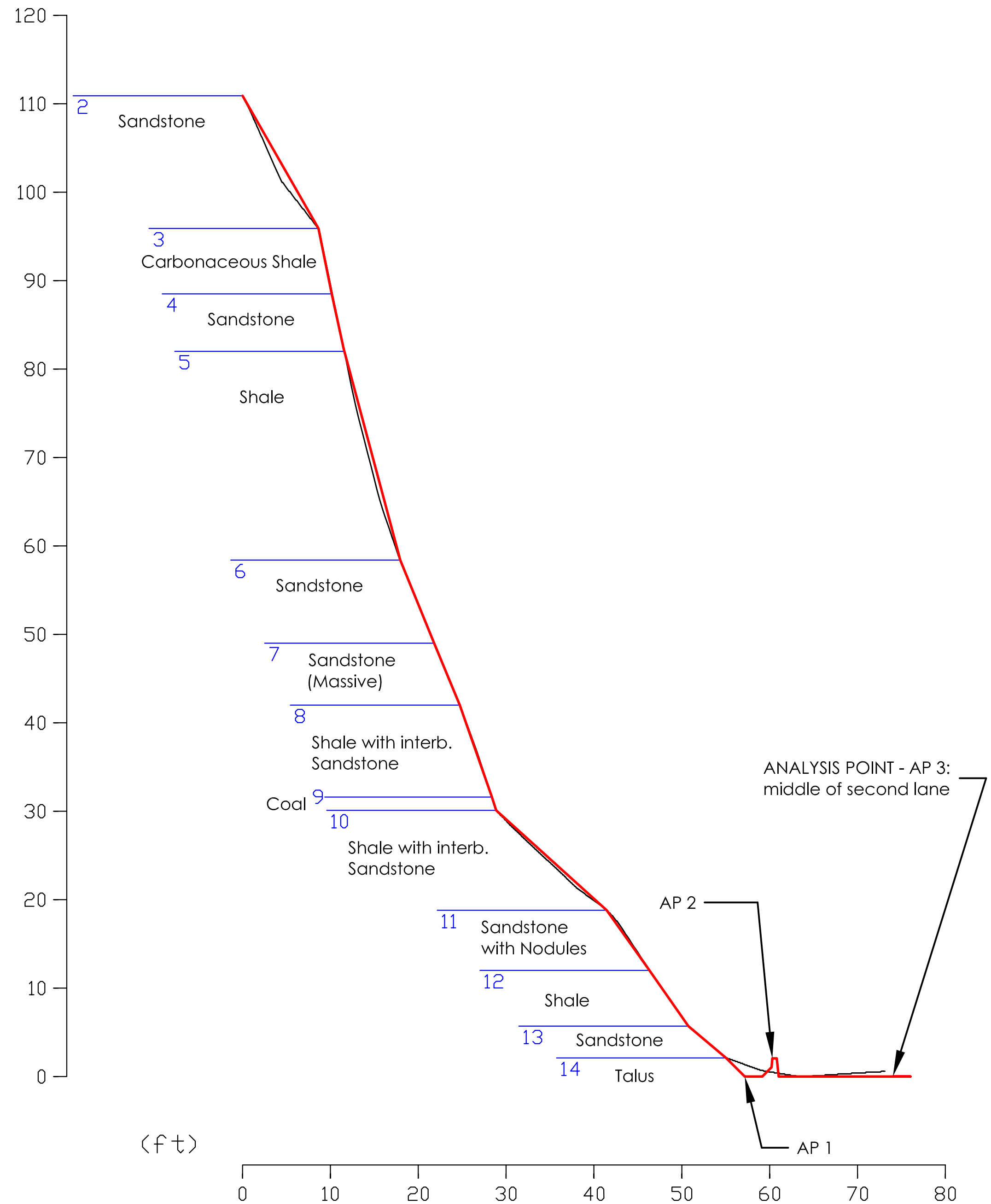
Photos are taken from the slope toe

SLOPE # 6: S.R. 0008 Northbound, Segment 270, Allegheny Co.

Height = 110.9 ft.   Avg. Slope angle = 60°

SUMMARY OF CRSP RESULTS - SLOPE 6 (Phase 2 w/barrier)

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)				Sphere Diam.$_{MAX}$ (ft)
		Rt min Rn min	1/2 Rt min Rn min	Rt min 1/2 Rn min	1/2 Rt min 1/2 Rn min	
2	% Rocks Passing AP3	21.0%	9.2%	0.2%	0.3%	4
	Max Bounce height (ft)	5.38	5.35	4.11	3.95	
	Max K.Energy (ft-lb)	205,016	146,690	103,933	90,640	
	Max Vel. (ft/sec)	41.43	34.98	29.51	27.64	
3	% Rocks Passing AP3	32.8%	29.9%	12.6%	12.1%	disk D=0.3 T=0.167'
	Max Bounce height (ft)	5.38	5.25	2.76	2.77	
	Max K.Energy (ft-lb)	66	47	27	29	
	Max Vel. (ft/sec)	38.46	32.37	25.62	26.27	
4	% Rocks Passing AP3	33.3%	35.4%	18.0%	15.4%	disk D=2 T=0.668'
	Max Bounce height (ft)	5.28	5.02	3.76	3.57	
	Max K.Energy (ft-lb)	11,463	8,976	5,645	5,677	
	Max Vel. (ft/sec)	38.04	33.34	26.71	26.83	
5	% Rocks Passing AP3	37.4%	36.8%	14.6%	16.2%	disk D=1 T=0.334'
	Max Bounce height (ft)	5.17	4.53	3.35	2.78	
	Max K.Energy (ft-lb)	1,220	922	678	575	
	Max Vel. (ft/sec)	34.93	30.40	27.02	25.15	
6	% Rocks Passing AP3	22.0%	27.4%	2.7%	0.8%	disk D=3 T=1'
	Max Bounce height (ft)	5.08	4.24	3.01	2.74	
	Max K.Energy (ft-lb)	28,941	24,027	17,583	15,553	
	Max Vel. (ft/sec)	32.71	29.94	25.46	24.78	
7	% Rocks Passing AP3	17.4%	18.3%	No rocks passed AP2	No rocks passed AP2	4
	Max Bounce height (ft)	5.09	3.53			
	Max K.Energy (ft-lb)	130,013	98,897			
	Max Vel. (ft/sec)	32.98	28.93			
8	% Rocks Passing AP3	46.8%	48.0%	9.9%	2.0%	disk D=2' T=0.668'
	Max Bounce height (ft)	4.09	2.98	2.68	1.73	
	Max K.Energy (ft-lb)	6,659	5,560	4,485	4,111	
	Max Vel. (ft/sec)	28.24	27.23	24.28	24.33	
9	% Rocks Passing AP3	35.5%	32.8%	2.4%	0.5%	0.5
	Max Bounce height (ft)	3.25	2.71	2.18	2.14	
	Max K.Energy (ft-lb)	159	135	121	88	
	Max Vel. (ft/sec)	26.82	25.25	24.37	20.54	
10	% Rocks Passing AP3	47.8%	37.1%	1.1%	No rocks passed AP2	disk D=1.5' T=0.501'
	Max Bounce height (ft)	3.01	2.68	2.22		
	Max K.Energy (ft-lb)	2,123	1,777	1,648		
	Max Vel. (ft/sec)	25.77	24.54	23.86		
11	% Rocks Passing AP3	14.2%	3.0%	No rocks passed AP2	No rocks passed AP2	2.5
	Max Bounce height (ft)	1.94	2.22			
	Max K.Energy (ft-lb)	15,185	11,015			
	Max Vel. (ft/sec)	24.28	20.68			
12	% Rocks Passing AP3	No rocks passed AP2	No rocks passed AP2	No rocks passed AP2	No rocks passed AP2	0.4
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					
13	% Rocks Passing AP3	No rocks passed AP2	No rocks passed AP2	No rocks passed AP2	No rocks passed AP2	1.5
	Max Bounce height (ft)					
	Max K.Energy (ft-lb)					
	Max Vel. (ft/sec)					



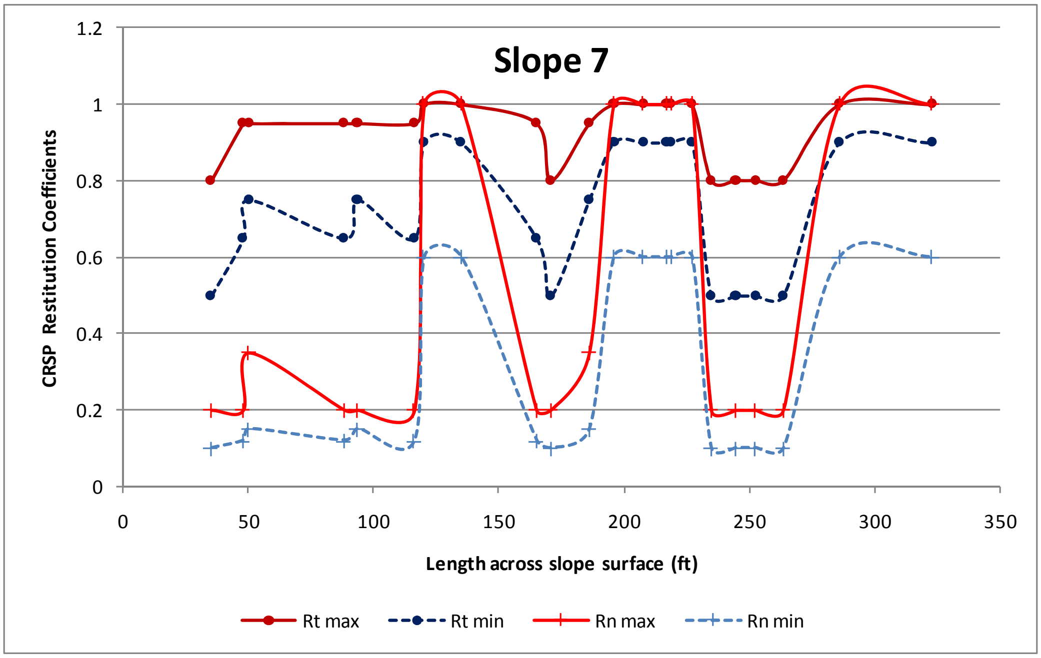
SLOPE # 6: S.R. 0008 Northbound Segment 270, Allegheny Co.

Scale 1 : 20

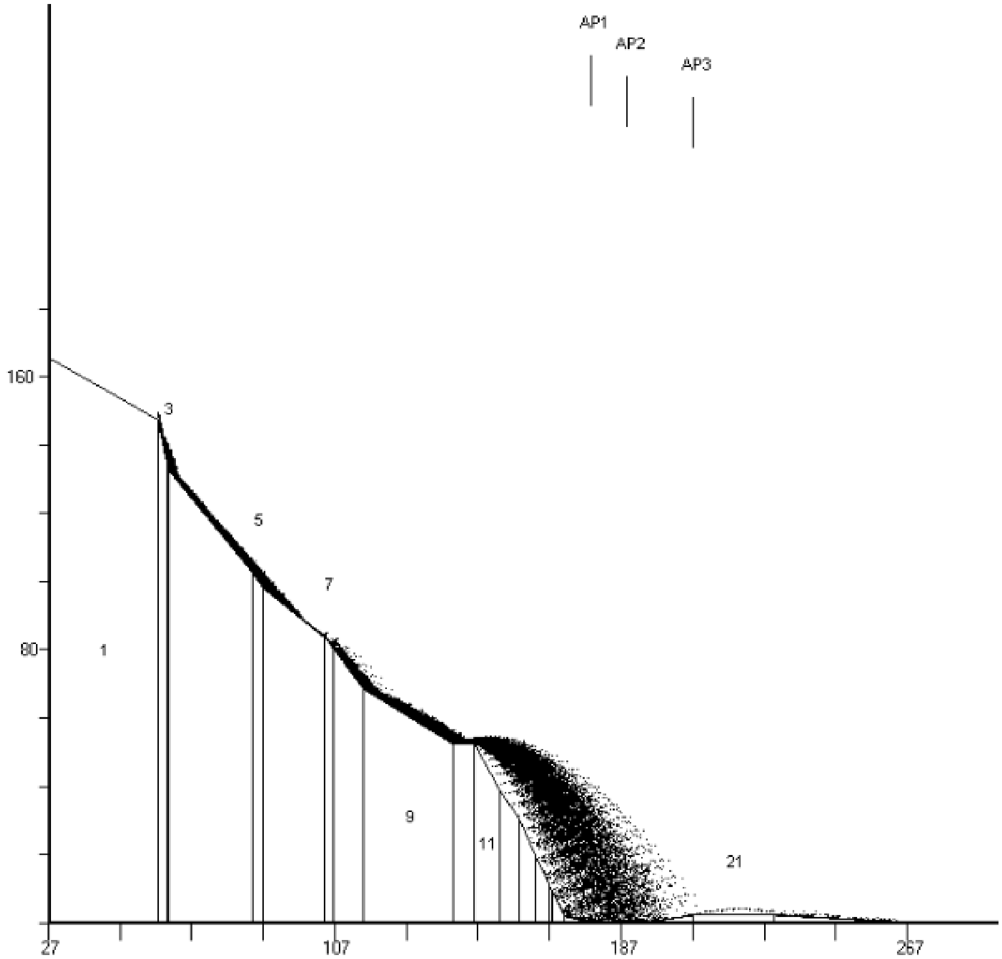
APPENDIX F-7

SLOPE 7 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 7: S.R. 0060 Northbound, Segment 180, Beaver Co.



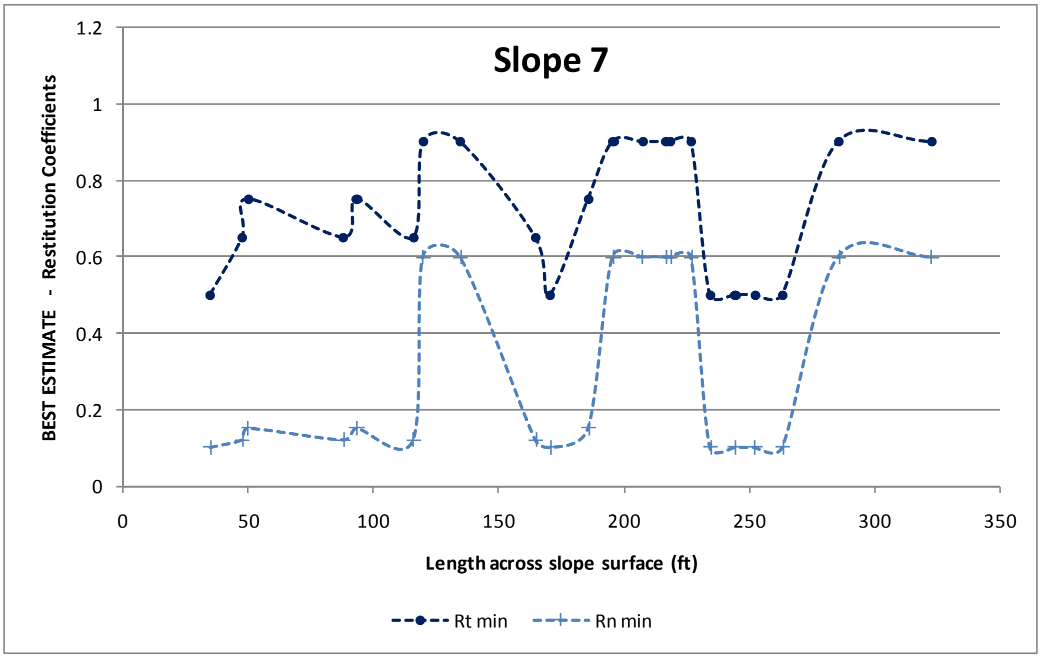
Tangential and Normal restitution coefficients **recommended by CRSP authors**



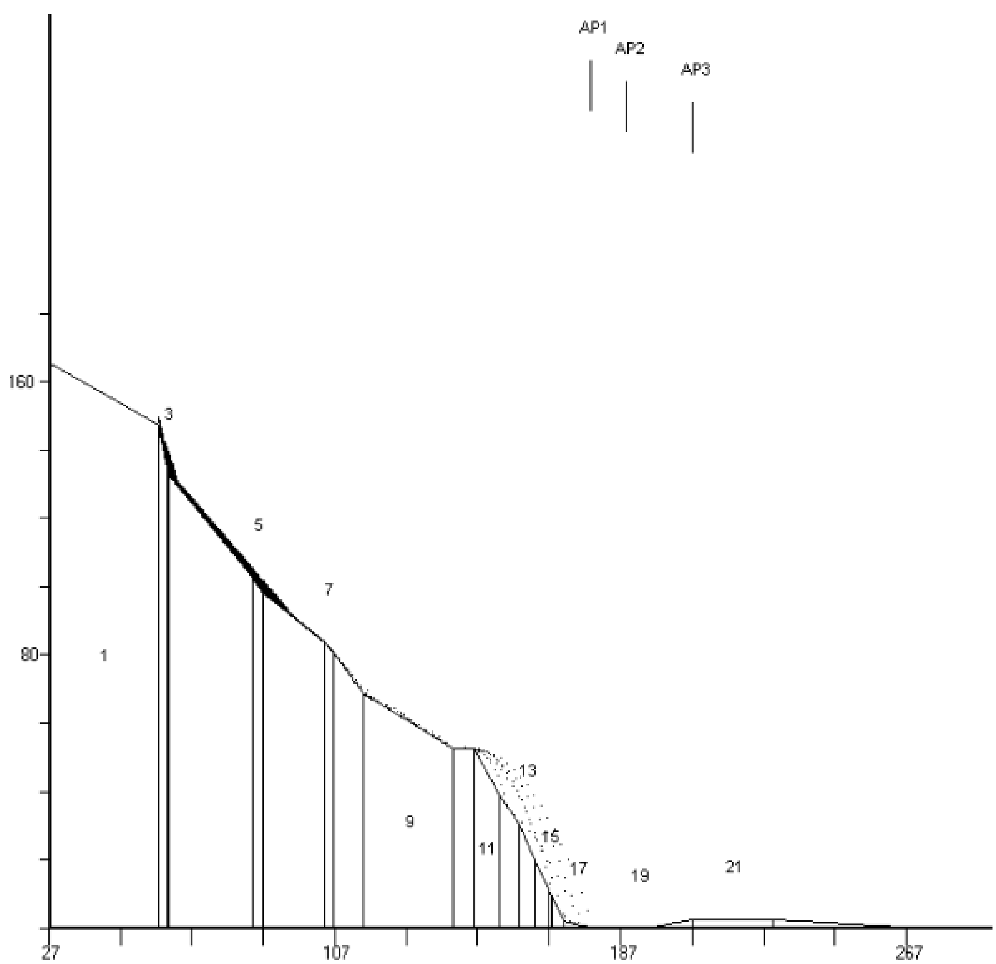
Sample of CRSP results

Rocks falling from layer # 2, Shale, D_{max} = 5 ft, with ***Rt max*** *and* ***Rn max****.*

SLOPE # 7: S.R. 0060 Northbound, Segment 180, Beaver Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 2, Shale, D_{max} = 5 ft, with ***Rt min*** *and* ***Rn min****.*

SLOPE # 7: S.R. 0060 Northbound, Segment 180, Beaver Co.

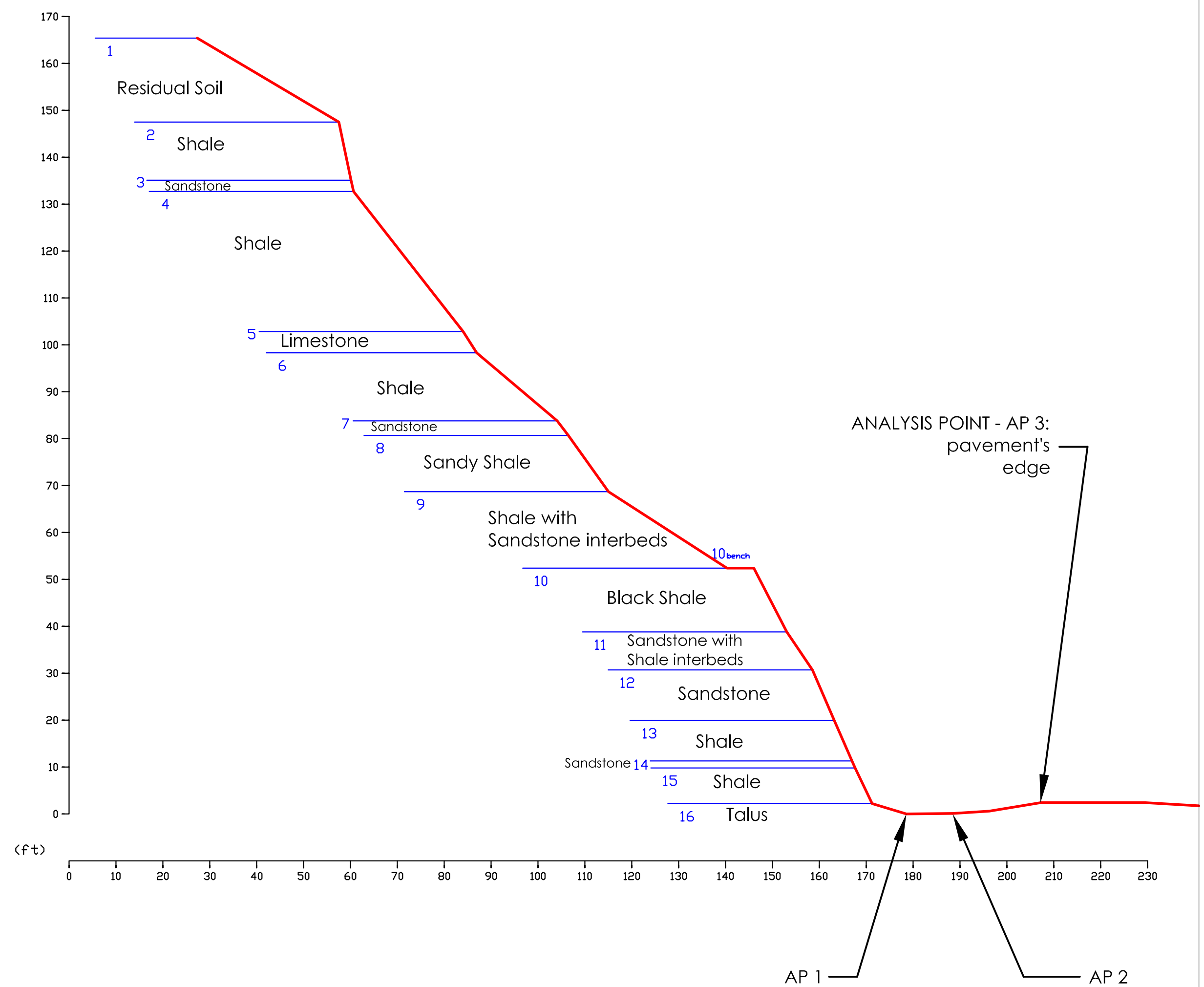
Good trench performance: Larger rocks from upper layers do not reach the road edge.

SLOPE # 7: S.R. 0060 Northbound, Segment 180, Beaver Co.

Height = 165.4 ft Avg. Slope angle = 49°

SUMMARY OF CRSP RESULTS - SLOPE 7

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn) min	mid1	mid	mid2	max	Sphere Diam.MAX (ft)
2	Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	0.2%	10.7%	47.8%	Disc D=5ft T=1ft
	Max Bounce height (ft)			0.01	6.37	20.70	
	Max K.Energy (ft-lb)			5,300	256,454	254,433	
	Max Vel. (ft/sec)			8.36	66.89	66.69	
3	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	1.1%	16.9%	34.1%	Cylind D=1.75ft L=3.5ft
	Max Bounce height (ft)			0.01	4.93	13.45	
	Max K.Energy (ft-lb)			4,638	96,267	105,634	
	Max Vel. (ft/sec)			12.34	63.42	66.51	
4	% Rocks Passing AP3	No rocks passed AP3	0.1%	0.9%	3.7%	10.8%	Disc D=0.6ft T=0.167ft
	Max Bounce height (ft)		0.00	0.01	0.03	0.06	
	Max K.Energy (ft-lb)		15	56	92	142	
	Max Vel. (ft/sec)		9.14	17.46	22.49	28.00	
5	% Rocks Passing AP3	No rocks passed AP3	0.1%	1.4%	3.2%	9.5%	1ft
	Max Bounce height (ft)		0.01	0.01	0.04	0.07	
	Max K.Energy (ft-lb)		44	374	1,131	2,040	
	Max Vel. (ft/sec)		4.84	14.04	24.54	32.95	
6	% Rocks Passing AP3	No rocks passed AP3	0.2%	1.3%	4.0%	9.9%	Disc D=0.6ft T=0.167ft
	Max Bounce height (ft)		0.00	0.01	0.03	1.15	
	Max K.Energy (ft-lb)		4	37	79	168	
	Max Vel. (ft/sec)		4.68	14.22	20.83	30.29	
7	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	1.0%	5.2%	11.1%	1.5ft
	Max Bounce height (ft)			0.01	0.03	0.04	
	Max K.Energy (ft-lb)			1,960	3,905	5,818	
	Max Vel. (ft/sec)			17.49	24.81	30.13	
8	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	0.3%	4.2%	7.7%	Disc D=1.5ft T=.5ft
	Max Bounce height (ft)			0.00	0.03	0.04	
	Max K.Energy (ft-lb)			647	1,541	3,192	
	Max Vel. (ft/sec)			13.72	21.27	30.49	
9	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	0.0%	0.0%	0.0%	Disc D=1ft T=.333ft
	Max Bounce height (ft)			0.00	0.00	0.00	
	Max K.Energy (ft-lb)			0	0	0	
	Max Vel. (ft/sec)			0.00	0.00	0.00	
11	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	0.5%	7.9%	10.2%	Disc D=1ft T=0.333ft
	Max Bounce height (ft)			0.01	0.03	0.04	
	Max K.Energy (ft-lb)			30	42	89	
	Max Vel. (ft/sec)			15.37	18.27	26.64	
12	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	0.0%	7.3%	14.8%	1ft
	Max Bounce height (ft)			0.00	0.01	0.03	
	Max K.Energy (ft-lb)			0	435	797	
	Max Vel. (ft/sec)			0.00	15.14	20.57	
13	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	18.8%	5ft
	Max Bounce height (ft)					1.21	
	Max K.Energy (ft-lb)					135,820	
	Max Vel. (ft/sec)					24.15	
14	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	0.3%	Disc D=4.5ft T=1.5ft
	Max Bounce height (ft)					0.01	
	Max K.Energy (ft-lb)					4,299	
	Max Vel. (ft/sec)					6.86	
15	% Rocks Passing AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	No rocks passed AP3	2ft
	Max Bounce height (ft)						
	Max K.Energy (ft-lb)						
	Max Vel. (ft/sec)						
16	% Rocks Passing AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	No rocks passed AP1	Disc D=1ft T=0.333ft
	Max Bounce height (ft)						
	Max K.Energy (ft-lb)						
	Max Vel. (ft/sec)						



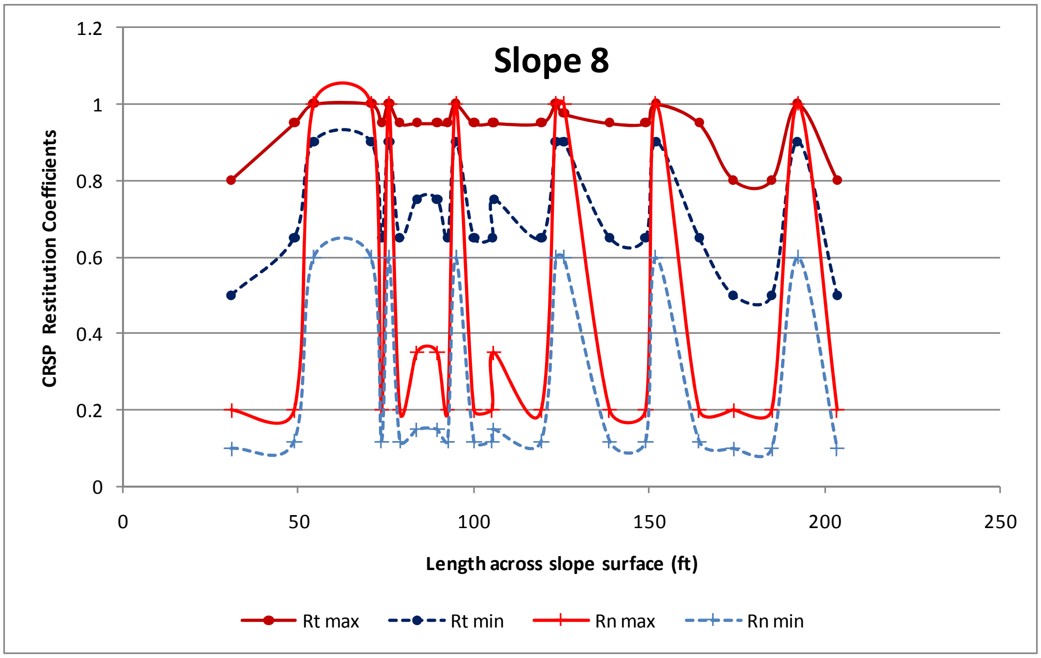
SLOPE # 7: S.R. 0060 Eastbound, Segment 180, Beaver Co.

Scale 1 : 40

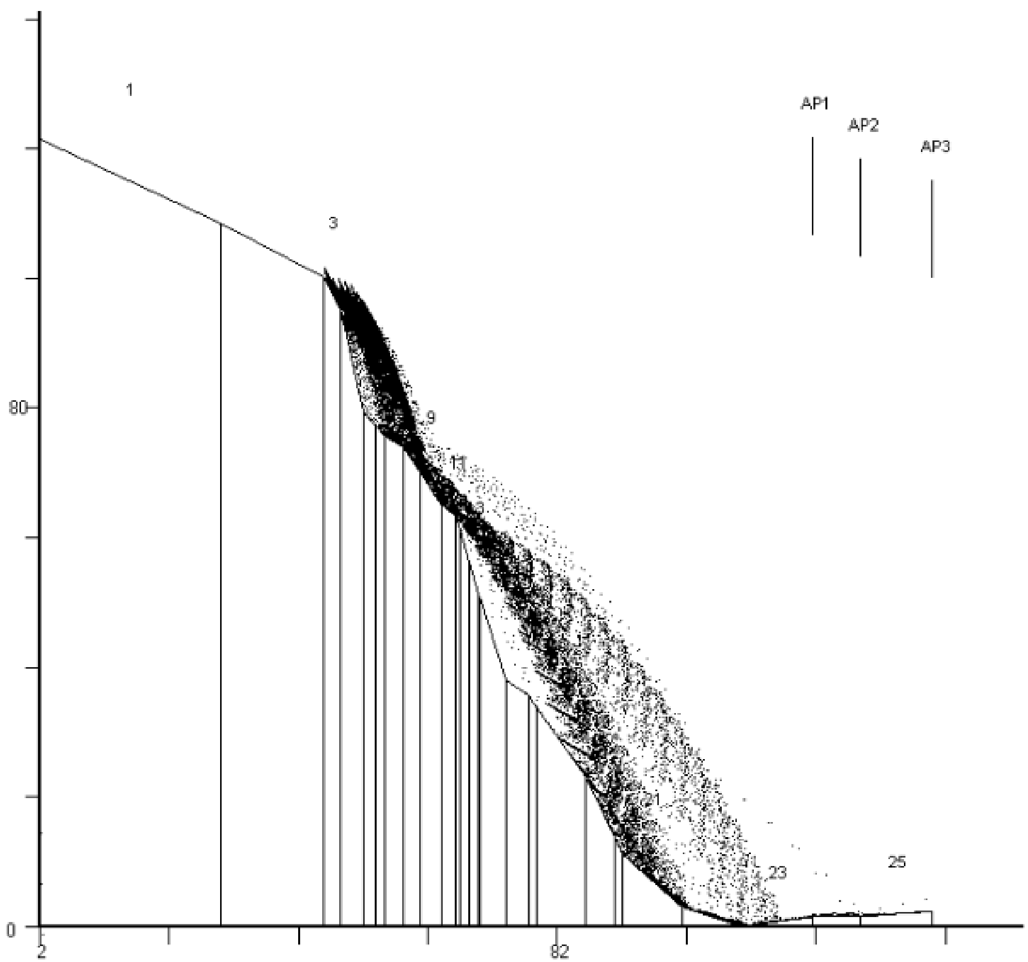
APPENDIX F-8

SLOPE 8 COMPILATION OF RESULTS AND PHOTOGRAPHS

SLOPE # 8: S.R. 0422 Westbound, Segment 311, Lawrence Co.



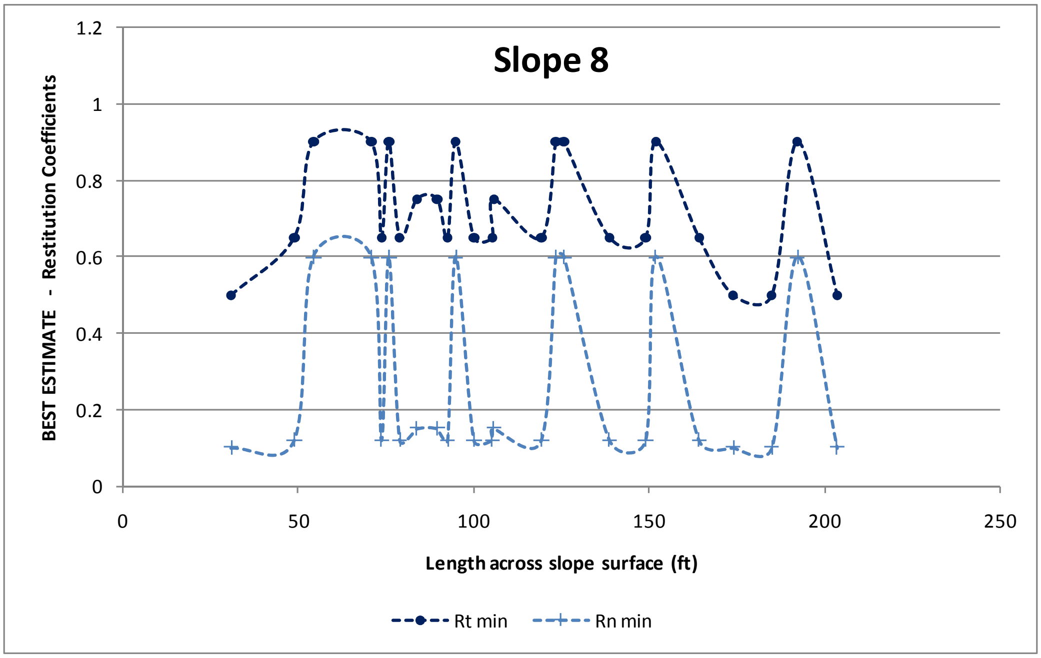
Tangential and Normal restitution coefficients **recommended by CRSP authors**



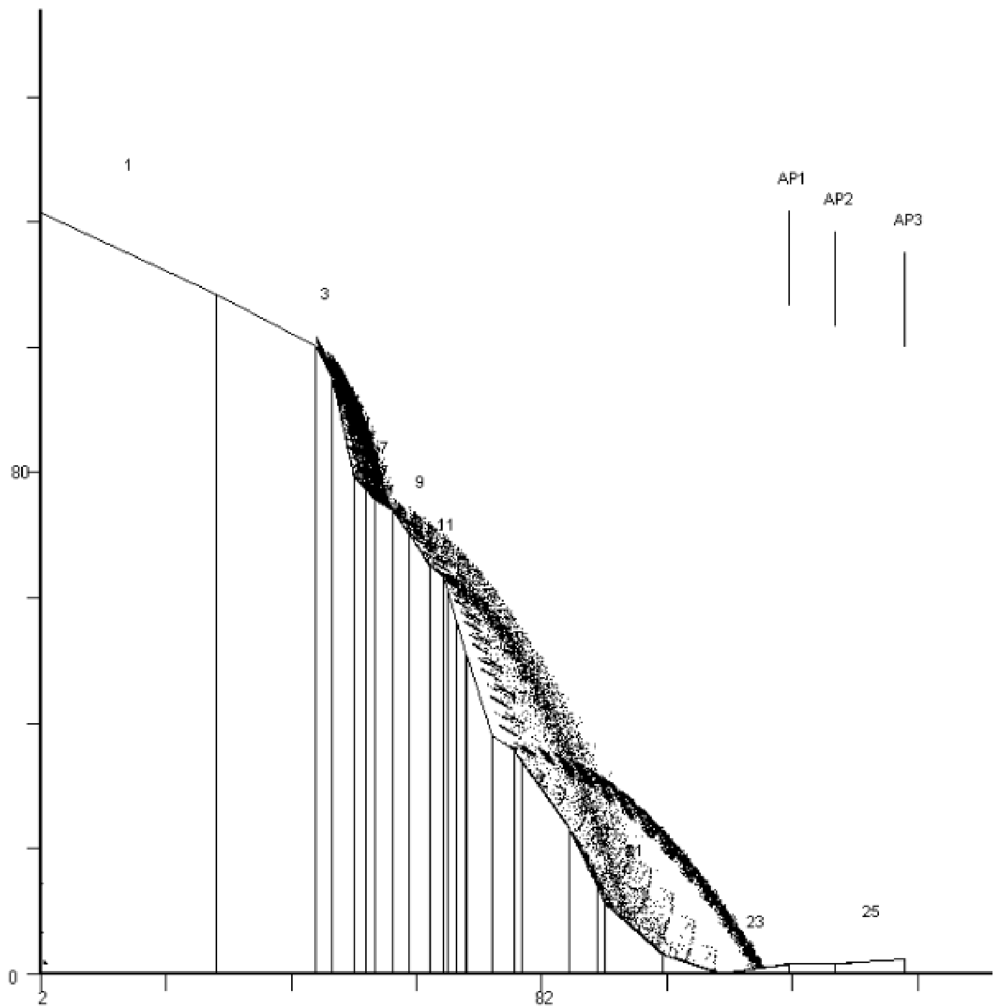
Sample of CRSP results

Rocks falling from layer # 3, Shale, D_{max} = 3 ft, with ***Rt max*** *and* ***Rn max.***

SLOPE # 8: S.R. 0422 Westbound, Segment 311, Lawrence Co.



Tangential and Normal restitution coefficients **that best fit field observations**



Sample of CRSP results

Rocks falling from layer # 3, Shale, D_{max} = 3 ft, with ***Rt min*** *and* ***Rn min.***

SLOPE # 8: S.R. 0422 Westbound, Segment 311, Lawrence Co.

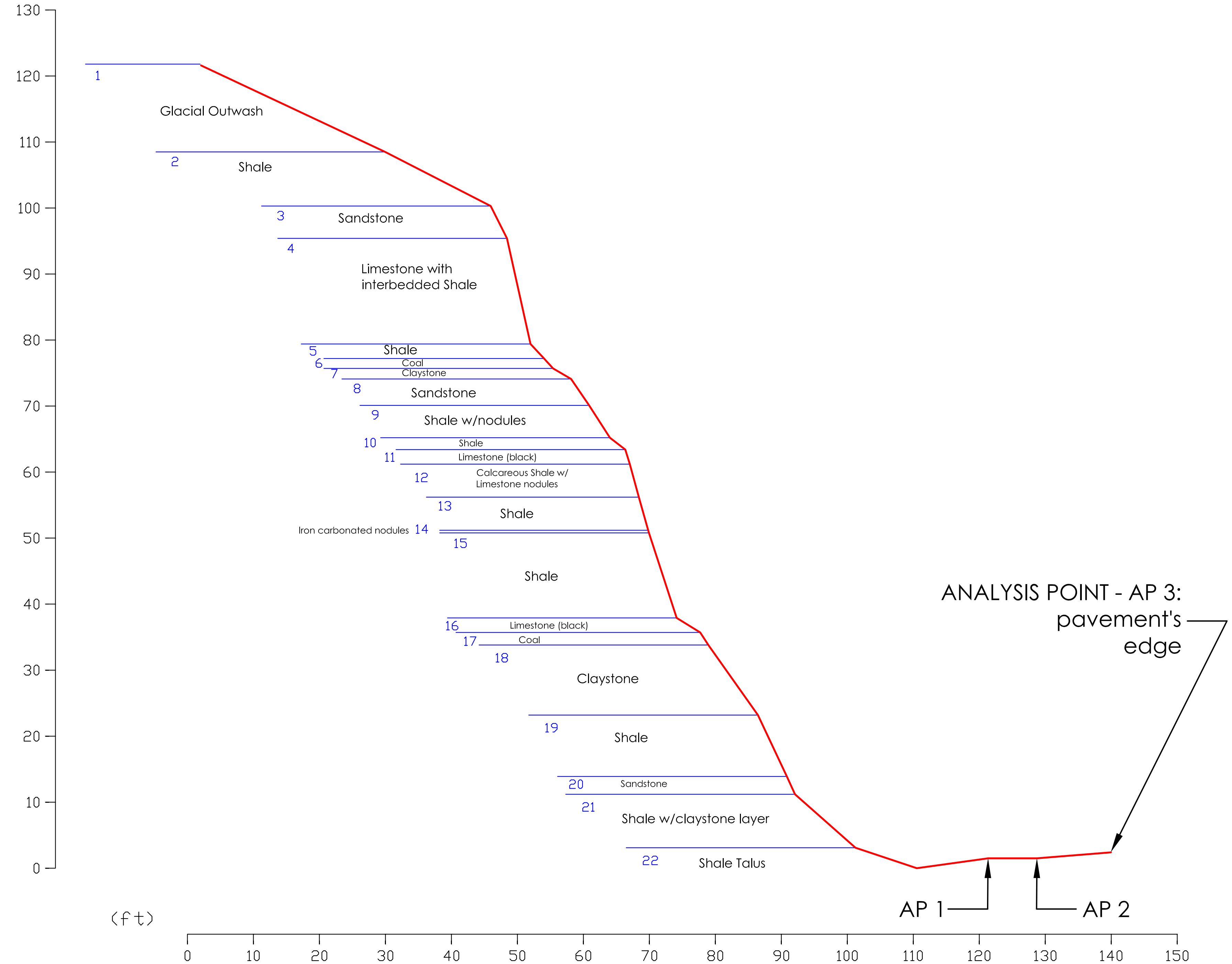
During winter season slope 8 exhibits more rock-fall events

SLOPE # 8: S.R. 0422 Westbound, Segment 311, Lawrence Co.

Height = 121.6 ft   Avg. Slope angle = 58°

SUMMARY OF CRSP RESULTS - SLOPE 8

Layer #	1000 rocks per simulation	Possible Restitution Coefficients (Rt, Rn)					Sphere Diam.$_{MAX}$ (ft)
		min	mid1	mid	mid2	max	
2	% Rocks Passing AP3				0.1%	0.4%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.00	0.00	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	0	23	
	Max Vel. (ft/sec)				3.04	22.58	
3	% Rocks Passing AP3			54.2%	82.3%	84.7%	
	Max Bounce height (ft)	No rocks	No rocks	0.01	0.01	1.81	3
	Max K.Energy (ft-lb)	passed AP3	passed AP3	30,642	65,230	77,847	
	Max Vel. (ft/sec)			24.55	35.82	39.13	
4	% Rocks Passing AP3		0.8%	45.7%	81.1%	93.3%	
	Max Bounce height (ft)	No rocks	0.01	0.32	1.34	1.97	cylinder D=1.5 L=3'
	Max K.Energy (ft-lb)	passed AP3	8,561	22,307	23,255	29,363	
	Max Vel. (ft/sec)		21.22	34.47	35.05	39.30	
5	% Rocks Passing AP3		0.1%	2.6%	17.6%	32.7%	
	Max Bounce height (ft)	No rocks	0.00	0.01	1.04	2.00	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	1	13	41	55	
	Max Vel. (ft/sec)		6.04	17.39	30.34	35.15	
6	% Rocks Passing AP3		0.6%	32.8%	93.1%	97.5%	
	Max Bounce height (ft)	No rocks	0.00	0.04	1.19	1.99	1.5
	Max K.Energy (ft-lb)	passed AP3	185	4,046	7,090	7,623	
	Max Vel. (ft/sec)		5.40	25.24	33.58	34.63	
7	% Rocks Passing AP3				0.6%	1.0%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.01	0.01	disk D=0.1 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	1	3	
	Max Vel. (ft/sec)				15.38	24.47	
8	% Rocks Passing AP3			11.4%	51.7%	82.8%	
	Max Bounce height (ft)	No rocks	No rocks	0.01	0.84	1.97	disk D=1 T=0.334'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	465	1,033	1,042	
	Max Vel. (ft/sec)			21.46	32.20	32.15	
9	% Rocks Passing AP3			0.3%	24.5%	62.2%	
	Max Bounce height (ft)	No rocks	No rocks	0.01	0.74	1.87	disk D=0.7 T=0.234'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	4	301	334	
	Max Vel. (ft/sec)			8.01	29.75	31.26	
10	% Rocks Passing AP3			0.1%	2.6%	8.7%	
	Max Bounce height (ft)	No rocks	No rocks	0.00	0.01	1.50	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	1	13	36	
	Max Vel. (ft/sec)			5.05	17.01	28.37	
11	% Rocks Passing AP3			0.6%	17.2%	65.7%	
	Max Bounce height (ft)	No rocks	No rocks	0.01	0.67	1.90	2ft
	Max K.Energy (ft-lb)	passed AP3	passed AP3	1,351	13,721	13,994	
	Max Vel. (ft/sec)			9.51	30.45	30.63	
12	% Rocks Passing AP3			0.4%	10.1%	34.3%	
	Max Bounce height (ft)	No rocks	No rocks	0.00	0.01	0.12	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	1	20	40	
	Max Vel. (ft/sec)			4.74	21.45	29.90	
13	% Rocks Passing AP3				4.4%	19.6%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.01	0.01	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	12	30	
	Max Vel. (ft/sec)				16.36	25.91	
14	% Rocks Passing AP3				7.2%	45.0%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.01	0.01	.7ft
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	111	264	
	Max Vel. (ft/sec)				13.17	20.25	
15	% Rocks Passing AP3			0.1%	3.2%	20.7%	
	Max Bounce height (ft)	No rocks	No rocks	0.00	0.01	0.01	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	1	9	18	
	Max Vel. (ft/sec)			5.66	14.50	20.23	
16	% Rocks Passing AP3			0.1%	21.8%	99.6%	
	Max Bounce height (ft)	No rocks	No rocks	0.00	0.01	0.01	2ft
	Max K.Energy (ft-lb)	passed AP3	passed AP3	340	4,106	6,942	
	Max Vel. (ft/sec)			4.76	16.52	21.46	
17	% Rocks Passing AP3				9.4%	94.9%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.01	0.01	1.5ft
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	900	2,883	
	Max Vel. (ft/sec)				11.91	21.30	
18	% Rocks Passing AP3				0.1%	6.7%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	0.01	0.01	disk D=0.1 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	0	1	
	Max Vel. (ft/sec)				8.58	14.74	
19	% Rocks Passing AP3					0.5%	
	Max Bounce height (ft)	No rocks	No rocks	No rocks	No rocks	0.01	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	passed AP3	1	
	Max Vel. (ft/sec)					6.39	
20	% Rocks Passing AP3						
	Max Bounce height (ft)	No rocks	No rocks	No rocks	No rocks	No rocks	3ft
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	passed AP3	passed AP3	
	Max Vel. (ft/sec)						
21	% Rocks Passing AP3						
	Max Bounce height (ft)	No rocks	No rocks	No rocks	No rocks	No rocks	disk D=0.3 T=0.167'
	Max K.Energy (ft-lb)	passed AP3	passed AP3	passed AP3	passed AP3	passed AP3	
	Max Vel. (ft/sec)						



SLOPE # 8: S.R. 0422 Westbound, Segment 311, Lawrence Co.

Scale 1 : 20