Design Optimization of Safety Benches for Surface Quarries through Rockfall Testing and Evaluation

Andrew Wilson Storey

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Committee Members:

Erik C. Westman, Chair
Mario G. Karfakis
Chester F. Watts

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(Abstract)

The research presented in this thesis results from efforts to evaluate current design methodologies for safety benches in surface aggregate quarries. Proper bench design is important for preventing rockfall related accidents and injuries without wasting the reserves held in the benches. An in depth analysis has been performed using the results from 230 rockfall tests conducted at two surface quarries. The goal of this project is to give practitioners the tools they need for improved bench design.

Principal Components and Cluster Analysis, techniques not previously applied to rockfall investigations, have been performed on the test data. The results indicate that both are valid analytical methods which show that the factors affecting the rollout distance of a rock are wall configuration, rock dimensions, and rock energy. The test results were then compared to the Ritchie Criteria, Modified Ritchie Criterion, Ryan and Pryor Criterion, Oregon Department of Transportation design charts, and RocFall computer simulations.

Analysis shows that the lognormal distribution curves fitted to the test data provide an excellent yet quick design reference. The recommended design method is computer simulation using RocFall because of the ease of simulation and the site specific nature of the program. For the two quarries studied, RocFall analysis showed that 20 ft benches with a 4 ft berm will hold over 95% of rockfalls, a design supported by the field testing. Conducting site-specific rockfall testing is also recommended to obtain realistic input parameters for the simulations and to provide design justification to regulatory agencies.

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1 Introduction

Rockfalls are a constant problem in surface mining. Natural conditions combined with mining methods serve to create a never ending problem. Blasting, combined with the inherent rock fractures and weathering, creates kinematically free blocks of rock. When the force envelope around a block is altered by pore water pressure from groundwater, ice wedging from freezes, roots from vegetation, or other phenomena, the block may fall out of the wall posing a danger to people and equipment (Hoek, Analysis of Rockfall Hazards, 2007).

When designing quarries, engineers account for these rockfalls. Safety benches are horizontal steps left in the wall of a surface mine to stop rockfalls from traveling further down the slope and endangering personnel or equipment on the working bench (Figure 1.1).

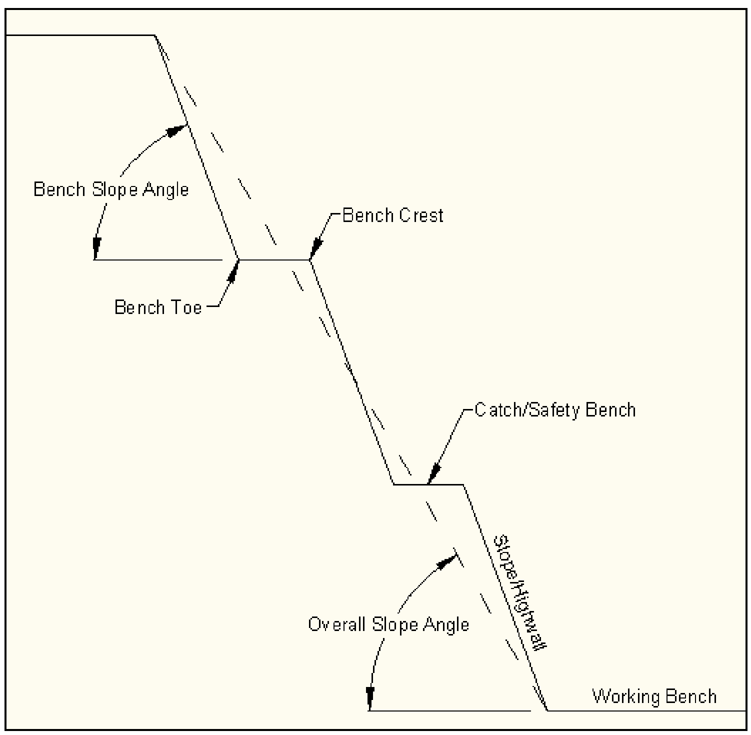


Figure 1.1: Surface Mine Cross Section

Also called catch benches, these terraces are left at regular intervals. Unfortunately, the factors that come into play in the design of the bench width are numerous, making for a difficult problem. Geology, blasting, safety, pit design, hydrology, acceptable risk, reserve estimation, cost, and many other factors impact the chosen bench width. The complicated problem has therefore led to minimally engineered designs. While rules of thumb and historically safe designs may be useful, relying on them can lead to unsafe conditions in certain cases or being too conservative in others. Aggregate producers do not want to injure people but cannot afford to leave salable material in an overly conservative catch bench. With the goals of improving safety and mining efficiency, this report aims to help producers by combining knowledge and research related to bench design in aggregate quarries and contribute to the creation a more accurate guideline for safety bench design.

A significant part of this work is field testing which has been performed in two aggregate quarries owned by Luck Stone Corp, an aggregate producer headquartered in Richmond, Virginia. The testing procedure consisted of rolling rocks of various sizes and shapes over the crest of typical quarry highwalls as well as highwalls with pronounced launch features. Launch features are irregularities in the slope which project the falling rock outward from the wall on impact. When dropped, the rocks rolled/fell down the slope, mimicking natural rockfalls. After the rocks reached the toe of the slope and come to rest, characteristics of the fall and the test conditions were recorded for each rock. The collected data includes: geology, impact distance, rollout distance, rock size (dimensions), wall height, and wall angle.

The data collected through the field work has been analyzed with previously unutilized methods in order to understand the major factors influencing a rockfall. Principal Components Analysis and Cluster Analysis, both spatial data analysis techniques, have been performed to extract the underlying influences on how far a rock will fall and roll. The author has not been able to find any examples of these methods being used for the analysis of rockfalls; thus, these techniques will be evaluated as a means for rockfall analysis. Principal Components Analysis and Cluster Analysis are being used with the goals of expanding the tools available to researchers and corroborating observations with rigorous analytical methods.

The results have also been compared to current safety bench design practices with the goal of validating or disproving the current methods as appropriate quarry design techniques. The Ritchie Criteria, the Modified Ritchie Criterion, the Ryan and Pryor Criterion, the Oregon Department of Transportation's (ODOT) design guide, and the geotechnical software program RocFall have all been compared to the project test results with the goal of determining the most accurate method for calculating safety bench width.

This thesis presents a detailed discussion of rockfall issues. The research efforts of previous and current investigators are reviewed, and a detailed description of the field work, designed from the previous efforts, performed for this research is presented. The results of the field work, Principal Components Analysis, Cluster Analysis, and design method comparisons are also reported. Finally, conclusions have been drawn from the results, and recommendations for action are given.

2 Literature Review

Rockfall is an issue which has affected the mining industry since people first started excavating the ground. Once exposed, many elements begin to work on the rock which will eventually lead to a fall. Slope designers have dealt with this problem through a variety of classification and remediation strategies. These issues will be reviewed in order to provide a foundation for the discussion of the research presented in this paper.

2.1 Safety

Most importantly, rockfalls are a safety concern. Between 2005-2009, 18 miners were killed in the United States while working in surface Metal/Non-Metal (M/NM) mines by material falling or sliding from a highwall, which accounts for 17.0% of the surface M/NM fatalities over that time period (Mine Safety and Health Administration). Unfortunately this problem occurs on a global scale. For example, the Spanish Association of Aggregate Producers, ANEFA, report that more than 20% of quarry incidents are caused by rockfalls, which is the highest cause of fatalities (Alejano, Pons, Bastante, Alonso, & Stockhausen, 2007). The cause of even a single injury or fatality is worthy of study, but the increased danger of rockfalls clearly warrants investigation. As a result, numerous scholars have undertaken research projects which aim to shed light on issue as a whole as well as the specific issues related to rockfalls.

2.2 Rockfall Causation

Two factors are prerequisites for a rockfall: a kinematically free block of rock and a change in the forces on that block. Before a rockfall can occur, the block must be free to release from the rest of the rock mass. Prior to mining, natural discontinuities and joints play the initial role in creating these blocks (Giani, 1992; Rossmanith & Uenishi, 1997; Hoek, Rippere, & Stacey, 2000). During operation, blasting extends current discontinuities and creates new fractures in the rock mass, which generates more potentially unstable blocks (Zou & Wu, 2001; Hagan & Bulow, 2000). For an uncontrolled production blast with a free face, the in situ rock may be damaged a distance of 1-1.5 times the face height into the rock mass, if not more (Hoek & Karzulovic, 2000). In addition, the rock mass may be subjected to more than one blast due to the multiple benches used in a surface mine. On the positive side, using controlled blasting techniques will reduce the amount of blast induced cracking which will improve the stability of a slope (Harries, 1982).

Even with blocks that are free to move, rockfalls will not occur unless the forces acting on the block change in such a way as to cause instability (Call & Savely, 1990; Hoek, 2007). These triggers are seemingly endless in the mining environment. The most important cause is water, and multiple studies have found that the majority of failures can be attributed to the presence of water (Pantelidis, 2009). More specifically, Hoek (2007) presents numerous causes. Increased pore water pressure from rain, runoff, or groundwater can force a block from the wall. Vegetation growing in the fractures in the wall can push blocks out as well as leverage blocks when swaying in the wind. Over time, freezing and thawing slowly wedge discontinuities open and force blocks loose. Physical and chemical weathering leads to weakening of the rock, thereby creating instability. Loss of the supporting material below a block can cause a rockfall, as well. This cause has led to the study of key blocks, which are blocks which allow movement of other blocks when removed from the wall. Identifying and securing these key blocks is important for wall stability. Rossmanith and Uenishi (1997) add cyclic temperature change to the list of causes, as supported by drillers and blasters' observations of numerous rockfalls in the early hours of the morning. The cycles of elongation and contraction due to the daily temperature change result in frictional slip and rock movement.

Hoek (2007) also suggests that rockfalls can be caused by blasting, construction, and other mechanical means with a potential for occurrence of one to two orders of magnitude higher than the aforementioned triggers. This statement means that miners must be extra careful because a mine meets Hoek's designation for increased chance of rockfall. With all of these sources of rockfall, mine designers are left to try to prevent rocks from falling or stop falling rocks from endangering personnel and equipment.

2.3 Slope Classification

The first step many practitioners take when designing a new slope or improving a current one is to classify or rate the slope based on instability. Many classification systems have been developed for or applied to slope evaluation, and a good system must be simple to understand, functional, based on easily obtained measurements, and exact enough for the application

(Wittreich, 1987). Numerous systems have been developed over the years for use in a variety of environments.

Some of the first classifications were developed by Terzaghi and Deere et al. In 1946, Terzaghi developed one of the first rock classification systems, the Rock Load Theory, which is mainly used for tunneling (Bhawani & Goel, 1999). Deere et al (1967) proposed the Rock Quality Designation index (RQD) as a means of assessing rock mass quality from core samples as part of a four step design template for structures in rock (Hoek, 2007). RQD has become a very basic measurement parameter and has been included in many classification systems since its inception.

In 1972, the Rock Structure Rating (RSR) developed by Wickham et al pioneered the use of individual quantitative ratings based on three parameters: geology, joint geometry, and groundwater/joint condition (Hoek E. , Rock Mass Classification, 2007). These three parameters are scored individually and then added together to obtain the overall RSR. This ground-breaking technique of combining ratings for different parameters has been subsequently adopted for most of the classification methods developed after 1972.

Two years later in 1974, Barton, Lien, and Lunde of the Norwegian Geotechnical Institute (NGI) proposed the Rock Mass Quality System (Q) by combining RQD, four joint parameters, and a Stress Reduction Factor into one rating after analyzing over 200 case histories of tunnels and caves (Bhawani & Goel, 1999). The four joint parameters are as follows:

1) Joint Set Number: total number of joint sets
2) Joint Roughness Number
3) Joint Alteration Number
4) Joint Water Reduction Factor: a measure of pore water pressure

The rating for each of these parameters is taken from tables developed from the case history analysis. The Stress Reduction Factor is also taken from a table based on rock condition and can be considered a measure of the total stress (Bhawani & Goel, 1999).

Bieniawski extended Terzaghi and Wickham's work in 1976 with the publication of the original Rock Mass Rating system (RMR) which uses 5 parameters and is well suited for tunneling (Bhawani & Goel, 1999; Hoek, Rock Mass Classification, 2007). The five parameters are:

1) Uniaxial Compressive Strength
2) RQD
3) Discontinuity Spacing
4) Discontinuity Condition
5) Groundwater

Just like the Q System, RMR uses tables for the selection of the values for each parameter. This system has also been revised over the years by Bieniawski and others as more case studies have been performed (Hoek, Rock Mass Classification, 2007). Although these classification schemes can be applied to rock slopes, most were designed for underground use. Practitioners should keep in mind that extending the use of a classification system can lead to problems (Palmstrom & Broch, 2006; Pantelidis, 2009).

Luckily, more specific attention has been given to surface rock mass classification in the past thirty years, and slope designers have a number of tools from which to choose. In 1979, Bieniawski added a discontinuity orientation parameter to RMR to make the system more suitable for rock slopes (Pantelidis, 2009). Similar to RMR, Romana developed the Slope Mass Rating (SMR) in 1985 for evaluation of rock slopes (Bhawani & Goel, 1999). The SMR includes three parameters accounting for joints and joint/slope interaction as well as a fourth parameter, an adjustment for excavation method (Bhawani & Goel, 1999). Another example is Rock Mass Number, which is an attempt to improve RMR. The Rock Mass Number system simply removes the Stress Reduction Factor but is the same as RMR in every other way. Removing the stress parameter eliminates the error associated with selecting that factor improving the overall rating. Palmstrom pulled the best from 15 rating systems in 1995 to develop the Rock Mass index (RMi) (Bhawani & Goel, 1999). RMi covers a variety of conditions and uses the following parameters (Palmstrom, 2010):

1) Uniaxial Compressive Strength
2) Joint Roughness
3) Joint Alteration
4) Joint Size
5) Joint Spacing

The Geologic Strength Index (GSI) is a more user friendly classification system which shies away from the quantitative nature of previous classification schemes. Developed by Hoek in 1994 and reworked into its current form by Hoek and Marinos, GSI uses an estimation of structure and surface conditions to obtain a rating (Marinos, Marinos, & Hoek, 2005). This system is more qualitative and is meant to provide an estimation of the properties of the rock without providing any recommendations for support or reinforcement, but an experienced person is required for appropriate ratings (Bhawani & Goel, 1999).

Many rock slope classification methods come from highway slope design. Highway slope design and mine slope design are essentially equivalent, and classification methodology can be used interchangeably for the two environments. The Oregon Department of Transportation (ODOT) developed the Rockfall Hazard Rating System (RFHS) with the objectives of rating slope's rockfall potential and helping determine allocation of funding (Santi, Russel, Higgins, & Spriet, 2008). RFHS has six parts which are as follows:

1) A single database for slope inventory
2) Preliminary rating into three categories A, B, or C; A is the highest rockfall potential
3) Detailed rating of the most hazardous slopes
4) Preliminary design for remediation of the worst slopes
5) Project development
6) Annual review

This process helps DOT's use resources efficiently and quickly improves the overall highway safety. The detailed rating (Step 4) is a quantitative and qualitative system using 12 parameters where a higher score indicates a more hazardous slope (Kliche, 1999). The 12 parameters used are slope height, ditch effectiveness, average vehicle risk, percent of decision sight distance, roadway width, block size/quantity per event, climate/presence of water, rockfall history, and four parameters based on joint conditions and erosion (Kliche, 1999).

An adaptation of Colorado's version of the RFHS is the Modified RFHS. Santi et al from the Colorado School of Mines rated 355 slopes in the state using five main categories: slope conditions, climatic conditions, geologic conditions, discontinuity conditions, and risk (See Table 2.I) (Santi, Russel, Higgins, & Spriet, 2008).

Table 2.I: Modified RFHS Parameters

Category	Parameter
Slope	Height
	Rockfall Frequency
	Average Slope Angle
	Launching Features
	Ditch Catchment
Climate	Annual Precipitation
	Annual Freeze/Thaw Cycles
	Seepage/Water
	Slope Aspect
Geology	Sedimentary Rock: Degree of Undercutting
	Sedimentary Rock: Jar Slake
	Sedimentary Rock: Degree of Interbedding
	Crystalline Rock: Degree of Overhang
	Crystalline Rock: Weathering Grade
	Block-in-Matrix Rock: Multiplier
	Block-in-Matrix Rock: Block Size
	Block-in-Matrix Rock: Block Shape
Discontinuities (only for Sed/Cr Rock)	Block Size/Volume
	Number of Sets
	Persistence and Orientation
	Aperture
	Weathering Condition
	Friction
Risk (Traffic)	Sight Distance
	Average Vehicle Risk
	Number of Accidents

These five categories contain the 12 parameters from the original RFHS and more. Using univariate least squares regression, the statically significant parameters were found and ranked based on importance. Equations were then created based on the three studied rock material types: crystalline, sedimentary, and block-in-matrix (Santi, Russel, Higgins, & Spriet, 2008). Block-in-matrix is material where the erosion of the matrix controls rockfall, for example glacial till or debris flow deposits. These equations can be used to give an estimated RFHS score without wasting time and resources collecting extraneous data. The presence of launch features and slope aspect were found to be the only two parameters significant for all slopes. For crystalline rocks, the other most significant parameters are slope height, degree of overhang, and persistence/orientation of joints (Santi, Russel, Higgins, & Spriet, 2008).

Specifically developed for mining, Rockfall Risk Assessment for Quarries (ROFRAQ) is a risk assessment method developed in 2008 for use in temperate climates (Alejano, Stockhausen, Alonso, Bastante, & Ramirez Oyanguren, 2008). ROFRAQ not only rates the condition of the wall but also accounts for risk. Using a probabilistic approach assuming that an accident occurs as a result of a chain of events, ROFRAQ rates the following six categories to obtain a final ranking:

1) Slope condition
2) Failure mechanism
3) Chance of triggering event
4) Likelihood of a rockfall reaching the mine bottom
5) Likelihood of a rockfall impacting personnel or equipment
6) Rockfall History

Taking the categories in order shows the chronology of a rock fall. These six ratings can then be combined to yield the chance of a rockfall causing an accident (Alejano, Stockhausen, Alonso, Bastante, & Ramirez Oyanguren, 2008). The most important rating is the likelihood of a rockfall impacting personnel or equipment. Similarly to ratings discussed previously, ROFRAQ uses a table of predetermined values to calculate the final score.

2.4 Slope Design

Once the slope(s) in a mine have been rated using an appropriate classification scheme, a practitioner can begin to create a slope design which balances safety, risk, and economics. Many slope stabilization methods are currently in use in mines throughout the world. These methods range from proper configuration of the slope to rock bolts and shotcrete. Hoek (2007) asserts that for protecting highways from rockfalls the most effective method is a catchment ditch at the toe of the slope. The equivalent for the mining industry would be a catch bench with a berm. As such, the design of catchment ditches in the highway industry and the catch berms in the mining industry have been extensively studied by researchers.

One of the pioneers in the study of slope catchment design is Arthur M. Ritchie of the Washington State Highway Commission. In 1963, Ritchie published design guidelines for catchment width and ditch depth based on his rockfall research (Ritchie, 1963). The guidelines were based on data from simulated rockfalls Ritchie caused by rolling rocks down various natural and manmade talus and quarry slopes (Pierson, Gullixson, & Chassie, 2001). Ritchie measured the distance the rocks landed and rolled from the toe of the slope as well as observed the rock's motion by recording each fall on 16-mm film (Ritchie, 1963). Ritchie also tested containment systems including a ditch, mimicked by an inclined wooden platform mounted on a truck, and rock fence (Ritchie, 1963). The design guidelines published by Ritchie became the standard for highway slope design until a change in the law prevented steep ditches next to roadways.

With the change in the law, Ritchie's design guide no longer applied for highway design. With the goal of creating a new design guide and filling in the gaps of Ritchie's work, ODOT undertook a comprehensive study of rockfalls; the results of which were published in 2001 (Pierson, Gullixson, & Chassie, 2001). The study was performed on a representative pre-split highwall in order to accurately replicate a highway slope. The comprehensive design charts are a result of over 11,250 rocks being rolled from slope heights of 40-80 ft, slope angles of 45°-90°, and catchment angles from flat to 4H:1V (Pierson, Gullixson, & Chassie, 2001). The charts are structured to help practitioners design for percent retention of rockfalls, which is an improvement from previous methods. ODOT's design charts allow users to optimize the slope design.

In addition to the ODOT study, numerous researchers have performed simulated rockfalls to better understand the design issues and parameters. Azzoni and de Freitas (1995) analyzed the results of rockfall testing in order to better understand the selection of the input parameters for rockfall computer simulation programs. Giani, Giacomini, Migliazza, and Segalini (2004) set up rockfall testing on two slopes with the goal of better understanding the motion of a rock during a fall as well as the parameters associated with a rockfall. Alejano, Pons, Bastante, Alonso, and Stockhausen (2007) simulated rockfalls using the program RocFall and used the results to create design charts giving designers a tool for safe slope design. Giacomini, Buzzi, Renard, and Giani (2008) dropped rocks in a quarry to better understand rock fragmentation during a fall, specifically focused on foliated rocks.

Many of the studies mentioned above used the results of the experimental testing to evaluate predictive methods. Furthermore, much research has gone into applying the results of highway slope research to mining (Ryan & Pryor, 2000). These predictive tools generally take one of three forms. The first and most basic is the form of an equation, usually connected to slope height, which calculates the recommended bench width. Many scholars have published equations including Call (1992) and Ryan and Prior (2000). Call's design equation is an application of Ritchie's recommendations applied to a mining environment, and Ryan and Pryor's version is an attempt to make Call's equation less conservative. Clearly, this method of bench design is very general and may not fit all situations but can be used as a starting point.

The second methodology uses design charts which account for more slope configurations and often includes data on percentage of rocks retained. The ODOT design charts take this form, for example (Pierson, Gullixson, & Chassie, 2001). Other researchers have chosen this form as well, including Alejano et al (2007). Most of the design charts include data on expected percent retention of rockfalls which allows practitioners to balance the competing demands of safety and cost.

The third form employs computer models to predict rockfall results. Numerous programs exist, and most allow the user to input a slope and material properties. Once the slope and materials have been entered into the program, a form of statistical analysis will be run in order to predict rockfalls. One of the first, Colorado Rockfall Simulation Program (CRSP), was developed in 1988 by Timothy J. Pfeiffer for his Master of Engineering thesis and v4.0 is currently available (Jones, Higgins, & Andrew, 2000). Published by Rocscience Inc, RocFall is another program which will simulate rockfall energy, velocity, bounce height, and endpoint based on user inputs (Rocscience Inc., 2010). A final example is STONE; a program which will assess rockfall risk on a more regional level using a digital terrain model and GIS capabilities (Guzzetti, Crosta, Detti, & Agliardi, 2002). Unfortunately, these programs are not 100% accurate; they are only as good as the input parameters and the analytical assumptions made in the calculations. For example, RocFall operates in two dimensions, but rocks obviously fall in three dimensions which results in inherent error.

In addition to research devoted to improving the quality of the simulation within the programs, many papers have been published regarding the selection of the parameters for the program inputs (Giani, Giacomini, Migliazza, & Segalini, 2004; Azzoni & de Freitas, 1995). For example, a help document published by Rocscience cites nine separate papers in addition to user feedback as guidance for RocFall input parameter determination (Rocscience Inc., 2010). The variability of material properties of a rock mass warrants testing the properties of the rock being simulated. If material testing has not been performed, the input parameters can be chosen by comparing simulation and experimental results. Matching the results of rolling rocks down an actual slope to the simulation can be achieved by adjusting the input parameters. Once the simulations match the experimental rockfalls, the programs can be used to design appropriate benches. These three forms of rockfall prediction are invaluable to a slope designer.

Unfortunately, the myriad of criteria and programs can cloud the issue of bench design further. The author believes that the existence of so many methods indicates that the task of rockfall prevention must be very case specific. No one criterion will cover everything. Luckily though, past research has laid out a clear path to follow when designing a slope, and practitioners can use the most appropriate tools available to create a safe, economic slope.

3 Testing Description

The rockfall testing performed for this project consists of rolling rocks of various sizes off a standard highwall in two quarries owned by Luck Stone Corp. Site 1 is a granite quarry and Site 2 is a diabase quarry. The section of highwall used for the tests was chosen to represent an average quality wall, as determined by the foremen at each site. The site foremen deal with the walls everyday and are the most qualified people to choose an average section of wall meaning the walls were not overly smooth or rough. The chosen walls were also away from production areas to avoid interfering with operations as well as remove distractions for safety reasons. In addition, a wall profile with a pronounced launch feature was chosen at Site 1 by the author.

3.1 Experimental Testing Setup

Before the actual testing began, the test setup was completed. Along the chosen wall sections 4 drop points were selected by so that the falling rocks would encounter the main features in the wall. In addition, a fifth profile was selected to encounter a major launch feature along another section of wall at Site 1. This setup led to nine total drop points: four average profiles at Site 1, one launch feature profile at Site 1, and four average profiles at Site 2. Figure 3.1, Figure 3.2, and Figure 3.3 show pictures of the walls for each of the nine profiles.

Figure 3.1: Picture of Wall from Site 1, Profiles 1-4

Figure 3.2: Picture of Wall from Site 1, Profile 5

Figure 3.3: Picture of Wall from Site 2, Profiles 1-4

These locations were profiled using a laser scanner to record the cross section. An example of a profile from Site 2, Profile 1, taken with a Laser Atlanta Profiler II can be seen in Figure 3.4, and all profiles can be seen in Appendix A.

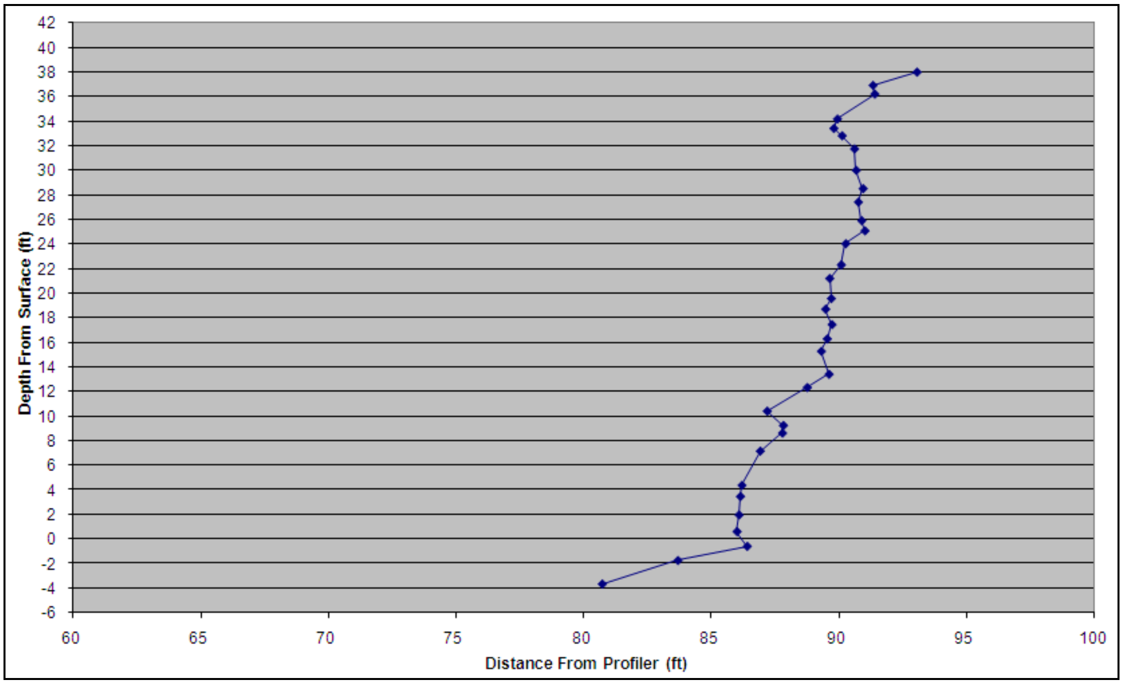


Figure 3.4: Example Output from Laser Profiler

At the crest of the wall, rocks of various sizes were collected and placed near the drop points. The rocks were classified into 5 size categories: 1 ft, 2 ft, 3 ft, 4 ft, and 5 ft. These classifications were determined by the length of the longest axis of each rock. Each classification was given ±6 in from the category size; therefore, a rock categorized as 2 ft could range from 18 in to 30 in (2 ft ±6 in) along the longest axis. Table 3.I contains the size range for each rock category used.

Table 3.I: Rock Size Categories

Rock Category	Size Range (in)
1 ft	6-18
2 ft	>18-30
3 ft	>30-42
4 ft	>42-54
5 ft	>54-66

The smallest rock had a length of 7 in, while the largest rock measured 60 in long. The selected rocks were not chosen to match certain shapes or sizes. The random aspect in the rock dimensions was desired so as to not skew the data. Figure 3.5 contains a chart showing the range of the rock lengths and widths.

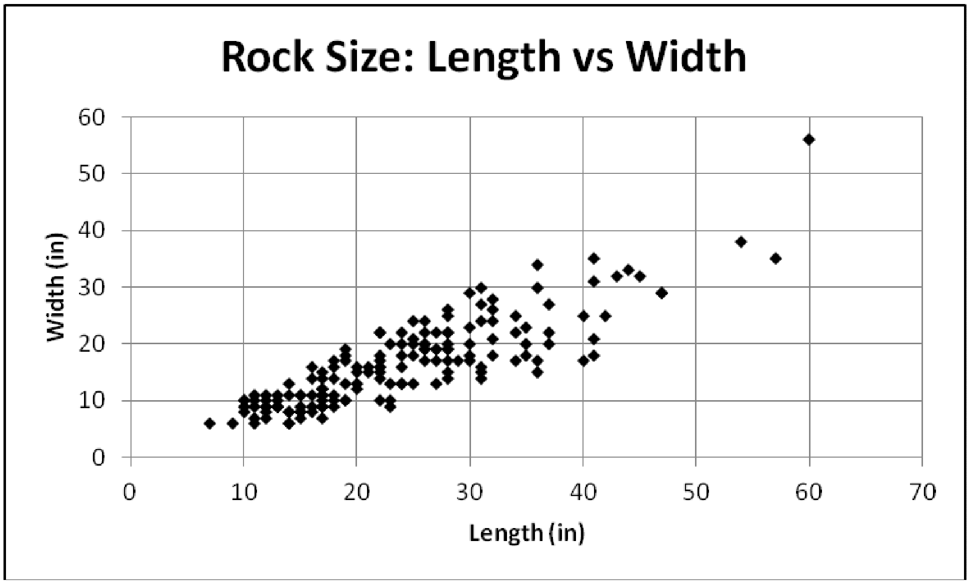


Figure 3.5: Rock Size Distribution

Not all the rocks were measured accurately for size due to safety concerns with being too close to the highwall, but observation of the unmeasured rocks agree with the size distribution shown in Figure 3.5. In addition to collecting the test rocks, a measurement grid was painted on the floor in 5 ft intervals from the toe of the wall.

3.2 Experimental Testing

Once setup was completed, the actual testing began. An excavator was used to remove a rock from the pile and gently push it off the highwall at the desired drop point. An excavator was chosen for safety, i.e. the machine sits away from the wall, and finesse, i.e. the bucket can push the rock off the wall while imparting minimal horizontal velocity which accurately mimics a natural rockfall. Before rolling a rock, a researcher would make sure everyone was away from the wall at the toe and then radio an all clear signal to the excavator operator. The operator would then roll a rock off the highwall crest. After checking the wall, a researcher would radio a hold signal, and the excavator operator would set the bucket on the ground away from the crest while the measurements were taken. While measuring, at least one person would always be looking at the wall, and no size or GPS measurements were taken on rocks within 10 ft of the toe, assuming it was safe to go that close. After everyone backed away from the wall, the process repeated. The measured parameters are rock length, rock width, drop point, impact distance, rollout distance, wall height, and wall angle. Figure 3.6 contains a plan view diagram showing how each of the rockfall distance parameters was measured.

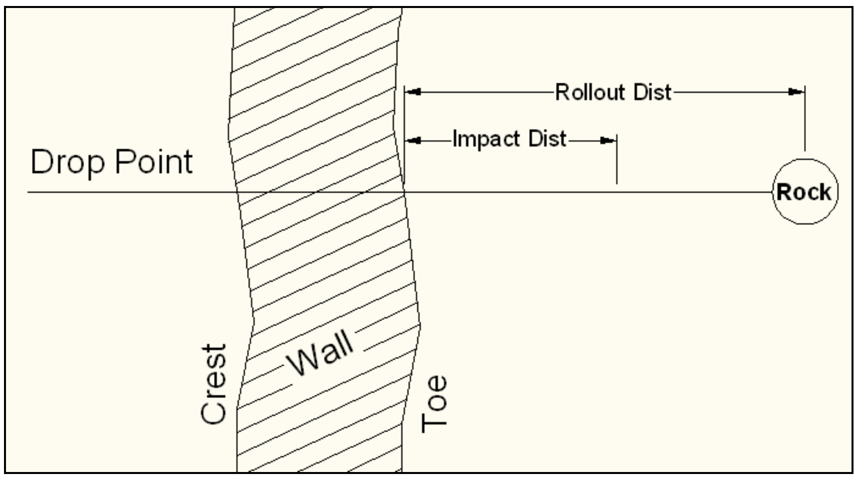


Figure 3.6: Measurement Parameters

The impact distance is the distance from the toe of the wall to where the rock first hits, and the rollout distance is the distance from the toe of the wall to where the rock ultimately comes to rest. In addition to these parameters, the location of the rock was recorded using a handheld GPS, a Trimble Geo XH 2005 Series. Not all rocks could be GPS located because of proximity to the wall or poor satellite positioning. Once the parameters had been recorded, the rock was moved outside of the test area to prevent rocks from hitting each other and skewing the results.

3.3 Testing Results

Rockfall testing was performed for a total of four days at the two sites, two days at each. A total of 230 rockfalls were simulated, but safety concerns only allowed full data collection for 162: 93 at Site 1 and 69 at Site 2. A summary of the testing results can be found in Table 3.II, and a table containing the complete results is shown in Appendix B.

Table 3.II: Testing Results Summary

Result	Site 1	Site 2	Total
# Rocks Rolled	114	116	230
Ave Impact Distance (ft)	8.7	6.7	7.6
Max Impact Distance (ft)	23	20	23
St. Dev. Impact Distance (ft)	5.2	3.2	4.3
Ave Rollout Distance (ft)	11.5	12.2	11.8
Max Rollout Distance (ft)	36	33	36
St. Dev. Rollout Distance (ft)	5.9	6.2	6.1

The results show the similarity between the two sites. The most significant difference, two feet, is in the average impact distance. This difference can be explained by the inclusion of a separate launch feature test at Site 1, which caused larger impact distances.

The impact and rollout distances can also be analyzed for distribution. The distribution of the impacts and rollouts can be seen in Figure 3.7.

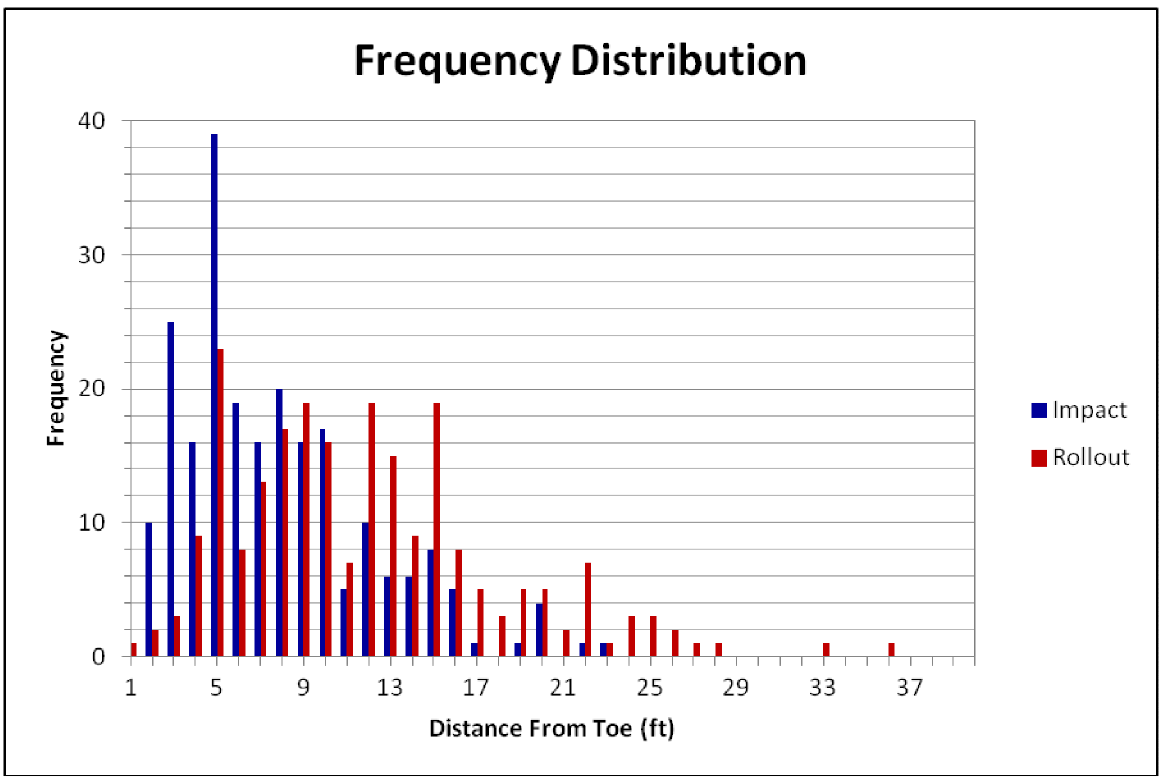


Figure 3.7: Impact and Rollout Frequency Chart

This trend indicates that most rockfalls will impact and rollout to distances within 15 ft of the toe, and a much smaller group will fall outside of this distance. Only 5.7% of trials impacted at a distance greater than 15 ft from the toe, and 21.1% of trials rollout out farther than 15 ft. Excluding the trials from the launch feature test at Site 1 leaves 0.5% of rocks impacting and 15.3% of rocks rolling out greater than 15 ft from the toe. The author suggests that the addition of a berm would serve as a barrier to rolling rocks further lowering the percentage of rocks which rolled past 15 ft from the toe. Such a berm was not included in the experimental testing for this research in order to obtain accurate, unhindered rollout data.

Visual inspection of Figure 3.7 shows a distribution skewed to the right which equates to a lognormal distribution. Using Microsoft Excel, the lognormal equations for the impact and rollout distributions were found and can be seen in Equations 3-1 and 3-2, respectively.

$$\left(\frac{1}{x(0.60)\sqrt{2\pi}}\right)e^{-\frac{(ln(x)-1.87)^2}{2(0.60)^2}} \quad \text{Equation 3-1}$$

$$\left(\frac{1}{x(0.56)\sqrt{2\pi}}\right)e^{-\frac{(ln(x)-2.38)^2}{2(0.56)^2}} \quad \text{Equation 3-2}$$

In both equations, x is a variable representing distance from the toe in feet. A graph of these equations can be seen in Figure 3.8 and the cumulative lognormal distributions can be seen in Figure 3.9.

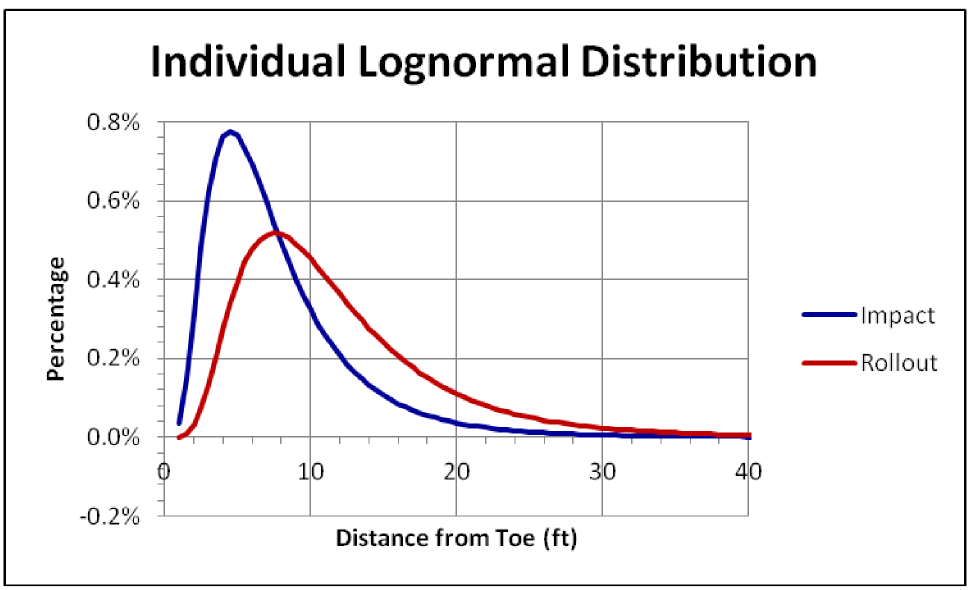


Figure 3.8: Individual Lognormal Distribution

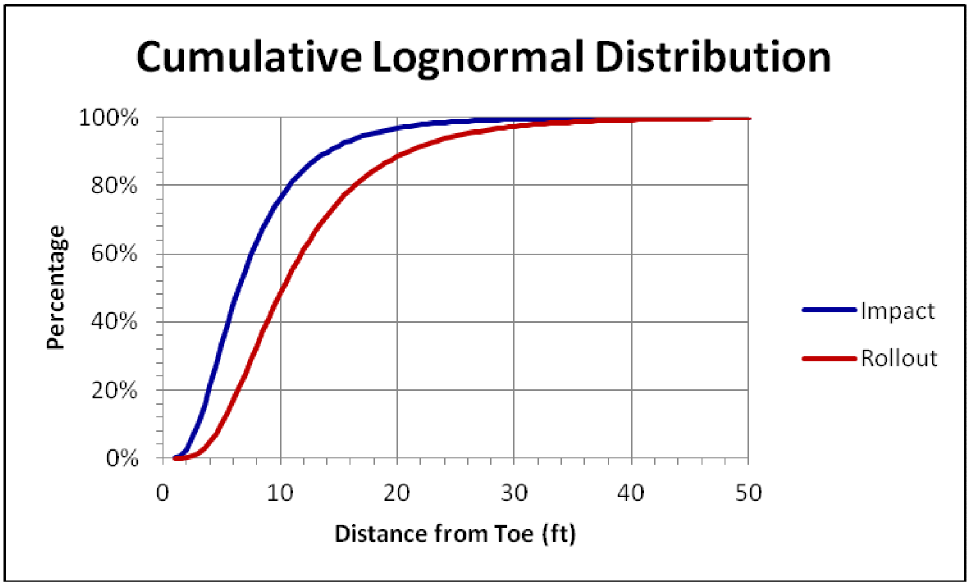


Figure 3.9: Cumulative Lognormal Distribution

These distributions, especially the cumulative rollout distribution, can be used as a basic predictive method for the percentage of rockfalls a bench of given width would retain. Additionally, the curves can be used in defense of a particular design because they are derived from actual rockfall data. The caveat is that this distribution data is site specific, and these curves must be calculated from rockfall data performed at each specific site. For the two sites test for this project, the curves show that 76.4% of rocks will impact within 10 feet from the toe. This result suggests that covering the floor with loose material in the zone 10 feet from the toe would cushion three out of four falling rocks. This cushion would reduce the energy of these rocks and prevent them from rolling out as far.

4 Spatial Data Analysis

4.1 Introduction of Methods

To begin the analysis of the data recorded during the rockfall testing, the most appropriate analytical methods were investigated. The data collected during the testing can be considered multivariate in nature meaning that each observation has several associated variables. For each rock, a value was recorded for length, width, impact distance, rollout distance, etc. This data is valuable for understanding the nature of a rockfall, but unfortunately, the complexity of the problem increases with the addition of more variables (Davis, 2002). Each variable can be thought of as an axis in multidimensional data space, but even the visualization of a graph with just three axes can be a challenge (O'Sullivan & Unwin, 2003). How much more difficult is visualization of a data set with six axes, like the one described in this paper?

To solve this problem, researchers have developed what is called multivariate analysis. Multivariate analysis enables researchers to wade through the abundance of variables and data more easily (Davis, 2002). Therefore, statistical methods of multivariate data analysis can be a very powerful tool for breaking down a data set of the kind described in this paper.

For analysis of this data, two specific methods were chosen with the goal of understanding the main factors of a rockfall. The first technique used was Principal Components Analysis in order to identify the most important factors affecting a rockfall. Secondly, Cluster Analysis was used to understand the structure of the data. The author has not found examples of these techniques applied to the study of rockfalls. Therefore, one aspect of this analysis is evaluation of these spatial data analysis methods for analyzing rockfall data.

Using the collected data, Principal Components Analysis (PCA) and Cluster Analysis can be performed in order to discover the relationships between the measured fall data. These spatial data analysis methods are suitable for this type of problem because of the variability inherent to a rockfall. For example, the same rock can be dropped from the same location and result in many different fall paths and final locations. The variability of the rock shape and rotation coupled with the uneven nature of a quarry wall result in a multitude of possible fall paths. PCA reduces the difficulty of the problem by identifying the major factors that influence a rockfall from the original data set (O'Sullivan & Unwin, 2003). Cluster Analysis applies taxonomy to the data with the goals of prediction of future events and identification of cause (Everitt, 1993).

Complete treatment of PCA and Cluster Analysis require more space than available in this paper. A good discussion of both with ties to geologic issues such as the one studied in this paper can be found in Davis (2002).

4.1.1 Principal Components Analysis

PCA is a technique based on the eigenvectors of a similarity matrix of the data, often a correlation matrix. PCA begins by creating this similarity matrix, and the matrix eigenvalues are the Principal Components (PC) of the data set. The number of eigenvalues equals the number of variables; therefore, a data set will have as many PC's as measured variables. In spite of this fact, the PC's are not the same as the original variables. PCs are underlying influences to which the measured variables point. Therefore, the results are open to a degree of interpretation because the results are subjective (Davis, 2002).

The PC's are based on eigenvalues, the principal axes of an ellipsoid created from the correlation matrix. The eigenvalues are orthogonal, unlike the vectors from the original data set (Campbell, Principal Components Analysis, 2010). Due to their orthogonality, the eigenvalues are uncorrelated which allows the major influences on the issue to be observed (Jackson, 2003). Using the PC's, each observation can be linearly transformed into a value uncorrelated with the remainder of the set (Jackson, 2003). This uncorrelated data set is useful for further analysis, such as Cluster Analysis, because the error associated with the correlation in the data set will have been eliminated.

The procedure is designed so that the PC's account for the variability in the data set. By definition, the first PC accounts for the largest percentage of variation in the data. The second PC accounts for the variance not explained by the first PC, and so forth. Therefore, summing the variance explained by each PC will yield the total variance in the data set. Additionally, the PC's may allow for simplification of the data. If the first three PC's account for 80% of the variance, only the scores for those three factors need be used in further analysis, for example.

As described above, PCA has two main benefits: the creation of an uncorrelated data set and the identification of the main factors which cause the observational variance. An uncorrelated data set is important for many data analysis techniques, but correlation is inherent in imperfect measurement techniques. PCA fixes this issue. PCA also highlights the most important factors influencing the observations, even if interpreting the PCs is difficult or subjective (O'Sullivan & Unwin, 2003).

4.1.2 Cluster Analysis

Grouping samples based on similar characteristics is important to discovering the meaning behind the raw data. A table full of measurements does not give a researcher any insight. By arranging the data into related sets, a researcher can better understand the issue through a deeper knowledge of prediction and aetiology, or cause (Everitt, 1993). Classification is a tool that begins to organize the data set into something more useful.

One method of data classification is Cluster Analysis. Generally speaking, Cluster Analysis takes a set of samples and groups the data according to similarity of measurement so that each group is “homogenous and distinct” (Davis, 2002, p. 487). The procedure begins by creating a matrix of similarity between each sample and every other. This matrix can be composed of the original data or the uncorrelated scores from PCA. To begin defining the clusters, the distance between measurements must be calculated. This step is accomplished with a measurement of similarity; a common one is the Euclidean Distance, which works well for ratio and interval type data (Campbell, Cluster Analysis, 2010). A linkage strategy must also be applied to the matrix to combine the individual samples into similar clusters based on the distance calculated between samples. Many linkage strategies exist including Centroid, Simple Average, and Minimum Variance. Once the samples have been sorted into clusters, the data can be displayed graphically and analyzed.

4.2 Methodology

The basic procedure performed for this analysis is described below. Microsoft Excel was used as an initial system of data storage and presentation. All statistical analyses were performed with NCSS Statistical software. Finally, Excel was also used for displaying the statistical results.

4.2.1 Principal Components Analysis

PCA has been selected to begin analyzing the rockfall testing data. Microsoft Excel has been used for data management and display, and NCSS Statistical software has been employed to perform the actual calculations.

After bringing the data into NCSS, the PCA command was chosen from the Multivariate Analysis menu. In the Principal Components window, the variables length, width, impact distance, rollout distance, wall height, and wall angle were chosen as the inputs for each tested rockfall. Figure 4.1 shows the parameters chosen for this analysis in NCSS.

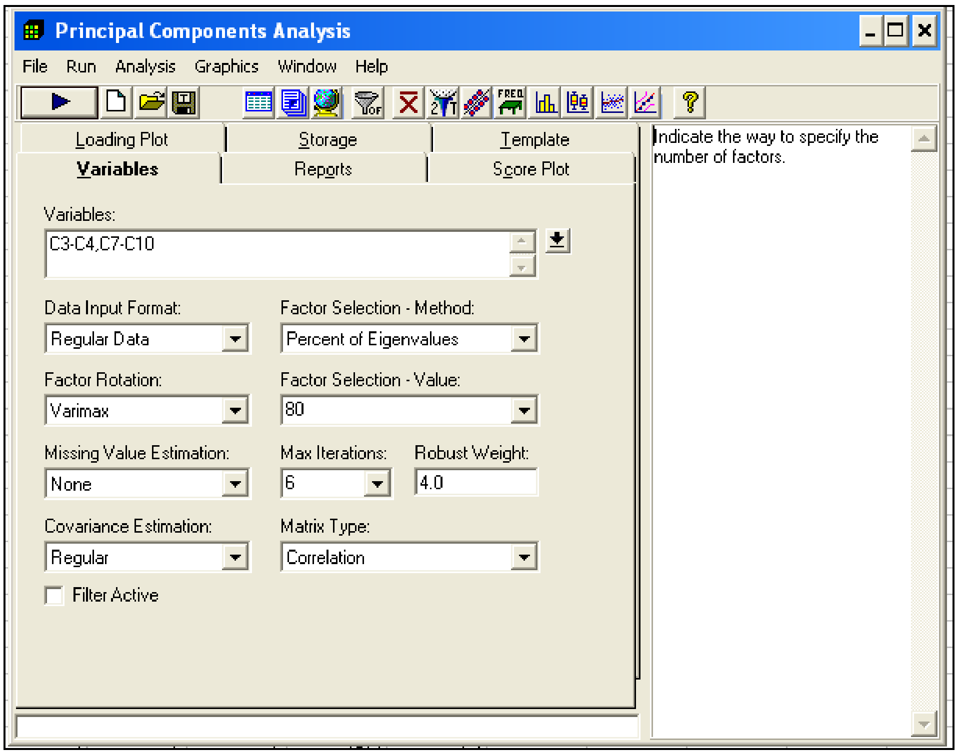


Figure 4.1: PCA Parameters

Once the inputs were chosen, the command was executed. The results were transferred back to Excel to be displayed for analysis. Additionally, the uncorrelated principal component scores were recorded for use in the subsequent cluster analysis.

4.2.2 Cluster Analysis

Cluster Analysis has been chosen to analyze the data collected from the rockfall testing. This analysis has been facilitated by the use of Microsoft Excel for data management and display and NCSS Statistical software for cluster analysis

The data for each sample was first recorded in a Microsoft Excel spreadsheet. This data was then brought into NCSS Statistical Software. In this program, the K-Means clustering command was chosen. In the Cluster Analysis window, the desired options were selected with the goal of finding three clusters. NCSS then outputted various statistical measures from the analysis and grouped the samples into the desired three clusters. The data was then copied into Excel where cluster graphs were created.

4.3 Results

Before accepting the results found from PCA and Cluster Analysis, both methods were evaluated specifically as analytical techniques. Prior uses of these techniques were investigated. Although no examples were found for rockfall data, both have been used for geologic data. Additionally, the rockfall data collected for this project meets the criteria of multivariate data for which PCA and Cluster Analysis are appropriate methods. Secondly, the results of the techniques were compared to prior research and observations. The similarity between the two again suggests that PCA and Cluster Analysis are valid methods for rockfall analysis.

4.3.1 Principal Component Analysis

From the PCA run on the test results, three main principal components were found. These three principal components account for 89.4% of the variation. The loading chart of PC-1 can be seen in Figure 4.2.

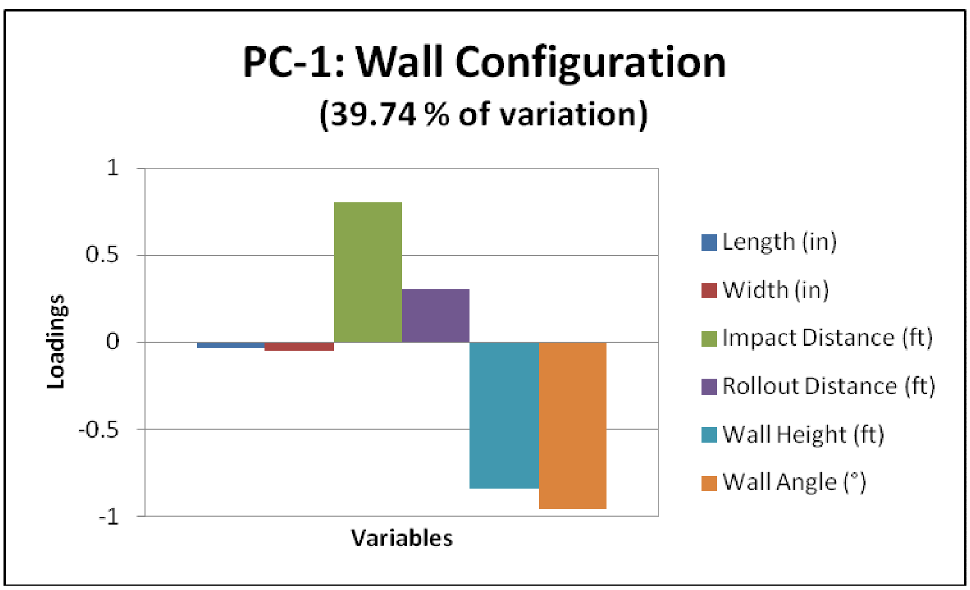


Figure 4.2: PC-1 Loading Chart

This first principal component is determined to be a factor related to wall configuration because wall height and angle clearly affect impact and rollout distances. The designation of this principal component is supported by observation of the rockfalls in the field. The configuration of the wall affected the impact distance, especially, as well as the rollout distance. The wall configuration controlled if the rock hit the wall at all and where it hit which, in turn, influenced the impact and rollout distances. Rocks which hit the wall tended to impact and rollout farther from the toe.

The loading chart of the second principal component can be seen in Figure 4.3.

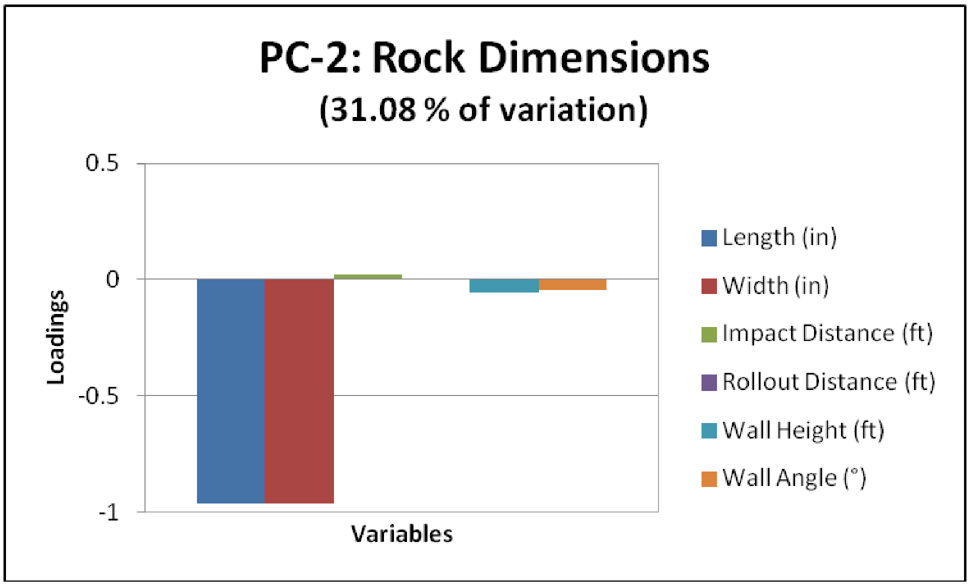


Figure 4.3: PC-2 Loading Chart

Rock size and shape clearly control the second principal component, which is expected to be an important characteristic in rockfalls. Field observations also support this principal component. Rock shape influenced the angular momentum of a rock as it fell and bounced on the wall and floor, and increased angular momentum led to greater rollouts. Rock size also influenced the rollout because larger rocks tended to roll out farther.

The loading chart of the third principal component can be seen in Figure 4.4.

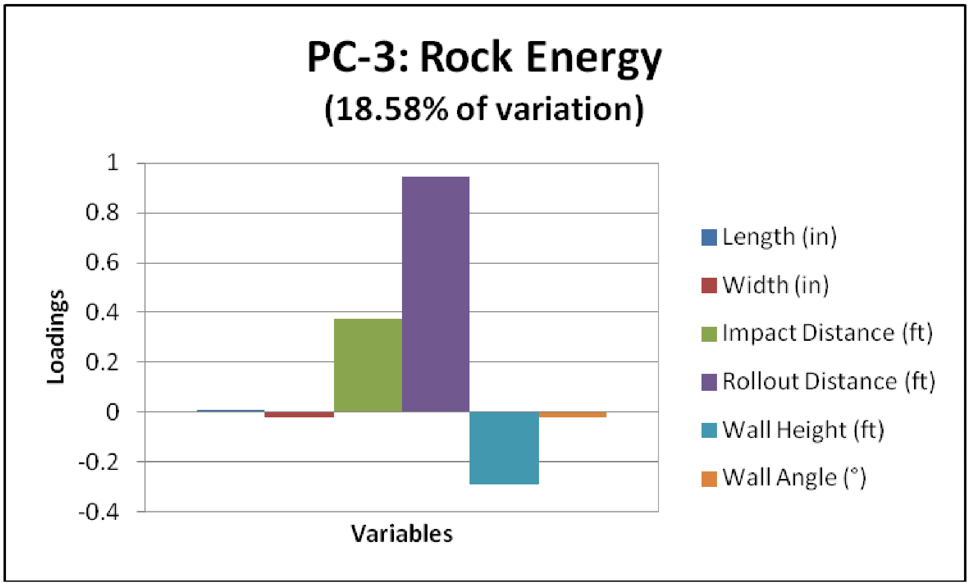


Figure 4.4: PC-3 Loading Chart

Analysis of this chart shows that the third principal component is related to the energy a rock gains during a fall, which is controlled by wall height. The loading emphasis on impact distance, rollout distance, and wall height suggest that the increased kinetic energy a rock gains from falling a greater distance is important.

4.3.2 Cluster Analysis

Cluster Analysis was performed on the uncorrelated PCA scores for each rock using the set of measured variables. After finding the scores for each principal component for each rock, Cluster Analysis was performed. Three clusters were found, and Figure 4.5 contains a graph of PC-1 and PC-2 divided into the clusters.

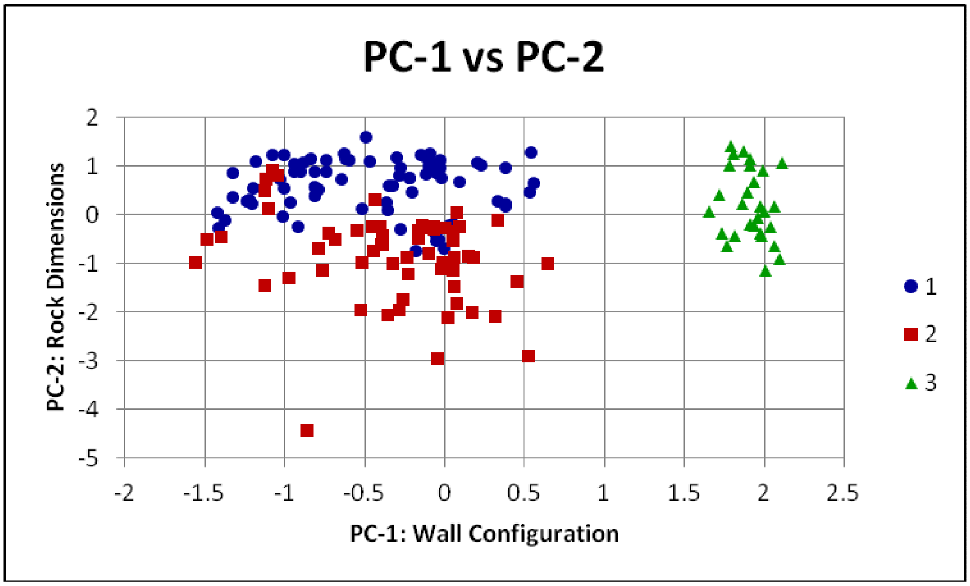


Figure 4.5: PC 1 vs. PC 2

Cluster 3 contains all the test rocks for the launch feature test, Profile 5, at Site 1. This result makes sense because the wall profile caused every rock to hit the wall, reducing the fall energy. Additionally, the launch feature test wall was the shortest wall of all the walls tested, which ranged from 42.7 ft to 45.5 ft. The distinction between Clusters 1 and 2 appears to be from rock size due to the horizontal distinction between the clusters. The average length and width for a rock in Cluster 1 is 18.5 in and 12.1 in, respectively, while a rock in Cluster 2 has an average length of 32.7 in and an average width of 23.3 in.

The next grouping analyzed was PC-1 and PC-3; a graph can be seen in Figure 4.6.

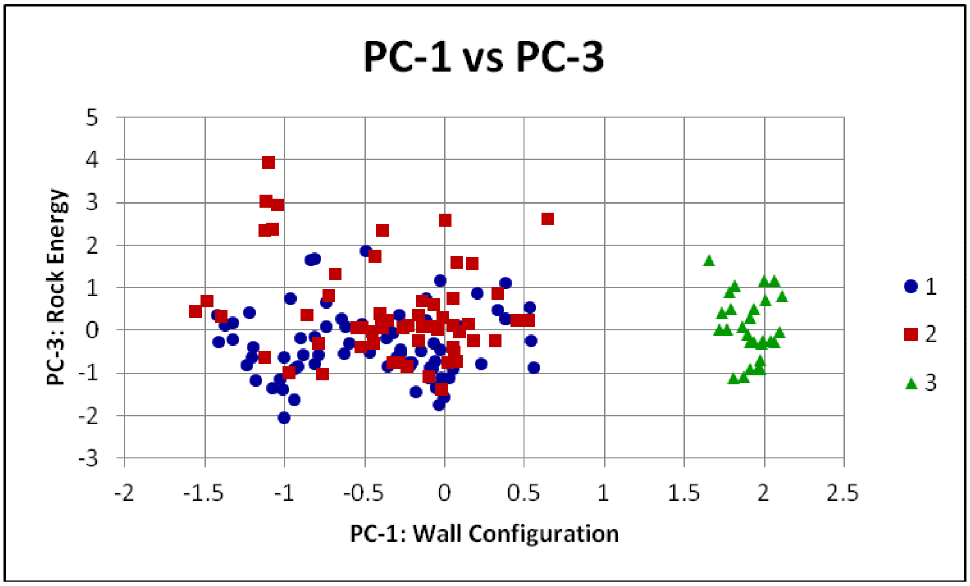


Figure 4.6: PC 1 vs. PC 3

Again, Cluster 3 is due to the launch feature test at Site 1. This cluster is so segregated because the wall configuration and amount of wall interaction was very different that the other tests. The presence of a launch feature sticking out approximately 10 ft from the wall caused every rock to contact the wall. Clusters 1 and 2 are much less defined through, potentially due to the less impact PC 3 has on the overall rockfall.

Finally, Figure 4.7 shows the graph of PC-2 and PC-3.

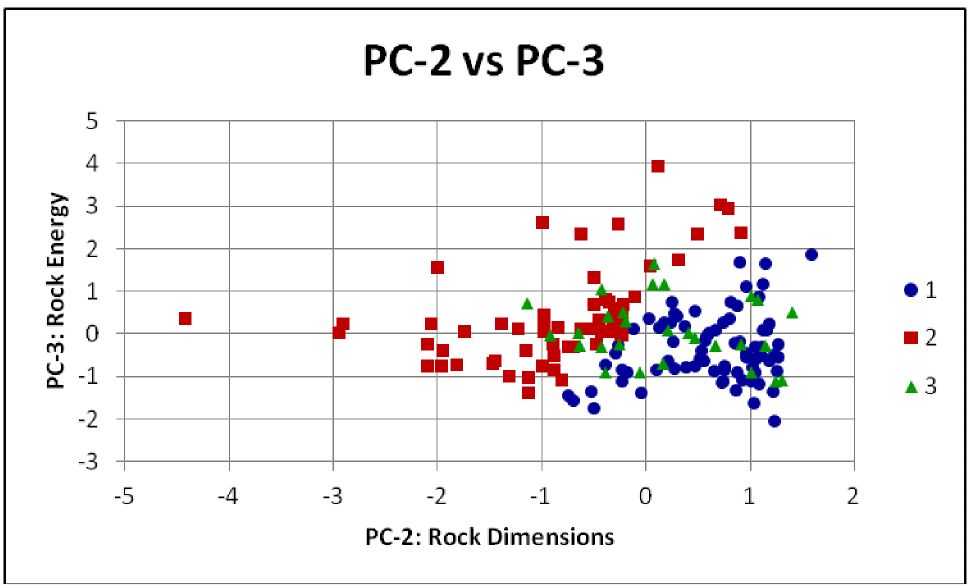


Figure 4.7: PC 2 vs. PC 3

Clusters 1 and 2 appear to be well defined along an axis between PC 2 and 3. Apparently, the combination of these two principal components is a key part of a rockfall for a normal quarry wall. Observations of the rockfalls support this trend. Larger rocks gained more energy due to their size and rolled out an average of farther than smaller rocks. The rocks in Cluster 1 are 14.2 in shorter in length and 11.2 in shorter in width, on average, than the rocks in Cluster 2, and these rocks impacted 1.1 ft closer to the toe and rolled out 3.1 ft less. This trend is not supported through observations of the largest rocks tested (4 ft and 5 ft) which tended to crater the toe on impact and only roll one to two feet, if at all. The scatter in Cluster 3 shows that irregular walls with large launch features change this aspect of a rockfall.

The results of the cluster analysis can also be plotted on other axes to help understand the data better. Figure 4.8 shows the clusters plotted against impact and rollout distances.

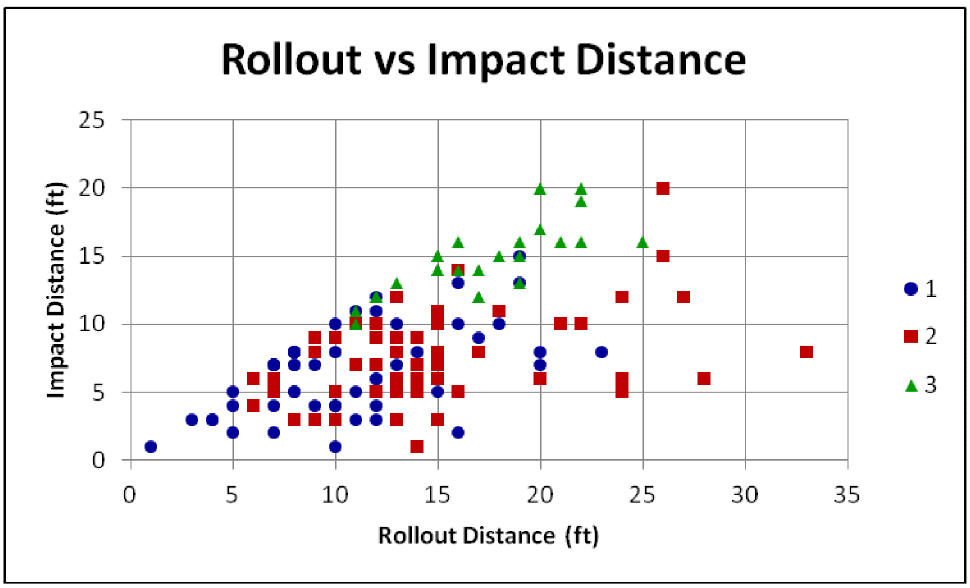


Figure 4.8: Impact vs. Rollout Distances

Again, Cluster 3 is from the launch feature test. A correlation exists between the impact and rollout distances; rocks that first hit farther from the toe tend to rollout farther. Although, uncertainty exists to whether or not the rocks rolled any farther than ones that landed closer to the toe. They may have had larger rollout distances because they simply started rolling farther from the toe. Figure 4.9 shows a graph of the clusters plotted against rock length and width.

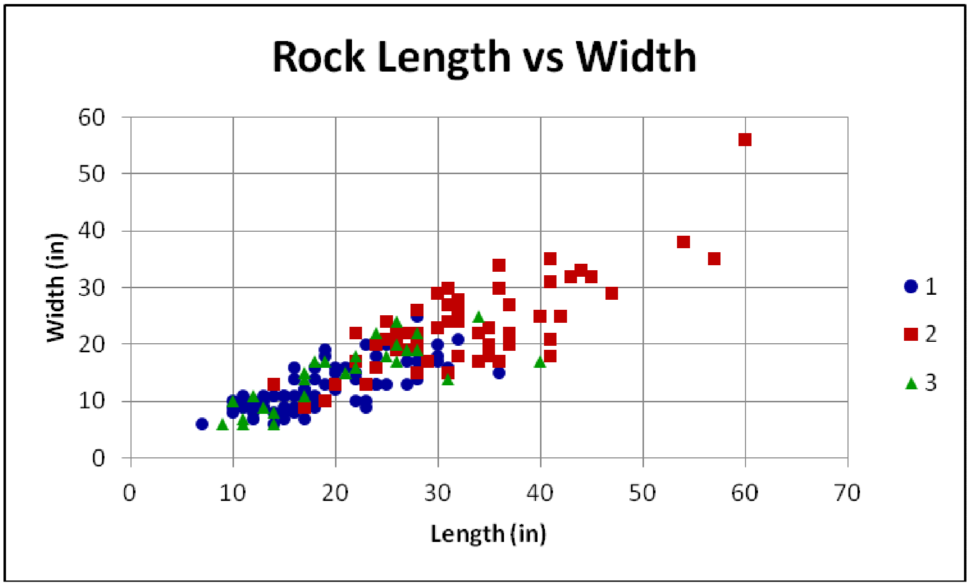


Figure 4.9: Rock Length vs. Width

This chart shows only a slight definition between Cluster 1 and 2 based on the length and width of the rocks. Again, this separation of clusters could be related to the overall size of the rocks since the larger rocks from Cluster 2 rolled farther.

To help understand the impact of the different site geologies, the clusters have been split up by site using the GPS measurement of final rock location. Figure 4.10 contains a graph of the three clusters for Site 1. The launch feature profile was not located near the other four profiles and is shown separately.

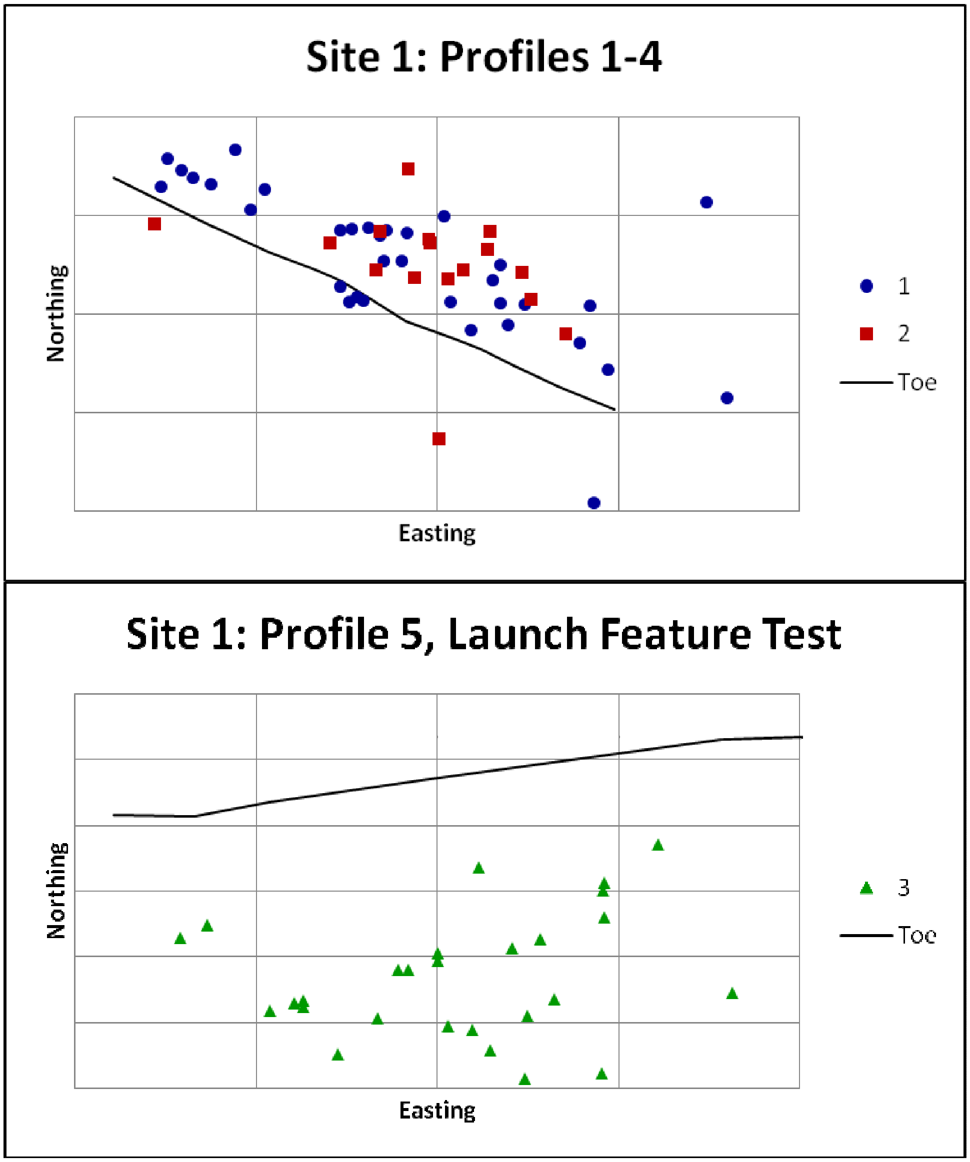


Figure 4.10: Site 1 Spatial Clusters

These charts corroborate the other analysis showing that the launch feature test was very different from the others. The wall configuration and increased rock/wall interaction has a very significant impact on a rockfall. Profiles 1-4 show little delineation between clusters, which could be due to poor precision in the GPS measurements. As shown, some points lie in the wall based on the GPS which is obviously an error. Figure 4.11 contains a graph of the three clusters for Site 2.

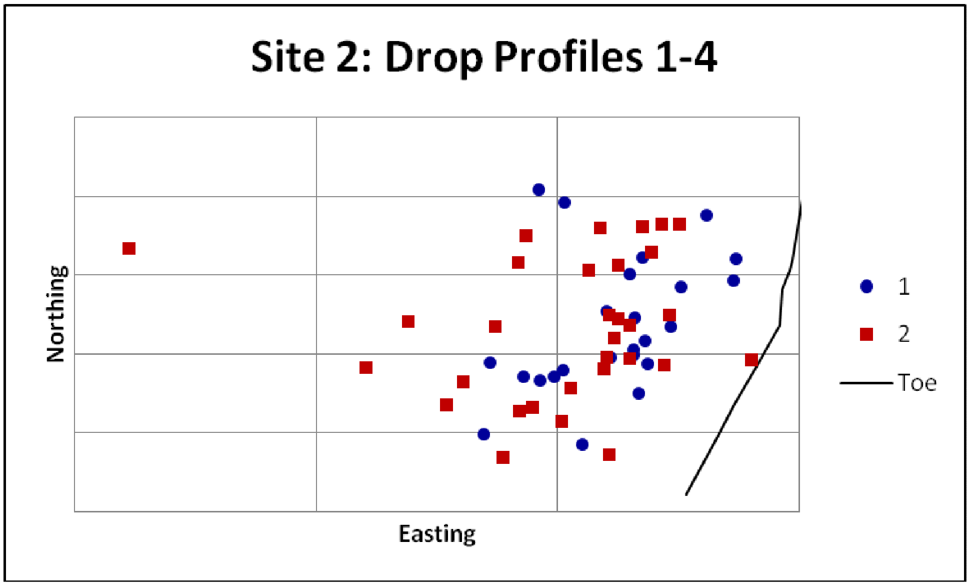


Figure 4.11: Site 2 Spatial Clusters

The chart for Site 2 is just as undefined as Site 1. But, appearances suggest more accurate GPS measurements because no points are located within the wall.

5 Alternative Design Methodology Analysis

5.1 Introduction of Methods

As stated previously, safety bench design is a complicated problem. As such, researchers have studied this issue extensively and proposed what they feel is the best design. In the same way, this report looks to expand this research area by presenting the best practices for safety bench design in surface quarries using the results of testing in two quarries. A number of criteria have been compared to the field testing performed for this work; the results of which will be discussed in detail.

An important note about this analysis is needed regarding the placement of berms on the end of a catch bench. Historically, berms have been placed on the crest of the bench. But after discussions with MSHA, Luck Stone has changed their berm placement so that the toe of the berm lies two feet from the bench crest. This location, as well as covering the crest side of the berm in fine material, reduces the risk of a rock falling from the berm and hitting personnel or equipment. As such, the berm designs used for the following evaluations have been placed two feet from the bench crest.

5.2 Ritchie Criteria

5.2.1 Ritchie Criteria Introduction

Some of the first research undertaken in the area of catch bench design was published by Arthur M. Ritchie, Chief Geologist of the Washington State Department of Highways, in 1963. Ritchie rolled rocks off a variety of walls, observed the rock's motion during the fall, and tested a range of ditch configurations at the toe. The results of the study include a design guide which can be used to select the appropriate ditch depth and distance between the pavement and the wall toe.

The work performed by Ritchie and the Washington State Department of Highways became the design standard highway slopes, and the guidelines were used extensively until a change in highway regulations. Ritchie's design includes a steep ditch, which is unsuitable for vehicles, not allowed for most slopes based on requirements of the American Association of State Highway and Transportation Officials (AASHTO) and in the current Manual on Uniform Traffic Control Devices (MUTCD) published by the US Department of Transportation (Pierson, Gullixson, & Chassie, 2001). See Figure 5.1 for a depiction of a Ritchie designed ditch versus an allowable ditch based on current standards.

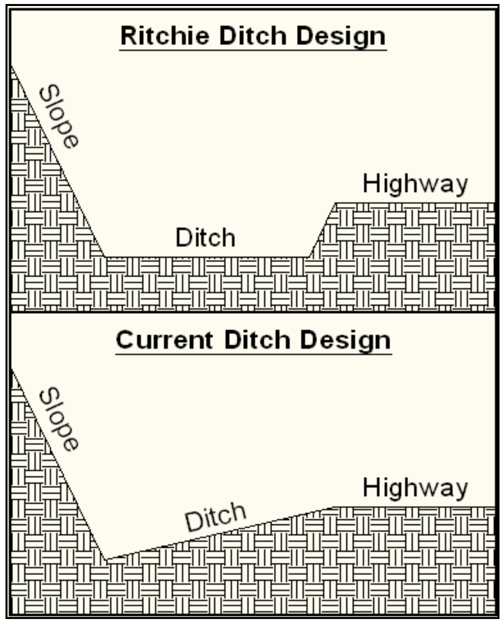


Figure 5.1: Ditch Design Comparison

The current ditch design allows vehicles to maintain control in the catchment area. This fact has led to adjustments of the Ritchie design guidelines which will be discussed below.

Although this study was performed with the intent of preventing rockfalls onto highways, the results can be directly applied to a quarry setting. The Ritchie ditch design closely resembles a catch bench at the toe of a highwall with a berm on the crest of the bench (See Figure 5.2).

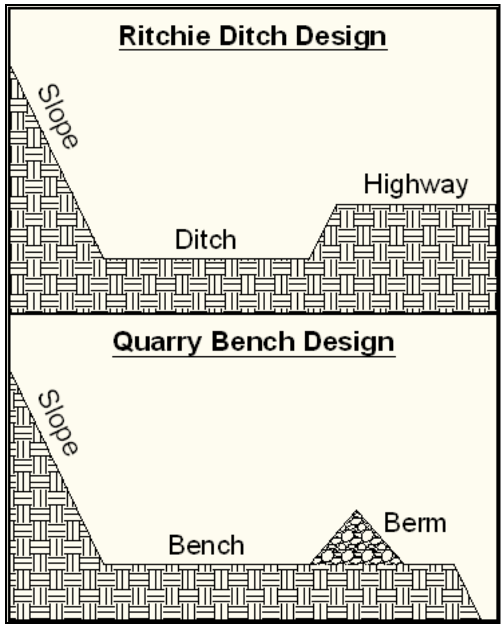


Figure 5.2: Ritchie Ditch, Quarry Bench Comparison

Additionally, the Ritchie's rockfall testing was performed on quarry, highway, and natural slopes which contain numerous launch features (Ritchie, 1963). Controlled blasting techniques were not used on the test slopes, which accurately mimics a typical quarry wall (Pierson, Gullixson, & Chassie, 2001). The design similarities are clear; therefore, the Ritchie design criteria have been analyzed against the data collected for this research.

5.2.2 Ritchie Criteria Methodology

To begin the comparison, the Ritchie design parameters of ditch width and berm height had to be found for each of the nine profiles tested for this research. Ritchie's design guide is based on slope height and overall slope angle. The nine profiles range in height from 42.7 ft to 45.5 ft and overall slope angle from 67.3° to 81.3°. These profile minimums and maximums yield a Ritchie ditch width of 17.5 ft and a berm height ranging from 4.7 ft to 6.2 ft. Because adjusting the berm height by 1.5 ft as the berm moves along a wall with changing slope angle is not practical, this analysis has set the berm height at 5.0 ft in order to minimize the total bench width due to the bench width a taller berm requires. Furthermore, the berm size has been calculated using a 37° angle of repose, an average value for crushed stone (Bullock, Haycocks, & Karmis, 1993; University of Portsmouth, 2001). Back calculating the bench width from Ritchie's ditch recommendations and the berm dimensions leads to a 26.1 ft bench.

To understand how the Ritchie bench design would have performed, cumulative percentage retained curves were created for each profile. The curve shows the percentage of rocks rolled off the profile that had impact or rollout distances less than or equal to a certain distance from the toe of the wall. These curves are graphed for each profile along with the Ritchie bench design for comparison.

5.2.3 Ritchie Criteria Results

The results of the comparison between the test data and the Ritchie criteria are presented based on percentage of rocks retained within a certain distance from the toe. In the report, Ritchie did not give guidance on the percentage of rocks that his design criteria would prevent from leaving the ditch, but an Oregon Department of Transportation study from 2001 found that the Ritchie criteria would retain 85% of rockfalls (Pierson, Gullixson, & Chassie, 2001). The results of this analysis will be similarly presented using percent retention. One note to keep in mind is that the actual test data was collected on flat ground without a berm in place. It is assumed that a rock encountering the inner portion of the berm will only be slowed. Therefore, the test data are assumed to have rolled out farther than if a berm had been in place during testing. On the other hand, rocks that land on the outer portion of a berm will not be slowed by the berm. With these assumptions, the berm crest is a key location for analysis.

All profiles were included in the first profile group that was analyzed. Figure 5.3 and Table 5.I contain the cumulative percentage retained curves and specific data taken from the curves, respectively, for all profiles.

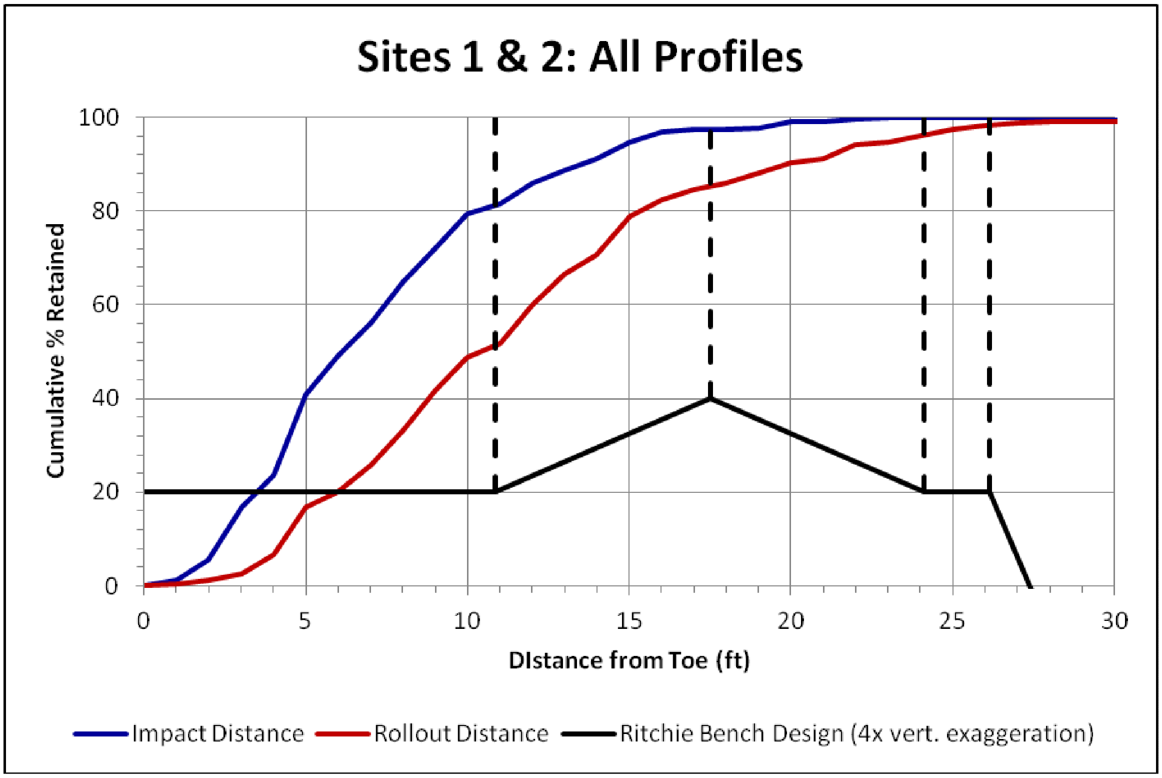


Figure 5.3: Ritchie Catchment Graph - All Profiles

Table 5.I: Ritchie Catchment Data – All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	81.3	51.3
Berm Crest	97.3	85.1
Outer Berm Toe	100.0	96.2
Bench Crest	100.0	98.3

The values are the impact and rollout retentions at the berm crest, the Ritchie recommended value. At the berm crest, 97.3% of impacts and 85.1% of rollouts would be retained within the berm crest on the 26.1 ft bench. The 85% result agrees with the results ODOT's study, but in actuality, the rollout retention is likely higher because the test data were not slowed by the presence of a berm during testing. Furthermore, the outer berm toe and bench crest rollout retentions may be misleading because hitting the outer half of a berm may cause a rock to roll farther than one landing on a flat surface.

The next profile group to be analyzed includes all profiles except the pronounced launch feature profile, Profile 5 at Site 1. Figure 5.4 and Table 5.II contain the cumulative percentage retained curves and specific data taken from the curves, respectively, for all profiles excluding the launch feature profile from Site 1.

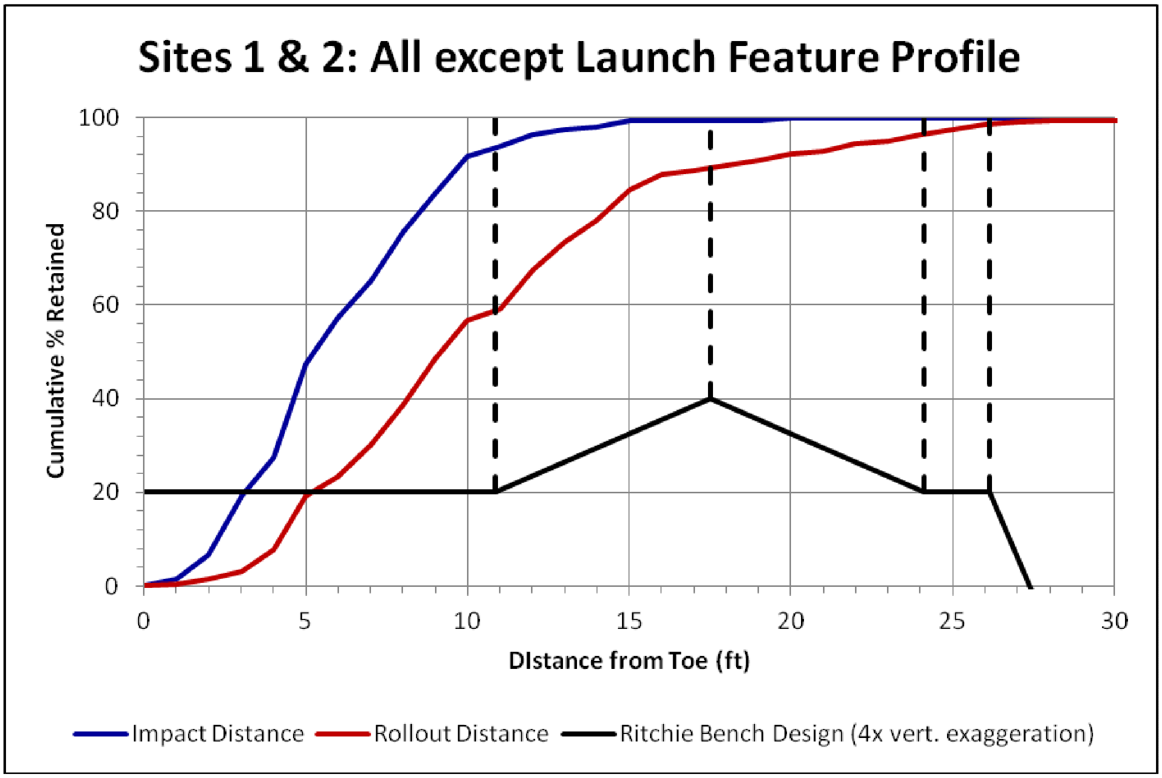


Figure 5.4: Ritchie Catchment Graph – All Profiles except Site 1 Profile 5

Table 5.II: Ritchie Catchment Data – All Profiles except Site 1 Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	93.6	58.8
Berm Crest	99.0	90.3
Outer Berm Toe	100.0	96.6
Bench Crest	100.0	98.5

At the berm crest, 99.0% of impacts and 90.3% of rollouts will be retained within the berm crest. Both values are higher retentions than when the launch feature profile is included in the analysis. This result clearly indicates that launch features within a wall cause rocks to fall and roll farther from the toe, which supports the results from other studies and rockfall observations.

Since geology has been shown to play a significant role in rockfalls, the data were then separated by Site and analyzed. The granite quarry, Site 1 will be discussed first, and the cumulative percentage curves and data table can be seen in Figure 5.4 and Table 5.IV, respectively.

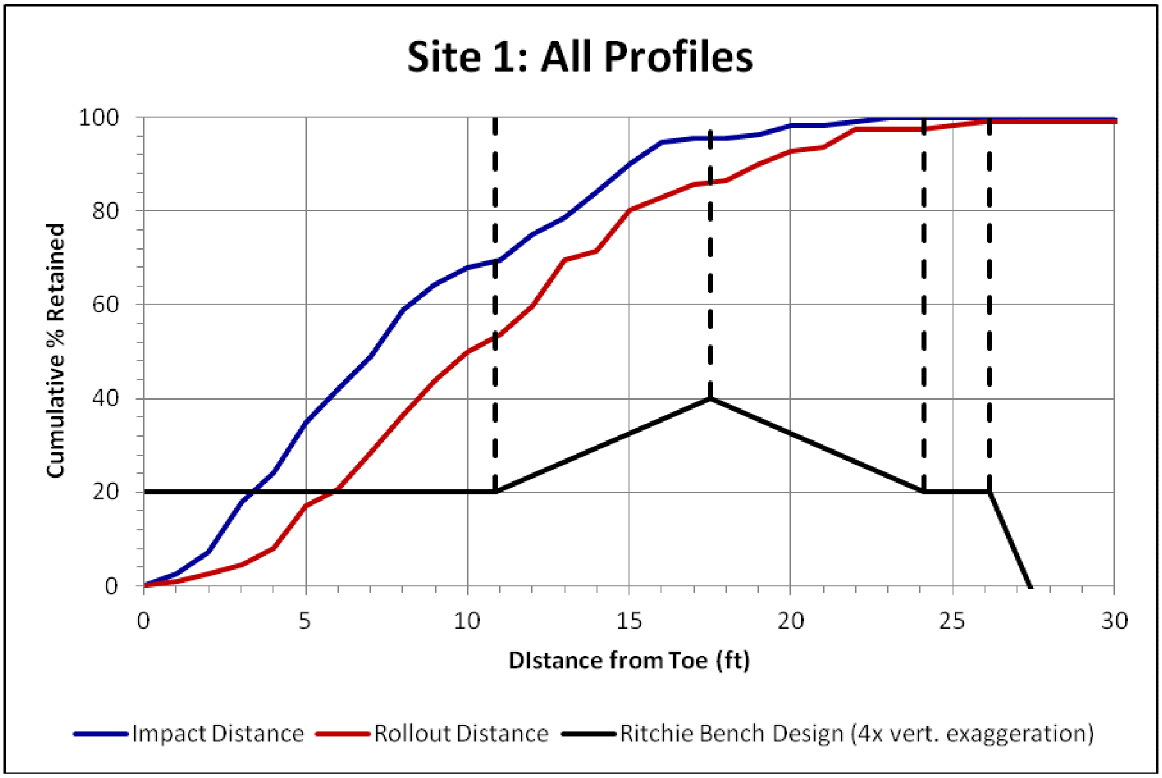


Figure 5.5: Ritchie Catchment Graph – Site 1, All Profiles

Table 5.III: Ritchie Catchment Data – Site 1, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	69.4	53.1
Berm Crest	95.3	86.2
Outer Berm Toe	100.0	97.4
Bench Crest	100.0	99.1

At the berm crest, 95.3% of impacts and 86.2% of rollouts will be retained within the Ritchie design width. Both values are similar to the data using all the profiles. Next, Profiles 1-4 from Site 1 was analyzed without the launch feature profile, Profile 5. Figure 5.6 and Table 5.IV contain the results of the analysis on this profile group.

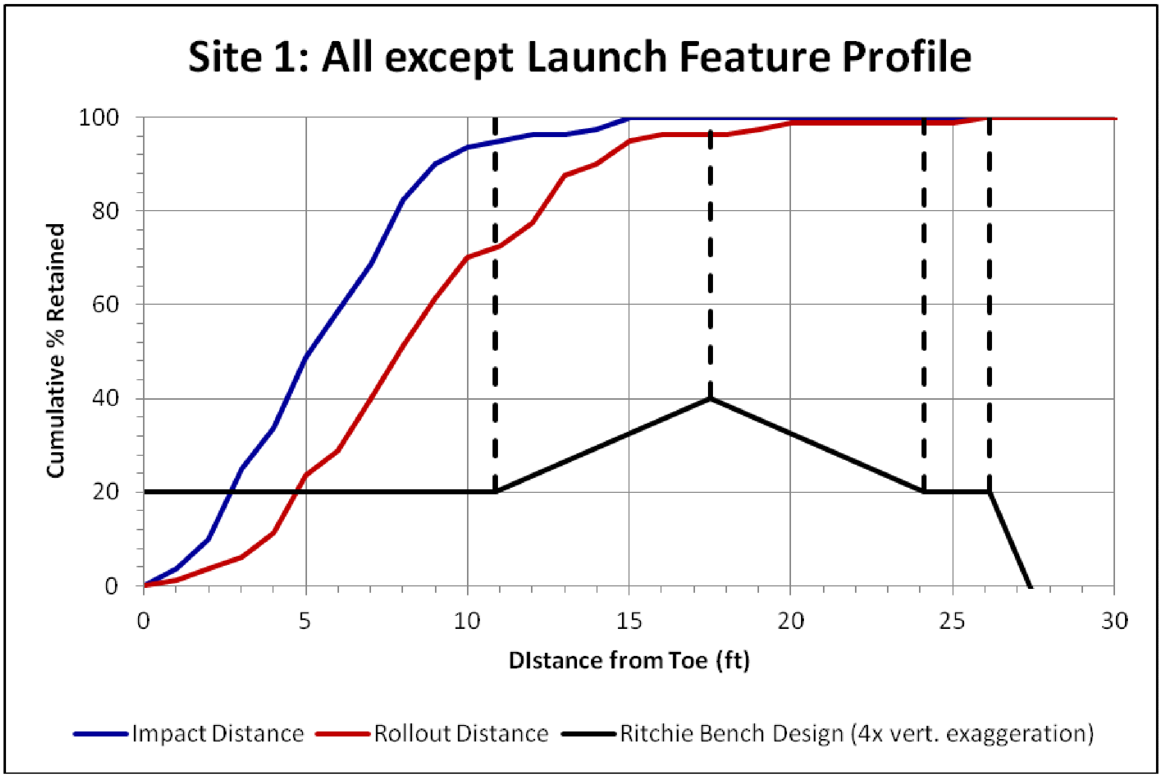


Figure 5.6: Ritchie Catchment Graph – Site 1, All Profiles except Profile 5

Table 5.IV: Ritchie Catchment Data – Site 1, All Profiles except Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	94.8	72.2
Berm Crest	100.0	96.0
Outer Berm Toe	100.0	98.6
Bench Crest	100.0	100.0

At the berm crest, 100% of impacts and 96.0% of rollouts will be retained within the Ritchie design width. By excluding the launch feature profile in this analysis, the true impact can be seen. Without the launch feature tests, all test rocks fell within the berm crest, and the rollout retention increased by 10%. Estimating the impact of a berm on the test data leads the author to believe that all rocks would have been retained with Ritchie's design in this case.

Site 2, the diabase quarry will be discussed next. Figure 5.7 shows the cumulative percentage curve, and Table 5.V shows the retention values from the key bench design locations.

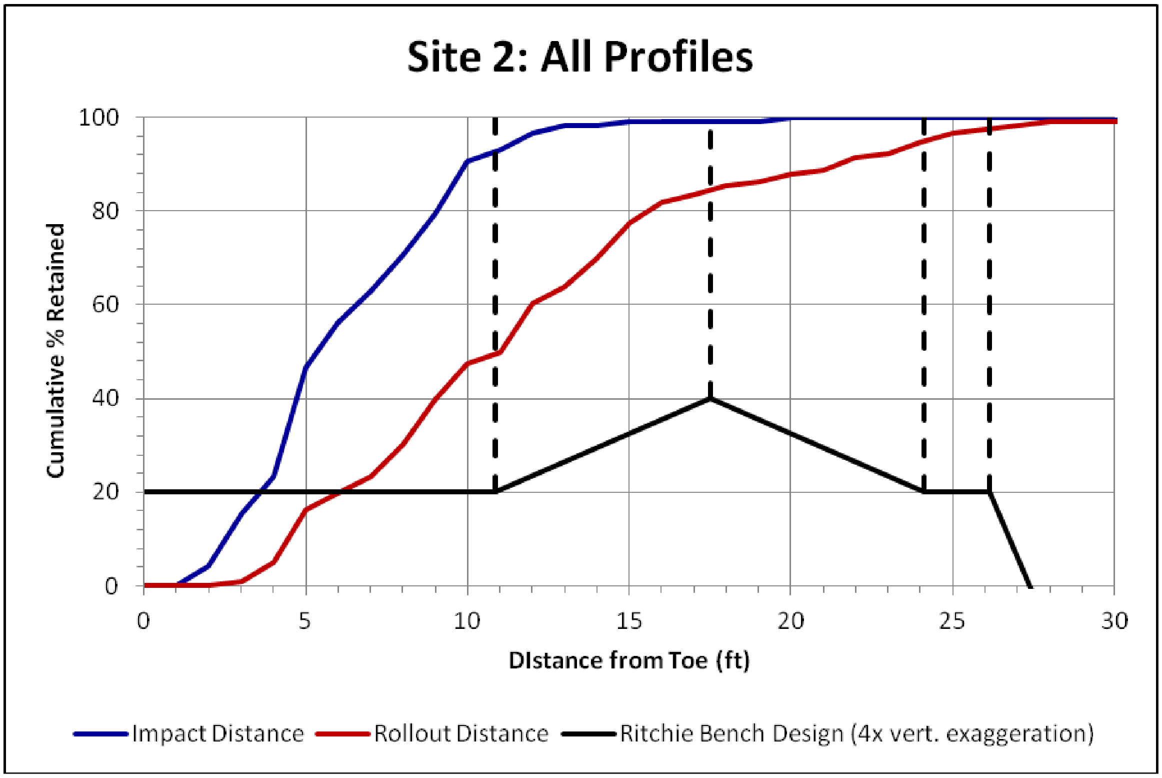


Figure 5.7: Ritchie Catchment Graph – Site 2, All Profiles

Table 5.V: Ritchie Catchment Data – Site 2, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	92.8	49.7
Berm Crest	98.9	84.5
Outer Berm Toe	100.0	95.1
Bench Crest	100.0	97.5

At the berm crest, 98.9% of impacts and 84.5% of rollouts will be retained within berm. The higher impact retention and lower rollout retention indicate that the rocks from this site rolled farther than the rocks at Site 1 by 2.7 ft, on average. This result could be attributed to geology, but observations from testing indicate that the rocks at Site 2 hit tended to hit the wall with increased frequency. Especially when the rocks hit low in the wall, the contact imparted strong angular momentum. The increased angular momentum is the suspected cause of the difference between the impact and rollout retentions. Again, the rollout retention near 85% agrees with ODOT's findings but would higher if a berm was included in the test.

5.3 Modified Ritchie Criterion

5.3.1 Modified Ritchie Criterion Introduction

Applying the Ritchie design criteria directly to an open pit mining environment can be difficult because Ritchie only tested a limited number of bench/slope configurations (Ryan & Pryor, 2000). Therefore, Dr. Richard Call of Call & Nicholas, Inc. developed the Modified Ritchie Criteria (Equation 5-1) for surface mining trying to optimize bench width in light of the tradeoffs between safety and cost (Alejano, Pons, Bastante, Alonso, & Stockhausen, 2007).

$$\text{Bench Width (m)} = 0.2 \times \text{Bench Height (m)} + 4.5\ \text{m} \qquad \text{Equation 5-1}$$

This equation is based on bench height, one of the most important criteria controlling how far a rock will roll from the toe of the slope (Ryan & Pryor, 2000). An important note is that Equation 5-1 is written using meters. Most sources found by the author apply the equation this way, including Call and Savely (1990) and Ryan and Pryor (2000). In contrast, one source lists the equation using units of feet (Call, 1992). After comparing the sources and evaluating the data in meters and feet, the author has decided to use the meters version, converted to feet, as this version seems more appropriate.

The Modified Ritchie Criteria has become well used as a design guide as evidenced by its inclusion in the *SME Mine Engineering Handbook*. This criterion has been designed for open pit mining and is used in the industry; therefore, analysis of this method is warranted.

5.3.2 Modified Ritchie Criterion Methodology

To begin, the Modified Ritchie design width had to be found for each of the nine profiles using Equation 5-1. The design widths range from 23.3 ft to 23.9 ft due to the changing bench heights. The design width used for the discussed cases is the average of the widths of all profiles included in the profile group. Because the Modified Ritchie Criterion is based off the Ritchie Criteria, the same berm height of five ft with a 37° angle of repose will be used to allow for equivalent comparison.

To understand how the Modified Ritchie bench design would have performed, cumulative percentage retained curves were created for each profile. The curve shows the percentage of rocks rolled off the profile that had impact or rollout distances less than or equal to a certain distance from the toe of the wall. These curves were graphed for each profile along with the bench design for comparison.

5.3.3 Modified Ritchie Criterion Results

The results of the comparison between the test data and the Modified Ritchie Criterion are presented based on percentage of rocks retained within a certain distance from the toe. One note to keep in mind is that the test data was collected on flat ground without a berm in place. It is assumed that a rock encountering the inner portion of the berm will only be slowed. Therefore, the test data are assumed to have rolled out farther than if a berm had been in place during testing. On the other hand, rocks that land on the outer portion of a berm will not be slowed by the berm. With these assumptions, the berm crest is a key location for analysis.

All nine profiles were included in the first profile group that was analyzed. Figure 5.8 and Table 5.VI contain the cumulative percentage retained curves and specific data taken from the curves, respectively, for all profiles.

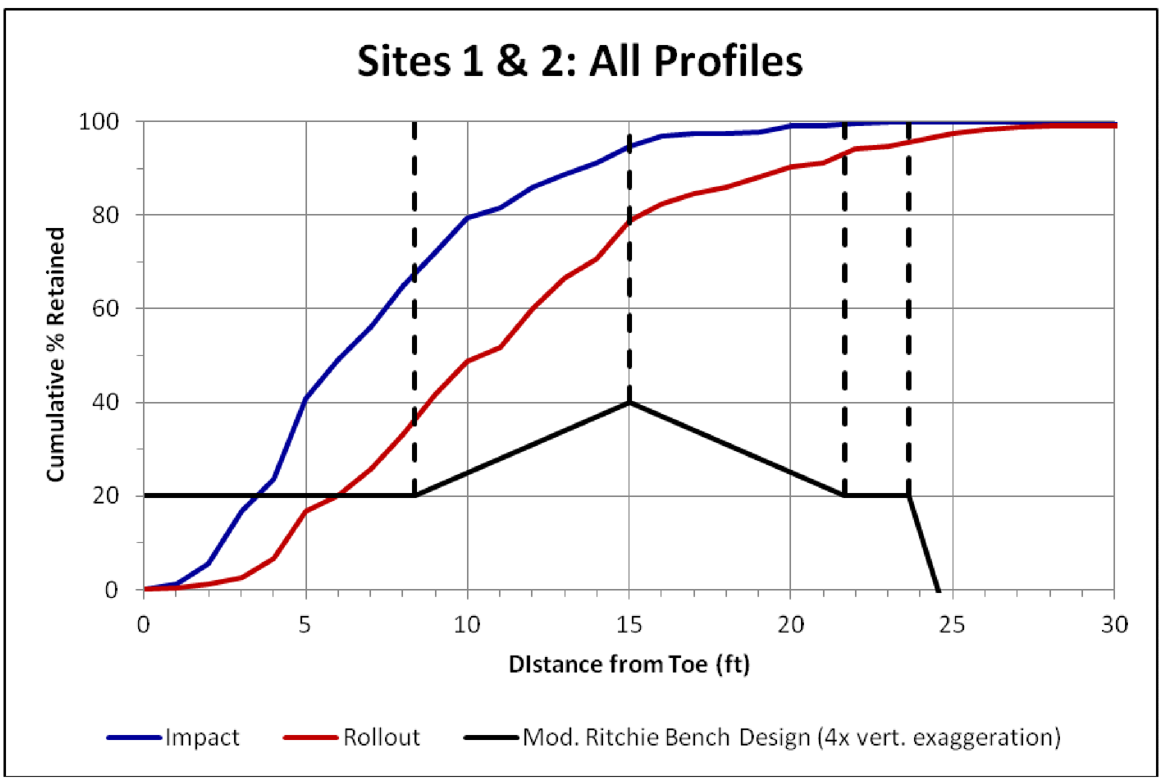


Figure 5.8: Modified Ritchie Catchment Graph - All Profiles

Table 5.VI: Modified Ritchie Catchment Data - All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	67.6	36.5
Berm Crest	94.8	79.0
Outer Berm Toe	99.5	93.2
Bench Crest	100.0	95.7

At the berm crest, 94.8% of impacts and 79.0% of rollouts will be retained. The berm crest is 15.0 ft from the toe of the wall which was back calculated from the Modified Ritchie bench width of 23.65 ft. The percent retention of impacts is 0.5% less and the percent retention of rollout is 7.2 % lower than the Ritchie design. This result shows that the Modified Ritchie Criterion is less conservative. Again, the outer berm toe and bench crest rollout retentions may be misleading because hitting the outer half of a berm may cause a rock to roll farther than one on a flat surface.

The next profile group to be analyzed looked at all profiles except the pronounced launch feature profile, Profile 5 at Site 1. Figure 5.9 and Table 5.VII contain the cumulative percentage retained curves and specific data taken from the curves, respectively, for all profiles excluding the launch feature profile from Site 1.

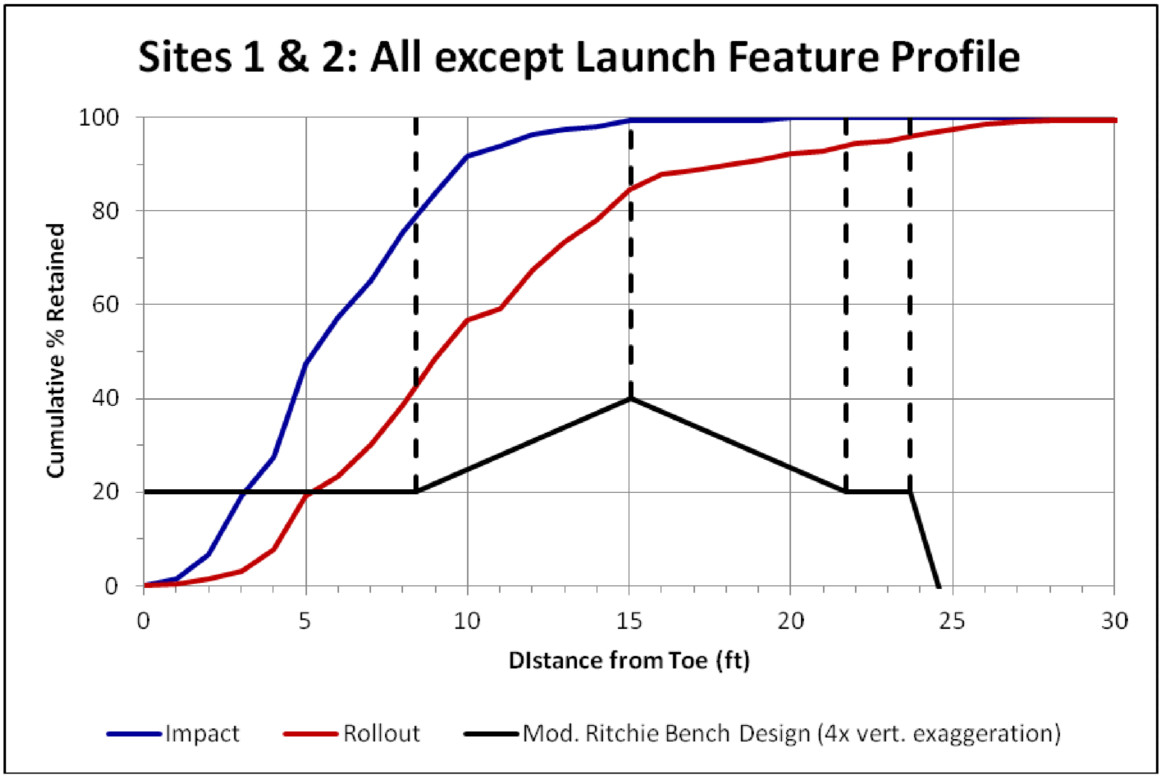


Figure 5.9: Modified Ritchie Catchment Graph – All Profiles except Site 1 Profile 5

Table 5.VII: Modified Ritchie Catchment Data – All Profiles except Site 1 Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	78.9	42.8
Berm Crest	99.5	84.9
Outer Berm Toe	100.0	93.9
Bench Crest	100.0	96.0

At the berm crest, 99.5% of impacts and 84.9% of rollouts will be retained. The berm crest is 15.1 ft from the toe of the wall which was back calculated from the Modified Ritchie bench width of 23.69 ft. The percent retention of impacts is 0.5% more and the percent retention of rollout is 5.4 % less than the Ritchie design. The value of removing launch features from the wall can be seen from the comparison to the results including Site 1 Profile 5 (Figure 5.8 and Table 5.VI). A wall with no/fewer launch features, especially major ones, will not cause rocks to roll as far from the toe.

The granite quarry, Site 1, will be discussed first within the site specific comparison, and the cumulative percentage curves and data table can be seen in Figure 5.10 and Table 5.VIII, respectively.

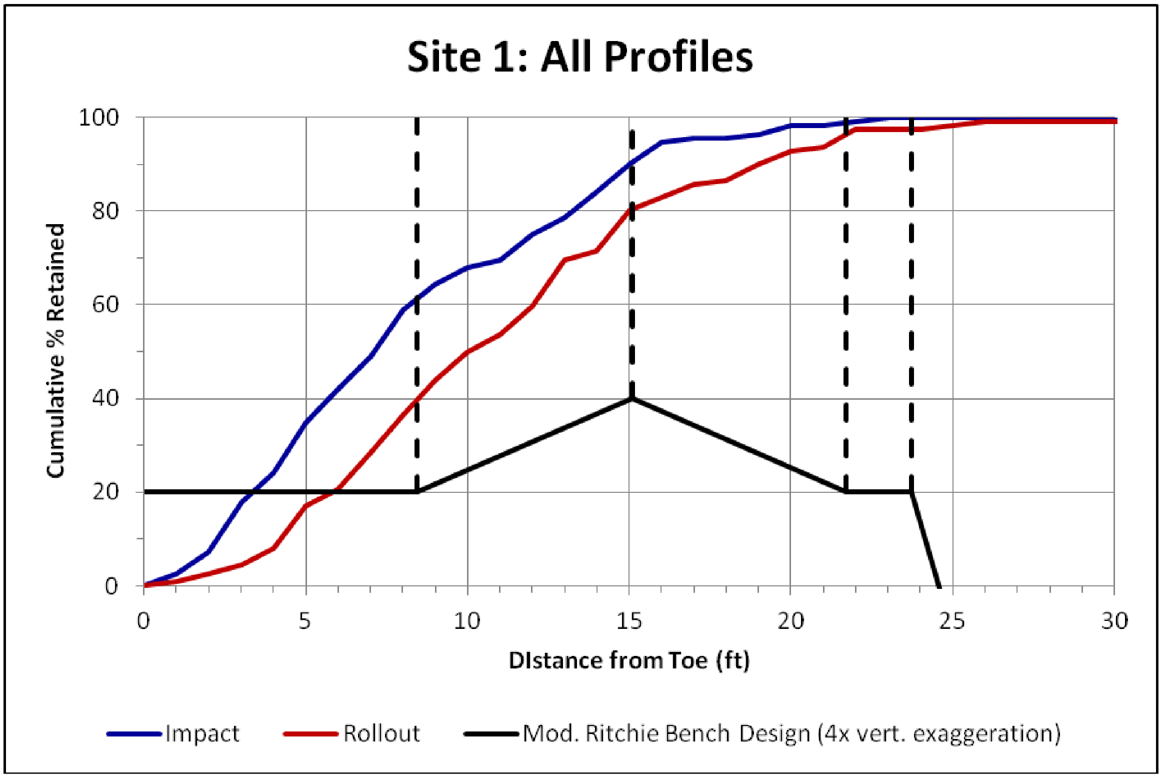


Figure 5.10: Modified Ritchie Catchment Graph – Site 1, All Profiles

Table 5.VIII: Modified Ritchie Catchment Data – Site 1, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	61.3	39.8
Berm Crest	90.5	80.6
Outer Berm Toe	99.0	96.3
Bench Crest	100.0	97.8

At the berm crest, 90.5% of impacts and 80.6% of rollouts will be retained within the Modified Ritchie design of 15.1 ft from the toe for the berm crest. The design bench width is 23.71 ft. While the rollout retention is similar to the data using all profiles, 1.6% higher, the impact retention is 4.3% less. This fact is most likely the result of the increased impact of the launch feature profile trials on the total number of trials due to the exclusion of Site 2 data. Compared to the Ritchie results, the less conservative nature of this criterion is shown again because the impact and rollout retentions are 4.8% and 5.6% less respectively. Next, Profiles 1-4 from Site 1 will be analyzed without the launch feature profile, Profile 5. Figure 5.11 and Table 5.IX show the results of the analysis on this profile group.

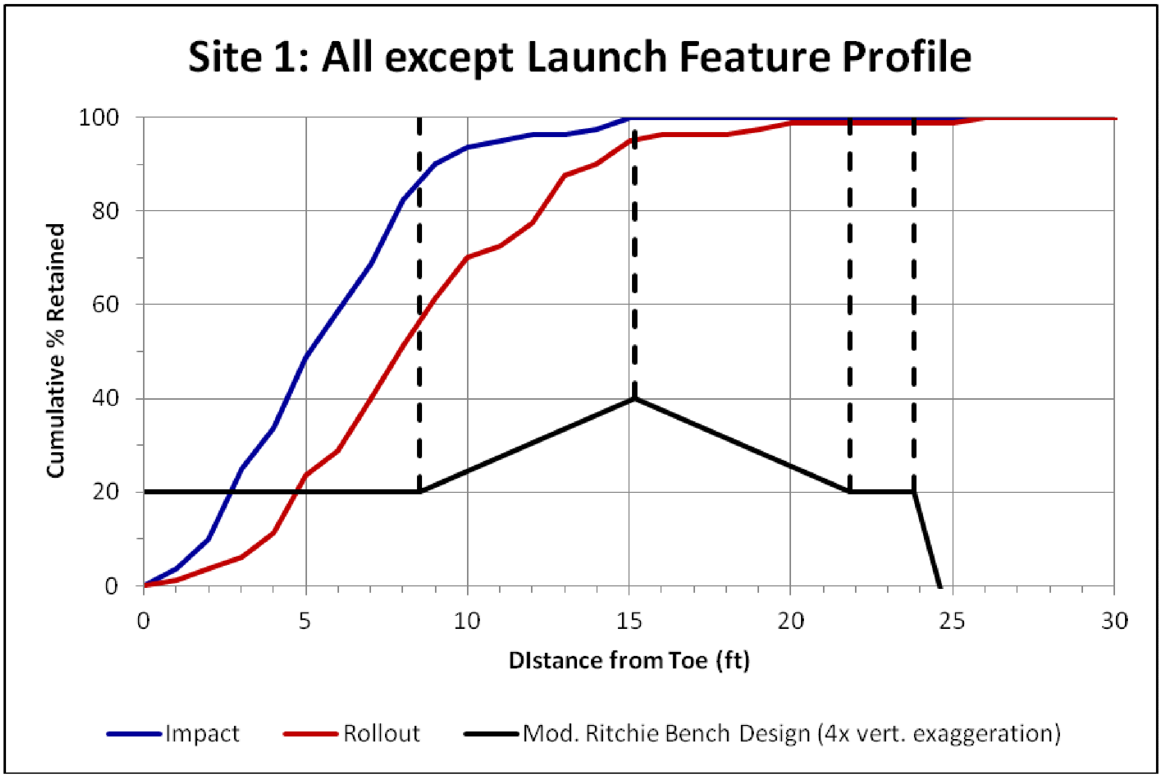


Figure 5.11: Modified Ritchie Catchment Graph – Site 1, All Profiles except Profile 5

Table 5.IX: Modified Ritchie Catchment Graph – Site 1, All Profiles except Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	86.6	56.7
Berm Crest	100.0	95.2
Outer Berm Toe	100.0	99.0
Bench Crest	100.0	99.1

At the berm crest, 100% of impacts and 95.2% of rollouts will be retained within a berm crest design distance of 15.2 ft and bench design width of 23.81. By excluding the launch feature profile in this analysis, the true impact can be seen. Without the launch feature tests, all test rocks fell within the berm crest, and the rollout retention increased by 14.6%. Estimating the impact of a berm on the test data leads the author to believe that all rocks would have been retained with this design in this case. Furthermore, these values compare closely with Ritchie's design criteria.

Site 2, the diabase quarry will be discussed next. Figure 5.12 shows the cumulative percentage curve, and Table 5.X shows the retention values from the key bench design locations.

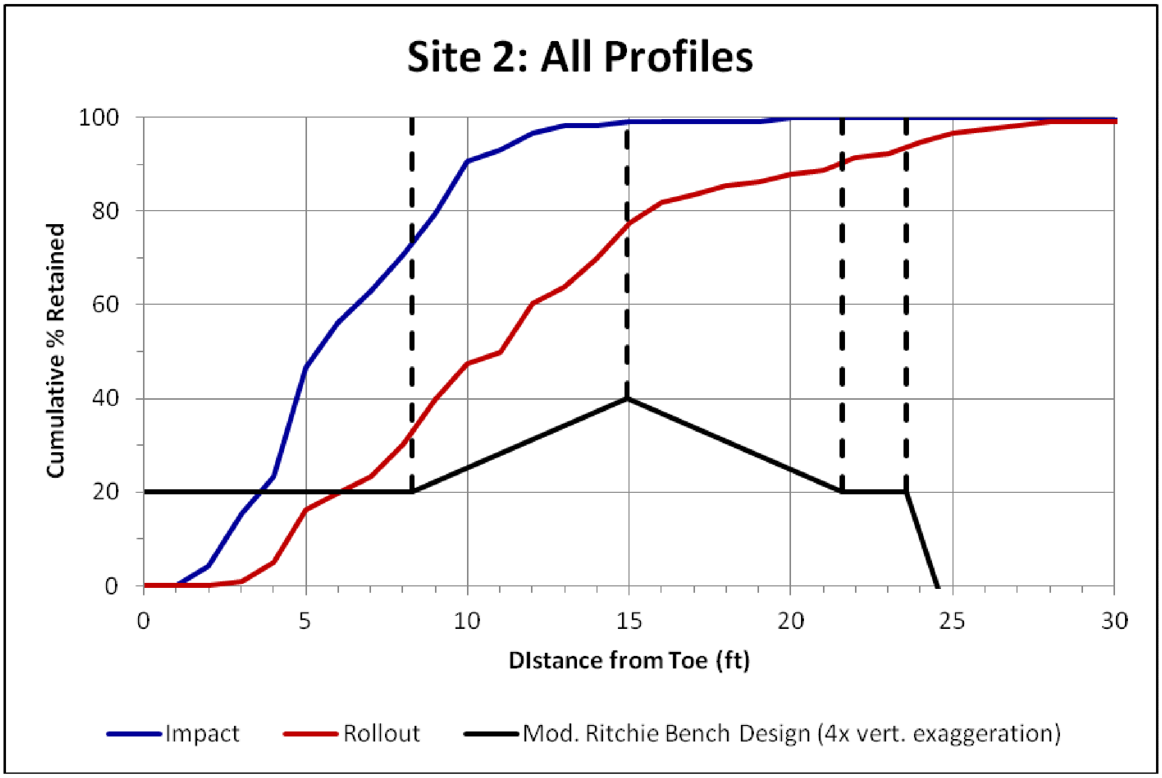


Figure 5.12: Modified Ritchie Catchment Graph – Site 2, All Profiles

Table 5.X: Modified Ritchie Catchment Data – Site 2, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	73.3	33.0
Berm Crest	99.1	77.1
Outer Berm Toe	100.0	90.3
Bench Crest	100.0	93.7

At the berm crest, 99.1% of impacts and 77.1% of rollouts will be retained within berm. The Modified Ritchie berm design distance is 14.9 ft and the bench width is 23.57 ft. The 18.1% lower rollout retention again indicates the rocks from Site 2 rolled farther, possibly a byproduct of geologic differences. Compared to Ritchie's design, the impact retention is very similar, 0.2% higher, but the rollout retention is 7.4% less, indicating a less conservative design.

5.4 Ryan and Pryor Criterion

5.4.1 Ryan and Pryor Criterion Introduction

Once the Modified Ritchie Criteria was published, studies performed found the criteria to be conservative (Ryan & Pryor, 2000). By starting with different factors, Ryan and Pryor derived Equation 5-2.

$$\text{Bench Width (m)} = 0.17 \times \text{Bench Height (m)} + 3.5\text{ m} \qquad \text{Equation 5-2}$$

The Ryan and Pryor Criterion is proposed to be less conservative than the Modified Ritchie Criterion developed by Call. Therefore, this criterion was analyzed against the test data from this study as a comparison.

5.4.2 Ryan and Prior Criterion Methodology

To begin, the Ryan and Prior design width had to be found for each of the nine profiles using Equation 5-2. The design widths range from 18.7 ft to 19.2 ft due to the changing bench heights. The design width used for the discussed cases is the average of the widths of all profiles included in the profile group. Because the Ryan and Prior Criterion is based off the Modified Ritchie Criteria, the same berm height of five ft with a 37° angle of repose will be used to allow for equivalent comparison.

Just like the Ritchie and Modified Ritchie designs, the Ryan and Prior Criterion has been evaluated using cumulative percentage retained curves were created for each profile. The curve shows the percentage of rocks rolled off the profile with impact and rollout distances less than or equal to a certain distance from the toe of the wall. These curves were graphed for each profile along with the bench design for comparison.

5.4.3 Ryan and Prior Criterion Results

The results of the comparison between the test data and the Ryan and Prior Criterion are presented based on percentage of rocks retained within a certain distance from the toe. One note to keep in mind is that the test data was collected on flat ground without a berm in place. It is assumed that a rock encountering the inner portion of the berm will only be slowed. Therefore, the test data are assumed to have rolled out farther than if a berm had been in place during testing. On the other hand, rocks that land on the outer portion of a berm will not be slowed by the berm. With these assumptions, the berm crest is a key location for analysis.

All nine profiles were included in the first profile group that was analyzed. Figure 5.13 and Table 5.XI contain the cumulative percentage retained curves and specific data taken from the curves, respectively, for all profiles.

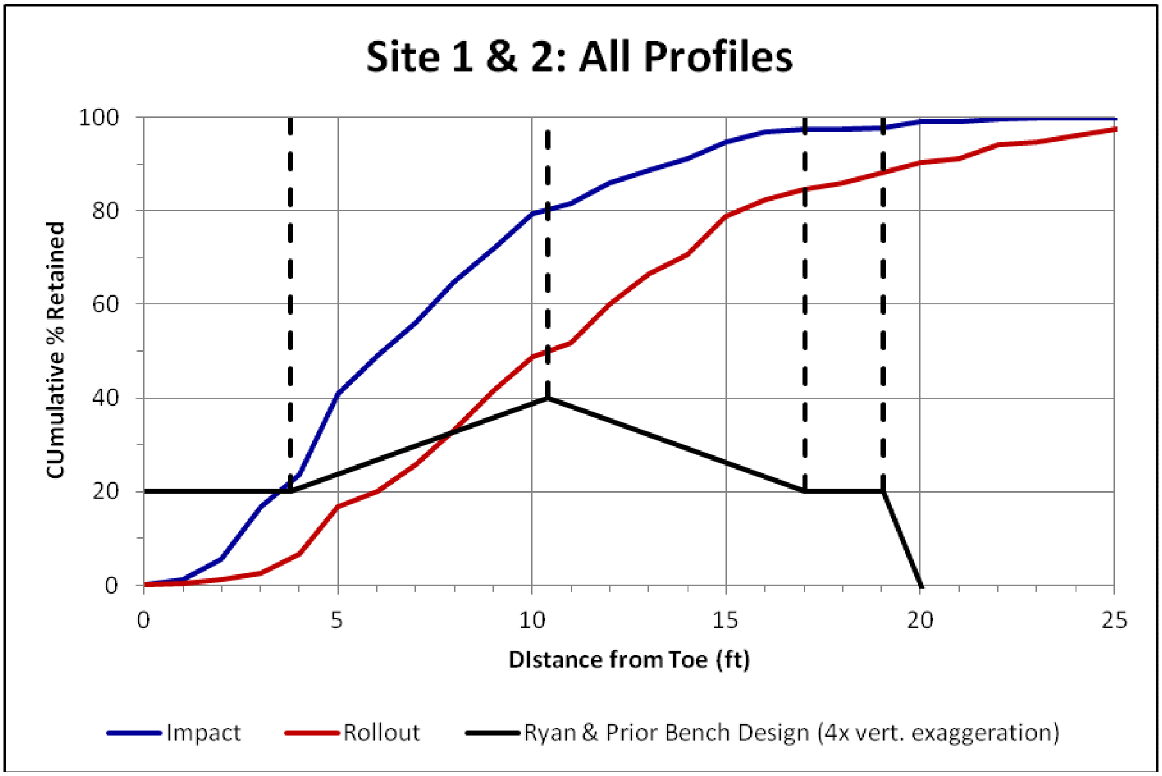


Figure 5.13: Ryan and Prior Catchment Graph - All Profiles

Table 5.XI: Ryan and Prior Catchment Data - All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	22.1	5.7
Berm Crest	80.3	49.9
Outer Berm Toe	97.4	84.7
Bench Crest	97.9	88.2

The full bench width using the Ryan and Prior criterion is 19.04 ft. At the berm crest of 10.4 ft from the toe, the impact retention is 80.3%, and the rollout retention is 49.9%. These values are 17.0% and 35.2% lower, respectively, than the equivalent values calculated using the Ritchie and Modified Ritchie Criteria. Only keeping one out of two rocks on the bench is also not acceptable for a quarry design, but the presence of a berm would serve to increase the rollout retention.

The next profile group to be analyzed includes all profiles except Profile 5 from Site 1. The curves can be seen in Figure 5.14 and the key data are found in Table 5.XII.

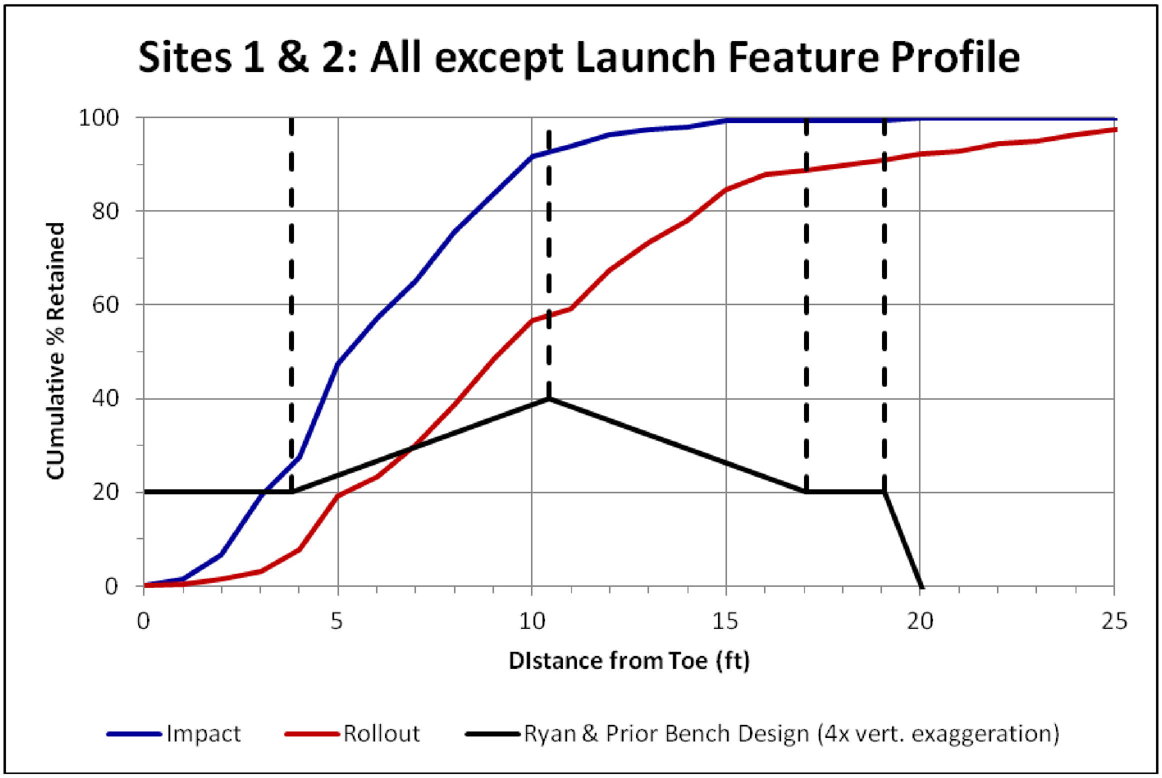


Figure 5.14: Ryan and Prior Catchment Graph – All Profiles except Site 1 Profile 5

Table 5.XII: Ryan and Prior Catchment Data – All Profiles except Site 1 Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	25.9	6.7
Berm Crest	92.7	57.7
Outer Berm Toe	99.7	88.8
Bench Crest	99.9	90.9

Removing Profile 5 changes the bench design width to 19.07 ft, but the berm crest to remains 10.4 ft. The berm crest impact retention increases to 92.7%, and the rollout retention increases to 57.7% compared to the all profile values. Even without the launch feature profile in the data set, the retention percentage is still not acceptable for a quarry bench design.

The data has also been analyzed by site. Taking Site 1 first, Profiles 1 through 5 have been analyzed first. Figure 5.15 and Table 5.XIII contain the results of this profile group.

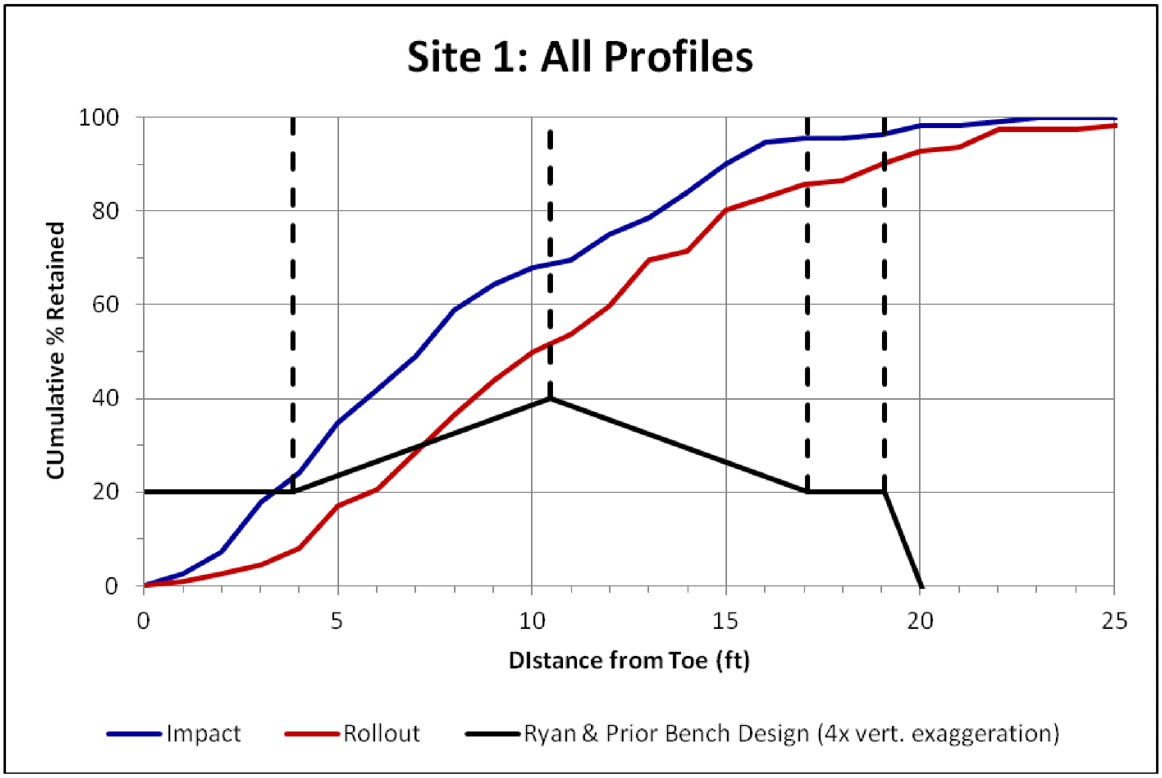


Figure 5.15: Ryan and Prior Catchment Graph – Site 1, All Profiles

Table 5.XIII: Ryan and Prior Catchment Data – Site 1, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	23.0	7.4
Berm Crest	68.7	51.6
Outer Berm Toe	95.6	85.8
Bench Crest	96.6	90.4

For this profile group, the bench crest is 10.5 ft from the toe, and the total design bench width is 19.09 ft. At the bench crest, 68.7% of rockfall impacts will be retained, and 51.6% of rollouts will be held on the bench. These results again support the pervious claim that the Ryan and Prior Criterion is too conservative for quarry design.

Profile 5 from Site 1 has been removed in the next profile group. The results of the analysis using Site 1, Profiles 1 through 4 can be seen in Figure 5.16 and Table 5.XIV.

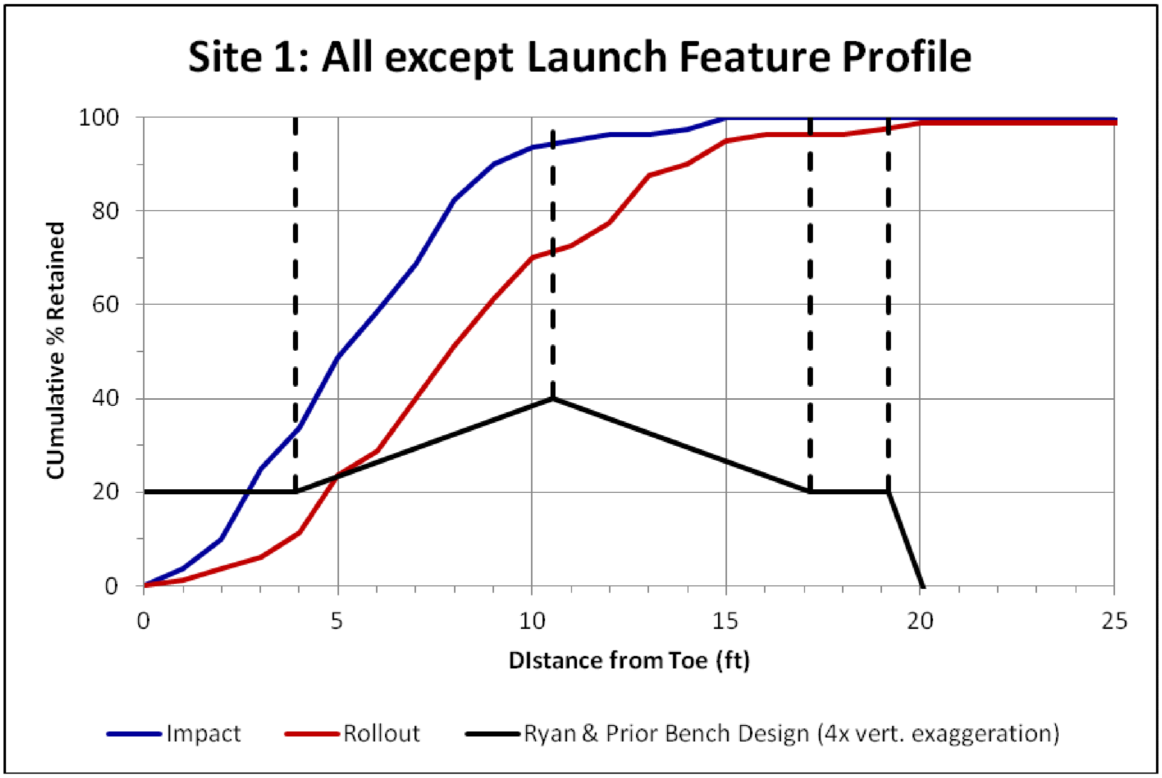


Figure 5.16: Ryan and Prior Catchment Graph – Site 1, All Profiles except Profile 5

Table 5.XIV: Ryan and Prior Catchment Data – Site 1, All Profiles except Profile 5

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	33.0	10.8
Berm Crest	94.4	71.4
Outer Berm Toe	100.0	96.7
Bench Crest	100.0	97.7

By removing Profile 5, the bench width increases to 19.18 ft, thereby increasing the distance of the berm crest from the toe to 10.6 ft. Similarly, the impact and rollout retentions increase to 94.4% and 71.4%, respectively, gains of 25.7% and 19.8%. The launch feature greatly impacts the retention of the bench; therefore, preventing these features is important for safety.

Lastly, Profiles 1 through 4 have been analyzed from Site 2. The cumulative percent retained curves can be seen in Figure 5.17, and the location data taken from the curves can be found in Table 5.XV.

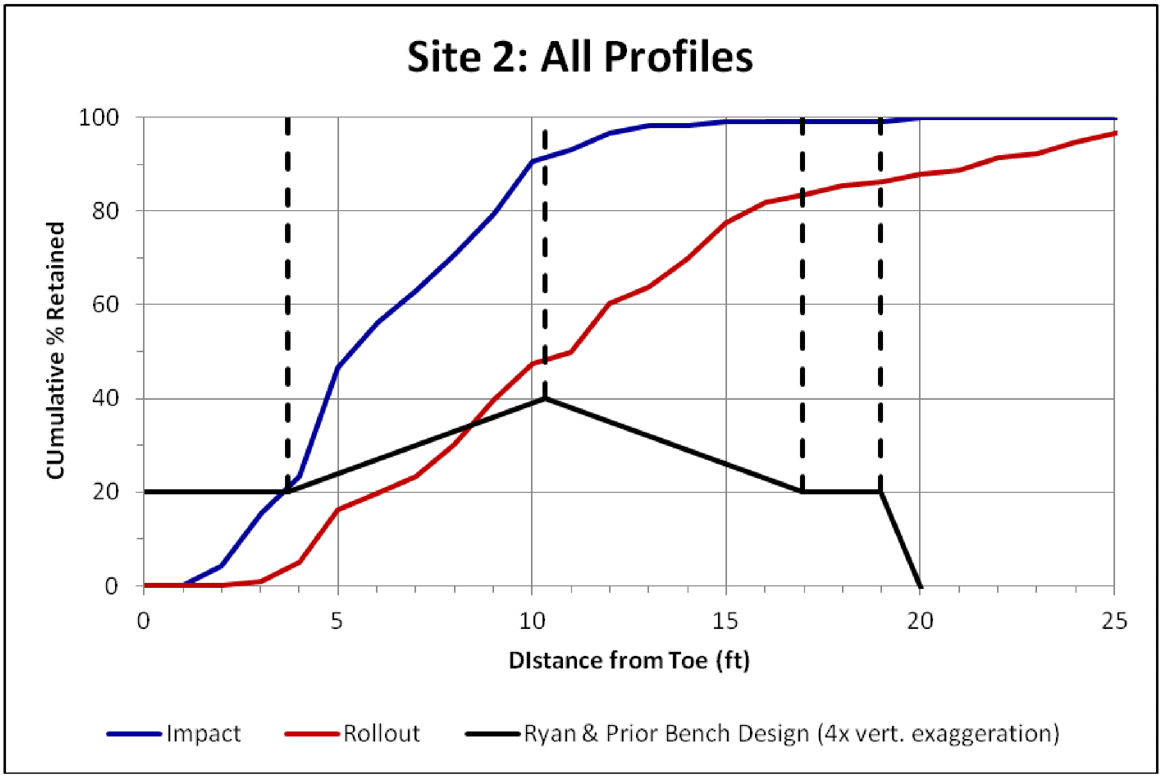


Figure 5.17: Ryan and Prior Catchment Graph – Site 2, All Profiles

Table 5.XV: Ryan and Prior Catchment Data – Site 2, All Profiles

Location	Impact % Retention	Rollout % Retention
Inner Berm Toe	20.9	3.9
Berm Crest	91.4	48.3
Outer Berm Toe	99.5	83.6
Bench Crest	99.8	86.2

For this profile group, the bench width is 20.50 ft, and the berm crest is from the toe to 10.3 ft. While the impact retention of 91.4% at the berm crest remains high, the rollout retention of 48.3% is 23.1% lower than the retention percentage from Site 1, Profiles 1-4. This difference is most likely due to the increased wall contact observed during the testing at Site 2. Again, the rollout retention percentage near 50% is not acceptable for quarry design.

5.5 Oregon Department of Transportation Design Guide

5.5.1 Oregon Department of Transportation Design Guide Introduction

In 2001, the Oregon Department of Transportation (ODOT) published a report detailing the results of a research study performed from 1997-2001. This report summarized the data of extensive rockfall testing into user friendly design charts for practitioners in the area of highway slope design. ODOT recognized a lack of consistent slope design practices within government agencies throughout the country (Pierson, Gullixson, & Chassie, 2001). The organization looked to fill in the research gaps in the area of slope design to improve safety, reduce costs, and aid practitioners. Therefore, ODOT led a project funded by seven state DOT's and the Federal Highway Administration to provide the research data needed to meet these goals (Pierson, Gullixson, & Chassie, 2001).

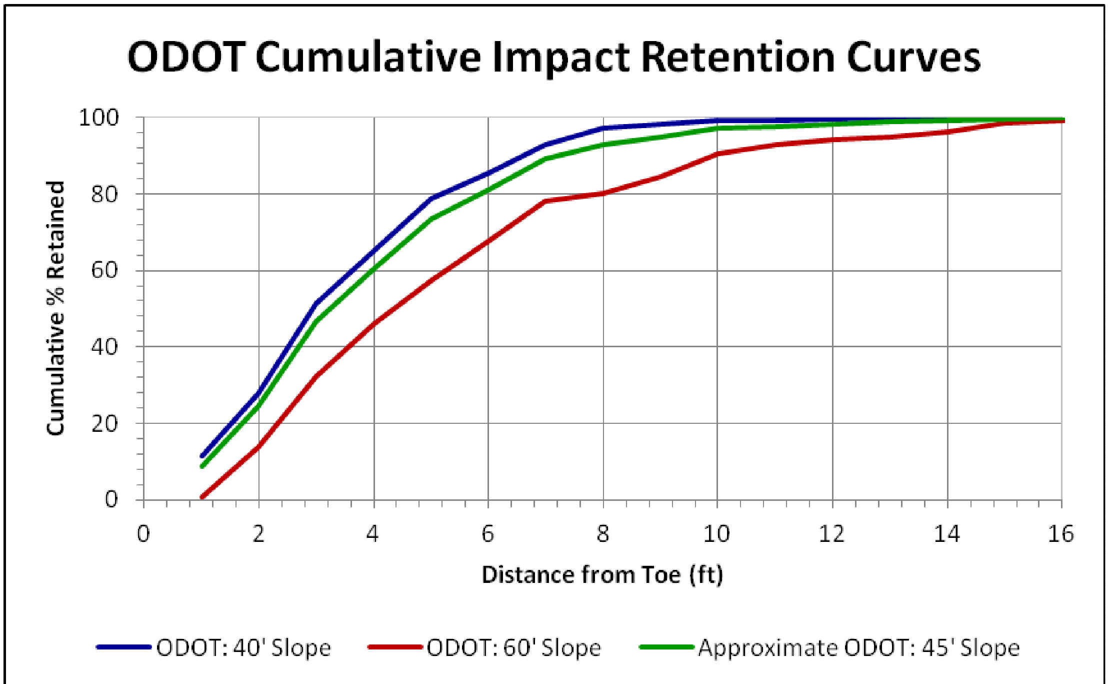
This project consisted of many simulated rockfalls with the data being compiled into user friendly design charts. Over the five years, 11,250 rocks were rolled in sets of 250 from slopes with heights of 40, 60, and 80 ft and angles of 45°, 53.1° 63.4°, 76.0°, and 90°. Additionally, the three catchment area configurations were used in the trials: flat, 6H:1V, and 4H:1V (Pierson, Gullixson, & Chassie, 2001). The size of the rocks ranged from 1-3 ft in diameter. For each rockfall trial, a rock was rolled from the crest of the wall and the rock size, wall height, wall angle, catchment slope, impact distance, and rollout distance (See Figure 3.6 for a schematic of impact and rollout distances). Once all the slope and catchment configurations had been tested, ODOT compared the results to Ritchie's criteria, RocFall computer simulations, and created design charts for use in designing new slopes and evaluating current ones. Furthermore, the report included qualitative observations of the rockfalls.

Similarly to Ritchie's work, the ODOT study is geared for highway slope design, but, the application of this research to a quarry highwall is logical step to take. Highway slope designers and mine slope designers share the goal of keeping people and equipment safe from falling rocks in the most cost effective manner. Therefore, the testing performed for this project will be compared with the results included in the ODOT report.

5.5.2 Oregon Department of Transportation Design Guide Methodology

A different approach was taken to analyze the ODOT report data than the criteria based on Ritchie's design. The cumulative percent retained curves are still used. But because the testing performed for this report is similar to the testing performed by ODOT, the data can be directly compared. The impact and rollout data for slope/catchment configuration is included in the ODOT report, but the ODOT data had to be interpolated for comparison to the test data performed at the two sites in this study. The average wall slope for the nine profiles tested is

76.5°. The closest slope tested by ODOT is 76°, a small enough difference for accurate comparison. With regard to wall height, the average wall height of the nine profiles for this report is 44.4 ft. The ODOT test data for a 40 ft and 60 ft wall was taken and the data interpolated to yield a curve representative of 45 ft. Again the difference is small enough for accurate comparison. The 40 ft, 45 ft, and 60 ft curves for impact and rollout retention taken and calculated from the ODOT report can be seen in Figure 5.18.



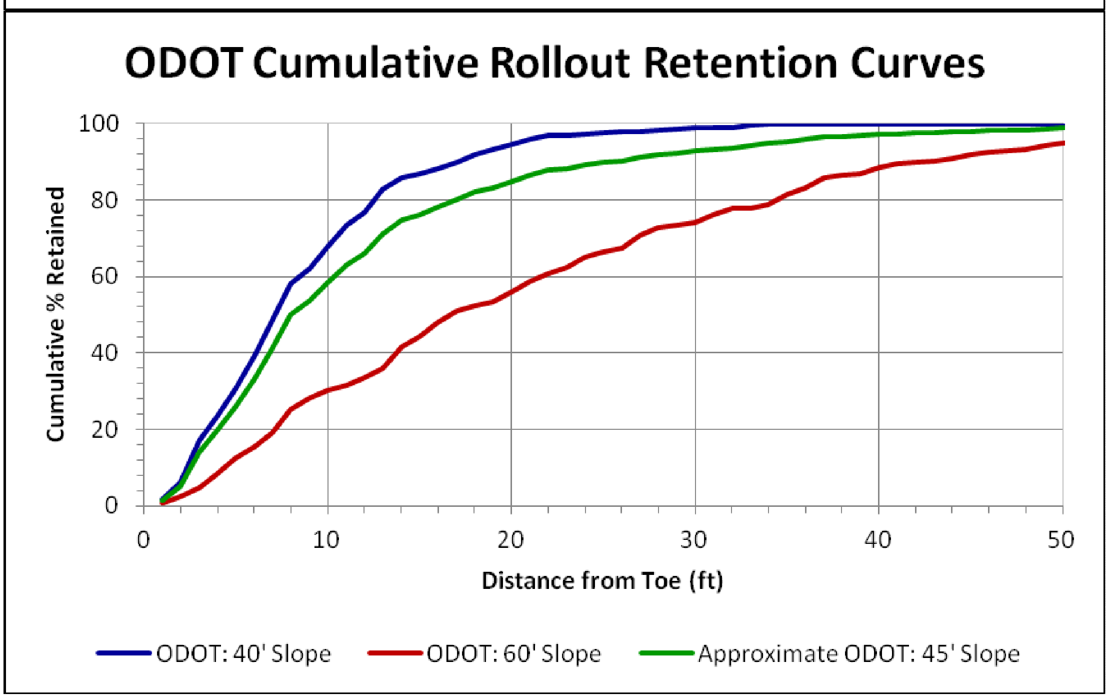


Figure 5.18: ODOT Impact and Rollout Retention Curves

Finally because this study's testing used a flat catchment at the toe, the ODOT test data using a flat catchment at the toe was incorporated into this analysis. Once the cumulative percent impact and rollout retention curves had been calculated for the ODOT testing, they could be compared to the curves found from the testing performed for this report. The differences between the two were found for the key design locations of 75%, 80%, 85%, 90%, and 95% retention.

5.5.3 *Oregon Department of Transportation Design Guide Results*

The results of the ODOT study and this research have been analyzed by comparing the cumulative percentage retained curves for rockfall impacts and rollouts. This data can be accurately compared because the slope/catchment configurations for the two tests are equal on average. Unlike the Ritchie based criteria, the ODOT results can be more accurately interpreted because no berm was used during the trials. One assumption is that the addition of a berm will only prevent rollouts. The results of the testing comparison can be seen in Figure 5.19.

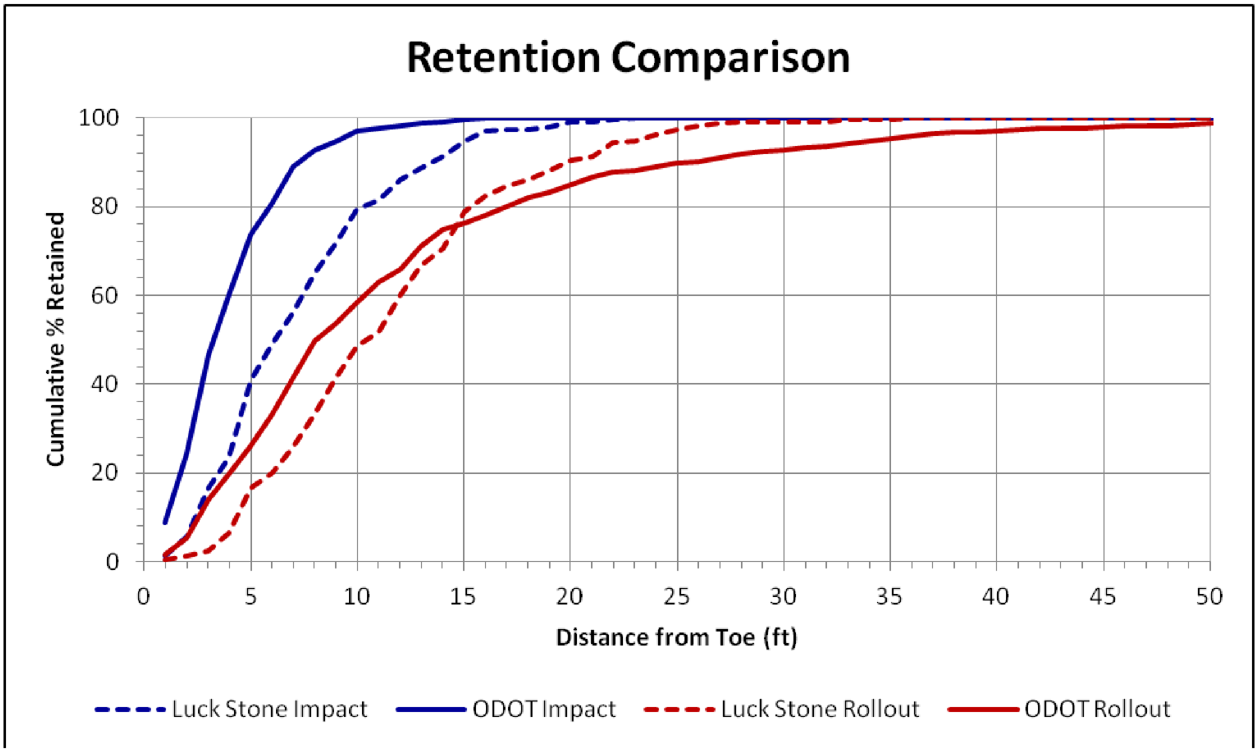


Figure 5.19: ODOT/Luck Stone Retention Comparison Graph

A cursory look at the graph shows that the ODOT rockfalls impacted closer to the toe than the Luck Stone testing by approximately 44%. This result makes sense due to the differences in the blasting techniques used in the creation of the test walls. The ODOT study used presplit blasting to create a smooth wall, whereas, the Luck Stone walls were blasted without any type of smooth blasting technique. A normal production wall in a quarry will certainly contain more launch features than a presplit face. These launch features will cause rocks to land farther from the toe, as evidenced by the impact retention curves. The rollout retention curves are more closely aligned, with the ODOT data showing a wider distribution. The curves cross at the value of approximately 14.6 ft. The wider distribution could be attributed to a number of causes such as rock shape, toe compaction, and number of launch features. Without more detailed information about the ODOT testing conditions, pinpointing the exact cause of the discrepancy is not possible.

In order to better compare the curves, the retention percentage at the aforementioned key design locations have been calculated from the curves. Table 5.XVI holds this data.

Table 5.XVI: ODOT/Luck Stone Retention Comparison Data

	Cumulative % Retained Footage				
Parameter	**75**	**80**	**85**	**90**	**95**
Test Impact	9.4	10.3	11.8	13.5	15.1
Test Rollout	14.5	15.3	17.3	19.8	23.2
ODOT Impact	5.2	5.9	6.5	7.2	9.1
ODOT Rollout	14.2	17.0	20.1	25.6	34.4

By simply subtracting the ODOT data from the Luck data, the difference between the two (See Table 5.XVII), as well as the percentage difference can be calculated (See Table 5.XVIII). Negative values indicate that the ODOT data is farther from the toe than the Luck Stone data.

Table 5.XVII: ODOT/Luck Stone Retention Data Footage Difference

	Cumulative % Retained Footage (ft)				
Parameter	**75**	**80**	**85**	**90**	**95**
Impact	4.2	4.4	5.3	6.3	6.0
Rollout	0.3	-1.7	-2.8	-5.8	-11.2

Table 5.XVIII: ODOT/Luck Stone Retention Data Percentage Difference

	Cumulative % Retained Footage (ft)				
Parameter	**75**	**80**	**85**	**90**	**95**
Impact	44.8%	42.9%	44.9%	46.5%	39.7%
Rollout	2.4%	-10.8%	-16.1%	-29.0%	-48.4%

The percentage difference shows that the impact distances for the Luck Stone data are 37.9%-46.5% greater than the ODOT data, resulting from smoother walls. On the rollout side, the Luck Stone data starts out higher but gets steadily lower than the ODOT data quickly. Throwing out the launch feature test does not improve the rollout retention data dramatically either (See Table 5.XIX).

Table 5.XIX: Retention Data Percentage Difference w/o Site 1 Profile 5

	Cumulative % Retained Footage (ft)				
Parameter	75	80	85	90	95
Impact	34.7%	31.4%	29.1%	25.9%	20.3%
Rollout	-6.3%	-18.6%	-32.8%	-40.7%	-49.3%

While the discrepancy between the impact retention improves, the rollout retention difference becomes larger. Analysis of these results shows that a direct comparison between the two data sets cannot be made. The conditions of the walls are too different. The additional launch features of a quarry wall work to increase the impact distance by projecting rocks farther from the toe. Furthermore, the smooth wall appears to cause farther rock rollouts, which could be due to numerous factors.

5.6 RocFall Computer Simulation

5.6.1 RocFall Computer Simulation Introduction

Like many issues in the mining industry, the application of computer technology has improved our understanding. For the issue of safety bench design, numerous computer programs have been developed, including Colorado Rockfall Simulation Program (CRSP), RocFall, and STONE. For this project, RocFall v4.503, produced by Rocscience, Inc. located in Ontario, Canada, was chosen. This choice came from the program's wide spread use, as evidenced by previous research, ease of operation, and use by Luck Stone Corp.

RocFall simulates rock trajectories over a wall profile in two dimensions. The lumped-mass method is used in the calculations, meaning rock shape and volume are not considered and the rock mass is located at a single point (Alejano, Pons, Bastante, Alonso, & Stockhausen, 2007). Therefore, shape and size must be accounted for by adjustment of the input parameters in the program (Rocscience Inc., 2003). To begin, the user either draws a slope profile in the program or imports one from an outside source. A rockfall starting location(s) called a seeder is then placed at the desired location on the slope. Once the various rock and slope parameters are chosen, RocFall will simulate rockfalls for the desired repetitions in the style of a Monte Carlo simulation. The values of rock energy, velocity, and, most importantly, end point are recorded and can be graphed.

Because RocFall was designed for simulating rockfalls and uses rollout distance as a main output, this program is an obvious choice for comparison to the data gathered for this project.

5.6.2 Simulation Methodology

For this project, RocFall is being used to extend the actual rockfall trials performed. The limits of time and money prevent performing the number of trials on the scale that RocFall can simulate. Once the parameters of the simulation have been selected to accurately reflect the properties of the slopes, simulations can be performed for various slope and bench configurations. Analysis of the simulation's results will then allow selection of the most appropriate bench configuration.

To begin, each profile was prepared for simulation. The nine drop point profiles taken using the laser profiler were brought into RocFall. Three materials were then created using the program's Material Editor to represent the three surfaces a falling rock could encounter during the testing: Rock, Talus, and Floor. Rock represents the intact hard rock that makes up the highwall. From observations, the wall rock appeared competent and unweathered with some build up of small size material on the horizontal surfaces. Talus represents material which was piled up against the toe of the wall, a remnant of the previous blast pile. The talus material tended to be uncompacted with a large size range; blocks over six inches in size down to fine dust comprised the talus. Floor represents the material from which the floor was created. This material was gravel-like and appeared to have a smaller size range from visual inspection. Additionally, the floor material tended to be less compacted near the toe with compaction increasing as distance from the toe increased, a trend most likely caused by increased equipment traffic farther from the toe. Figure 5.20 shows an example profile from RocFall with the Rock in blue, Talus in red, and Floor in green.

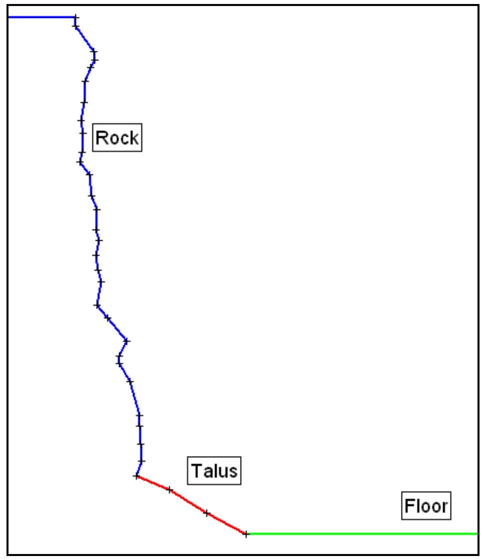


Figure 5.20: Example RocFall Profile

Once the profiles were brought into the program, the material parameters were input for each material type. RocFall allows the user to specify seven material parameters: the mean and standard deviation for the coefficient of normal restitution (R_n), the mean and standard deviation for the coefficient of tangential restitution (R_t), the mean and standard deviation for the friction angle (Φ), and the standard deviation of slope roughness. R_n and R_t are between zero and one and represent the normal and tangential components of surface elasticity, essentially how much energy is absorbed or given back to an object upon collision. A value of one represents a perfectly elastic collision. Φ is the critical angle which determines if an object will continue to slide or come to rest on the surface (Rocscience Inc., 2003). Finally, slope roughness in RocFall is calculated as a normal distribution based on the entered standard deviation. During the simulation, this distribution is used to alter the initial angle of each surface to model roughness (Rocscience Inc., 2003). The initial values for each of these parameters were chosen based on site geology, material type, parameters used in previous Luck Stone Corp. simulations, and recommendations provided by Rocscience Inc.

In addition to the material parameters, RocFall allows the user to select other simulation options. The options of considering angular velocity and scaling R_n by velocity were chosen. Considering angular velocity accurately models the testing because the rocks clearly spun during the trials, and choosing this option is recommended by Rocscience Inc (Rocscience Inc., 2003). Scaling R_n by velocity was chosen based on research showing that the characteristics of impact change as velocity increases. At low velocity, the impact tends to be much more elastic than a high velocity impact which is less elastic due to more rock fracturing and cratering of the impact surface (Pfeiffer & Bowen, 1989). Additionally, this choice was supported by more accurate simulations. Within the option of scaling R_n by velocity, the K factor, a constant used in the calculation of the R_n scaling factor, was also selected. Seeder settings were chosen next. The horizontal velocity was set for 0.1 ft/s to model the slight outward velocity given to the rock by the excavator. Each seeder mean mass and standard deviation was set for the average approximate rock weight for the rocks dropped over each profile calculated from the measured rock size. For example, the volume of all rocks dropped over Profile 1 at Site 1 was calculated along with the volumetric standard deviation. The average rock volume was then found and multiplied by the rock density to yield average rock mass for Profile 1. Table 5.XX shows the mean mass and standard deviations used for each profile.

Table 5.XX: RocFall Seeder Mass Inputs

Site	Profile	Mass (lb)	Standard Deviation (lb)
1	1	220	18
	2	461	63
	3	470	63
	4	460	26
	5	298	25
2	1	353	44
	2	476	48
	3	338	51
	4	426	56

Once all of these inputs were chosen, a sensitivity analysis was performed to help understand the impact of each parameter on the results of the simulations. The parameters included in the sensitivity analysis are R_n, standard deviation of R_n, R_t, standard deviation of R_t, Φ, standard deviation of Φ, standard deviation of slope roughness, seeder rock mass, standard deviation of seeder rock mass, and the K factor. Each parameter was individually adjusted up to 30% more and less than the original value. An example graph displaying the results can be seen in Figure 5.21 for Site 2, Profile 1, at the distance from the toe where 85% of the rocks were retained on the bench.

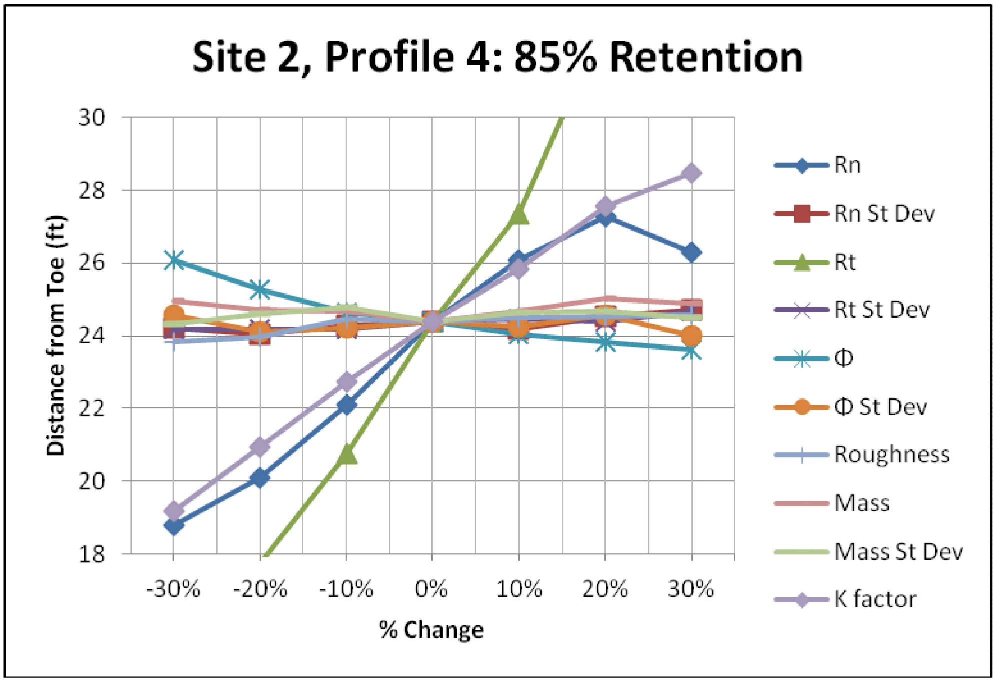


Figure 5.21: Example Sensitivity Analysis Graph

This graph shows that R_t has the greatest impact on the results of the simulation with R_n and the K factor close to tied for second most influential. Additionally, the restitution coefficients and K factor show positive a positive correlation with distance from the toe, whereas Φ, the fourth most influential, displays a negative correlation. The dip in R_n shown at 30% increase may be due to scaling R_n by velocity because this trend was found upon repeated trials to check for error. The other parameters show minimal impact on the results, even with large change.

The next step in this analysis was to calibrate the simulations to the actual test results. This step ensures that the simulations will accurately model the actual testing. For this project, calibration was performed using cumulative percent retained curves for the real test data. For each of the nine profiles, a curve was created using the measured parameter, rollout distance, which matches the predominant data output from RocFall. The curve, an example of which can be seen in Figure 5.22, shows the percentage of rocks rolled off the profile that had rollout distances less than or equal to a certain distance from the toe of the wall.

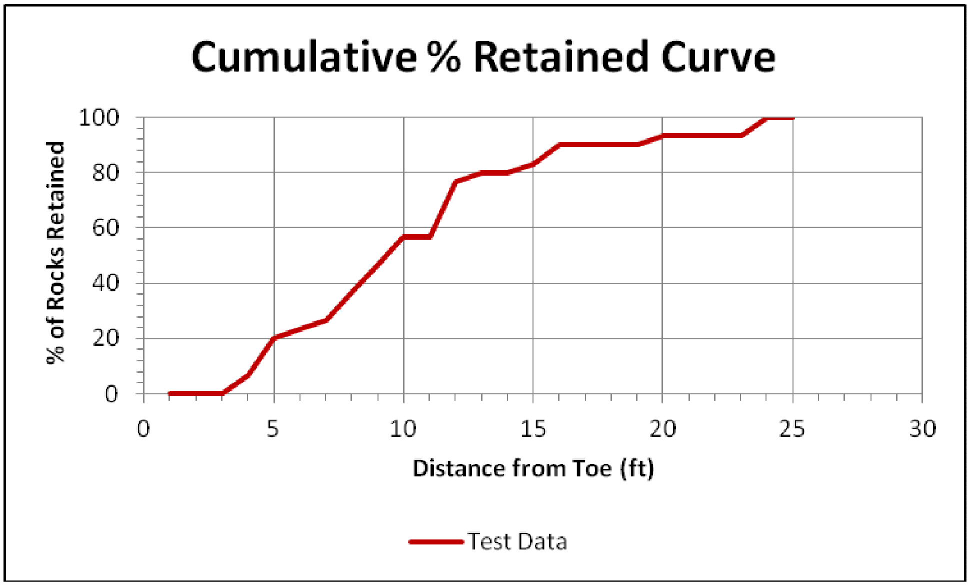


Figure 5.22: Example Cumulative Percent Retained Curve for Real Test Data

The curves are not smooth due to the limited number of rocks rolled off each profile. Once these curves had been created, each profile was brought into RocFall. The actual curves were compared to the cumulative percent retained curves from the simulations to calibrate the RocFall input data. Figure 5.23 shows the graph of the profile found in Figure 5.22 with the cumulative percentage curve from the RocFall test data. Appendix C contains the curves for all nine profiles.

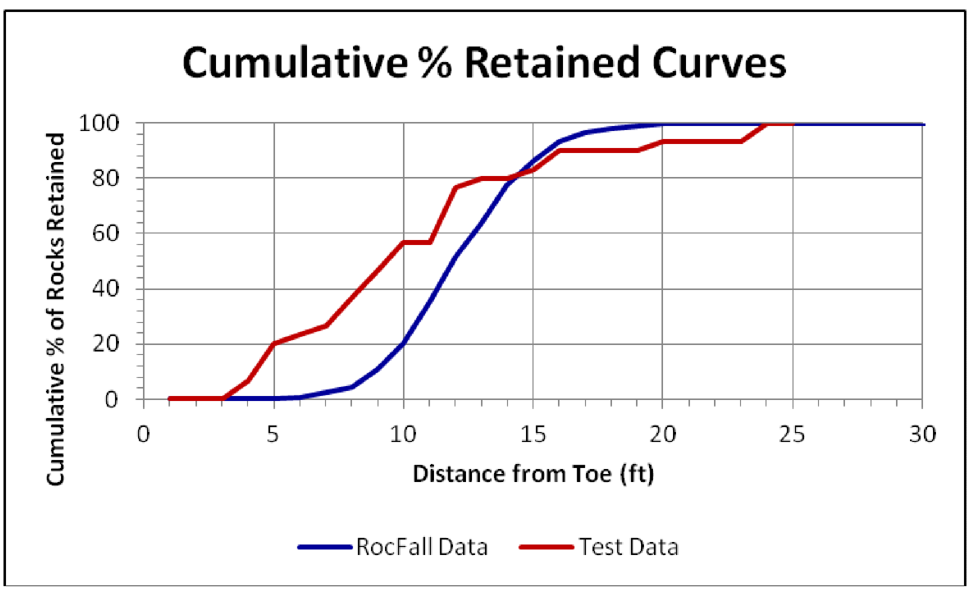


Figure 5.23: Example Test Data/RocFall Data Comparison

The RocFall curve is smoother than the real test data curve because 1000 trials were used in the simulations. To calibrate the parameters, the two curves were compared at five points: 75%, 80%, 85%, 90%, and 95% retention using distance from the toe in feet as the variable. This method compares the curves at key design locations and mimics a procedure found in similar research by Alejano, et al (2007). This process was repeated for each profile, and the differences between the curves, or error, was found. The overall goal of the calibration is to match the real test data curve and the RocFall data curve as closely as possible. Keeping the results of the sensitivity analysis in mind, the input parameters were repeatedly adjusted to minimize the total error for each site as well as the individual error for each comparison location. The parameters which yielded the minimum error are shown in Table 5.XXI.

Table 5.XXI: RocFall Input Parameters

Parameter	Site 1			Site 2		
	Rock	Talus	Floor	Rock	Talus	Floor
Rn: Mean	0.45	0.15	0.35	0.52	0.29	0.34
Rn: St Dev	0.10	0.05	0.05	0.05	0.07	0.07
Rt: Mean	0.80	0.40	0.70	0.97	0.69	0.73
Rt: St Dev	0.10	0.05	0.05	0.05	0.07	0.07
Φ: Mean (°)	30	50	35	30	50	35
Φ: St Dev (°)	2	2	2	2	2	2
Roughness: St Dev (°)	4	10	5	2	10	5
K Factor	30			30		

Sites 1 and 2 are granite and diabase, respectively, and the geologic differences between these two rock types warrants using two sets of parameters.

In the calculation of error, the testing results were considered the baseline. Equation 5-3 shows the basic calculation of the difference.

$$\textbf{Test Data (ft)} - \textbf{RocFall Data (ft)} = \textbf{Data Difference(ft)} \qquad \text{Equation 5-3}$$

RocFall data further from the toe than the test data end up negative and data closer to the toe are positive. Table 5.XXII and Table 5.XXIII contain the distance from the toe of each comparison location for each profile divided by site found during testing.

Table 5.XXII: Site 1 Test Data

Site 1	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	9.75	10.60	12.80	16.20	21.05
2	12.00	12.30	12.60	12.90	13.80
3	12.88	13.60	14.35	14.90	15.90
4	8.75	9.30	9.73	10.30	11.15
5	19.50	20.60	21.30	21.70	23.20

Table 5.XXIII: Site 2 Test Data

Site 2	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	11.83	13.00	15.25	16.00	21.00
2	14.00	17.40	23.40	24.60	26.80
3	11.92	12.80	13.77	15.10	16.55
4	17.75	19.20	20.43	21.40	24.20

Table 5.XXIV and Table 5.XXV contain the distance from the toe of each comparison location for each profile divided by site found using RocFall.

Table 5.XXIV: Site 1 RocFall Simulation Data

Site 1	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	12.41	13.41	16.48	21.98	24.69
2	10.31	10.59	11.01	11.42	12.22
3	7.67	8.12	9.10	11.81	15.93
4	12.34	12.64	13.15	13.76	14.86
5	19.69	20.38	21.10	22.03	23.54

Table 5.XXV: Site 2 RocFall Simulation Data

Site 2	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	13.76	14.22	14.78	15.55	16.27
2	13.73	14.50	15.71	17.39	20.52
3	14.98	15.80	16.46	17.52	18.97
4	22.95	23.55	24.23	25.01	26.32

By simply subtracting the values using Equation 5-3, the differences can be found and are shown in Table 5.XXVI and Table 5.XXVII.

Table 5.XXVI: Site 1 Testing/RocFall Differences

Site 1	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	-2.66	-2.81	-3.68	-5.78	-3.64
2	1.69	1.71	1.59	1.48	1.58
3	5.21	5.48	5.25	3.09	-0.03
4	-3.59	-3.34	-3.42	-3.46	-3.71
5	-0.19	0.22	0.20	-0.33	-0.34

Table 5.XXVII: Site 2 Testing/RocFall Differences

Site 2	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	-1.93	-1.22	0.47	0.45	4.73
2	0.27	2.90	7.69	7.21	6.28
3	-3.06	-3.00	-2.69	-2.42	-2.42
4	-5.20	-4.35	-3.80	-3.61	-2.12

Converting the differences to percentages results in the data found in Table 5.XXVIII and Table 5.XXIX.

Table 5.XXVIII: Site 1 Percentage Difference

Site 1	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	-27.32%	-26.47%	-28.78%	-35.67%	-17.28%
2	14.06%	13.93%	12.58%	11.45%	11.45%
3	40.49%	40.26%	36.59%	20.73%	-0.18%
4	-41.02%	-35.88%	-35.11%	-33.57%	-33.30%
5	-0.95%	1.06%	0.93%	-1.54%	-1.48%

Table 5.XXIX: Site 2 Percentage Difference

Site 2	Cumulative % Retained Footage (ft)				
Profile	75	80	85	90	95
1	-16.28%	-9.36%	3.08%	2.82%	22.55%
2	1.96%	16.68%	32.84%	29.30%	23.45%
3	-25.66%	-23.46%	-19.54%	-16.04%	-14.61%
4	-29.28%	-22.65%	-18.62%	-16.86%	-8.74%

Overall for Site 1, the RocFall simulations are 9.48 ft less than the actual test data over a total of 361.16 ft for a percentage error of -2.63%. For Site 2, the RocFall simulations are 5.80 ft less than the actual test data over a total of 356.40 ft for a percentage error of -1.63%. Again, the negative value reflects that the RocFall simulations project the rocks to be farther from the toe than the actual test results, which reflects a more conservative approach to the simulations.

The distribution of the RocFall curves were also compared to the distribution curves from the actual test data. These curves were only compared using rollout distance because RocFall does not output data on impact distance. Figure 5.24 contains the cumulative lognormal distribution curves for the actual test data and the RocFall simulation data.

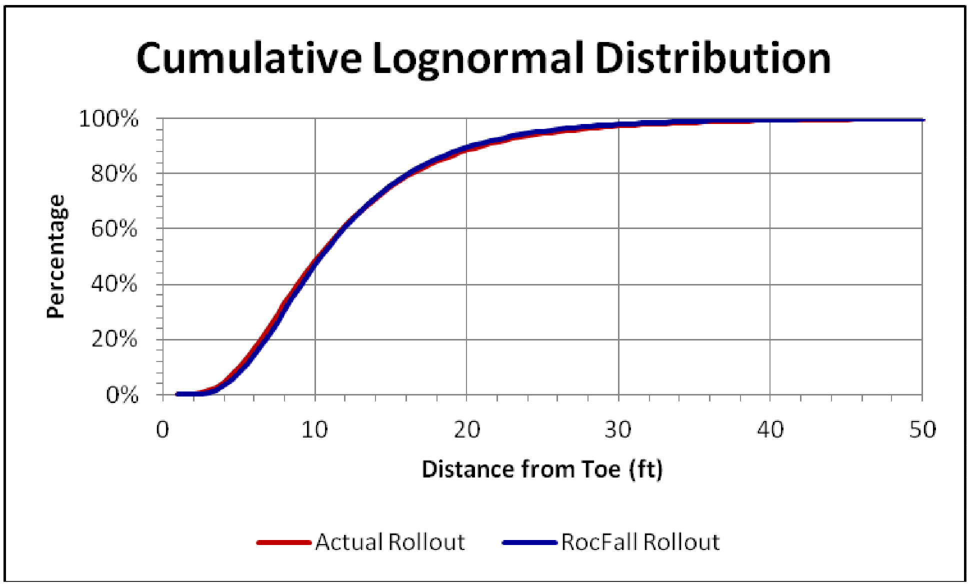


Figure 5.24: Cumulative Distribution Comparison

As the graph shows, the distribution curves are very closely aligned. The average difference between the curves is 4.56%. This small difference again supports the choice of the input parameters and the accuracy of the RocFall simulations.

The error cannot be brought to zero for a number of reasons. First, RocFall is only a 2-D program, and each rock rolls down the linear profile. Observations from the testing show that the rocks did move laterally as they fell in many trials, which RocFall cannot model. The profile might leave out a launch feature that rocks did hit or include one that they did not. Second, RocFall cannot accurately model rock size and shape, which leads to inherent error. Third, the size range of the Talus material piled at the toe of the wall was very large. Any impact on a large rock in the Talus would lead to a drastically different result than a rock hitting minus 1 in material. Modeling this wide range of material characteristics in RocFall is difficult. The chosen inputs represent the optimum error because the error inherent to RocFall cannot be fully removed

5.6.3 Simulation Results

In RocFall, simulations were run using various slope configurations in order to test the impact on rockfalls. For each of the nine slope profiles, five bench widths (15 ft, 20 ft, 25 ft, 30 ft, and 35 ft), three berm heights (3 ft, 4 ft, and 5 ft), and two toe conditions (talus and no talus) were tested for a total of 270 simulations. The results of the simulations have been compiled into design charts in the style of previous research in order to more easily understand the data as well as provide a quick reference for designers. In addition, observations about the bench widths, berm heights, and toe conditions have been made.

The data from the simulations has been compiled into design charts by site. The different geologic conditions warrant the separate analysis. Appendix D contains graphs from which the design charts were created. The design charts, one for each toe condition, for Site 1 can be seen in Figure 5.25.

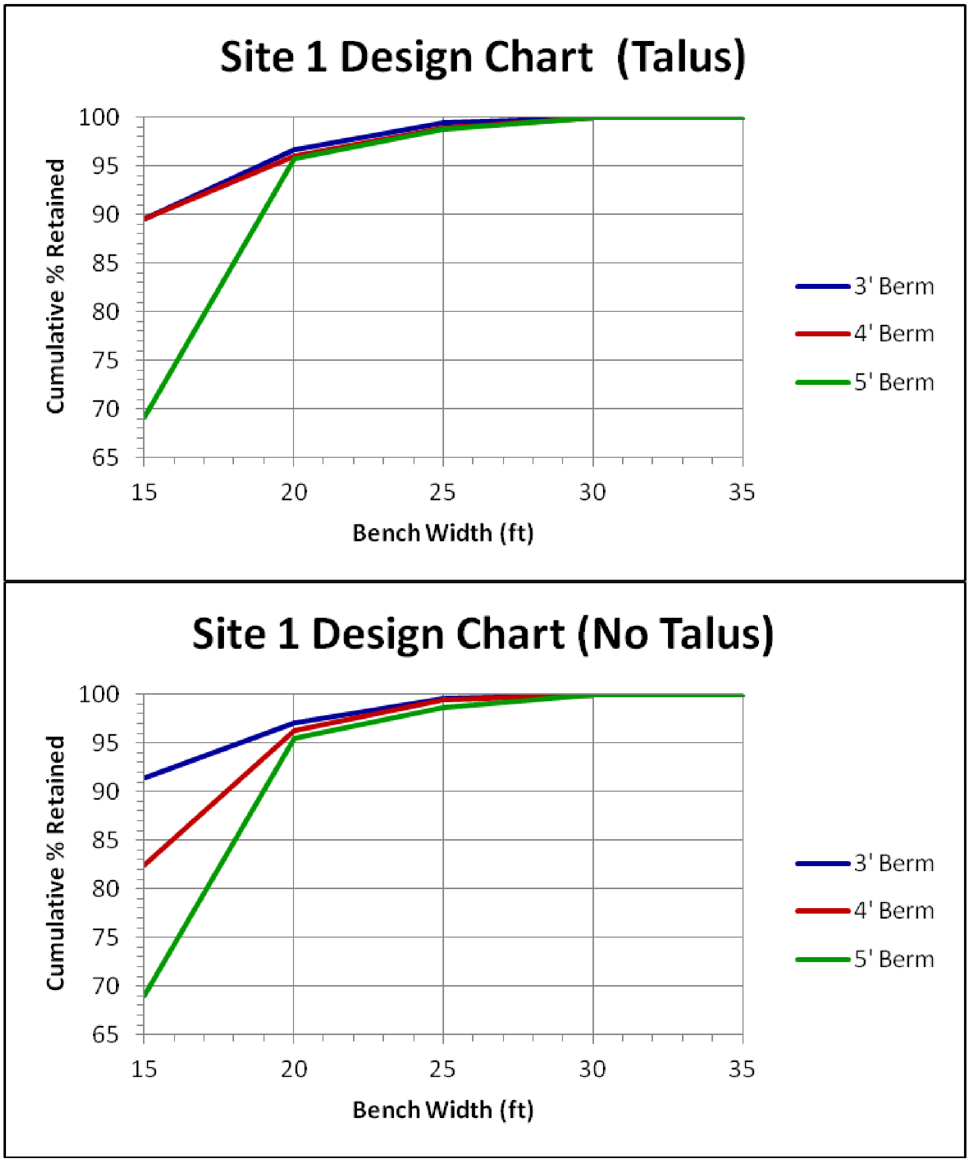


Figure 5.25: Site 1 Design Charts

To create these charts, the simulation data for Profiles 1-4 was taken together. As expected, the percentage of rockfalls contained on the bench increases with bench width. Additionally, the impact of the berm height decreases as bench width increases. The larger berm retains fewer rockfalls, for small bench widths, because the increased berm height moves the berm crest closer to the toe, as shown in Figure 5.26.

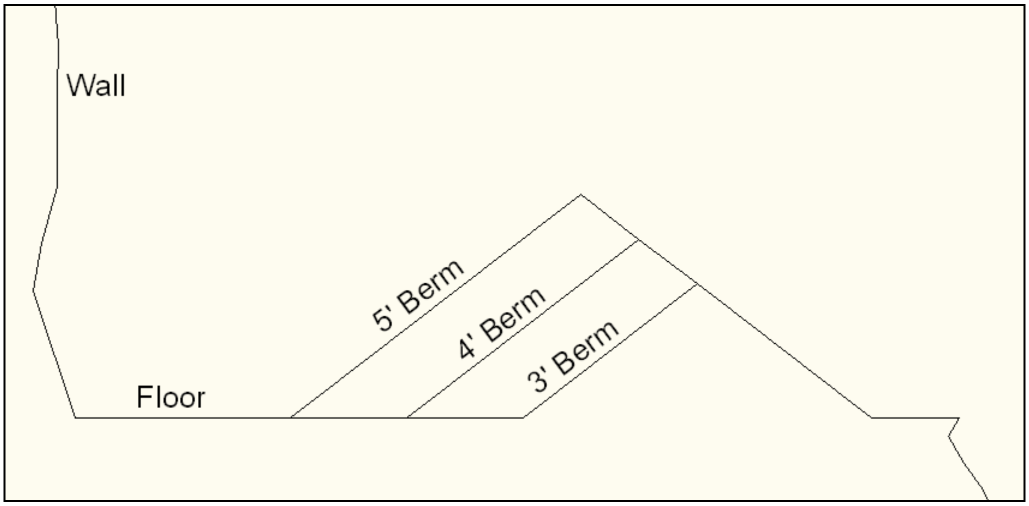


Figure 5.26: Berm Crest Location

For comparison, design charts, also divided by toe condition, were created for the launch feature profile, Profile 5, seen in Figure 5.27.

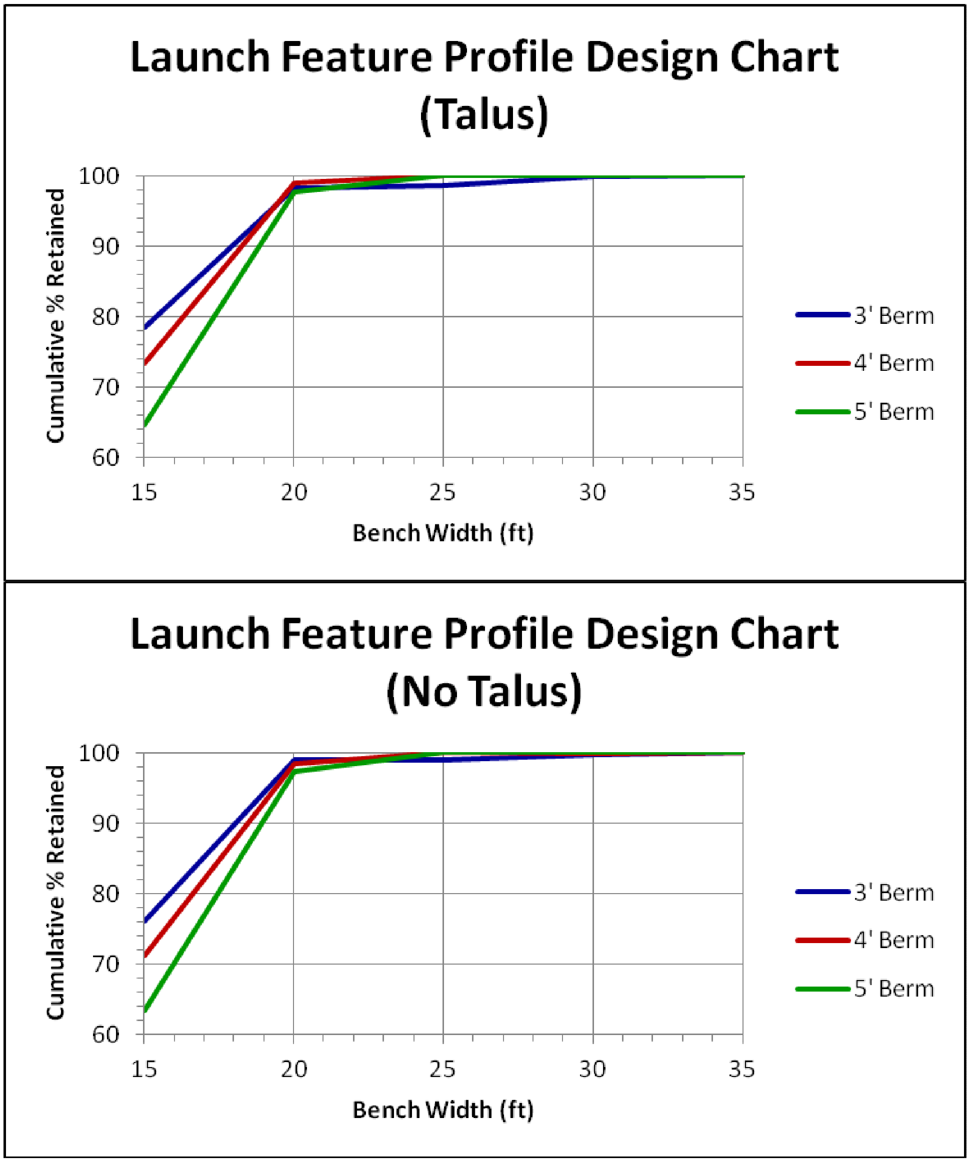


Figure 5.27: Site 1 Launch Feature Design Charts

The impact of the launch feature is apparent with smaller bench widths especially for the 3 ft and 4 ft berms. In spite of the launch feature, the simulations show that the berms work well for stopping rollouts.

The design charts created from the Site 2 simulations can be seen in Figure 5.28.

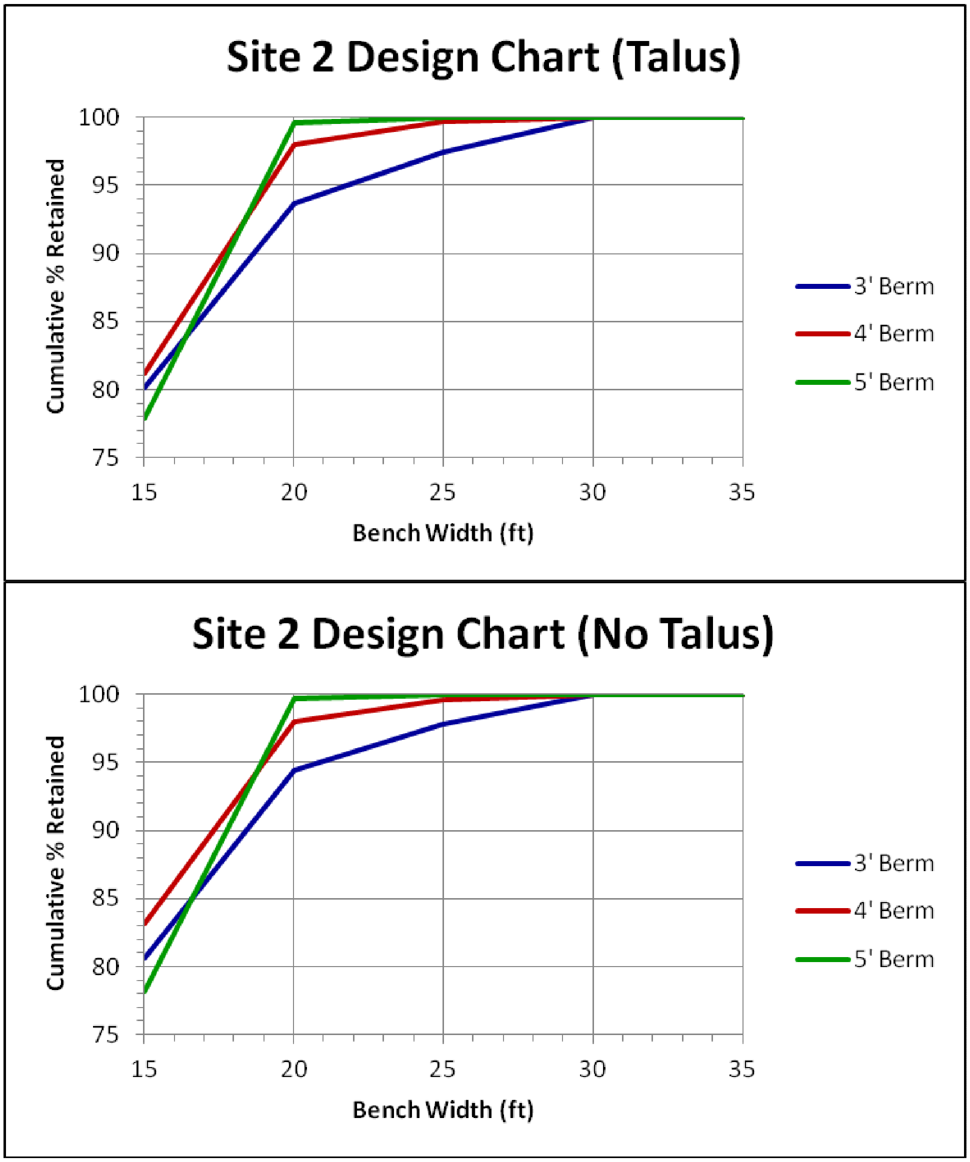


Figure 5.28: Site 2 Design Charts

The charts show the difference from Site 1. At smaller widths, the rockfall percentage retained is much more consistent than Site 1, but the opposite is true as bench width increases. This discrepancy may stem from the smaller volume of talus at the toe for the Site 2 profiles. Additionally, the larger berm was found to stop more rocks at Site 2 than Site 1. This result is attributed to the 2 ft greater impact distance for Site 1. The 3 ft berm's crest is further from the toe (Figure 5.26) than the 5 ft berm, which enables it retain rocks with larger impact distances.

In addition to the design charts, general observations about the impact of the bench width, berm height, and toe condition can be made. With regard for bench width, the trend is clear, larger benches retain a higher percentage of rockfalls. For example, 100% of all simulated rockfalls were retained on the 35 ft bench. The most significant increase in percentage retained shown in all the charts comes between 15 ft and 20 ft. The height of the berm yielded contradictory results between Sites 1 & 2. For Site 1, the 3 ft berm retained a higher percentage of rockfalls than the 4 ft and 5 ft berms for the same bench widths and toe conditions, but the opposite is true for the Site 2 simulations. This discrepancy is due to the different crest locations of the 3 and 5 ft berms and the higher (2 ft) impact distance at Site 1. At both sites though, the 4 ft berm appears to be the best compromise between rockfall stopping power and berm size. Finally, two toe conditions were tested: with talus and without talus. As previously described, the talus material is the talus material is rock remaining from the previous blast which has been left in a pile against the toe. One simulation was performed with the talus in place, just like the actual testing, and another simulation was run after removing the talus from the profile, as shown in Figure 5.29.

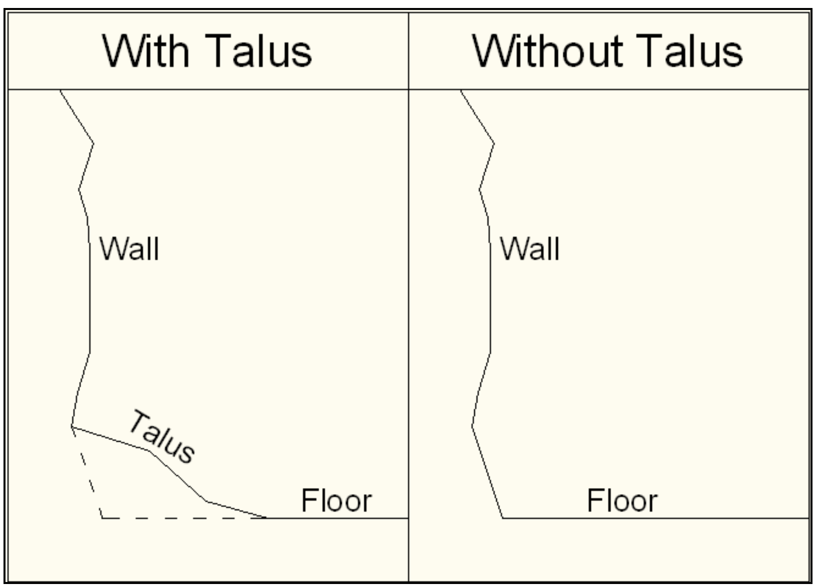


Figure 5.29: Talus vs. No Talus

The most significant impact of the talus material on the rockfall retention percentage only appears for low percentages. Figure 5.30 shows an example graph from Site 2 showing the difference between the talus and no talus simulations.

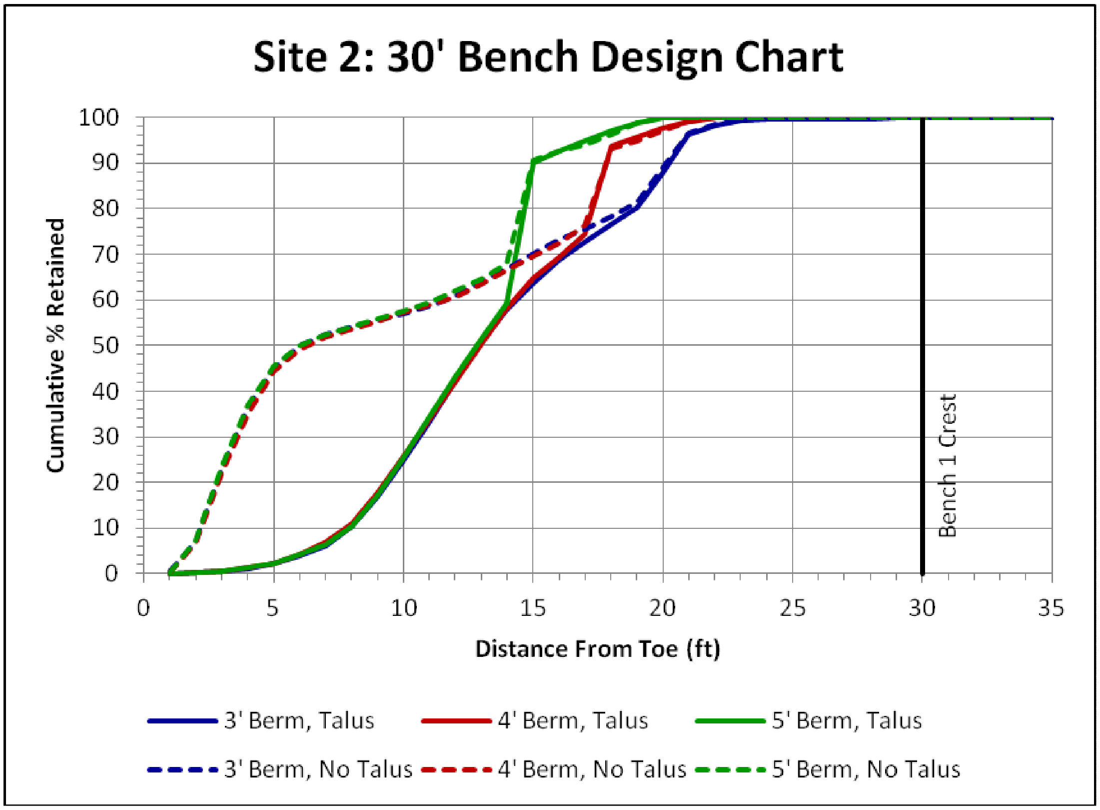


Figure 5.30: Example Talus Impact

The difference exists for percentages which are typically impractical for designs. This result indicates that the increased angular momentum given to a rock impacting the talus slope is counteracted by the cushioning effect of the unconsolidated material.

6 Conclusions and Recommendations

Studying the results of the previously described analyses allows a number of conclusions to be drawn. A number of key insights about rockfalls can be seen in the data. From this new understanding, recommendations can be given regarding rockfall analysis and safety bench design.

6.1 Spatial Data Analysis

After performing the Principal Components Analysis (PCA) and Cluster Analysis, a number of conclusions can be drawn supported by the techniques and field observations. First, both PCA and Cluster Analysis are valid techniques for evaluating rockfall data. The similarity of the PCA and Cluster Analysis results to observations support this statement. In future studies, PCA and Clusters Analysis can be used to better understand the underlying factors and structure influencing rockfalls.

From PCA, wall configuration, rock dimensions, and rock energy were found to be the underlying factors which control the majority of the variance in rockfall impact and rollout. Therefore, these factors need to be accounted for in any wall evaluation method that is used in order to accurately predict the rockfall potential and risk of a wall. The author recommends that the following criteria be included in any wall evaluation method, at minimum:

1) Slope Angle (Wall Configuration)
2) Slope Height (Wall Configuration, Rock Energy)
3) Launch Features (Wall Configuration, Rock Energy)
4) Block Size (Rock Dimensions)

Cluster Analysis was performed in order to better understand the structure of the rockfall data, and this goal has been met. Launch features are found to have a dramatic effect on a rockfall. The tightly-grouped clusters from Site 1 and the launch feature test prove this statement. Therefore, launch features must be carefully studied and/or remediated before safety bench construction. These launch features result in larger impact distances which may cause rocks to fly over the berm, if the berm is placed too close. Secondly, the distinction between Clusters 1 and 2 indicates that larger rocks (2-3.5 ft) tended to impact and rollout farther by 1.1 ft and 3.1 ft, respectively. This increase is most likely due to the increased energy of the larger rock because of the additional mass. To prevent these larger rocks from rolling off the bench, a berm of at least 4 ft is recommended.

On a procedural note, Cluster Analysis using the uncorrelated PCA scores was found to yield more significant results than simply using the measured variable. Therefore, cluster analysis using the uncorrelated PCA scores is recommended for future analyses.

6.2 Alternative Design Methodology

The results of the analysis of the Ritchie Criteria, Modified Ritchie Criterion, Ryan and Pryor Criterion, ODOT design charts, and RocFall simulations have led the author to a number of conclusions and recommendations.

The RocFall simulation and the associated site-specific rockfall testing is the recommended method for design of safety benches in quarries. The wall specific nature of this method yields a design well suited for the target wall. The ability to simulate thousands of trials using material data tailored for each wall is important for accurate design without wasting time or money actually conducting those rockfall tests. The one drawback is that some site-specific rockfall testing (1-3 days) such as the testing performed for this project must be performed at each site in order to yield the most realistic results, but this cost is worth the reward. Once this testing has been performed, the slope designer can accurately model any wall to achieve the optimum design. RocFall simulations also allow the designer to design for multiple benches, which is important in a quarry. Therefore, the procedure described in section 5.6 RocFall Computer Simulation is recommended as the best design practice.

Specifically for walls of similar angle and height to the ones tested for this project, the author recommends a safety bench width of 20 ft from the toe and a 4 ft berm on the bench crest with 2-3 feet between the toe of the berm and the crest. From the design charts (Figure 5.25 and Figure 5.28), this bench design will retain greater than 97% of all rockfalls.

With regard to the lognormal distribution data, the equations can be used as a quick design reference and an accuracy check for RocFall simulations. The actual test data distribution should be compared to the RocFall distribution to validate the selection of the input parameters and ensure accurate simulations. Furthermore, the actual distribution data can be used to justify a design to regulatory agencies.

Recommendations can also be made for the other methods evaluated. Overall, the Ritchie design criteria for highway slope design can be applied to quarry bench design. In the studied cases, the bench width and berm design would retain a high percentage of impacts (>95%) while preventing a high percentage of rocks escaping the berm (>85%), especially for walls without prominent launch features. But depending on conditions, Ritchie's criteria may be too conservative as shown here and suggested by other research. The Modified Ritchie design criterion is applicable for quarry bench design, also. In the studied cases, the bench width and berm design would retain a high percentage of impacts (>90%) while preventing a large percentage of rocks escaping the berm (>77%). This criterion is also less conservative than the Ritchie design criteria by approximately 5%-8% in the rollout retention which may be beneficial in certain situations. The Ryan and Prior Criterion is much less conservative than the Ritchie or Modified Ritchie Criteria. By examining the critical location of the berm crest, the author suggests that this criterion is far too aggressive to be used for quarry bench design, for example the design will only retain one of two rockfall impacts in some cases.

The only caveat for these conclusions comes from the impact that a berm would have on the rollout retention. Since no berm was used during the testing, a true determination on these criteria cannot be made until more research is performed. The inclusion of a berm during testing would only serve to increase the rollout retention. For example, the inclusion of a berm in the RocFall simulations increased the retention by at least 5%.

With regard to the ODOT design charts, the author proposes that the differences in the blasting practices during the creation of the wall prevent direct use of the charts for a quarry wall. For impact distance, the Luck Stone test data appears to be approximately 44% greater than the ODOT data for each location examined. For rollout distance, the ODOT data gradually increase compared to the Luck Stone data as the retention percentage increases. Therefore, the relationship between the ODOT and Luck Stone data is difficult to pin down. Additionally, extrapolating this relationship to walls of different angles and heights would lead to inherent error. Thus, the author recommends testing quarry walls with slope angles and heights equivalent to the ODOT tests before attempting to apply the design charts to quarry bench design.

6.3 General Design Practices

Through the testing and analyses, the author has observed trends which correlate with best design practices for a bench of any width. These practices will help to prevent rockfalls from occurring, impacting and rolling as far, and becoming hazardous.

With regard to quarry bench design, the author recommends the following best practices. First, a berm on the end of the bench is a must. This berm should be approximately 4 ft high. The height will not allow rocks to roll over the berm, provide more catchment volume, and keep the berm crest from being too close to the wall. The location of the berm should be 2-3 ft away from the bench crest which will prevent rocks rolling over the berm and falling over the wall. Furthermore, covering the crest side of the berm with fine material will reduce the chance of a berm rock falling and hurting someone as well. This berm location will also build in a cushion in case back break from blasting is more than expected. Second, the talus material at the toe should be cleaned up as much as possible. Although the RocFall simulations show that talus does not significantly impact rockfall results at high retention percentages, removing the talus removes a main mechanism for converting fall energy into rolling energy. Additionally, the talus material will naturally compact over time, which will tend to increase the rollouts of rocks hitting the talus material. In place of the talus, evaluation of the lognormal distributions of the impact and rollout distances suggest that placing loosely compacted, well draining material in a flat, level layer on the bench 0 to 10 ft from the toe will reduce rollouts.

As discussed, blasting has a significant impact on the condition of a wall. Therefore, the use of some form of controlled blasting is recommended for final highwalls. The most effective type of controlled blasting must be determined on a wall-to-wall basis, but reducing the blast damage on the wall will greatly reduce the potential for rockfall.

The results of the analyses show that prominent launch features increase the impact and rollout distances of falling rocks by approximately 8 to 9 ft. For final walls, profiling the wall with a laser profiler to look for launch features is suggested. If found, the feature should be removed or the bench should be designed to account for the increased impact and rollout distances.

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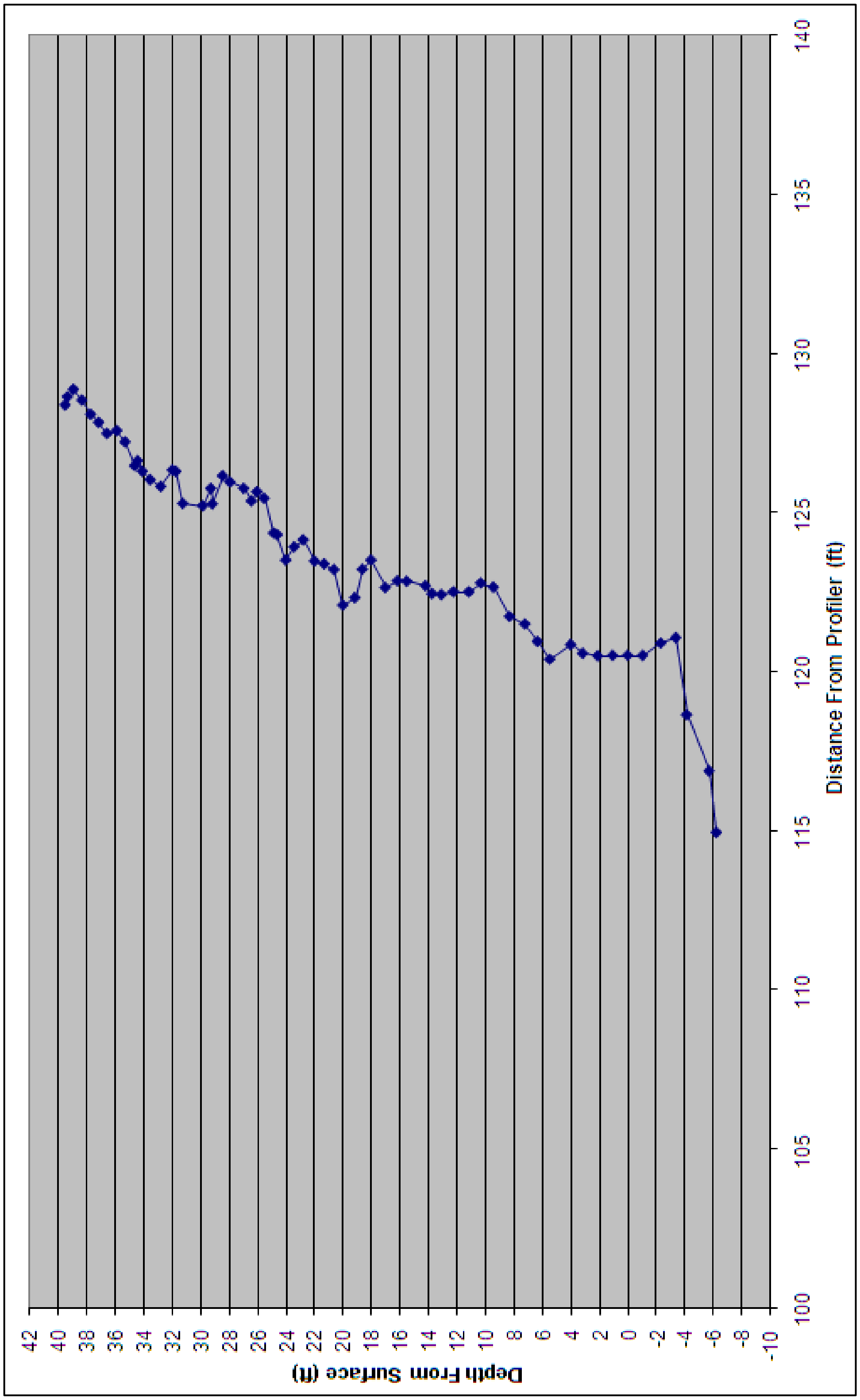
Appendix A

Wall Profiles

Site 1: Profile 1



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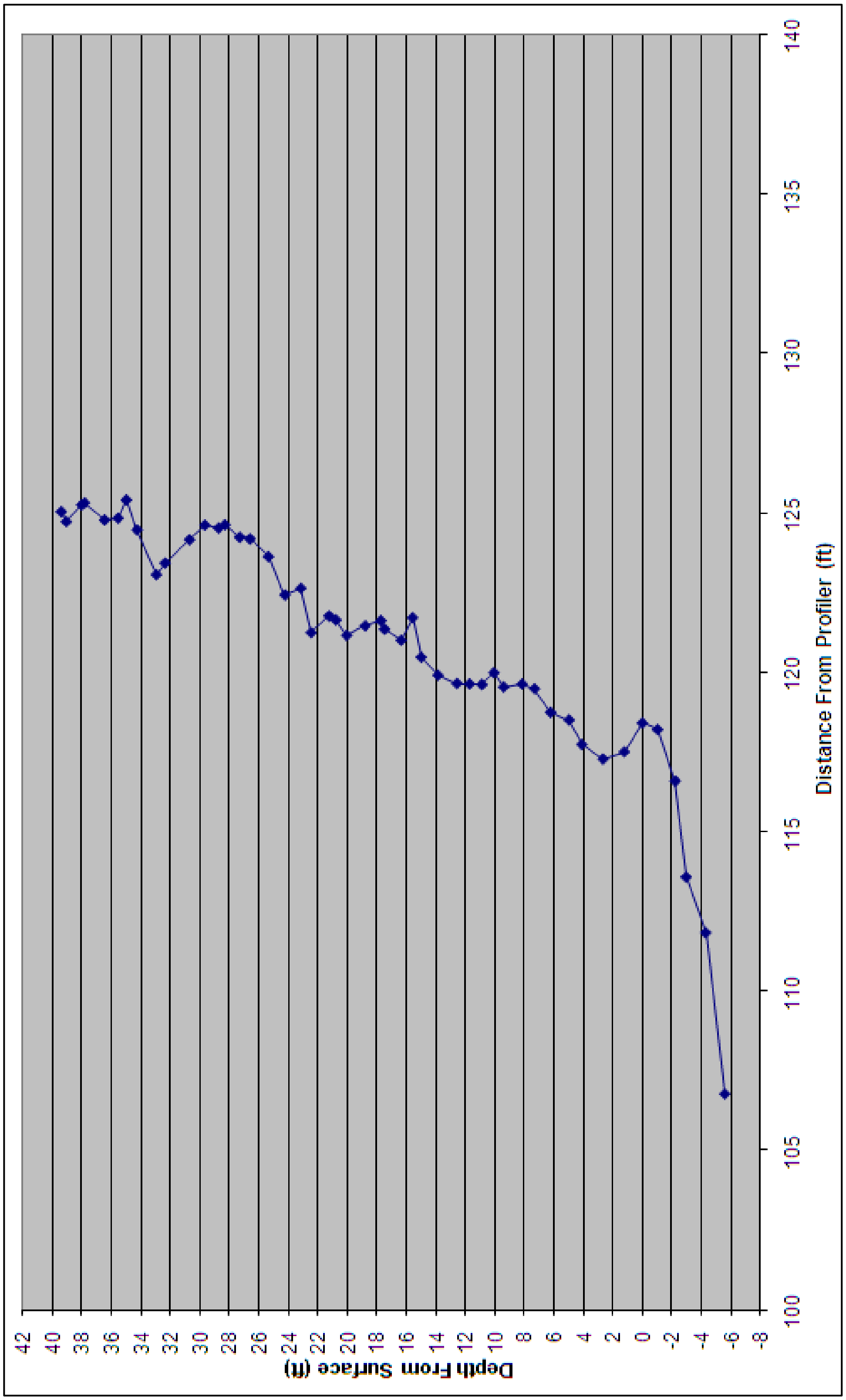

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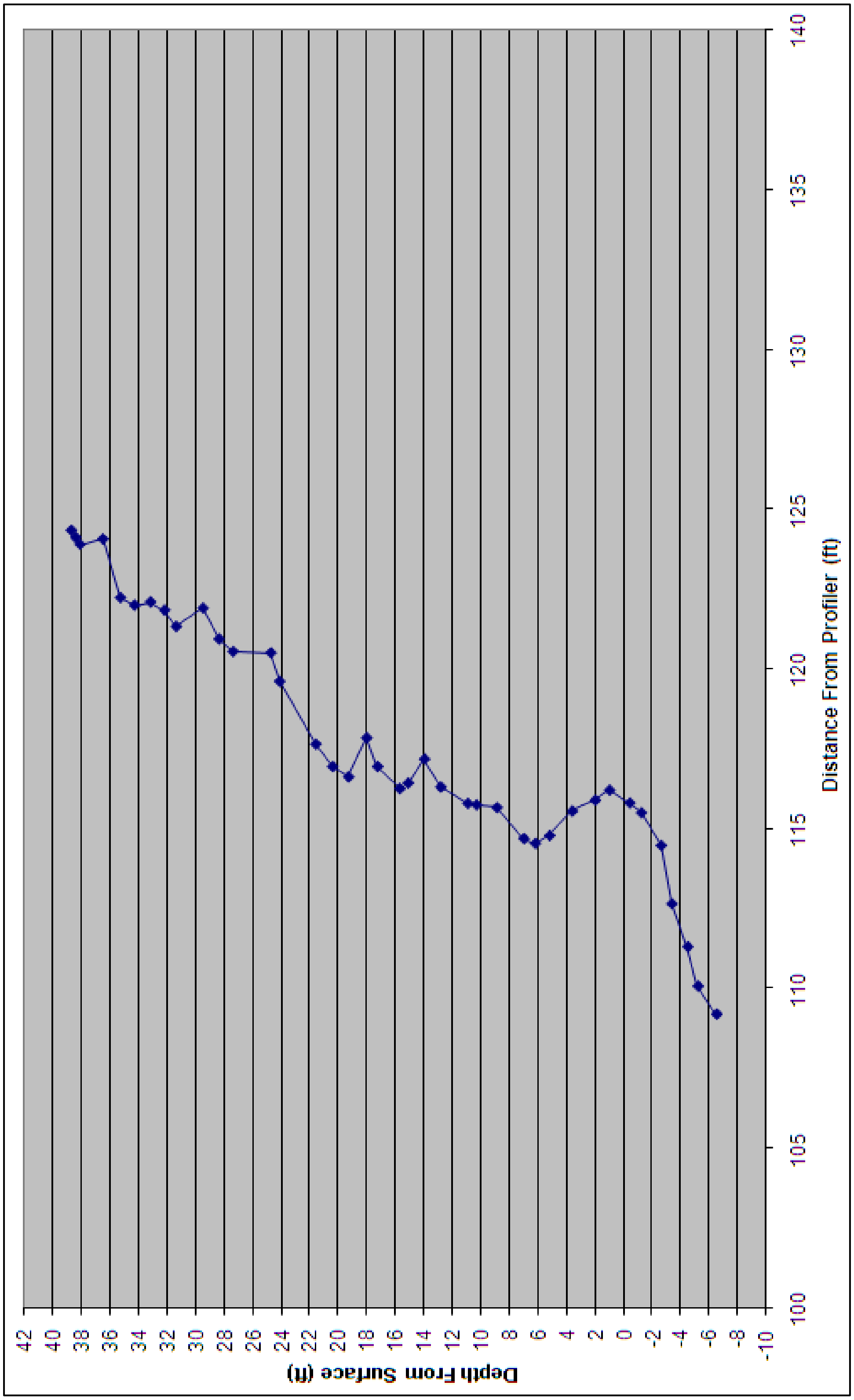

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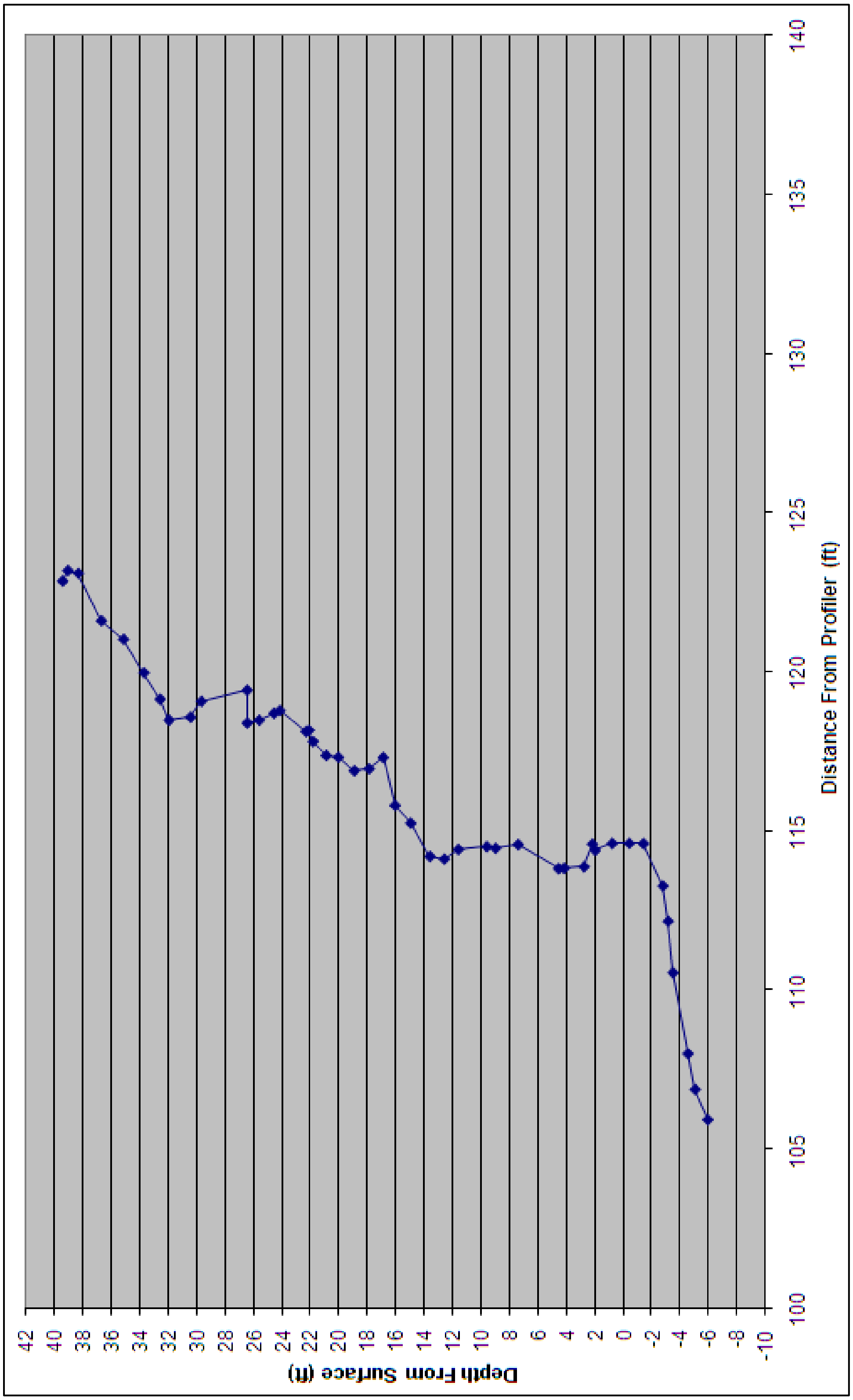

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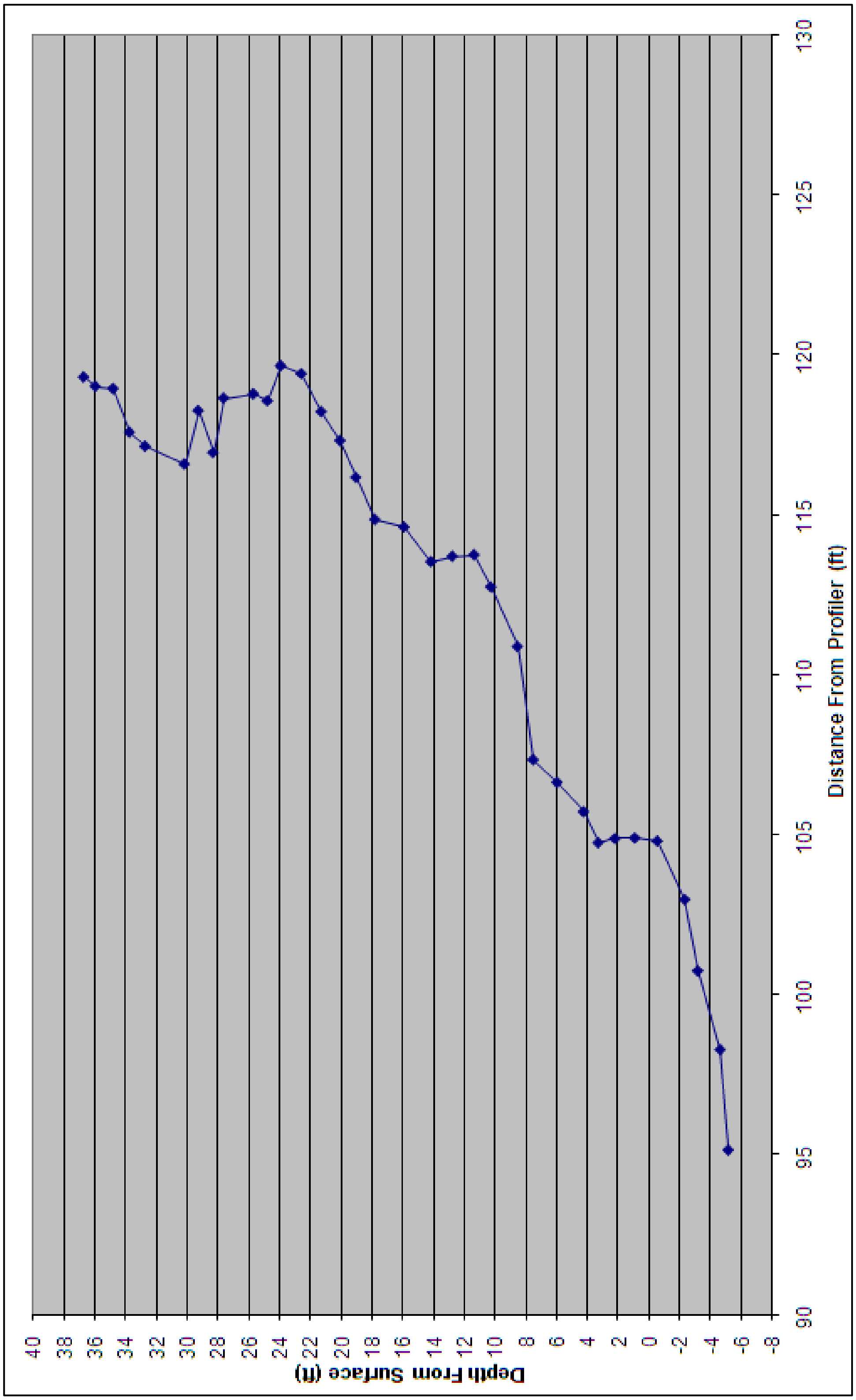

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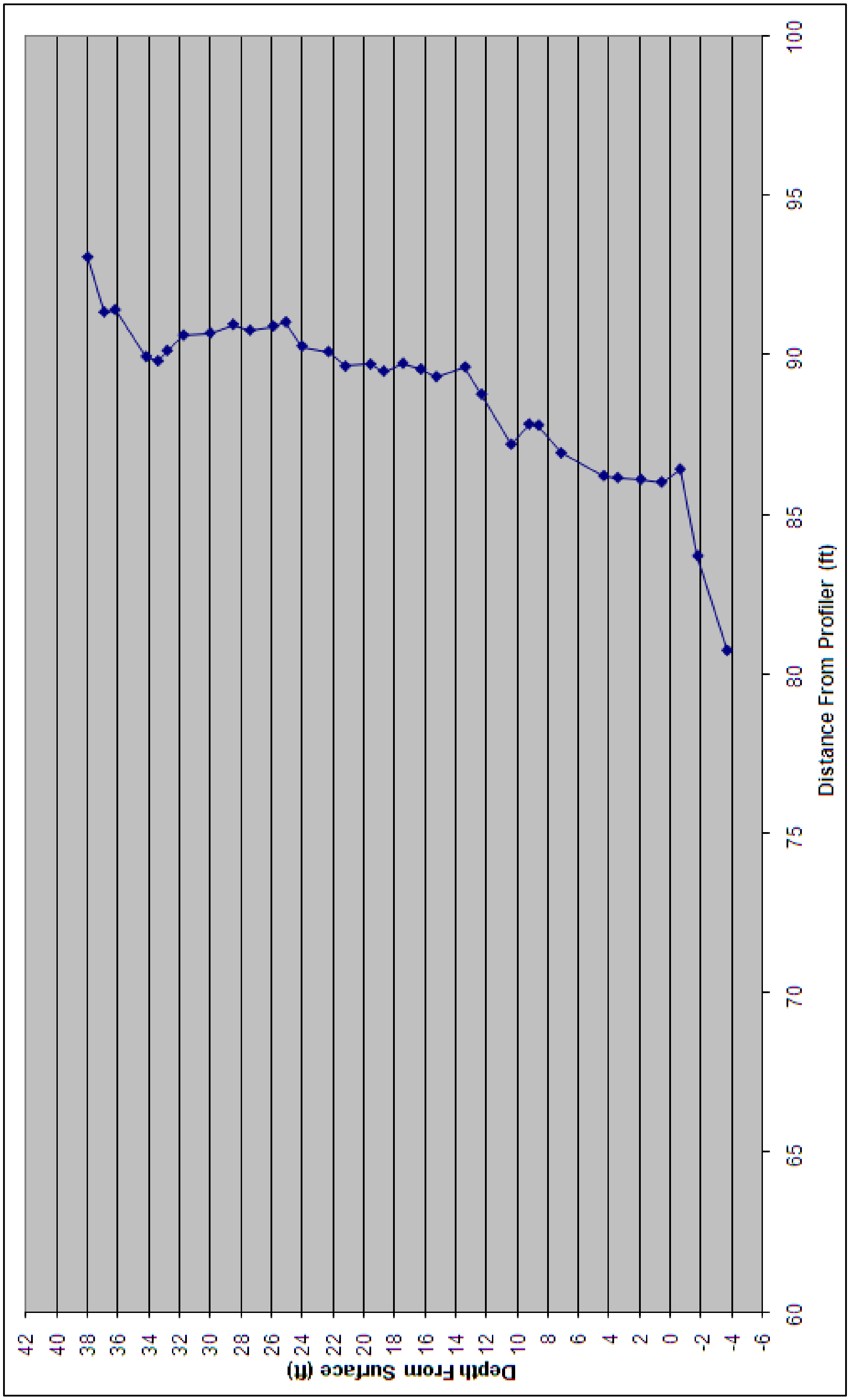

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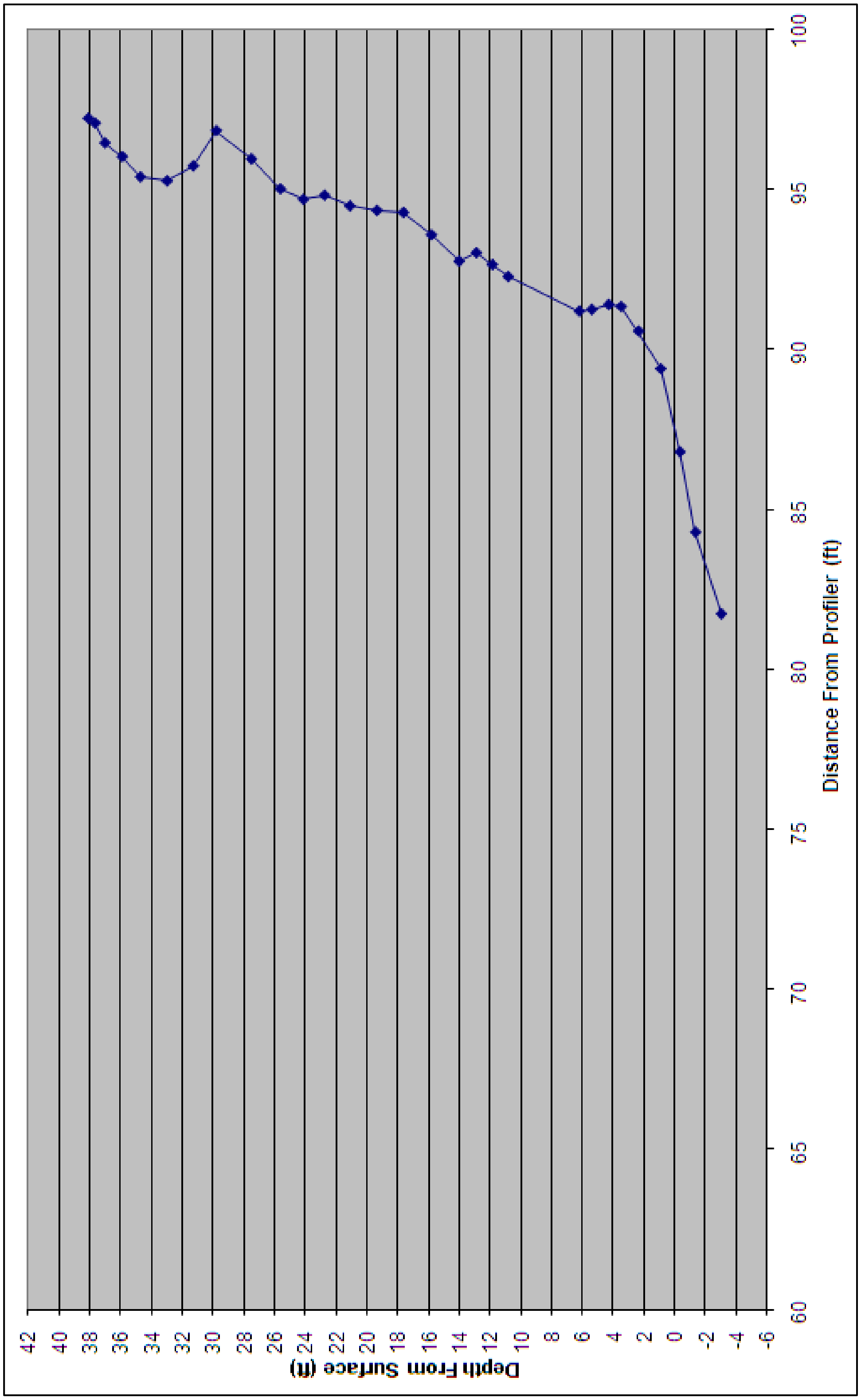

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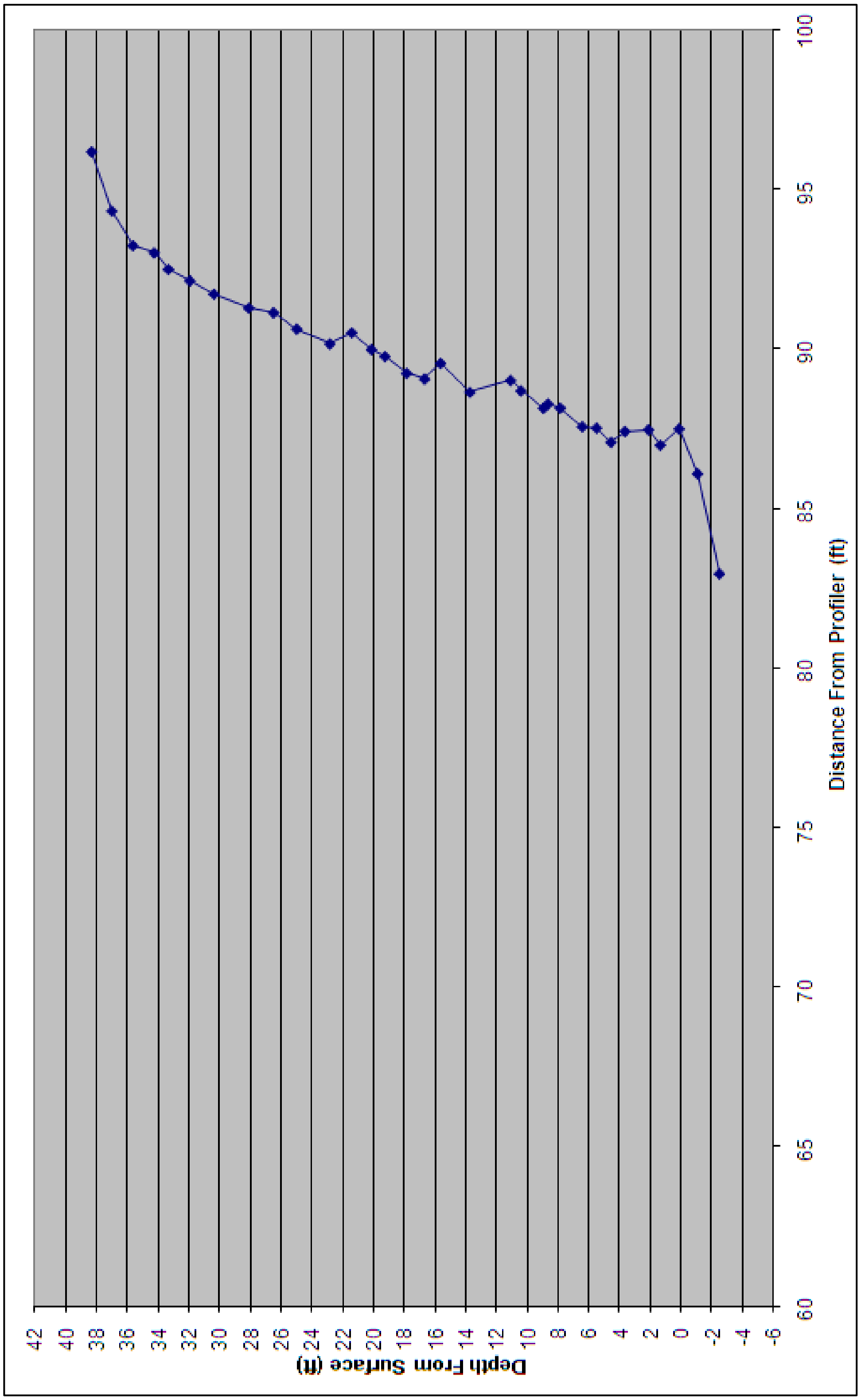

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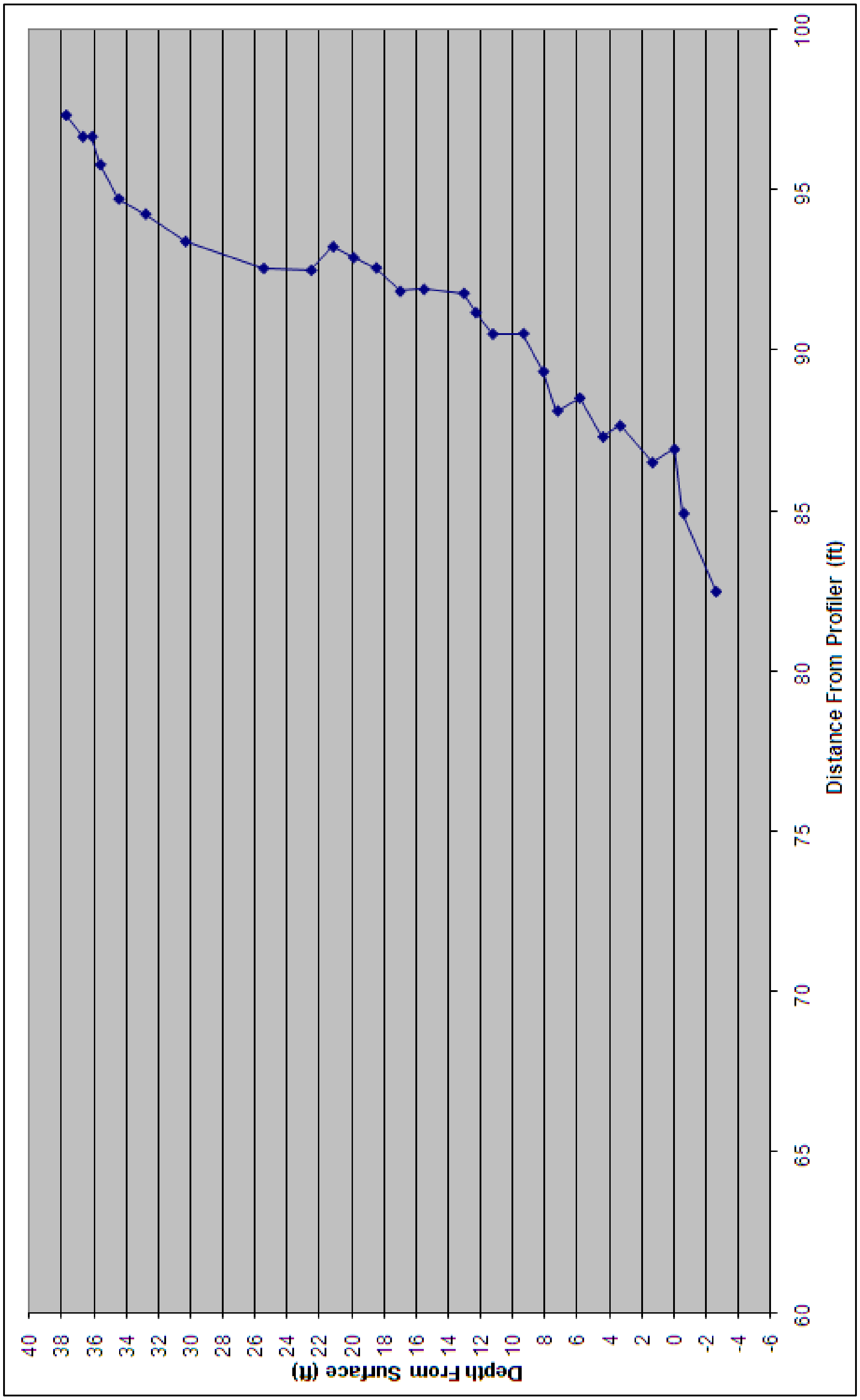


Appendix B

Experimental Data

Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
1	1	2	22	10	2.20	1	9	10
1	2	2	19	10	1.90	1	15	26
1	3	1	14	11	1.27	1	15	19
1	4	1	15	7	2.14	1	11	11
1	5	1	15	8	1.88	1	7	8
1	6	1	12	8	1.50	1	1	1
1	7	1	17	7	2.43	1	3	3
1	8	2	25	20	1.25	1	5	7
1	9	2	20	12	1.67	1	5	8
1	10	3	32	28	1.14	1	6	6
1	11	1	18	11	1.64	2	4	5
1	12	1	11	9	1.22	2	3	4
1	13	1	17	10	1.70	2	3	10
1	14	1	15	8	1.88	2	2	5
1	15	1	15	11	1.36	2	6	6
1	16	2	20	15	1.33	2	4	12
1	17	2	24	18	1.33	2	3	4
1	18	2			No Data	2	<5	<5
1	19	3			No Data	2	<5	<5
1	20	2	30	23	1.30	2	9	9
1	21	3	36	30	1.20	2	3	8
1	22	3	37	27	1.37	2	4	6
1	23	2	28	22	1.27	2	3	15
1	24	3	31	27	1.15	2	1	14
1	25	2			No Data	2	2	4
1	26	1	15	9	1.67	3	10	10
1	27	1	16	9	1.78	3	7	7
1	28	1	12	7	1.71	3	8	8
1	29	1			No Data	3	5	5
1	30	1			No Data	3	5	5
1	31	1	13	10	1.30	3	7	7
1	32	1	11	11	1.00	3	8	8
1	33	2	22	22	1.00	3	7	15
1	34	2			No Data	3	8	15
1	35	2	25	21	1.19	3	14	16
1	36	3	41	31	1.32	3	9	9
1	37	4	44	33	1.33	3	8	9
1	38	3	42	25	1.68	3	9	9

Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
1	39	1			No Data	4	5	5
1	40	1	12	10	1.20	4	10	12
1	41	1	17	9	1.89	4	7	7
1	42	1	18	10	1.80	4	8	8
1	43	2	28	17	1.65	4	8	8
1	44	3	32	21	1.52	4	6	6
1	45	3	34	22	1.55	4	10	11
1	46	3	36	15	2.40	4	5	5
1	47	2	28	25	1.12	4	4	7
1	48	2	30	29	1.03	4	6	7
1	49	5	60	56	1.07	2	8	13
1	50	4	54	38	1.42	3	9	13
1	51	1	17	9	1.89	1	8	10
1	52	1	18	16	1.13	1	7	7
1	53	2	19	13	1.46	1	8	8
1	54	2			No Data	1	2	2
1	55	2			No Data	1	7	15
1	56	1			No Data	1	5	5
1	57	2			No Data	1	4	4
1	58	2	23	20	1.15	2	3	12
1	59	2	22	15	1.47	2	2	7
1	60	2	30	17	1.76	2	1	10
1	61	2	27	22	1.23	2	3	13
1	62	2	28	14	2.00	2	3	13
1	63	1	18	14	1.29	2	4	9
1	64	2	19	18	1.06	2	3	8
1	65	2	20	16	1.25	2	6	13
1	66	1	16	14	1.14	3	7	13
1	67	2	24	13	1.85	3	6	12
1	68	2	25	24	1.04	3	12	13
1	69	2			No Data	3	8	9
1	70	2	26	19	1.37	3	5	13
1	71	2	19	19	1.00	3	5	14
1	72	2	30	18	1.67	3	8	9
1	73	3	34	17	2.00	3	6	20
1	74	1			No Data	4	3	3
1	75	1			No Data	4	2	2
1	76	1			No Data	4	3	5
1	77	2	27	13	2.08	4	4	10

Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
1	78	2	27	17	1.59	4	9	9
1	79	3	32	24	1.33	4	5	10
1	80	2	30	20	1.50	4	6	7
1	81	1	14	6	2.33	5	14	15
1	82	1	10	10	1.00	5	20	20
1	83	1	11	6	1.83	5	11	11
1	84	2			No Data	5	23	36
1	85	1	17	14	1.21	5	14	16
1	86	1	18	17	1.06	5	14	17
1	87	1			No Data	5	13	13
1	88	1	13	9	1.44	5	12	12
1	89	1	11	7	1.57	5	10	11
1	90	1	12	11	1.09	5	15	15
1	91	1	9	6	1.50	5	15	19
1	92	1	14	8	1.75	5	16	21
1	93	2	21	15	1.40	5	20	22
1	94	1			No Data	5	13	13
1	95	2	24	22	1.09	5	16	22
1	96	2	26	20	1.30	5	12	12
1	97	2	22	18	1.22	5	12	12
1	98	1	17	15	1.13	5	12	17
1	99	2	26	24	1.08	5	12	17
1	100	2	25	18	1.39	5	16	19
1	101	2	26	17	1.53	5	15	18
1	102	1	17	11	1.55	5	14	15
1	103	2	19	17	1.12	5	13	13
1	104	2	28	19	1.47	5	14	15
1	105	2	22	16	1.38	5	19	22
1	106	2	28	22	1.27	5	15	15
1	107	2	22	16	1.38	5	16	25
1	108	3	31	14	2.21	5	15	15
1	109	2	27	19	1.42	5	13	19
1	110	4			No Data	5	22	22
1	111	3	34	25	1.36	5	17	20
1	112	4			No Data	5	20	
1	113	3	40	17	2.35	5	16	16
1	114	4			No Data	5		
2	1	1	11	10	1.10	1	7	20
2	2	1	13	9	1.44	1	4	10

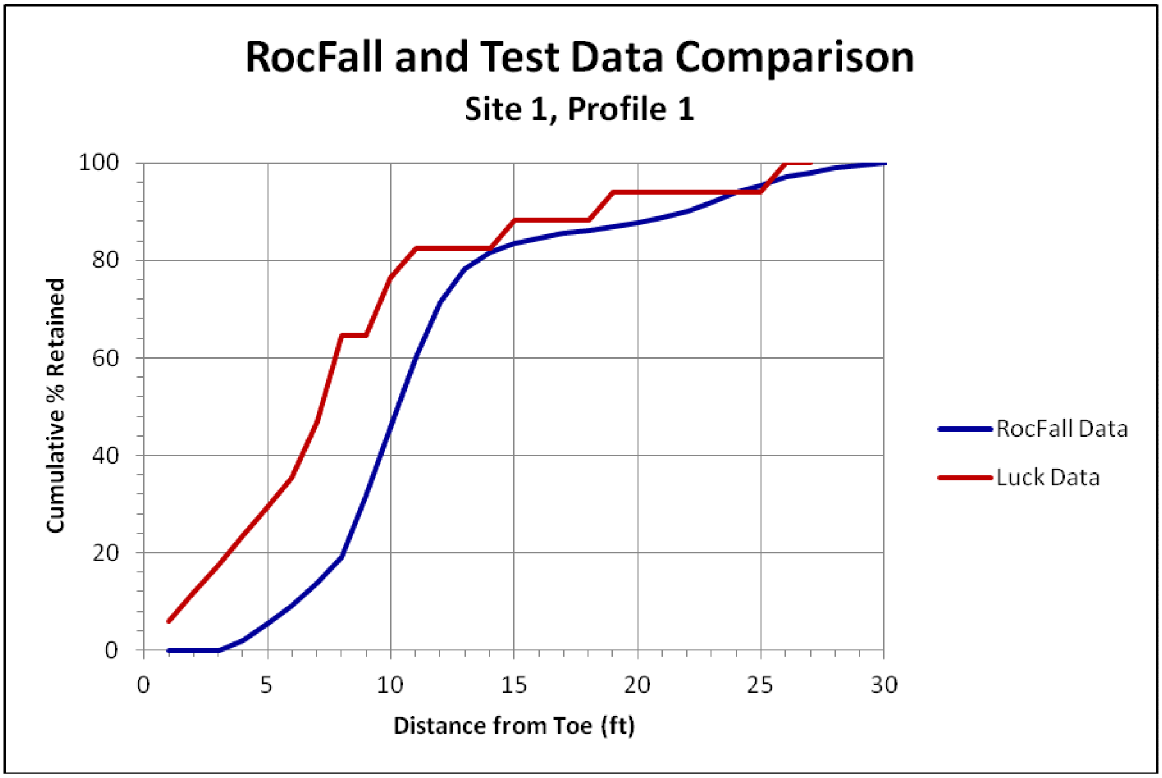
Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
2	3	1	10	10	1.00	1	7	8
2	4	1	10	9	1.11	1	3	9
2	5	1	12	9	1.33	1	5	12
2	6	1			No Data	1	4	5
2	7	1	15	11	1.36	1	5	15
2	8	1			No Data	1	5	5
2	9	1			No Data	1	5	5
2	10	2	21	16	1.31	1	2	16
2	11	2			No Data	1	4	9
2	12	1			No Data	1	5	7
2	13	2	19	10	1.90	1	5	13
2	14	3	35	20	1.75	1	5	10
2	15	2	28	20	1.40	1	5	16
2	16	2	28	19	1.47	1	5	12
2	17	2			No Data	1	4	4
2	18	2			No Data	1	5	8
2	19	2			No Data	1	5	5
2	20	3	31	16	1.94	1	7	9
2	21	1	17	11	1.55	2	5	8
2	22	1	14	13	1.08	2	6	28
2	23	1	13	9	1.44	2	3	10
2	24	1			No Data	2	8	8
2	25	1	11	9	1.22	2	10	13
2	26	1			No Data	2	7	7
2	27	1	16	11	1.45	2	8	14
2	28	1	17	12	1.42	2	12	12
2	29	1			No Data	2	2	8
2	30	2	26	20	1.30	2	9	14
2	31	3	32	18	1.78	2	7	11
2	32	3	36	17	2.12	2	12	24
2	33	2			No Data	2	2	6
2	34	2	27	19	1.42	2	11	15
2	35	2			No Data	2	5	8
2	36	2	23	9	2.56	2	6	12
2	37	2	23	13	1.77	2	10	21
2	38	2	22	17	1.29	2	8	33
2	39	2	28	26	1.08	2	5	7
2	40	2			No Data	2	6	25
2	41	1			No Data	3	5	5

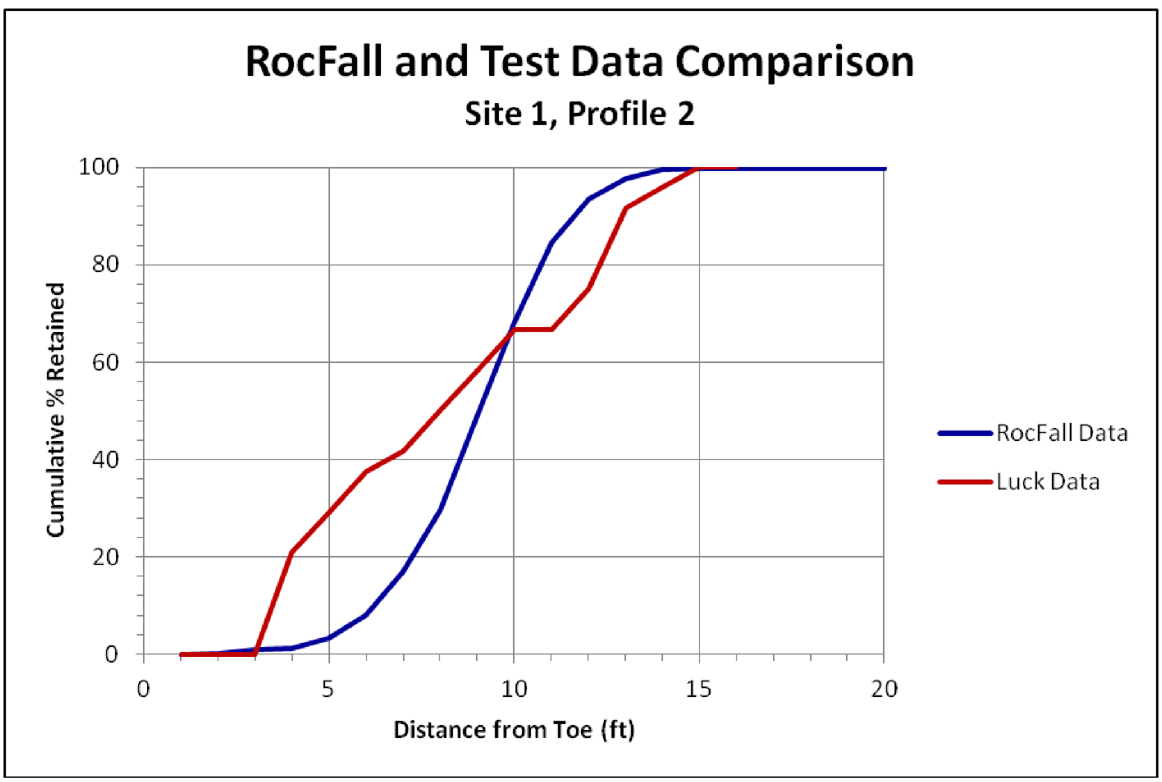
Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
2	42	1	13	11	1.18	3	3	11
2	43	2			No Data	3	2	5
2	44	1			No Data	3	3	5
2	45	1			No Data	3	4	4
2	46	1			No Data	3	5	5
2	47	1	15	8	1.88	3	9	9
2	48	1	18	9	2.00	3	9	17
2	49	1			No Data	3	3	7
2	50	1	17	11	1.55	3	3	10
2	51	1	7	6	1.17	3	8	23
2	52	1			No Data	3	5	5
2	53	1	14	6	2.33	3	5	11
2	54	2			No Data	3	6	8
2	55	3	37	20	1.85	3	9	12
2	56	2			No Data	3	2	5
2	57	2			No Data	3	3	6
2	58	1	16	16	1.00	3	3	10
2	59	2			No Data	3	3	3
2	60	2			No Data	3	5	5
2	61	1			No Data	4	4	4
2	62	1	16	8	2.00	4	13	19
2	63	1	17	12	1.42	4	9	9
2	64	1	14	8	1.75	4	10	18
2	65	1	12	9	1.33	4	8	20
2	66	1	10	8	1.25	4	11	12
2	67	1			No Data	4	4	5
2	68	1			No Data	4	5	5
2	69	2	28	15	1.87	4	11	18
2	70	3	31	15	2.07	4	5	14
2	71	2			No Data	4	6	10
2	72	3			No Data	4	5	9
2	73	2			No Data	4	10	15
2	74	2			No Data	4	6	6
2	75	3	31	24	1.29	4	6	15
2	76	3	35	18	1.94	1	7	12
2	77	3	37	22	1.68	1	5	12
2	78	3			No Data	1	4	6
2	79	3	31	30	1.03	1	9	12
2	80	3			No Data	1	6	8

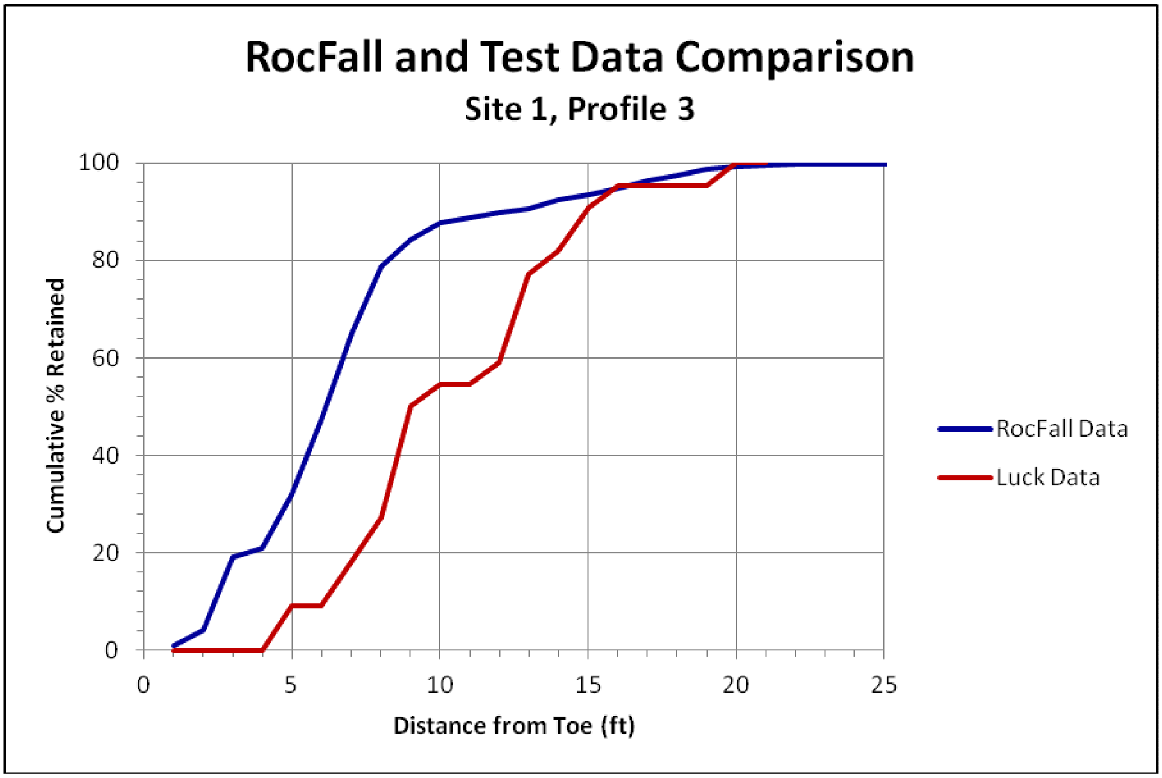
Site	Rock #	Size Class	Length (in)	Width (in)	Shape Factor (L/D)	Drop Profile	Impact Distance (ft)	Rollout Distance (ft)
2	81	1	17	9	1.89	1	6	24
2	82	2			No Data	1	3	4
2	83	4	47	29	1.62	1	3	10
2	84	4			No Data	1	5	12
2	85	2	20	13	1.54	1	5	24
2	86	3	41	21	1.95	2	9	10
2	87	3			No Data	2	10	25
2	88	3	36	34	1.06	2	6	13
2	89	3	32	26	1.23	2	3	9
2	90	2	26	22	1.18	2	5	13
2	91	2			No Data	2	9	9
2	92	4	45	32	1.41	2	5	14
2	93	4	43	32	1.34	2	3	9
2	94	2	29	17	1.71	3	6	14
2	95	3			No Data	3	7	12
2	96	2	22	22	1.00	3	7	14
2	97	2	24	20	1.20	3	8	17
2	98	3	35	23	1.52	3	8	15
2	99	3			No Data	3	4	4
2	100	3			No Data	3	8	14
2	101	3	41	35	1.17	3	10	12
2	102	5			No Data	3	9	9
2	103	2	22	14	1.57	4	10	16
2	104	2	24	13	1.85	4	10	15
2	105	2	25	13	1.92	4	10	15
2	106	2	24	16	1.50	4	10	22
2	107	2	26	19	1.37	4	12	27
2	108	2			No Data	4	8	9
2	109	2	23	10	2.30	4	13	16
2	110	3	41	18	2.28	4	20	26
2	111	3			No Data	4	12	16
2	112	3	40	25	1.60	4	10	15
2	113	4			No Data	4	9	10
2	114	4	47	29	1.62	4	10	22
2	115	5	57	35	1.63	4	10	15
2	116	5			No Data	4	15	22

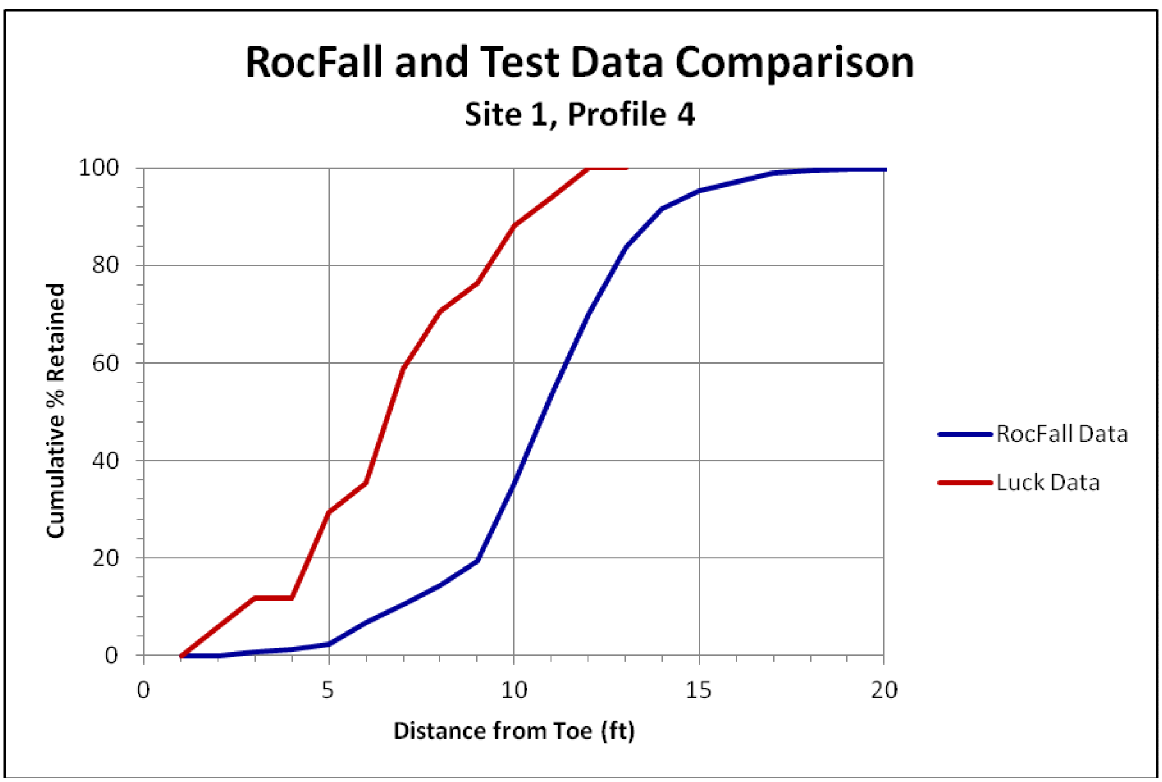
Appendix C

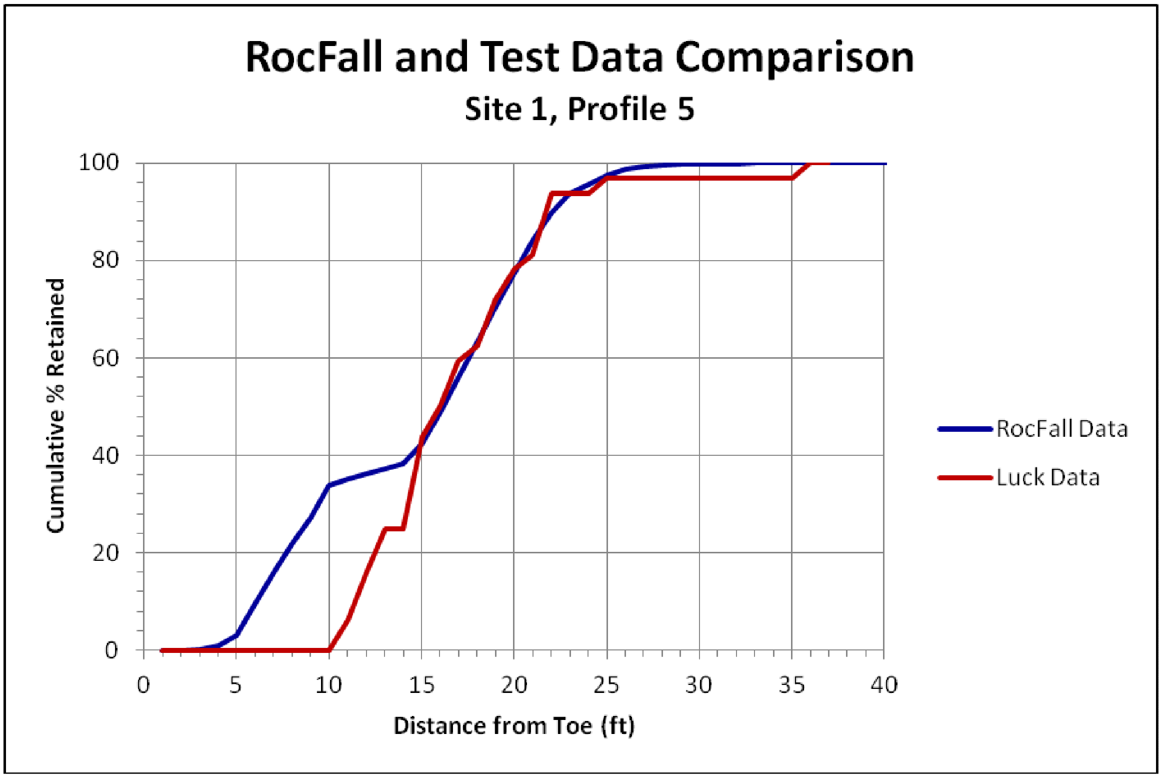
Actual and RocFall Cumulative
Percentage Retained Curves

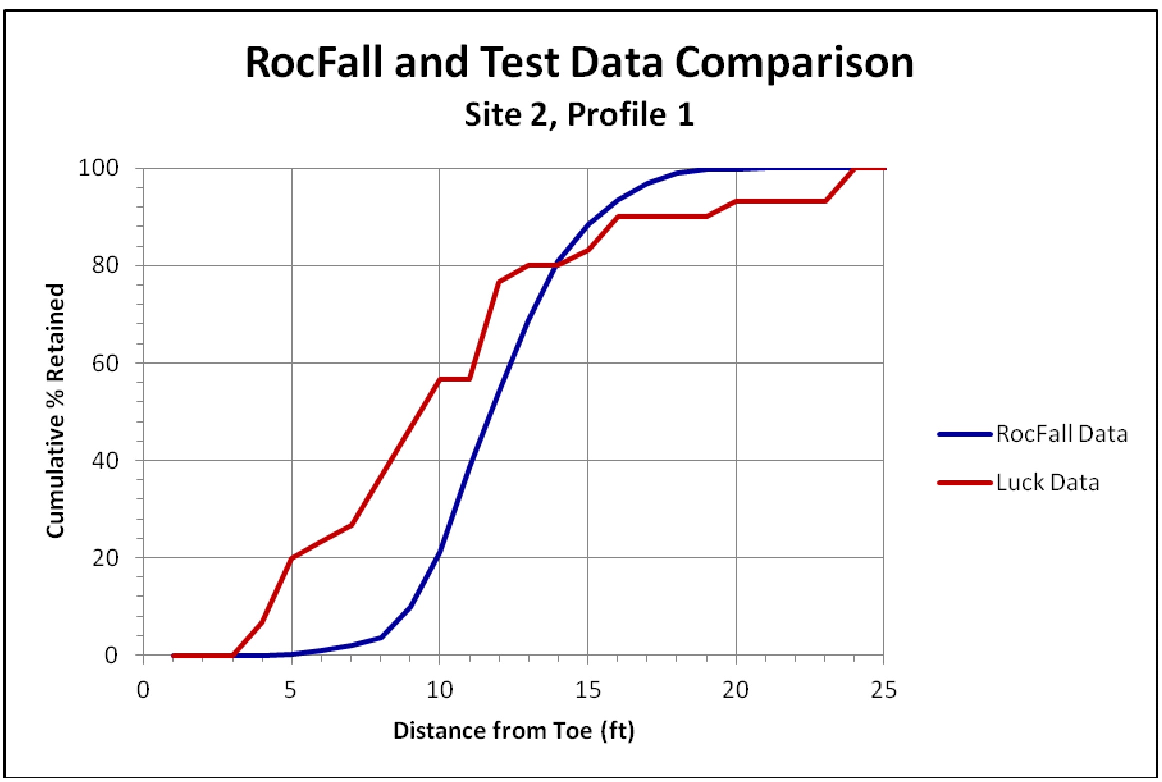

RocFall and Test Data Comparison
Site 1, Profile 1
Cumulative % Retained
Distance from Toe (ft)
0
20
40
60
80
100
0
5
10
15
20
25
30
RocFall Data
Luck Data

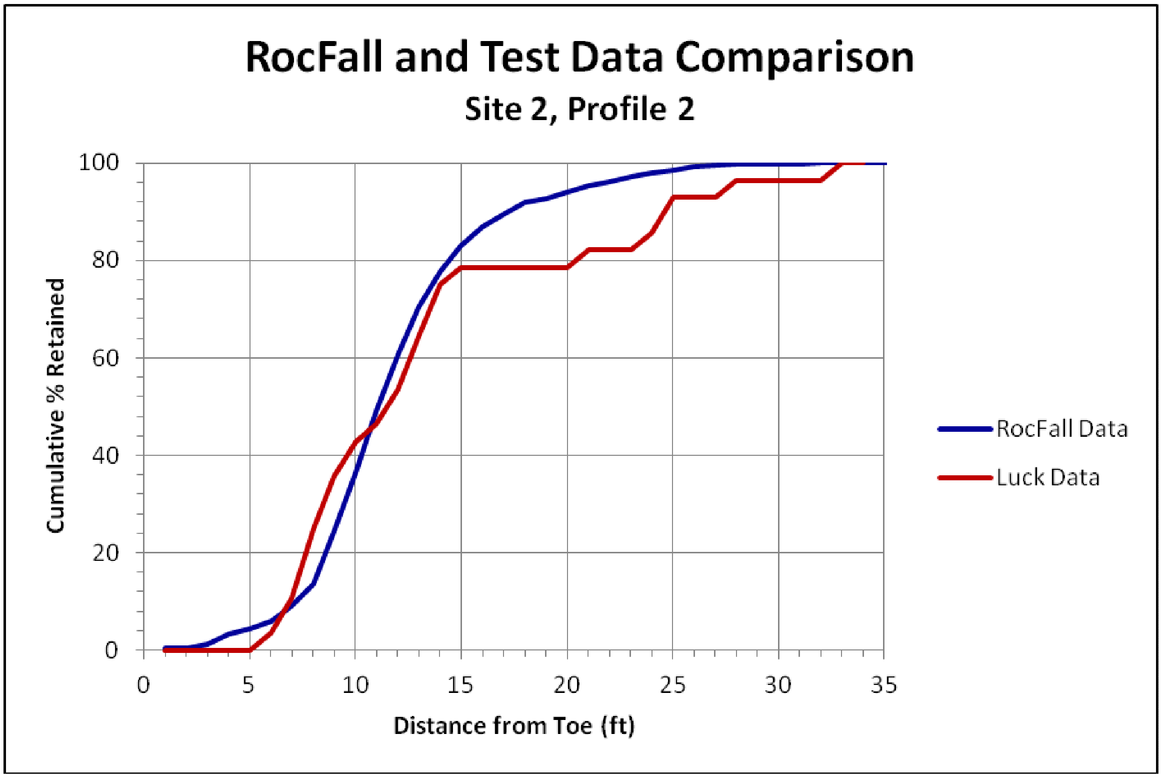

RocFall and Test Data Comparison
Site 1, Profile 2
Cumulative % Retained
Distance from Toe (ft)
0
20
40
60
80
100
0
5
10
15
20
RocFall Data
Luck Data

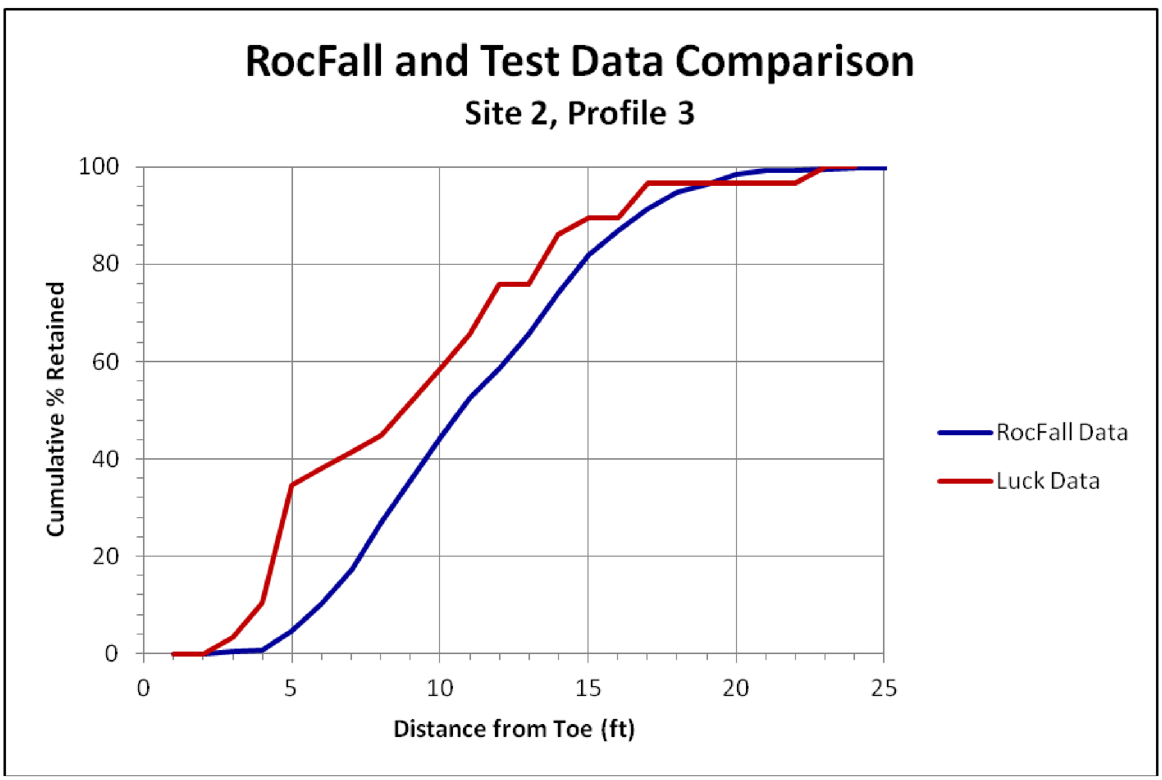

RocFall and Test Data Comparison
Site 1, Profile 3
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
25
Distance from Toe (ft)
RocFall Data
Luck Data

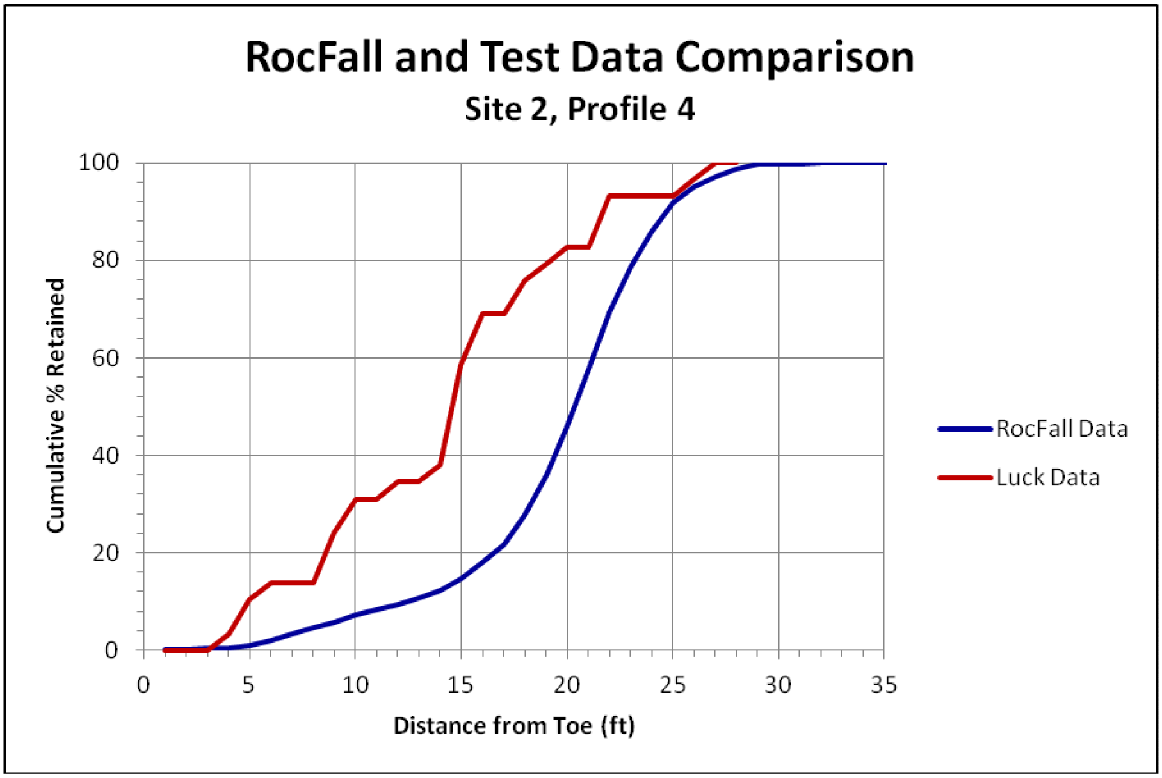

RocFall and Test Data Comparison
Site 1, Profile 4
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
Distance from Toe (ft)
RocFall Data
Luck Data


RocFall and Test Data Comparison
Site 1, Profile 5
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
Distance from Toe (ft)
RocFall Data
Luck Data


RocFall and Test Data Comparison
Site 2, Profile 1
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
25
Distance from Toe (ft)
RocFall Data
Luck Data

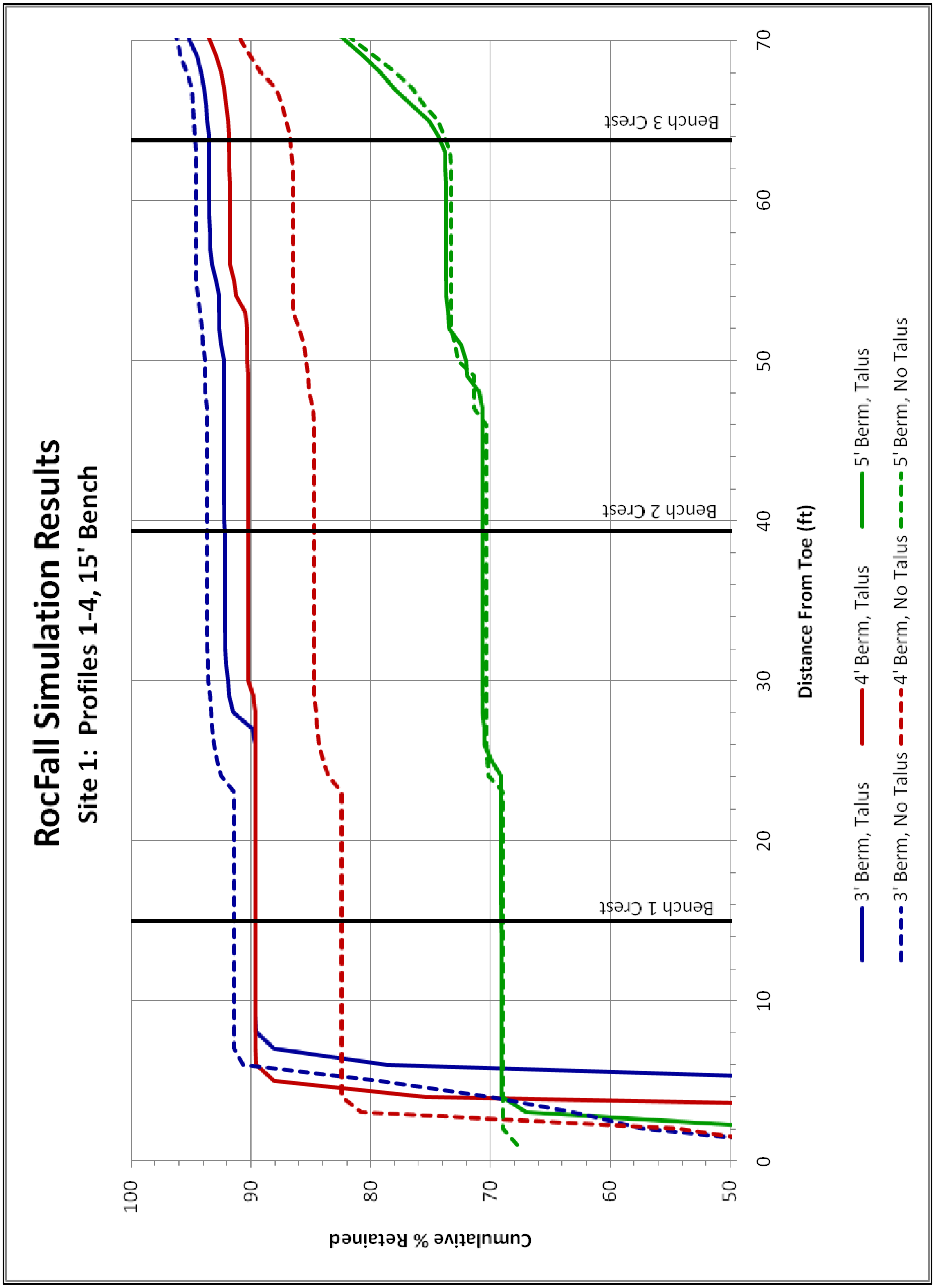

RocFall and Test Data Comparison
Site 2, Profile 2
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
25
30
35
Distance from Toe (ft)
RocFall Data
Luck Data

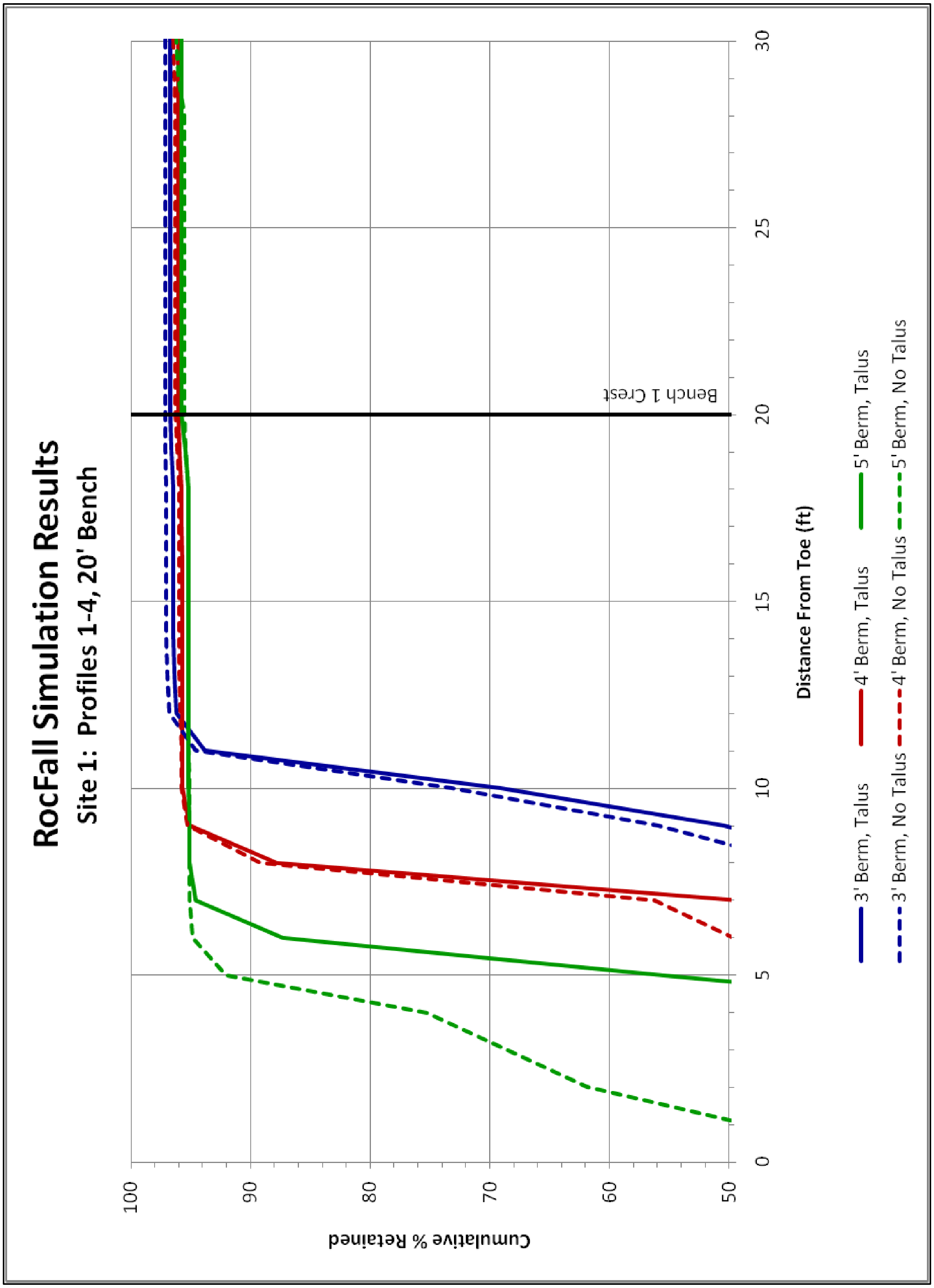

RocFall and Test Data Comparison
Site 2, Profile 3
Cumulative % Retained
100
80
60
40
20
0
0
5
10
15
20
25
Distance from Toe (ft)
RocFall Data
Luck Data

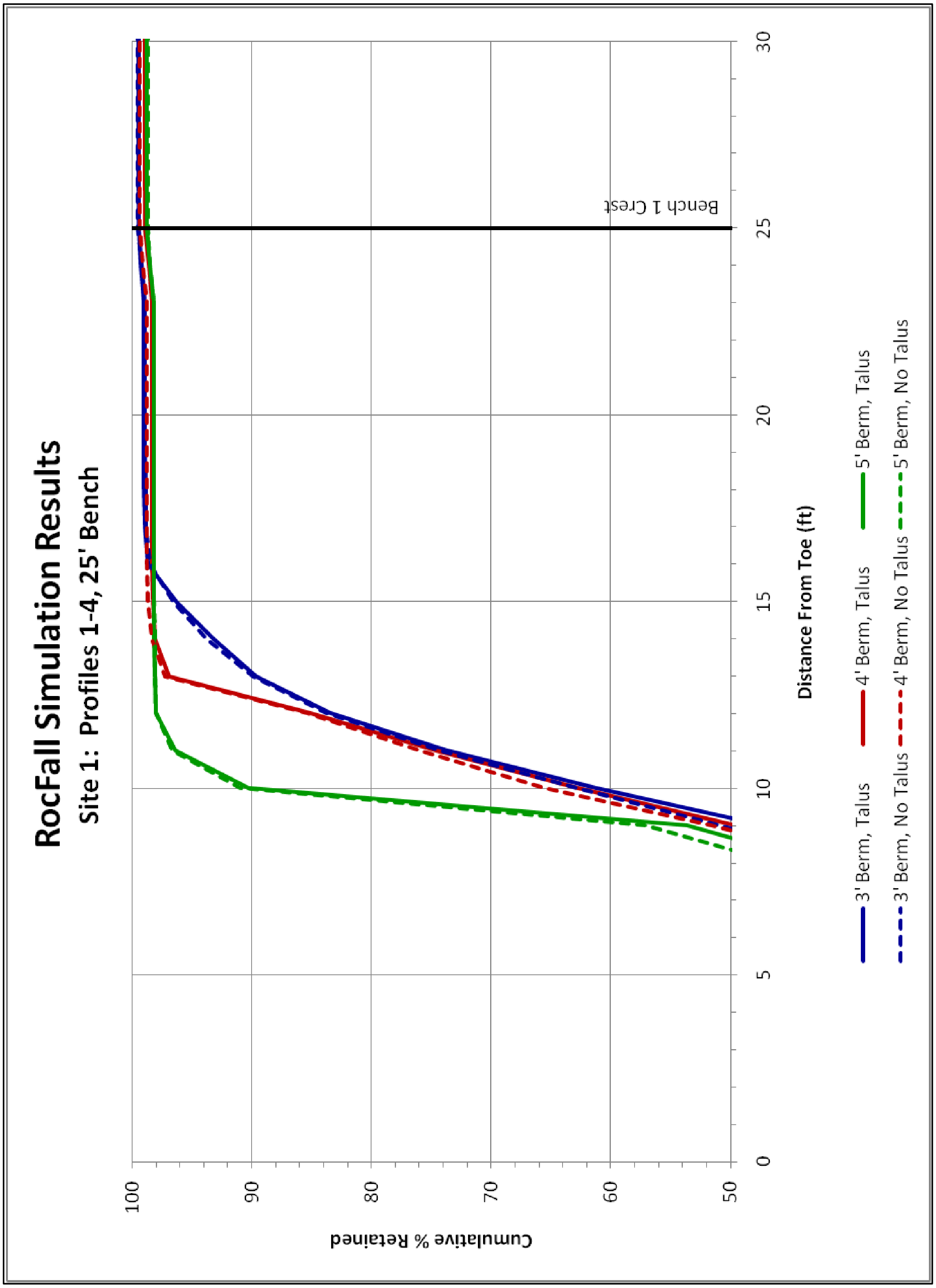

RocFall and Test Data Comparison
Site 2, Profile 4
Cumulative % Retained
0
20
40
60
80
100
0
5
10
15
20
25
30
35
Distance from Toe (ft)
RocFall Data
Luck Data

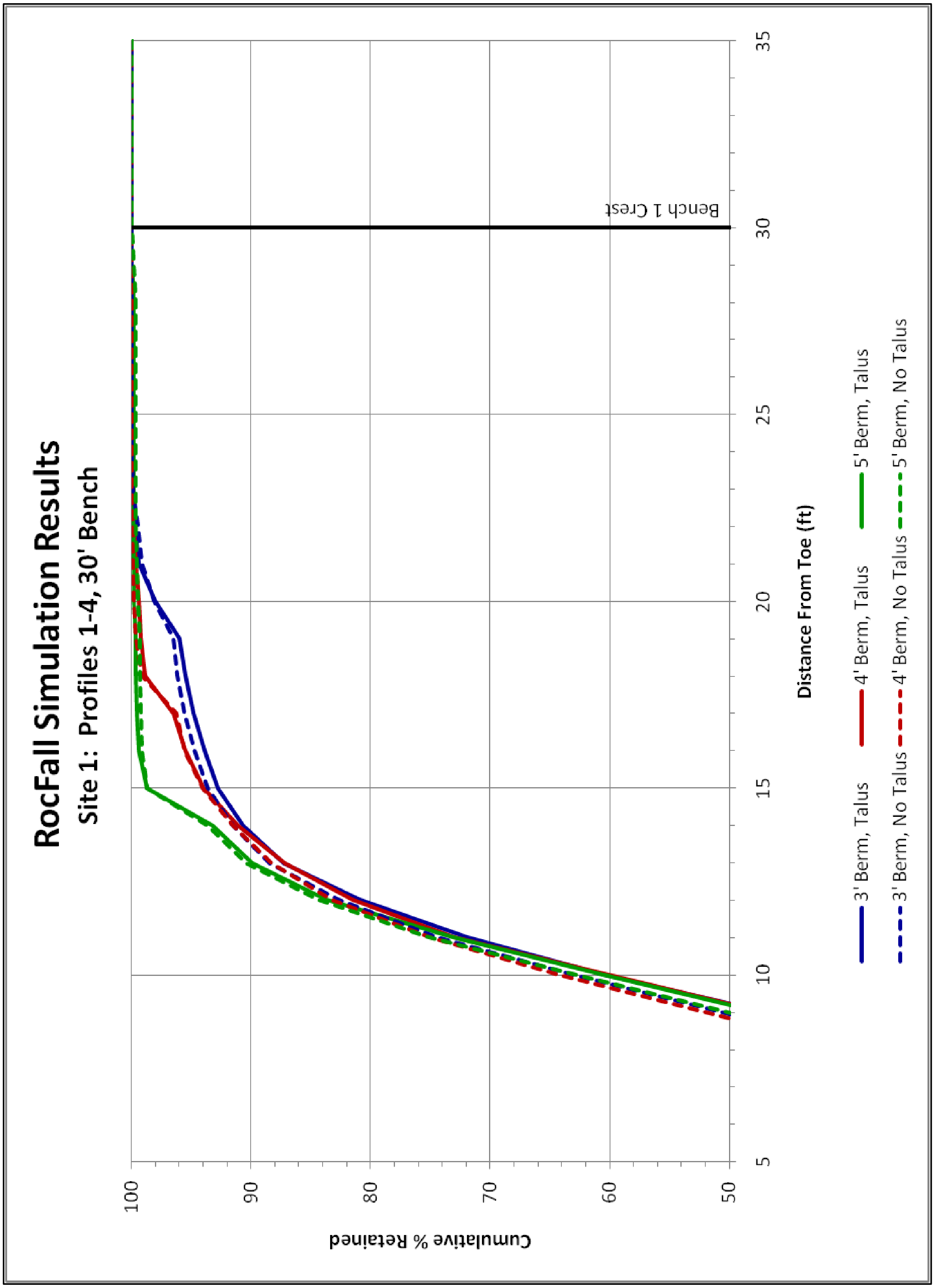
Appendix D

RocFall Simulation Results Graphs

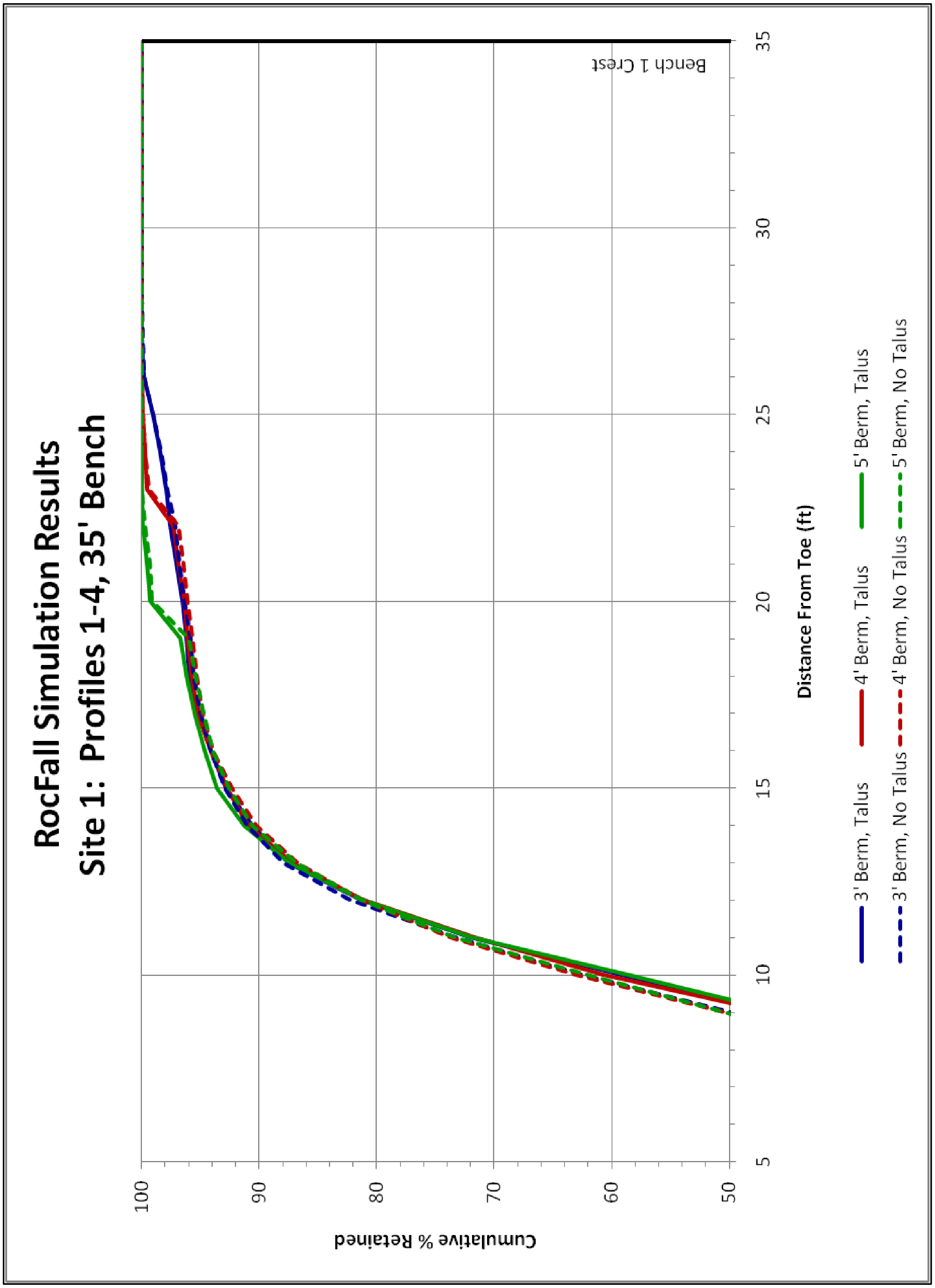

RocFall Simulation Results
Site 1: Profiles 1-4, 15' Bench
Cumulative % Retained
100
90
80
70
60
50
0
10
20
30
40
50
60
70
Distance From Toe (ft)
Bench 1 Crest
Bench 2 Crest
Bench 3 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

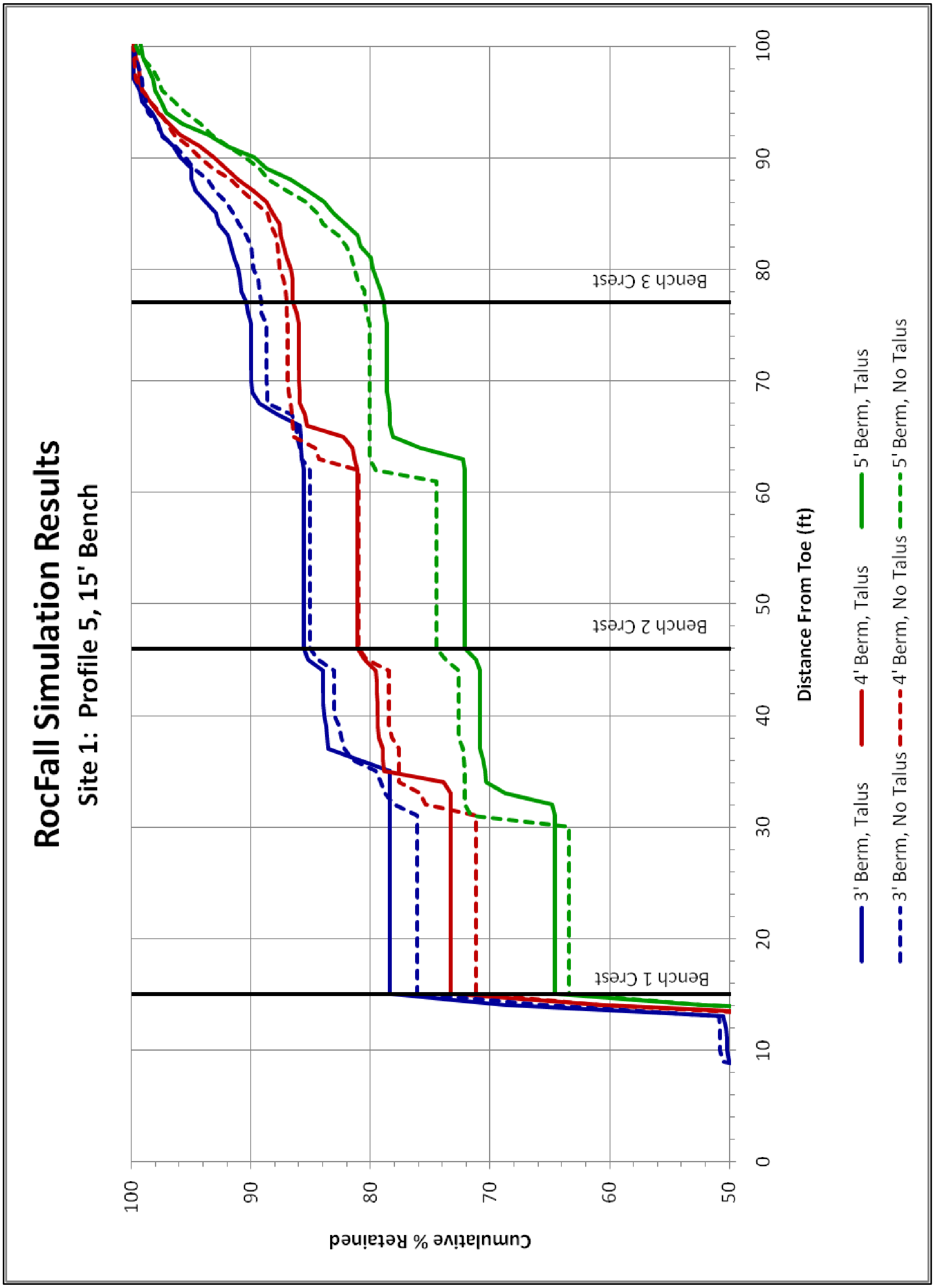

RocFall Simulation Results
Site 1: Profiles 1-4, 20' Bench
Cumulative % Retained
100
90
80
70
60
50
0
5
10
15
20
25
30
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

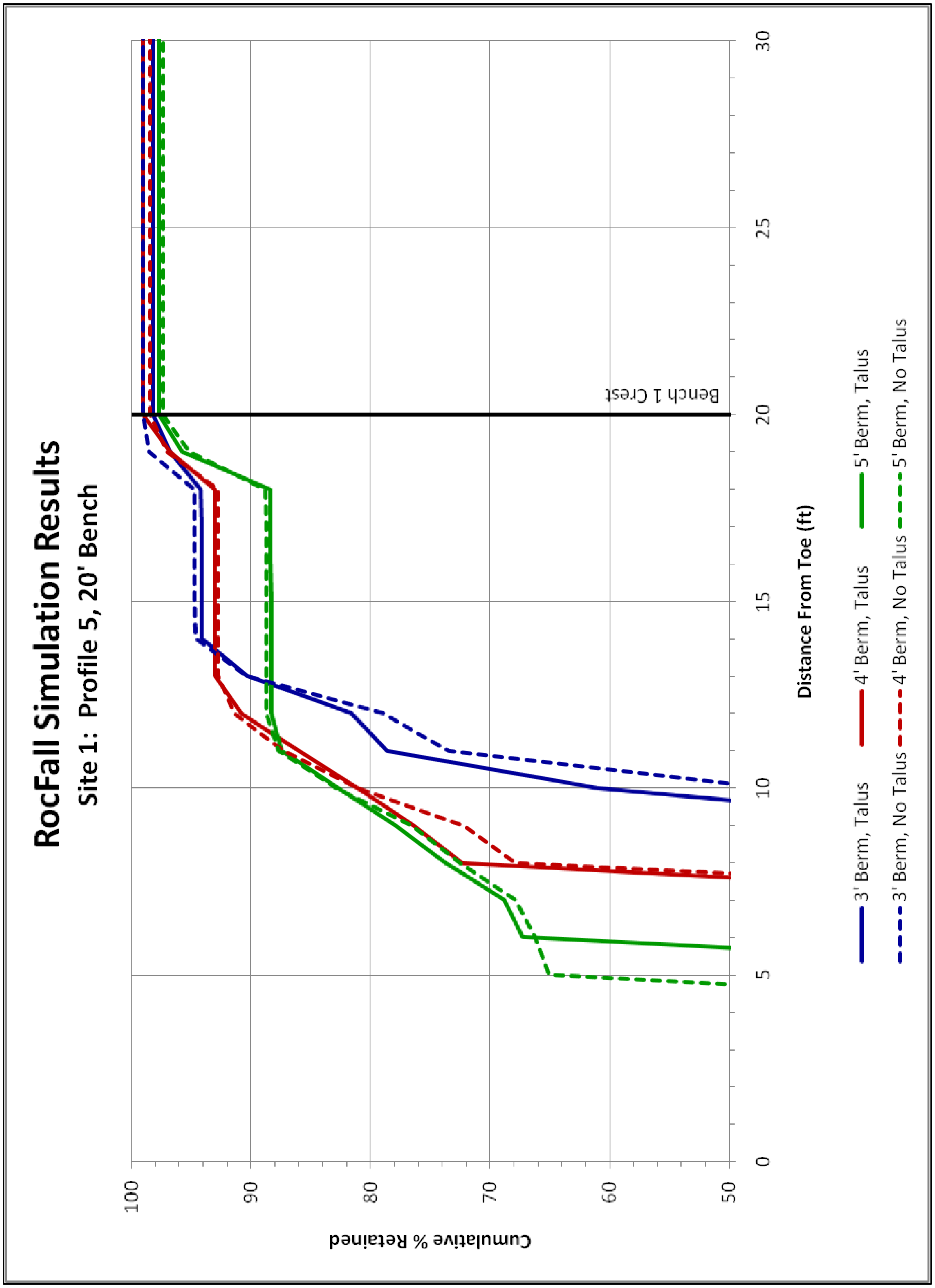

RocFall Simulation Results
Site 1: Profiles 1-4, 25' Bench
Cumulative % Retained
Distance From Toe (ft)
Bench 1 Crest
100
90
80
70
60
50
0
5
10
15
20
25
30
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

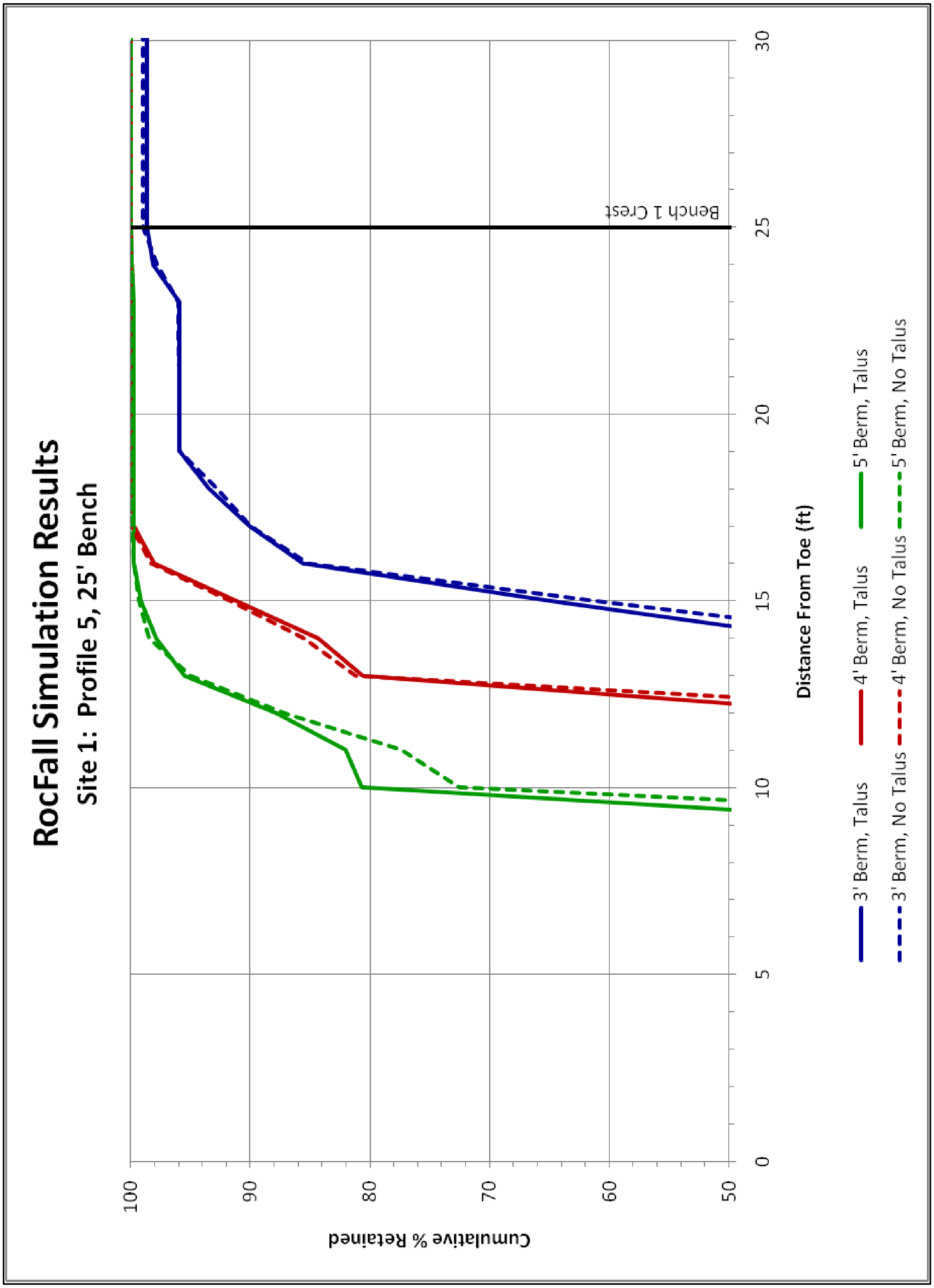


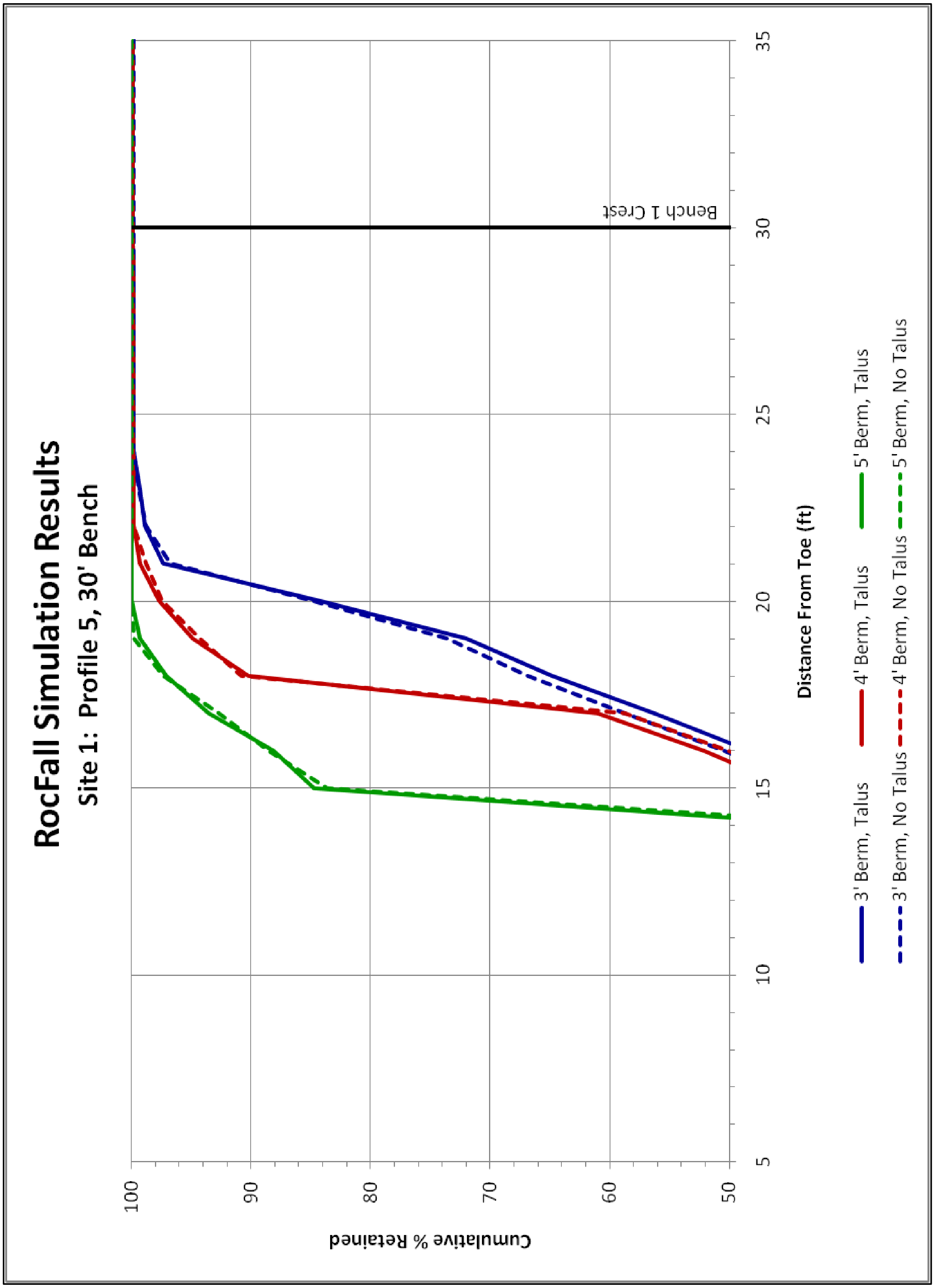
RocFall Simulation Results
Site 1: Profiles 1-4, 30' Bench
Cumulative % Retained
100
90
80
70
60
50
5
10
15
20
25
30
35
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

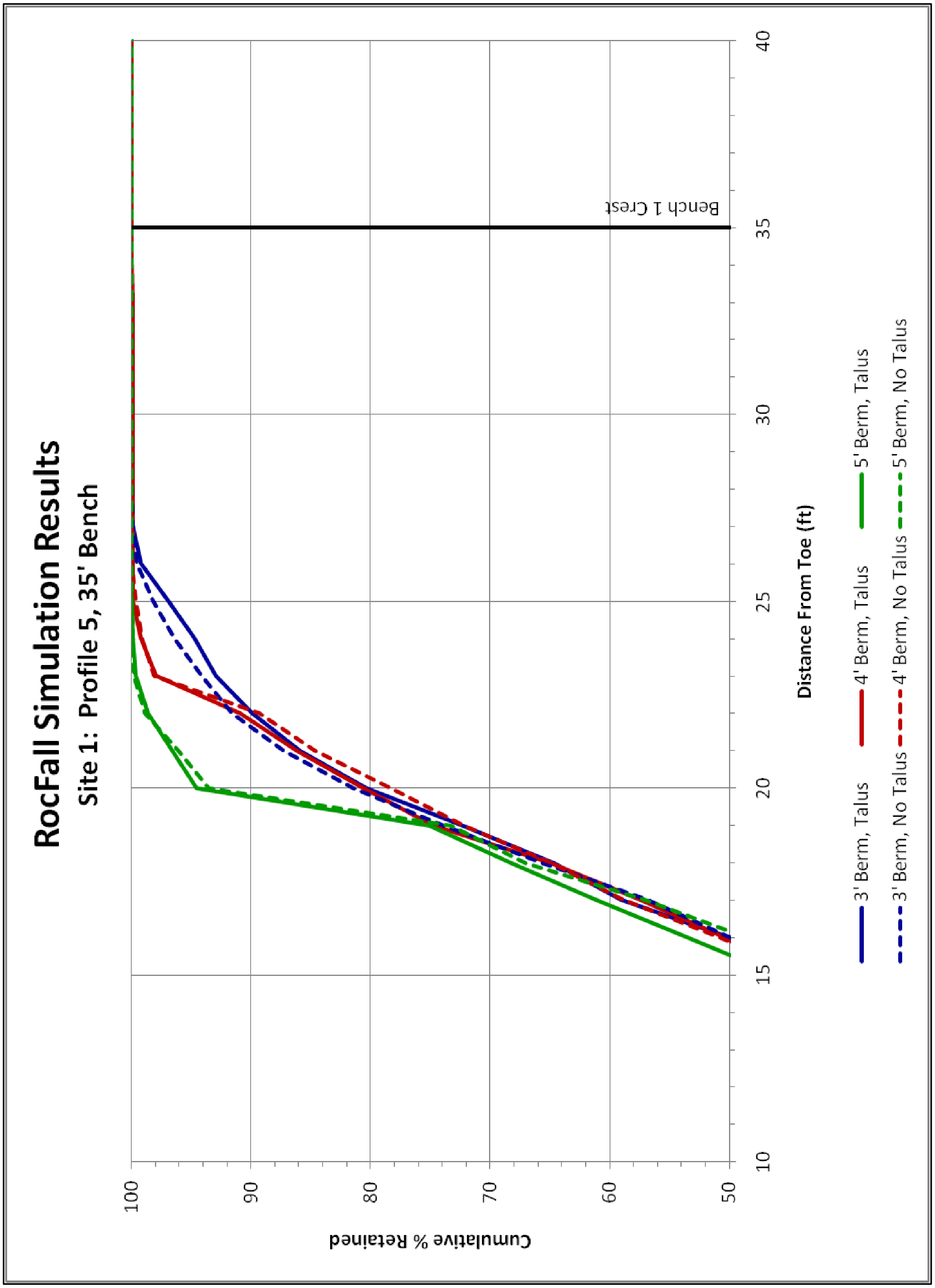

RocFall Simulation Results
Site 1: Profiles 1-4, 35' Bench
Bench 1 Crest
Cumulative % Retained
100
90
80
70
60
50
5
10
15
20
25
30
35
Distance From Toe (ft)
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

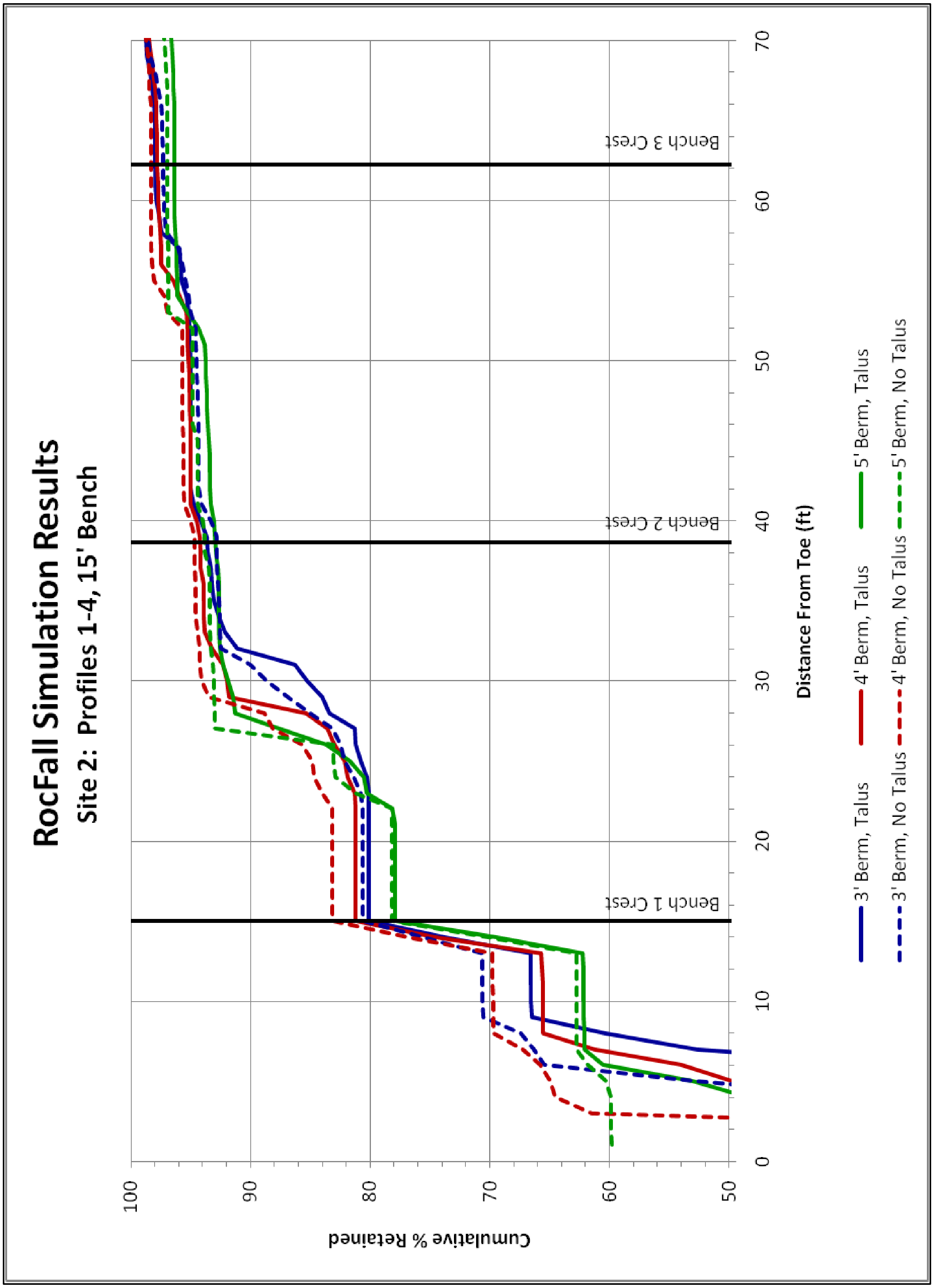

RocFall Simulation Results
Site 1: Profile 5, 15' Bench
Cumulative % Retained
100
90
80
70
60
50
0
10
20
30
40
50
60
70
80
90
100
Distance From Toe (ft)
Bench 1 Crest
Bench 2 Crest
Bench 3 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

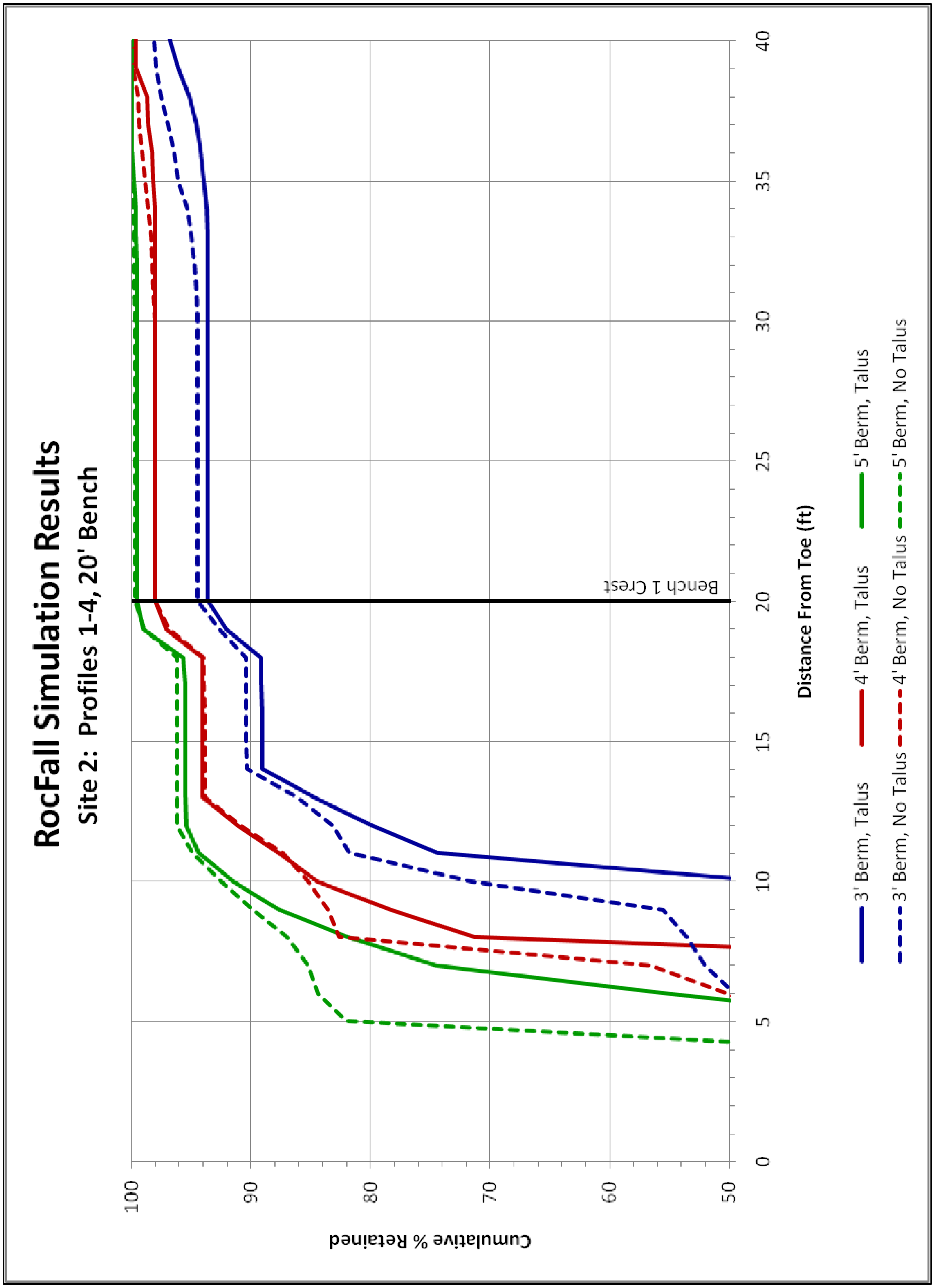

RocFall Simulation Results
Site 1: Profile 5, 20' Bench
Cumulative % Retained
100
90
80
70
60
50
0
5
10
15
20
25
30
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

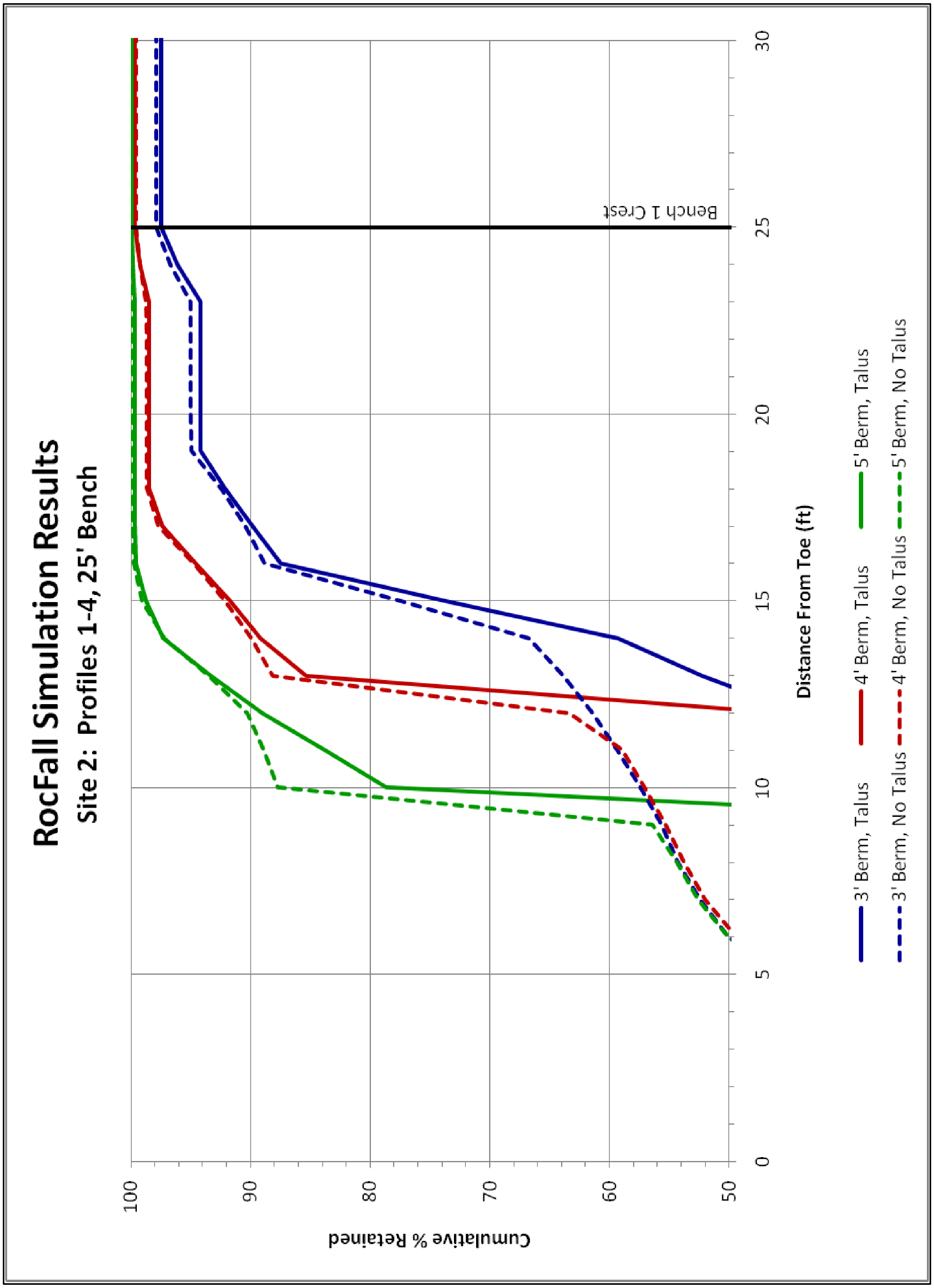

RocFall Simulation Results
Site 1: Profile 5, 25' Bench
Cumulative % Retained
100
90
80
70
60
50
Distance From Toe (ft)
0
5
10
15
20
25
30
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

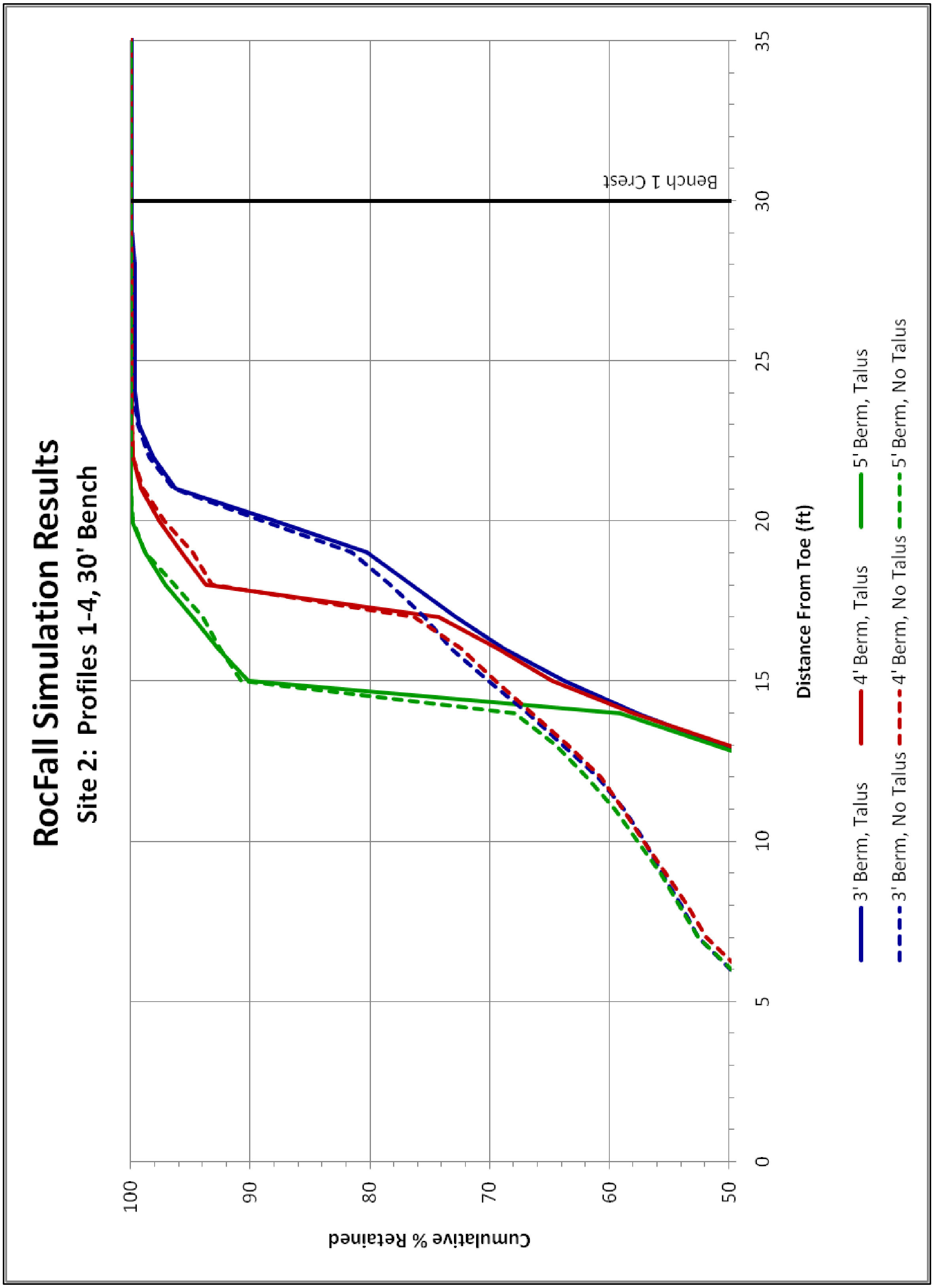

RocFall Simulation Results
Site 1: Profile 5, 30' Bench
Cumulative % Retained
100
90
80
70
60
50
Distance From Toe (ft)
5
10
15
20
25
30
35
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus

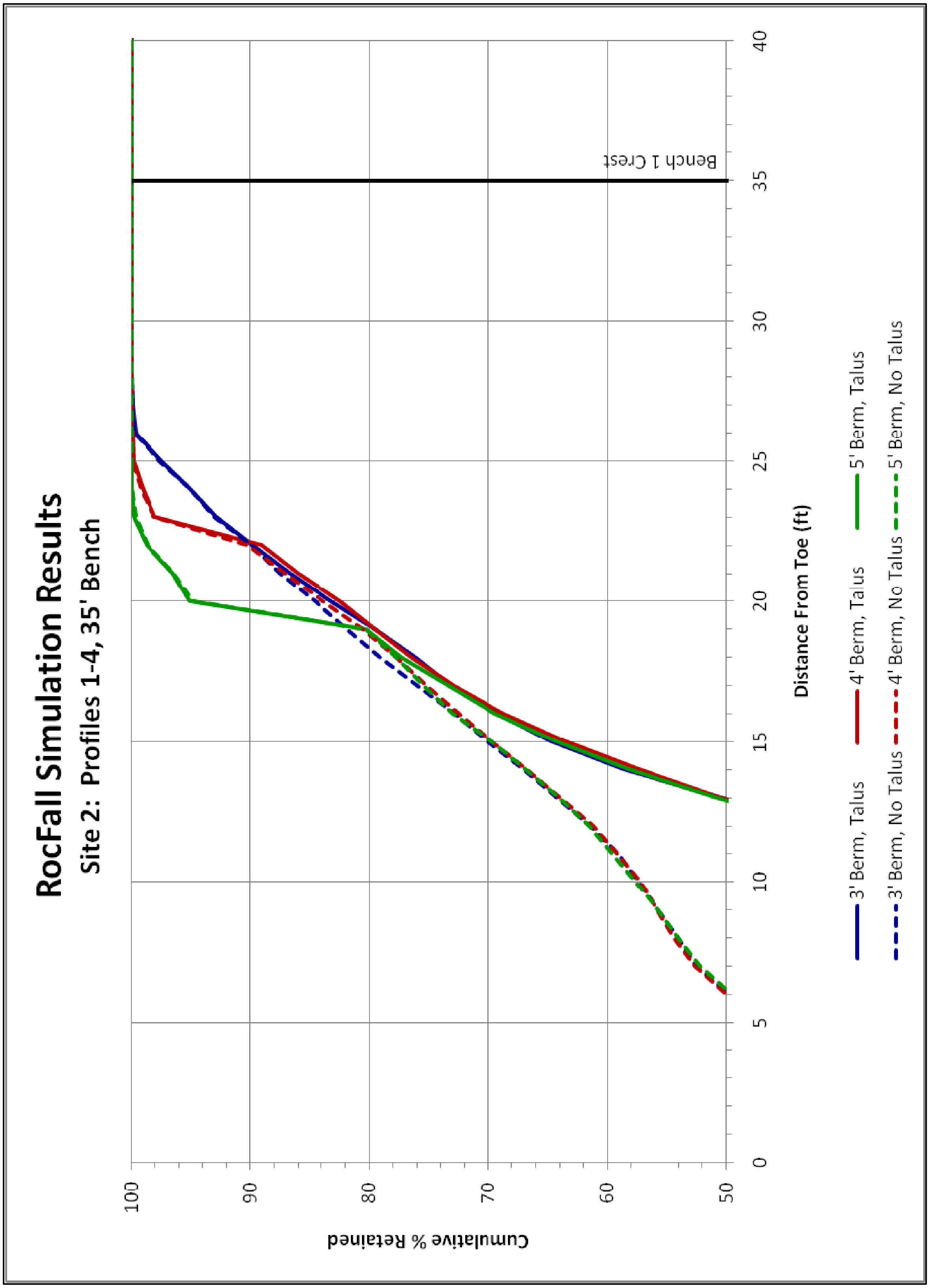

RocFall Simulation Results
Site 1: Profile 5, 35' Bench
Cumulative % Retained
100
90
80
70
60
50
10
15
20
25
30
35
40
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus


RocFall Simulation Results
Site 2: Profiles 1-4, 15' Bench
Cumulative % Retained
100
90
80
70
60
50
0
10
20
30
40
50
60
70
Distance From Toe (ft)
Bench 1 Crest
Bench 2 Crest
Bench 3 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus


RocFall Simulation Results
Site 2: Profiles 1-4, 20' Bench
Cumulative % Retained
100
90
80
70
60
50
Distance From Toe (ft)
0
5
10
15
20
25
30
35
40
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus


RocFall Simulation Results
Site 2: Profiles 1-4, 25' Bench
Cumulative % Retained
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus


RocFall Simulation Results
Site 2: Profiles 1-4, 30' Bench
Cumulative % Retained
100
90
80
70
60
50
0
5
10
15
20
25
30
35
Distance From Toe (ft)
Bench 1 Crest
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus


RocFall Simulation Results
Site 2: Profiles 1-4, 35' Bench
Bench 1 Crest
Cumulative % Retained
100
90
80
70
60
50
0
5
10
15
20
25
30
35
40
Distance From Toe (ft)
3' Berm, Talus
4' Berm, Talus
5' Berm, Talus
3' Berm, No Talus
4' Berm, No Talus
5' Berm, No Talus