ROCKFALL CATCHMENT AREA DESIGN GUIDE

FINAL REPORT
SPR-3(032)

Metric Edition

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16. Abstract

The data gathered from an exhaustive research project consisting of rolling a total of approximately 11,250 rocks off vertical; 4V:1H;2V;1H;1.33V:1H;1.0V:1.0H slopes of three different heights (12.2, 18.3, and 24.4 meters) into three differently inclined catchment areas (flat, 1V:6H and 1V:4H) has been used to develop design charts for dimensioning rockfall catchment areas adjacent to highways. A standard suite of 250 rocks was rolled for each slope and catchment area configuration tested. The standard suite included 100 rocks averaging 0.3 meters in diameter, 75 rocks averaging 0.6 meters in diameter and 75 rocks averaging 0.9 meters in diameter. The data was evaluated using statistical and graphical methods. The design charts are presented in a "practitioner-friendly" form that can be used to rapidly size rockfall catchment areas that satisfy specific rock catching/retention requirements. Based on cut slope angle and height and catchment area slope, the design charts estimate the catchment area widths required to retain a given percentage of rockfall ranging up to 99 percent.

Design guidelines and step-by-step design procedures are presented and illustrated with three worked example design problems. Seven actual highway project case study examples are also presented. They illustrate the practical application of the design procedure and design charts and/or use of site-specific rock rolling to aid in the rockfall mitigation design.

This report documents the test methods, the fieldwork performed, the data gathered, the means of analysis, the research results and sample application of the design charts. The data results in both tabular and graphical form are included in the Appendices. The Appendices also include the detailed project case study application examples.

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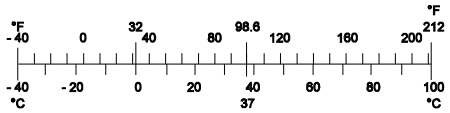
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
		AREA		
ft^2	square feet	0.093	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		ENERGY		
ft-lb	foot-pounds	1.35582	joules	J
ft-T	foot-tons	2.71164	kilojoules	kJ
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
		AREA		
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		ENERGY		
J	joules	0.73756	foot-pounds	ft-lb
kJ	kilojoules	0.36878	foot-tons	ft-T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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Execution of the study and preparation of the final report was a collaborative effort. Larry A. Pierson, Senior Engineering Geologist, Landslide Technology, provided overall project management. C. Fred Gullixson, Senior Engineering Geologist, ODOT Region 1, was in charge of recording field data and preparing the data summaries and design charts. Ronald G. Chassie, FHWA Senior Geotechnical Engineer (Retired) provided technical consulting, report preparation, review and final editing.

A hard working ODOT crew consisting of the following personnel carried out the project fieldwork: Jim Kendall, James Kirby, Bob Colby, Mike Fisher, and T. Anderson. John Marks, ODOT Geotechnical Services assisted with project and contract management. John Kazmierski, ODOT video services, shot video footage at selected times. Many thanks to all these good people for their dedicated and professional work.

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A Technical Advisory Committee (TAC) of highly experienced engineering geologists and geotechnical engineers was formed from the contributing agencies to guide the project and to critically review the work and this document. TAC members were:

Dave Stanley	Chief Geologist	Alaska DOT
John Lawson	Chief Geotechnical Engineer	Arizona DOT
John Duffy	Senior Engineering Geologist	California DOT
Mike Vierling	Engineering Geologist II	New York State Thruway Authority
Don Turner	Geotechnical Services Unit	Oregon DOT
Bill Trolinger	Chief Geotechnical Engineer	Tennessee DOT
Steve Lowell	Chief Engineering Geologist	Washington DOT
Mark Falk	Geological Engineer	Wyoming DOT
Barry Siel	Senior Geotechnical Engineer	FHWA-CFLHD, Denver, CO
Alex Yatsevitch	Engineering Geologist 3	New York DOT

The TAC provided the overall quality assurance needed to assure a high-quality effort and the development of a practitioner-friendly and practitioner-oriented Design Guide. Their contributions are gratefully acknowledged and sincerely appreciated.

DEDICATION TO ARTHUR M. RITCHIE

This report is dedicated to the memory of Arthur M. Ritchie (deceased August 1988). Mr. Ritchie spent a long and productive career as the Chief Geologist with the Washington State Department of Highways. In 1963, the Transportation Research Board (TRB) published a technical paper authored by Mr. Ritchie titled "An Evaluation of Rockfall and Its Control." Ritchie's paper summarized the results of a rockfall research project conducted by Washington State.

Ritchie's innovative and pioneering work was the first practical and comprehensive study of rockfall generated from actual highway slopes. The work included rolling hundreds of rocks off highway and state-owned quarry and talus slopes across Washington State and measuring and recording (including 16mm motion pictures) the paths and distances the rocks traveled. The work culminated in Mr. Ritchie developing a practical design criteria, in table form, that could be used to size the width of flat-bottomed rockfall catchment areas based on rock slope height, rock slope angle and depth of catchment area.

Mr. Ritchie's work was the first definitive work and practical design guidance presented to highway designers to better and more rationally design safer highways against rockfall. Throughout his career, Mr. Ritchie's contributions to highway engineering and the geotechnical profession were many and exemplary. The implementation of his research results has surely saved the lives of many people nationwide. The work covered by this report builds on Mr. Ritchie's original pioneering work.

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ROCKFALL CATCHMENT AREA DESIGN GUIDE

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GLOSSARY OF TERMS

The following terms are used in this report. The definitions given apply to the terms as used herein, and other uses and definitions may exist.

AASHTO – American Association of State Highway and Transportation Officials.

Clear Zone – The total roadside border area, starting at the edge of the traveled way that is wide enough to allow an errant driver to stop or regain control of a vehicle. This area might consist of a shoulder, a recoverable slope, and/or a nonrecoverable, traversable slope with a clear run-out area at its toe (Per MUTCD).

Catchment Area – The area between the roadway edge of pavement and the base (toe) of a rock cut slope used to restrict rockfalls from the roadway. The term is synonymous with ditch, rock fallout area, rockfall ditch, rockfall catch ditch, and catch ditch.

Catchment Area Width – The horizontal distance between the roadway edge of pavement and the base (toe) of a rock cut slope.

Controlled Blasting – Special blasting procedures, such as presplitting and cushion blasting, used to minimize blast damage to the final walls of rock slope excavations. Significantly reduces long-term rockfall compared to use of uncontrolled blasting methods.

CRSP – Acronym for the computerized Colorado Rockfall Simulation Program, which is used to model rockfall trajectories and energies based on known slope shapes and estimated properties.

Distribution – A statistical term used to describe the range of experimental data.

Ditch – Synonymous with catchment area.

Fallout Area – Synonymous with catchment area.

Foreslope – The portion of the roadway prism inclined downward from the edge of pavement toward the base of a cut or roadside ditch.

Histogram – A graphic representation of a frequency distribution. In other words, it is a graphical tally of data collected. Frequency histograms have been developed for both impact and roll out distance data points.

Impact Distance – The measured slope distance from the base of the rock cut slope to where a falling rock first strikes the ground.

Launch Feature – Any slope irregularity or deviation in the rock slope face that can be struck by a falling rock and changes the trajectory of the rock.

MUTCD – Manual on Uniform Traffic Control Devices, published by the Federal Highway Administration, U.S. Department of Transportation. Current edition: December 2000 (including Errata No. 1 dated June 14, 2001).

Outlier – A rockfall result (impact or roll out) that exists away from the body of collected experimental data.

Presplitting – A controlled blasting technique utilizing a row of closely spaced, lightly loaded blast holes drilled along the rock slope final excavation line and detonated at least 25 milliseconds before the production blast holes.

Ritchie Ditch – Rockfall catchment area (ditch) configuration and dimensions obtained from an empirical table developed by Washington State Department of Highways Geologist Arthur M. Ritchie in 1963.

Rockfall – The movement of rock from a slope that is so steep the rock continues to move down slope. The movement may be by free falling, bouncing, rolling or sliding.

Roll Out Distance – The furthest slope distance from the toe of the rock cut slope attained by a falling rock.

Standard Deviation – A measure of the variability of collected data. Statistically, it is equal to the square root of the arithmetic average of the squares of the deviations from the mean in a frequency distribution.

Standard Suite – The number of rocks rolled for each slope height and catchment area configuration tested. The standard suite included 100 rocks averaging 0.3 meters in diameter, 75 rocks averaging 0.6 meters in diameter and 75 rocks averaging 0.9 meters in diameter. The "diameter" dimension was measured along the longest axis. The actual diameter dimensions for each size category ranged within plus or minus 0.15 meters. For example, the 0.6-meter rocks varied from 0.45 to 0.75 meters in diameter along the longest axis.

Traveled Way – The portion of the roadway for the movement of vehicles, exclusive of the shoulders, berms, sidewalks and parking lanes (Per MUTCD).

EXECUTIVE SUMMARY

Rockfall is the movement of rock from a slope that is so steep the rock continues to move down slope. The movement may be by free falling, bouncing, rolling or sliding. Rockfalls along highways occur where natural slopes or rock slope excavations exist. When rockfalls reach the roadway they are a hazard to roadway users. Hundreds of millions of dollars are spent annually in the U.S. on rock slope maintenance and rockfall hazard mitigation on new and existing slopes. Many states have experienced injuries and deaths caused by rockfall. Annually, the legal claims and litigation costs resulting from rockfall are in the millions of dollars.

A rockfall catchment area is defined as the area between the roadway edge of pavement and the base of a cut slope, used to restrict rockfalls from the roadway. The use of catchment areas (ditches) to contain and restrict rockfall from the roadway is one of the best and most effective rockfall protective measures.

The current practice for designing highway rockfall catchment areas is not consistent throughout the United States. The principle reason no nationally adopted method for designing rockfall catchment areas exists is because only limited research has been conducted to provide designers with the data necessary to make informed design decisions. The limited research has led to many U.S. highway agencies desiring a more rational and better-quantified design criteria for sizing rockfall catchment areas.

Through a pooled fund effort funded by seven State DOT's and the FHWA, the Oregon DOT conducted an extensive research project consisting of rolling roughly 11,250 rocks off vertical; 4V:1H; 2V:1H; 1.33V:1H and 1V:1H rock cut slopes of three different heights (12.2, 18.3, 24.4 meters) into three differently inclined catchment areas (flat, 1V:6H and 1V:4H). The data gathered has been used to develop design charts for dimensioning rockfall catchment areas adjacent to highways.

The design charts are presented in a "practitioner-friendly" form. They can be used to rapidly dimension rockfall catchment areas to meet specific percent rockfall retention requirements. Based on rock cut slope ratio, vertical rock slope height and catchment area slope, the design charts provide an estimate of the required catchment area widths needed to retain up to 99 percent of rockfall. The same design charts can also be used to evaluate the effectiveness of existing catchment areas.

Design guidelines and a step-by-step design procedure are presented and illustrated with three example design problems. In addition, seven actual highway project case study examples prepared by experienced highway agency geotechnical practitioners are provided. They demonstrate the practical application of the design procedure and design charts and/or the use of site-specific rock rolling to aid in the rockfall mitigation design. The case study examples also illustrate other important design considerations, including constructibility and performing benefit/cost comparisons of alternate designs.

With tens of thousands of highway rock slopes in the U.S., many of which are decades old, 100 percent control of rockfall is not possible or economically practical. However, agencies can have greater confidence in making rockfall control design decisions using the results of this research project. Liability exposure will be reduced because design decisions are based on more current, detailed and specific research data.

1.0 INTRODUCTION

1.1 SIGNIFICANCE OF THE ROCKFALL PROBLEM

Rockfall is the movement of rock from a slope that is so steep the rock continues to move down slope. The movement may be by free falling, bouncing, rolling or sliding. See Figure 1.1.

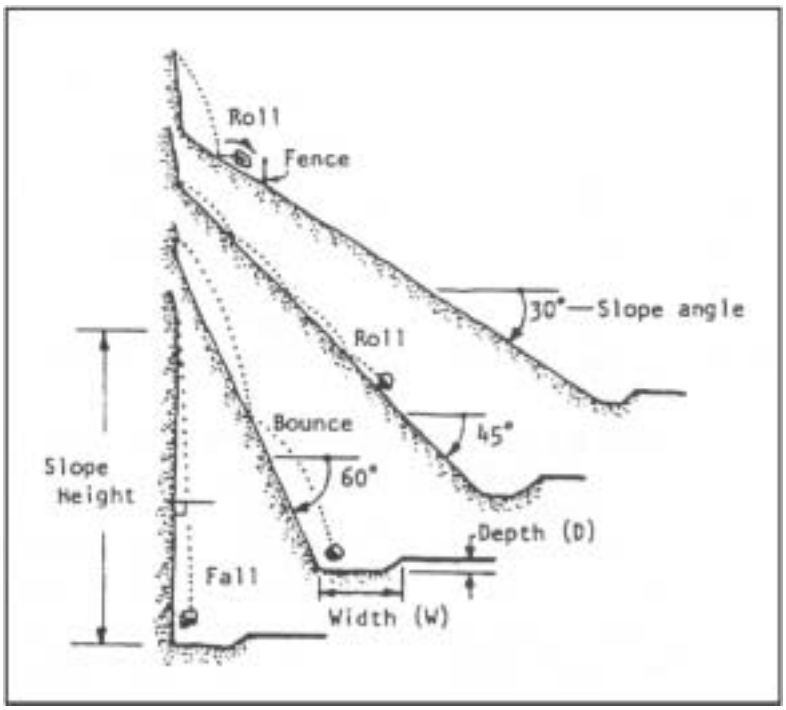


Figure 1.1: Rockfall travel modes (*Ritchie 1963*)

Rockfall is caused by many factors, including unfavorable rock structure (discontinuities), adverse groundwater-related conditions, poor blasting practices during original construction or reconstruction, climatic changes, weathering and tree levering (*Brawner 1994*). Rockfall along highways can occur where natural slopes or rock excavations exist. When such rockfalls reach the roadway they are a hazard to roadway users. Hundreds of millions of dollars are spent annually in the U.S. on rock slope maintenance and rockfall hazard mitigation on existing slopes and as part of reconstruction and new construction projects. Many states have had injuries and deaths caused by rockfall. Annually, the legal claims and litigation costs resulting from rockfall are in the millions of dollars.

1.2 ROCKFALL CATCHMENT AREA DESIGN PRACTICE

A rockfall catchment area is defined as the area between the edge of roadway pavement and the base of an adjacent slope that is used to restrict rockfall from reaching the roadway. The term catchment area is synonymous with ditch, rockfall ditch, rockfall catch ditch and rock fallout area. The use of catchment areas to mitigate rockfall hazards is one of the best and most effective rockfall protective measures.

The current practice for designing highway rockfall catchment areas is not consistent throughout the United States. Transportation agencies have design standards, but they are commonly based on a combination of factors such as economics, constructibility, maintenance and other safety related standards. In some cases, the design of catchment areas is loosely based on decades-old research. The result is a catchment area that may not be as effective at restricting rockfall from the roadway as assumed, or it may be over-designed, leading to unnecessary expenditures and impacts to the environment. Such catchment areas are routinely constructed even though they have not been evaluated or standardized through testing.

The principle reason no nationally adopted method for designing rockfall catchment areas exists is because only limited research has been conducted to provide designers with the data necessary to make informed design decisions. Prior to this research effort, the most comprehensive work done to develop fallout area design guidance was by Arthur M. Ritchie, Chief Geologist with the Washington State Department of Highways. In 1963, the Transportation Research Board (TRB) published a research report by Mr. Ritchie titled "An Evaluation of Rockfall and Its Control" (*Ritchie 1963*). This pioneering work was the first practical and comprehensive study of rockfall from actual highway slopes. The work included rolling hundreds of rocks off highway and state-owned quarry and talus slopes across Washington State. Ritchie measured and recorded the paths and distances the rocks traveled (including production of 16 mm motion pictures). The work culminated in a set of practical design criteria, in table form, that could be used to size the width of rockfall catchment areas based on slope height, slope ratio (angle) and depth of catchment area. This was the first research-based design guidance for safely containing rockfall.

Although pioneering, the Ritchie study was based on data collected from rolling only a few hundred rocks. While the 1963 Ritchie rockfall study was a major step forward, practitioners in years to follow recognized that the Ritchie criteria had some significant limitations (described in Section 2.2). The limitations led many U.S. transportation agencies to support Oregon DOT's research effort to develop a more current and better-quantified design criteria for sizing rockfall catchment areas.

1.3 RESEARCH PROJECT GOALS

The Oregon DOT research project had three main goals:

1. Investigate the nature of rockfall and identify how slope, catchment area and rockfall properties affect the rockfall retention at the base of vertical, 4V:1H, 2V:1H, 1.33V:1H, and

1V:1H slopes - for slope heights of 12.2, 18.3, 24.4 meters - and catchment area slopes of flat-bottom, 1V:6H and 1V:4H.

2. Develop improved, more precise design guidelines, including "practitioner-friendly" design charts, to assist with designing new or improved rockfall catchment areas that perform as intended with the minimum economic investment and environmental impact.

3. Provide design "flexibility" that allows designing catchment areas that will retain percentages of rockfall ranging up to 99 percent.

Funding for this research effort was obtained through a regional pooled-fund study. The participating State and Federal DOT agencies are listed in the Acknowledgments Section. Together these agencies contributed approximately $650,000 to accomplish the needed work. With this funding, a test site was developed, the data from rolling over 11,250 rocks was gathered and analyzed, and this report was prepared. The results are a significant step towards the development of an improved design procedure for rockfall catchment areas adjacent to rock cut slopes. The work covered by this report builds and improves on Mr. Ritchie's original pioneering work.

1.4 REPORT CONTENT SUMMARY

This report contains seven sections and seven appendices. Section 1 provides an introduction and defines the rockfall problem and goals of the research project. Section 2 describes past rock rolling research, including the ODOT 1994 pilot study which developed rockfall catchment area design charts for 4V:1H slopes. Section 3 summarizes the results of the more recent expanded rock rolling project conducted to develop catchment area design charts for additional slope angles ranging from vertical to 1V:1H. Section 4 presents catchment area design guidelines and worked example problems. Section 5 presents the full suite of design charts in an easy to use "practitioner-friendly" format. Section 6 presents summary conclusions and a listing of further research needs. Section 7 lists the report references.

Appendix A contains the summary histograms of the field data for the tested Ritchie ditch. Appendix B presents the entire set of rock rolling field data in tabular form for all the rock rolling tests. Appendix C contains the rockfall impact distance histograms. Appendix D contains the rockfall roll out distance histograms. Appendix E presents the rockfall energy data collected for the 2V:1H and 1.33V:1H test slopes. Appendix F presents the full suite of catchment area percent rockfall retention graphs. Appendix G contains seven case study application examples illustrating practical application of the design charts and/or the use of site-specific rock rolling to aid in the rockfall mitigation design in actual projects.

1.5 PROJECT BENEFITS

With information provided in this design guide, practitioners can either design new catchment areas or evaluate the effectiveness of existing catchment areas, and they can justify the expense of widening a catchment area based on the improved effectiveness that will be realized. They will also be able to design and construct catchment areas that will have a predictable rockfall retention capacity. The design charts are presented in a "practitioner-friendly" form that can be used to rapidly size rockfall catchment areas that satisfy specific rock catching/retention requirements. Based on cut slope angle, cut slope height and catchment area slope, the design charts estimate the required catchment area widths that will retain percentages of rockfall ranging up to 99 percent.

It is important to note that with tens of thousands of highway rock slopes in the U.S., many of which are decades old, 100 percent control of rockfalls is not possible or economically practical. Nonetheless, with the results of this research project, agencies can have greater confidence in making rockfall catchment design decisions. Liability exposure should be reduced because design decisions are based on more current, detailed and specific research data.

This report documents the test methods, the field work performed, the data gathered, the means of analysis, the research results and sample application of the design charts. The data are presented in both tabular and graphical form in the Appendices. The Appendices also include the detailed project case study application examples. An electronic copy of this report is available through the ODOT Research Internet web site http://www.odot.state.or.us/tddresearch.

1.6 REPORT TERMINOLOGY

To facilitate reading and understanding of this report, the reader is encouraged to review the Glossary of Terms presented at the beginning of the report (page ix). Readers are also advised that, based on consensus opinion of the project technical advisory committee, the term "rockfall catchment area" has been adopted for use in the report. Catchment area is synonymous with ditch, catch ditch, rock fallout area, rockfall ditch, and rockfall catch ditch. Within the report, the synonymous term "ditch" is sometimes used because that has been the common usage by practitioners, such as "Ritchie ditch." Also, the term ditch has been used on some of the figures.

2.0 BACKGROUND

2.1 1963 RITCHIE STUDY

Arthur M. Ritchie, Chief Geologist with the Washington State Department of Highways, published his study on rockfall entitled "Evaluation of Rockfall and Its Control" in 1963 (*Ritchie 1963*). The emphasis of Ritchie's study was to identify the characteristics of rockfall motion relative to a slope's configuration and height, and to determine the expected impact distance of a rockfall from the base of the slope. He also investigated how to effectively stop a falling rock that had considerable angular momentum once it landed in the catchment area. Based on this work, Ritchie drew several significant conclusions including the following:

1. Irrespective of a rock's shape or size, the rock's mode of travel down the slope is a function of the slope angle (refer to Figure 2.1).

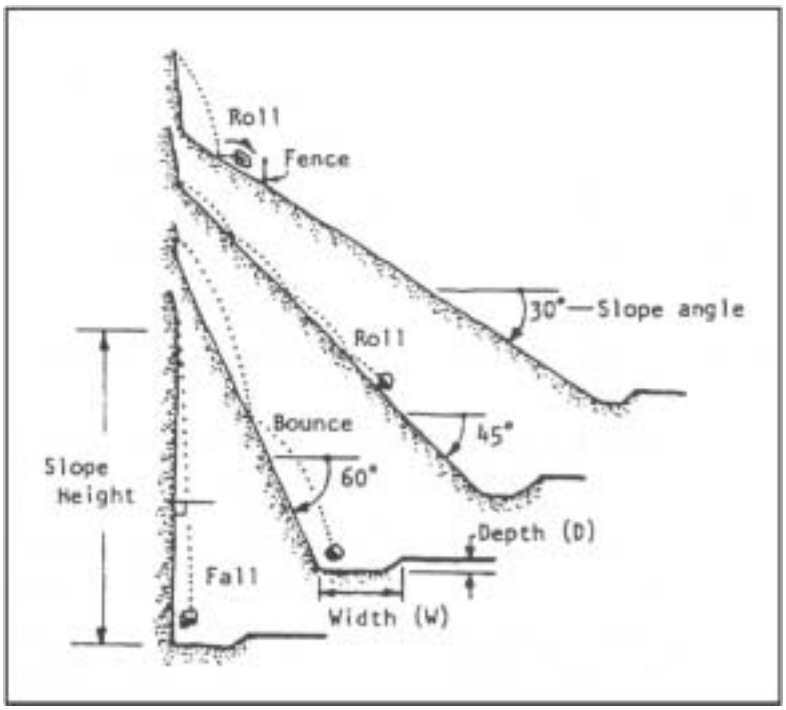


Figure 2.1: Rockfall travel modes (*Ritchie 1963*)

2. On steeper slopes, even though a rock's initial motion is by rolling, after a short distance the rock starts bouncing and then either continues bouncing along the slope or goes into free fall, depending on the slope angle.

3. Rocks that fall in trajectory (free fall) seldom give a high bounce after impact. Instead they change their linear momentum into angular momentum.

In addition, and more significant to the practice of highway design today, Ritchie prepared an empirical design table of recommended minimum rock catchment area width and depth, based on the slope height and slope angle. His table was later adapted into a design chart (refer to Figure 2.2) in the FHWA publication "Rock Slopes: Design, Excavation, Stabilization" (*FHWA 1989*).

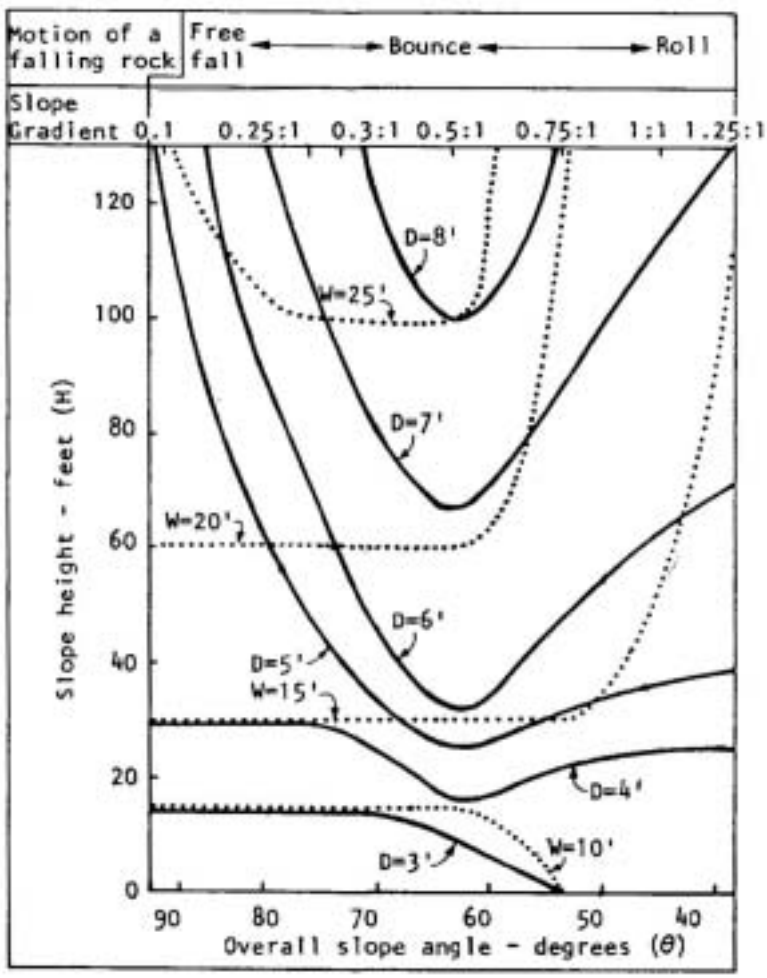


Figure 2.2: Ritchie's rockfall catch ditch design chart (*FHWA 1989*)

The chart version shown in Figure 2.2 made it easier for designers to interpolate between the cut slope heights, cut slope angles and catchment area (ditch) depths listed on Ritchie's original table.

Almost 40 years later, Ritchie's empirical table (or modified chart version) is still used by numerous state and local transportation agencies to dimension catchment areas. One of the major limitations of the Ritchie design criteria, however, is that Ritchie relied on the use of a deep, flat-bottom ditch with a steep 1V:1.25H foreslope next to the roadway to restrict rocks from rolling up onto the roadway. Such deep, steeply sloped ditches can rarely be used today, since they do not meet current MUTCD/AASHTO roadside clear zone safety requirements. Use of such deep ditches today is typically limited to only the most extreme rockfall hazard locations. As the more modern roadside clear zone safety requirements evolved, the Washington State Department of Transportation (WSDOT) modified Ritchie's original design criteria to allow a more gently sloped (1V:6H) catchment area as an alternate to the deep ditch design. The current 2001 WSDOT design criteria, contained in the WSDOT Roadway Design Manual, are shown on Figure 2 of the Washington State case study application example in Appendix G.

Subsequent to Ritchie's study, D'Appolonia, California DOT (Caltrans), and Evans have completed additional rockfall research work (*D'Appolonia 1979, McCauley, et al. 1985, Evans 1989*). In addition to these field studies, several rockfall computer simulation programs have been developed that can help predict the catchment area requirements. These programs were developed by Evert Hoek (consultant), Shie-Shin Wu (North Carolina DOT), and Tim Pfeiffer (Colorado and Oregon DOT, consultant) (*Hoek 1987, Wu 1987, Pfeiffer and Higgins 1990*). These programs are quite useful in predicting rockfall trajectories when detailed slope information is available. Pfeiffer's program "Rockfall" was used to evaluate catchment area configurations for this study.

2.2 LIMITATIONS OF RITCHIE RESEARCH

Pioneering as it was, the Ritchie study was based on data collected from rolling only a few hundred rocks. While the 1963 Ritchie rockfall study was a major leap forward, practitioners in years to follow recognized that the Ritchie criteria had some significant limitations. These include:

1. The Ritchie table always gives the same required catchment area width and height for a given slope height and slope ratio and does not provide a means for designing for varying percent rockfall retention levels based on a benefit/cost approach.

2. The Ritchie catchment area design is based on providing a catchment area wide enough that a rockfall's initial <u>impact</u> will be within the catchment area. The design relies on a 0.9 to 2.4-meter deep flat-bottom catchment area with a steep 1V:1.25H foreslope adjacent to the roadway to restrict rocks from rolling onto the roadway. Such steep-sided roadside catchment areas do not provide a recoverable slope for errant drivers and are not consistent with current roadside safety clear zone design standards. These catchment areas require some

form of guardrail or barrier on the road shoulder to keep vehicles from falling into the ditch and possibly overturning.

3. The Ritchie rock rolling was done primarily on "rough" non-presplit highway and quarry slopes and natural slopes, containing numerous launch features. Today's highway slopes are predominantly developed using controlled blasting techniques (presplit or cushion blasting) and thus are "smoother" with fewer launch features than those in the Ritchie study.

2.3 ODOT'S 1994 PILOT STUDY FOR 4V:1H SLOPES

During 1992-1994, ODOT, supported by FHWA, conducted an initial pilot research study at their Krueger Quarry Rockfall Test Site to gather rockfall performance data and to determine the value of this type of research. The study gathered data from rolling rocks down 4V:1H rock cut slopes of three different heights (12.2, 18.3 and 24.4 meters) into three differently inclined catchment areas (flat, 1V:6H and 1V:4H). See Figure 2.3.

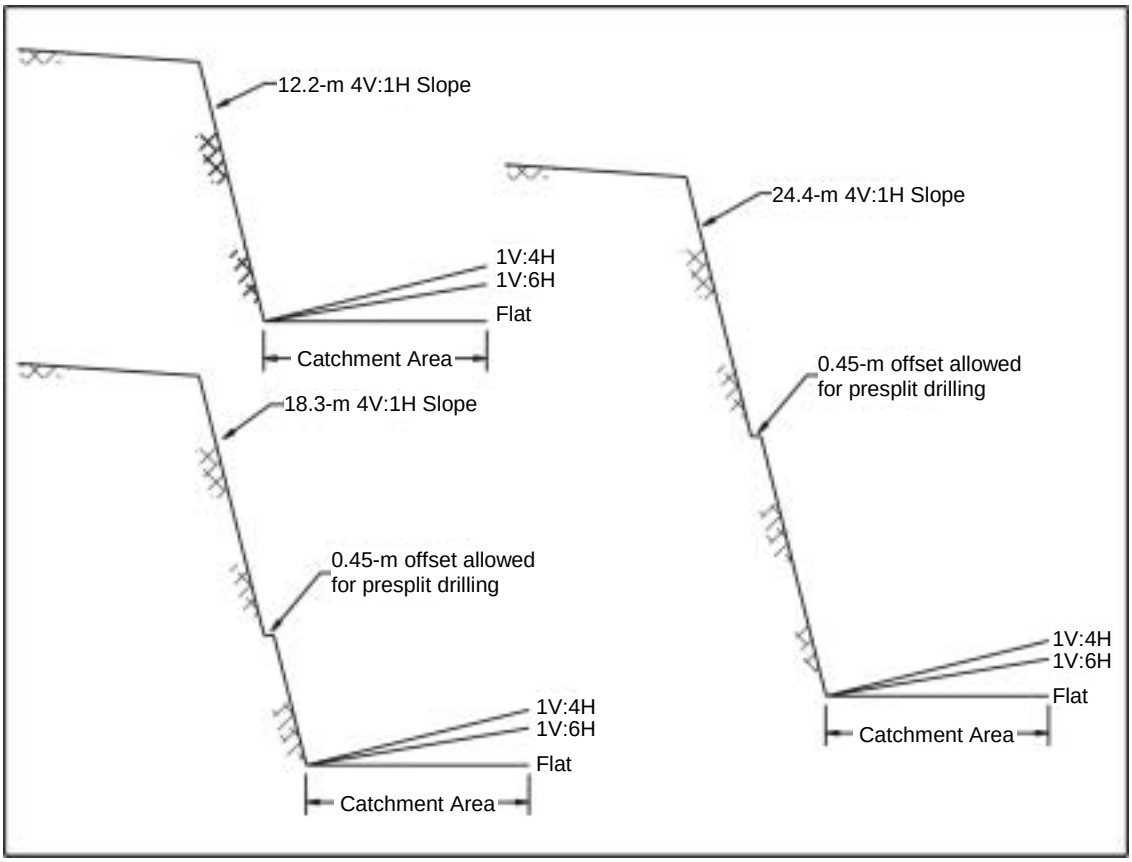


Figure 2.3: Tested slope heights and catchment area configurations (Pilot Study)

A report based on this work entitled "The Nature of Rockfall as the Basis for a New Catchment Area Design Criteria for 0.25H:1V Slopes" was published in 1994 (*Pierson, et al. 1994*). The report number is FHWA-OR-GT-95-05.

Several worthwhile results were realized by the pilot research effort. Rockfall frequency histograms were developed that showed the rockfall retaining ability of catchment areas of a particular width and catchment area slope. This information is important when decisions need to be made on rockfall mitigation at a site. Quantifying the potential for a rockfall to reach the roadway allows designers to consider how much benefit will be realized by a certain investment in construction dollars. When assessing existing sections of highway, this information is also useful for preparing a more precise catchment design, based on a benefit/cost analysis.

In the beginning, the research team speculated on the behavior of rockfall to formulate assumptions for the experimental designs. Without prior rockfall testing frequency to rely on, it was unknown what characteristic shape the distribution curves would take or how many rocks would have to be rolled to obtain one. The testing began with the assumption that the measurements recorded would provide the information required to develop a new design guideline for 4V:1H slopes.

The data obtained convinced the team that the level of effort in the pilot study was correct. Early on it became apparent that a sufficient number of rocks were being rolled to establish characteristic distributions. In fact, most conclusions probably could have been drawn based on a smaller data set. To be certain however, the research team rolled a "standard suite" of 250 rocks from each slope height and into each catchment area slope tested. A combination of graphical and statistical techniques provided an appropriate level of analysis.

When constructing new rockfall catchment areas associated with new or improved alignments, or when modifying existing catchment areas to reduce the risk of rockfall related incidents, a goal for rockfall control is usually followed. Normally, this goal is established to provide less than 100% control. Costs associated with 100% rockfall protection are usually unreasonably high: the acquisition of the required right of way, large excavation and construction cost and adverse environmental impact usually cannot be justified.

If the rockfall mitigation measure selected is to construct or improve a catchment area, then the probability of a rock escaping or clearing the catchment area must be included in the risk analysis. Using the results of the pilot research project, the research team was able to develop design guideline charts. These charts can be used to evaluate the likelihood of a rock reaching the roadway for a given catchment area of a particular dimension at the base of a 4V:1H slope. Designers now had a quantitative tool with which to determine the percentage of rocks they wish to retain. The design charts constituted a major advance in the "rational" design of rockfall catchment areas.

2.3.1 1994 Survey of Rockfall Catchment Area Design Practice

As an initial part of the 1992-1994 pilot project, a survey was conducted of all the state DOT's and federal agencies to determine what their method of designing (sizing) rockfall catchment

areas was and whether there was any standardization of design across the country. Thirty-one agencies responded. The questionnaire asked what their design standard/guideline was; how frequently they deviated from their standard; and what was their opinion of the Ritchie criteria.

Twelve agencies responded that they used the Ritchie criteria as their design standard. Of those agencies using the Ritchie criteria, most felt that it was adequate, but almost half felt it was conservative. Nine agencies had some other design standard, with three of these using the computerized Colorado Rockfall Simulation Program (CRSP) for sizing fallout areas.

Nearly a third of the respondents (10) indicated that they had no catchment area design standard. Most of these represented states where rockfall is a rare occurrence. Detailed survey results are tabulated in Pierson, et al 1994.

2.3.2 Comparison to a Ritchie Test Catchment Area (Pilot Study)

A.M. Ritchie published his pioneering work "Evaluation of Rockfall and Its Control" in 1963 (*Ritchie 1963*). For many states, it remains the basis for rockfall catchment area design. As part of the initial pilot research effort, 275 rocks were rolled from a 24.4 meter high 4V:1H slope into a “Ritchie” catchment to determine its effectiveness. For comparison purposes, the tested Ritchie catchment area was dimensioned according to the modified Ritchie design chart (see Figure 2.2) contained in the FHWA Rock Slopes Manual (*FHWA 1989*). The Ritchie catchment area dimensions obtained from the design chart are slightly different than some of the dimensions on Ritchie’s empirical table due to the curve smoothing done when formulating the chart. For an 18.3 to 24.4-meter high, 4V:1H slope, Ritchie’s original table calls for flat-bottom catchment area with dimensions of 6.1 meters wide and 1.8 meters deep with a 1V:1.25H foreslope. The modified FHWA chart gives dimensions of 6.7 meters wide and 1.9 meters deep with a 1V:1.25H foreslope.

The intent was to construct a test catchment area consistent with the modified FHWA chart. However, this did not occur. Due to a construction error, the “as-built” dimensions of the tested Ritchie catchment area were 7.3 meters wide, 2.0 meters deep with a flat bottom and 1V:1H foreslope (refer to Figure 2.4). This is wider and deeper and contains a steeper foreslope. Based on observed rockfall behavior, these modifications should make the tested ditch more effective than a standard Ritchie ditch.

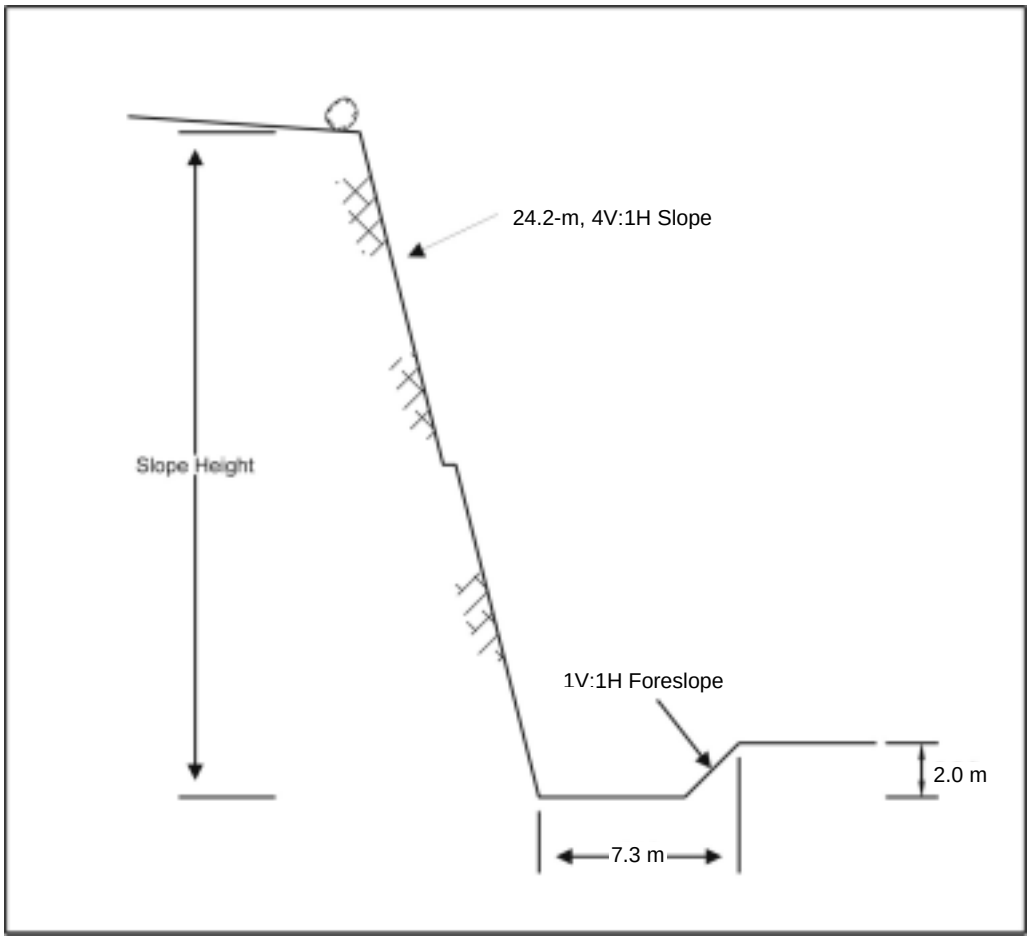


Figure 2.4: Tested Ritchie catchment area shape and dimensions

Figure 2.5 shows the comparison between the tested Ritchie catchment area data and the data obtained for the 24.4-meter high 4V:1H slope, for both the 1V:4H and 1V:6H catchment areas. Upon examination, the tested Ritchie catchment area compares favorably with both the 1V:6H and 1V:4H catchment area slopes. Predictably, the average impact distances (where the falling rock first hits the catchment area) for the three catchment area slopes are almost identical. Regarding roll out retention, the tested Ritchie catchment area showed a 0.6- to 0.9-meter reduction in roll out distance compared to the 1V:6H and 1V:4H catchment area slopes. Figure 2.6 shows the cumulative percentage of rocks retained for the tested Ritchie catchment area.

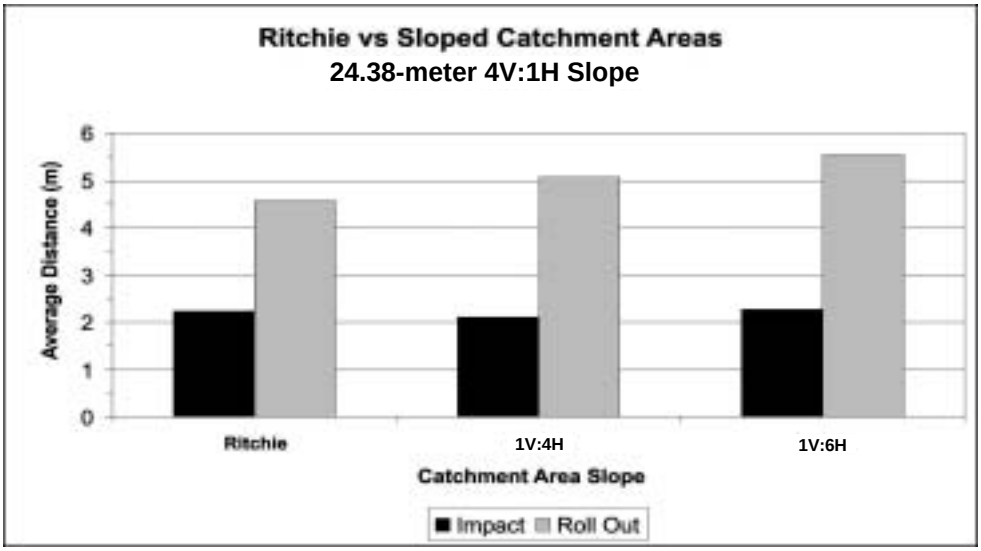


Figure 2.5: Comparison of tested Ritchie to 1V:4H and 1V:6H sloped catchment areas

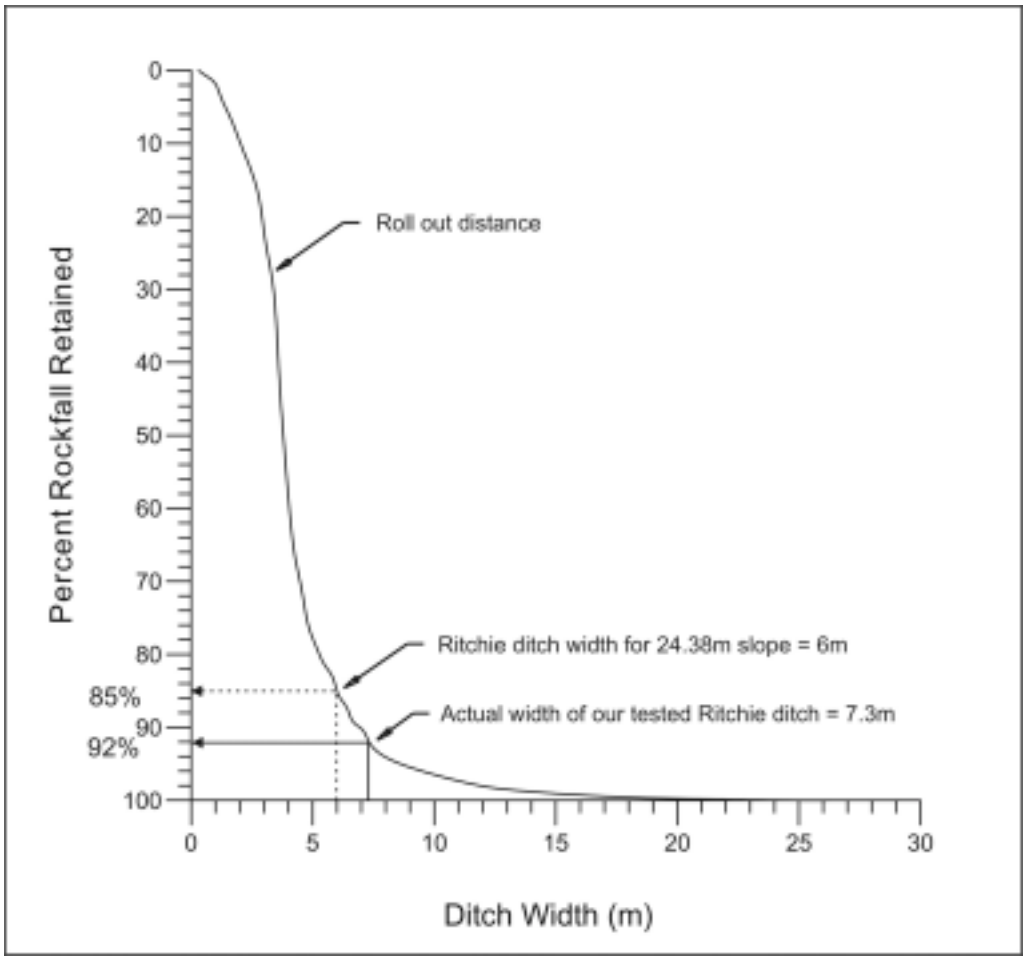


Figure 2.6: Cumulative percentage rockfall retained for tested Ritchie catchment area

Although the Ritchie shaped ditch used for testing was wider, deeper and contained a steeper foreslope than a standard Ritchie ditch, eight percent of the rocks were still able to escape the catchment area; 92 percent were retained. Had the catchment area been designed to a Ritchie width of 6.1 meters, per the original Ritchie design table, 41 rocks, or about 15 percent of the total, would have escaped the confines of the catchment area. In other words, the design would have provided a retention value of 85 percent. Of the 41 rocks, three rocks would have impacted beyond the catchment area and the remaining 38 would have landed within the catchment area and rolled through. This finding indicates that the original Ritchie guidelines are not as conservative as previously thought. Frequency histograms for the tested Ritchie catchment area are shown in Appendix A.

A Ritchie catchment area reduced the average roll out distances versus the 1V:6H and 1V:4H sloped catchment areas, but would have allowed 15 percent of rocks to reach the roadway. The most effective features of a Ritchie ditch are the overall depth and the steep 1V:1.25H foreslope. These features, however, are rarely incorporated into modern highway catchment areas primarily because catchment areas this deep, and with such a steep foreslope, offer no chance of recovery for an errant driver. The catchment area does not meet current roadway design standards for roadside clear zones.

2.3.3 Comparison with Computer Rockfall Simulation (Pilot Study)

Several state transportation departments now use computer simulation of rockfall as a tool to help in designing for rockfall. The most commonly used computer program is the Colorado Rockfall Simulation Program (CRSP), (*Pfeiffer and Higgins 1990*). This program provides estimates of probable bounce heights and velocities for rockfall. Recently, additional statistical data have been added providing probability distributions for velocity, energy and bounce height. The program is applicable to almost all slope configurations. It is more flexible than design criteria that require slopes of given configurations. Simulation, however, requires detailed site condition and slope geometry input data and assumptions; therefore accuracy varies, depending on the quality of the input data.

As part of the pilot research effort, rockfall simulation was used to aid in planning, by providing ranges of expected values for the 4V:1H slopes. It was found that the computer simulations tended to under-predict the rockfall roll out distance for the 24.4-meter slope height and over-predict the roll out distance for the 12.2-meter slope height.

Histograms of roll out distances for both the simulation data and the field data showed most of the rocks stopping close to the slope and a small percentage with very large roll out distances. Figure 2.7 shows a comparison of the actual field data versus the computer simulation prediction for the roll out distances. The data used is where 90 percent of the rockfall would be expected to have come to rest.

The data from the field tests was also compared to computer simulation data to evaluate the accuracy and applicability of the computer model simulations to extrapolate beyond the tested 12.2- to 24.4-meter slope heights. Computer simulation had previously been compared to

rockfall on less steep natural slopes, but data from a controlled study of 4V:1H presplit slopes and associated roll out distances were unavailable prior to the ODOT pilot study.

The computer simulation data agreed reasonably well with the field test data. Similar distributions were obtained and the effects of rock size and catchment area slope were also similar. This provided important verification that computer simulations, performed by experienced geotechnical personnel, could be used as a design tool for rockfall catchment areas when extensive field-testing is not practical or nonstandard slope or catchment area shapes are proposed.

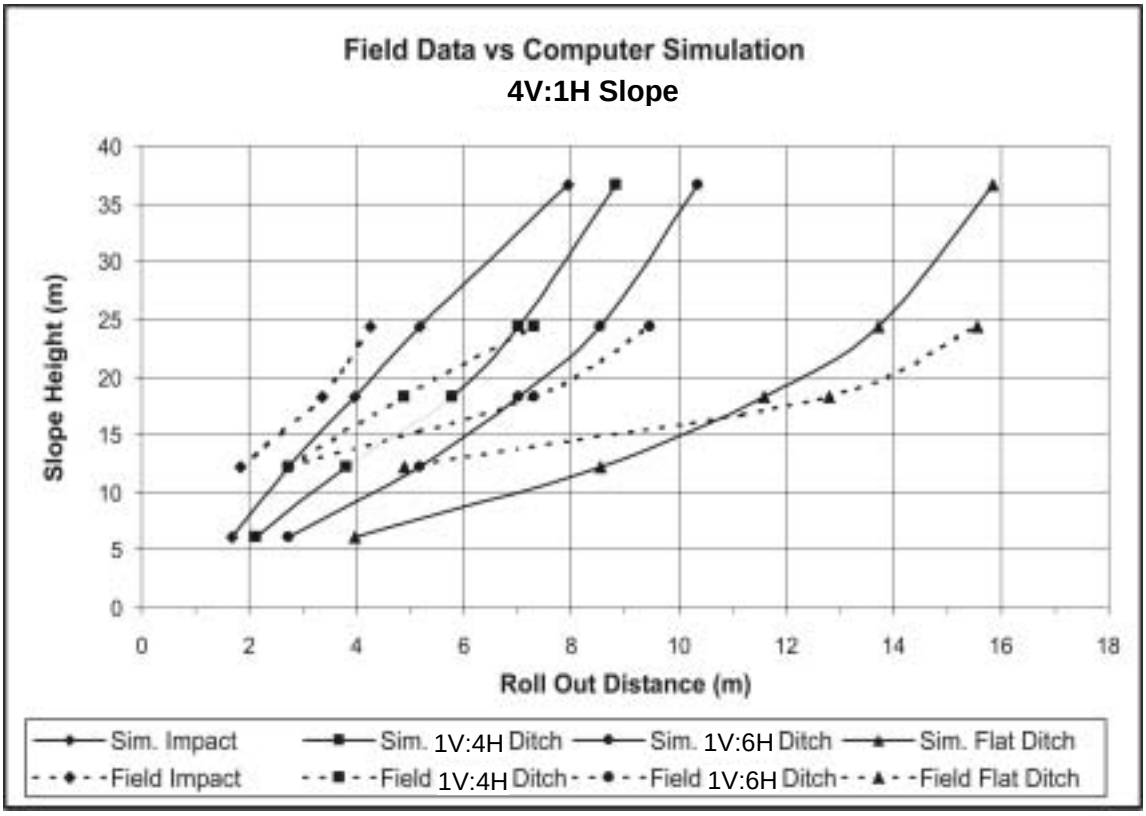


Figure 2.7: Field data and computer simulation comparison (4V:1H slope)

3.0 FULL SCALE TESTING OF ADDITIONAL SLOPES

The results of the 1992-1994 pilot research effort for the 4V:1H slope established the value of this type of research and prompted several State DOT's and the FHWA to participate in the evaluation of several more slope configurations. The additional slopes were tested through a pooled fund research project conducted between 1997-2001.

3.1 RESEARCH SITE TEST COMPONENTS

To conduct the field testing, the Oregon DOT Krueger Quarry Test Site needed to be expanded to accommodate four more slopes: vertical, 2V:1H, 1.33V:1H, and 1V:1H. All slopes needed to represent the types of conditions encountered adjacent to highways and needed to be at least 24.4-meter high. The area above the quarry face was relatively flat, making it ideal as a staging area for stockpiling the rock that was to be rolled. Access to the top existed but needed to be improved for all weather use.

A contractor was retained to drill and shoot the various cut slopes and provide the equipment needed to excavate the shot rock and slope the catchment areas. All cut slopes were shot in two 40-foot lifts. The cut slopes that were 1.33V:1H or steeper were developed using controlled blasting (presplitting). The flatter 1V:1H slope was developed using only production blasting. On the presplit slopes, a maximum 0.45-meter offset was allowed between lifts to accommodate the drilling equipment (see Figure 3.1).

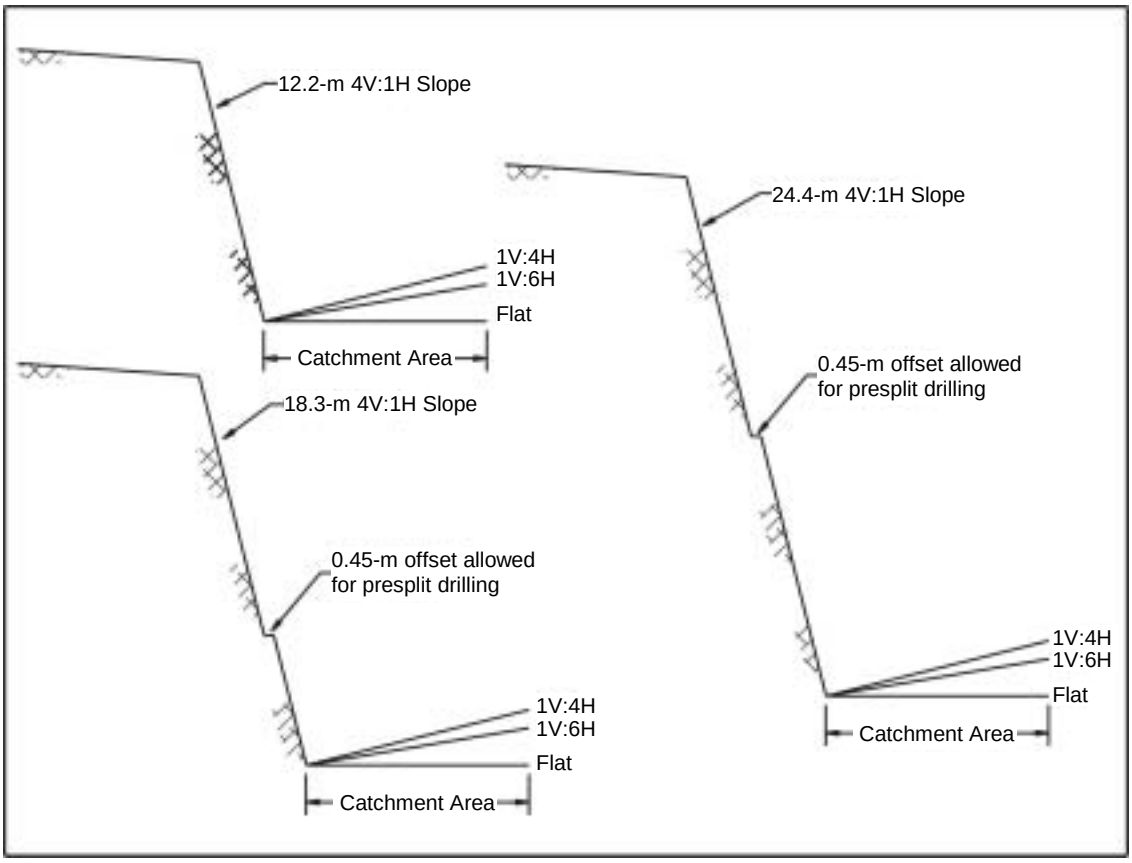


Figure 3.1: Tested slope height and catchment area configurations

For each slope angle, the top lift was excavated to create the first 12.2-meter high slope to be tested. Once testing was complete, the second lift was shot, but only the top 6.1 meters were removed to create the 18.3-meter high slopes. The remaining shot material was subsequently excavated to create the 24.4-meter high, test slopes. In order to optimize the economy of the research project, several slopes were constructed and tested simultaneously.

Consistent with the 1994 pilot project, three different catchment area configurations were tested for each cut height (Figure 3.1):

- a flat bottom catchment area;
- a catchment area that sloped toward the cut slope at a 1V:6H slope; and
- a catchment area that sloped toward the cut slope at a 1V:4H slope.

These are the configurations most commonly constructed adjacent to highways and are consistent with the current clear zone safety requirements.

The catchment area surface was comprised of shot rock with a minimal percentage of soil. Due to the method of excavation, the steepest (1V:4H) catchment area was tested first for each slope

height. The 1V:6H catchment area and then the flat-bottomed catchment area followed. This excavation method allowed the rockfall impact to occur on a material that would closely approximate conditions that would be encountered at the base of a newly constructed highway rock cut slope. Photos of the test site are shown in Figures 3.2, 3.3 and 3.4.

Figure 3.2: 24.4-meter high, 4V:1H presplit slope (Oregon test site)

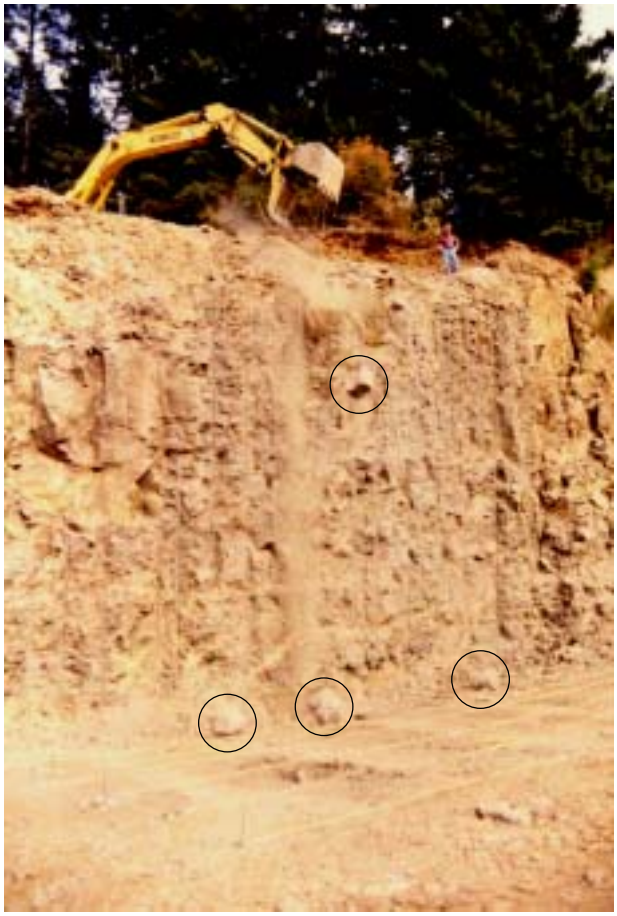


Figure 3.3: Rockfall testing; 12.2-meter high vertical presplit slope, 0.6-meter diameter rocks, 1V:4H catchment area foreslope. Circles denote test rocks.

Figure 3.4: Rockfall testing; 12.2-meter high vertical presplit slope. Circle denotes test rock. Grid lines (middle-right) are for measuring impact and roll out distances.

In all, more than 11,250 rocks were rolled at the research site, with at least 750 rocks rolled for each cut slope angle and height. Each catchment area slope received a "standard suite" of rocks, which included 100 rocks averaging 0.3 meters in diameter, 75 rocks averaging 0.6 meters in diameter and 75 rocks averaging 0.9 meters in diameter. The diameter dimension was measured along the longest axis. The actual dimensions for each size category ranged within plus or minus 0.15 meters. For example, the 0.6-meter rocks varied from 0.45 to 0.75 meters in diameter along the longest axis.

Two values were recorded for each rock that was dropped: the impact distance and the roll out distance. The impact distance was the measured slope distance from the base of the cut slope to the point where the rock first struck the ground. The roll out distance was the furthest measured distance that the rock attained from the base of the cut slope. The complete field test data are included in Appendix B.

How a rock falls influences where it impacts the catchment area. For example, if a rock strikes a protrusion in the cut face during its descent and is redirected away from the slope, it will have a

larger impact distance than if it stays close to the slope during its fall. An additional assumption, based on experience, was that inclining the catchment area would have some measurable effect on roll out distance. Based on these assumptions the analysis was divided into three primary parts:

1. Slope effects and impact distance;
2. Catchment area slope and roll out distance; and
3. Impact versus roll out distance.

3.2 SLOPE EFFECTS AND IMPACT DISTANCE

Impact distance is defined as the measured slope distance from the base of the rock cut slope to the point where a falling rock first strikes the ground.

A catchment area's slope, whether flat-bottom or inclined, has only slight influence on where a falling rock will first impact the catchment area. Conversely, a rockfall's point of impact can be strongly influenced by cut slope irregularities, commonly referred to as "launch features." These launch features include blasting offsets and other protrusions caused by the breakage properties of the rock and the means of excavation.

At the ODOT test site, even though the slopes tested were relatively smooth and uniform presplit slopes (for the 1.33V:1H and steeper test slopes), some slope irregularities were still present. The combined effects of these features were pronounced enough that certain preferred rockfall paths became prevalent. Figure 3.5 shows a representation of rocks falling from a 24.4-meter high 4V:1H slope and impacting in a flat catchment area. The most common preferred rockfall paths for this slope are labeled 'A', 'B', 'C' and 'D'. At least two factors are key to the development of preferred rockfall paths: the presence of launch features, and increasing slope height.

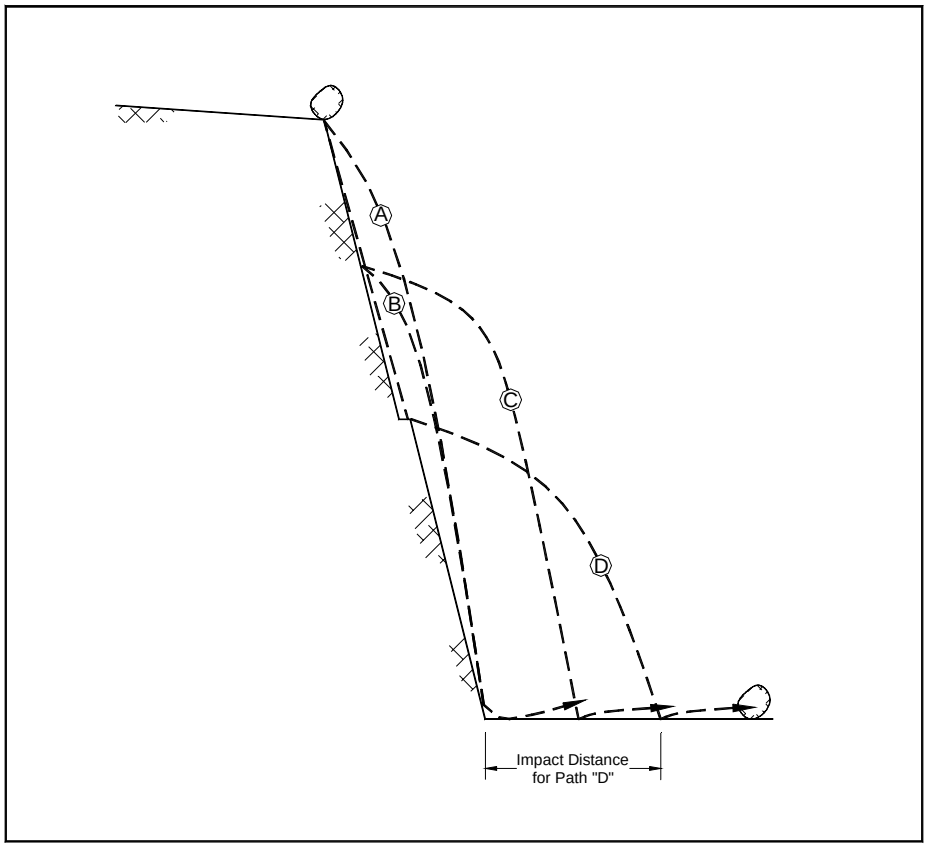


Figure 3.5: Preferred rockfall paths

Rocks that fall along path ‘A’ do not encounter the slope until just before impact, resulting in smaller impact distances measured from the base of the cut slope. Rocks following path ‘B’ strike the slope in two places, but do not strike launch features, thus resulting in a lower impact distance.

Those that encounter launch features on the slope are pushed farther away from the slope and follow paths similar to ‘C’ or ‘D’. “Launched” rocks tend to have greater impact distances, increasing the spread or dispersion of recorded impacts compared to rocks that do not strike launch features. Launch features change a rock’s vertical drop to horizontal displacement. Typically, the higher the rock velocity when it strikes a launch feature the greater the horizontal displacement.

Impact histograms have been developed as a method to show the distribution of data points and data trends. They are useful tools for visualizing the full range of field measurements. Included on the histograms is a cumulative percentage curve that allows practitioners to roughly estimate the percentage of rocks that impacted at a distance less than or equal to the distances shown along the horizontal axis at the base of the figure. Because the horizontal axis is not an actual scale, however, interpolating between the labeled distance values yields only an approximation. These histograms should not be used for design purposes.

Figures 3.6 through 3.8 show impact distance histograms for the 12.2-, 18.3- and 24.4-meter high 4V:1H slopes. The histogram for each slope height includes the 825 impact data points from the three catchment area slopes. They provide a graphical representation of frequency, or how often, a certain impact value was recorded. As included here, these figures are composite histograms for all three catchment area shapes tested. The histograms included in the appendices show individual histograms for each catchment area shape. The average impact values calculated from the field-measured data points were 1.1, 1.7 and 2.1 meters for the 12.2-, 18.3- and 24.4-meter high 4V:1H slopes, respectively. Because the distances shown along the horizontal axis are not scaled, these values cannot be directly determined from the histograms.

The observed impact results from the test slopes are consistent with observations and experience at actual highway rock cut slopes. This consistency adds credibility to the research results and demonstrates the validity of the findings. The complete set of Impact Distance Histograms is included in Appendix C.

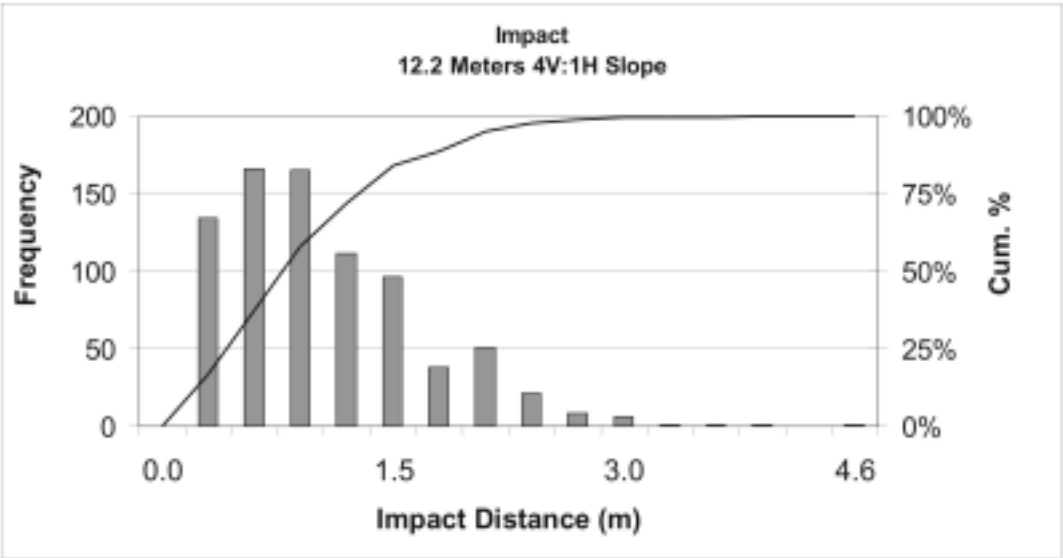


Figure 3.6: 12.2-meter impact histogram (4V:1H slope)

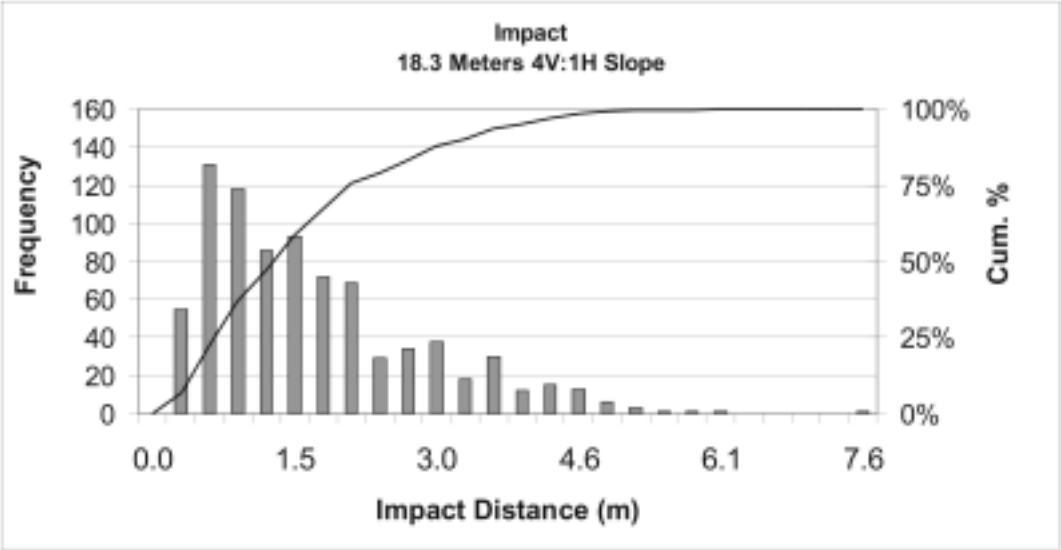


Figure 3.7: 18.3-meter impact histogram (4V:1H slope)

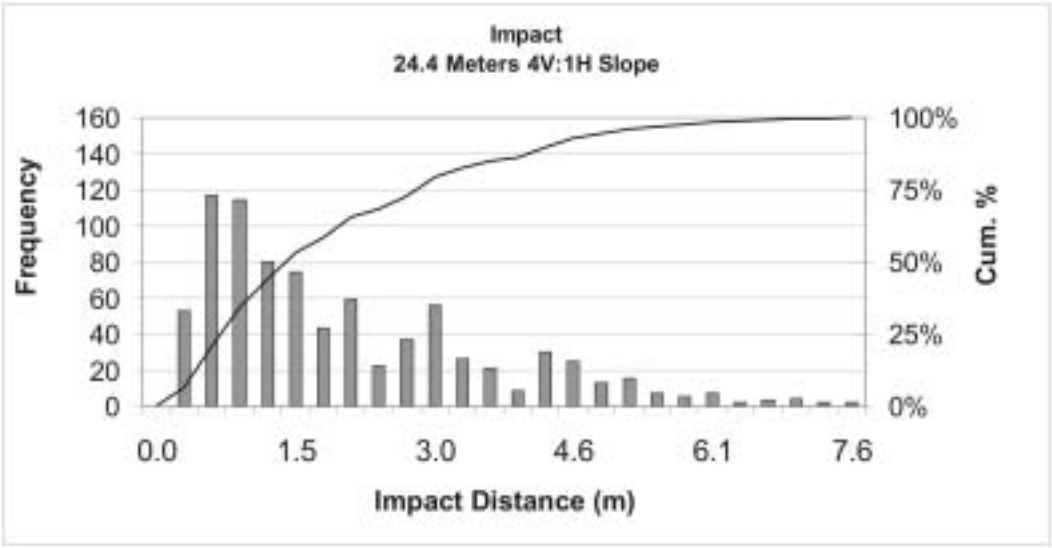


Figure 3.8: 24.4-meter impact histogram (4V:1H slope)

3.3 CATCHMENT AREA SLOPE AND ROLL OUT DISTANCE

Roll out distance is defined as the measured slope distance between the base of the cut slope and the <u>furthest</u> point the rock reaches from the base of the slope. Figure 3.9 shows a rock falling from a 24.4-meter high, 4V:1H slope, engaging a launch feature and impacting a 1V:4H bottom sloped catchment area at point ‘A’.

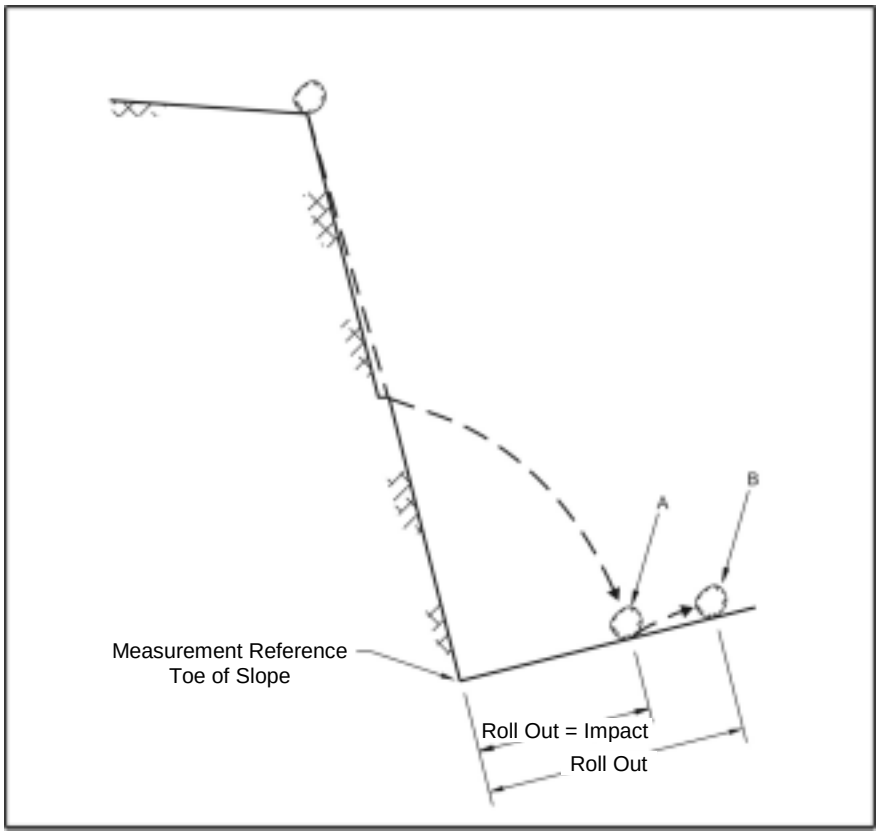


Figure 3.9: Definition of roll out distance

Two outcomes can occur:

1) The rock does not move beyond the point of impact, position 'A'. For this case, roll out distance equals impact distance. This outcome includes rocks that roll back toward the toe of the slope from the point of impact.

2) The rock impacts at position 'A', then rolls toward the road attaining a maximum distance from the base of the slope at position 'B'. In this case the roll out distance is greater than the impact distance.

Two conclusions can be drawn from rockfall behavior observations: 1) steeper sloped catchment areas tend to reduce roll out distance; and 2) higher slopes typically produce larger average roll out distances. Figure 3.10, compiled from the 4V:1H slope data, and Figure 3.11 from the 1V:1H slope data, illustrate these relationships well. Using the flat sloped catchment area as a basis, the average roll out distance for all heights combined was reduced by 37% in the 1V:6H sloped catchment area and 51% in the 1V:4H sloped catchment areas for the 4V:1H slope and by 48% (1V:6H) and 66% (1V:4H) for the 1V:1H slope.

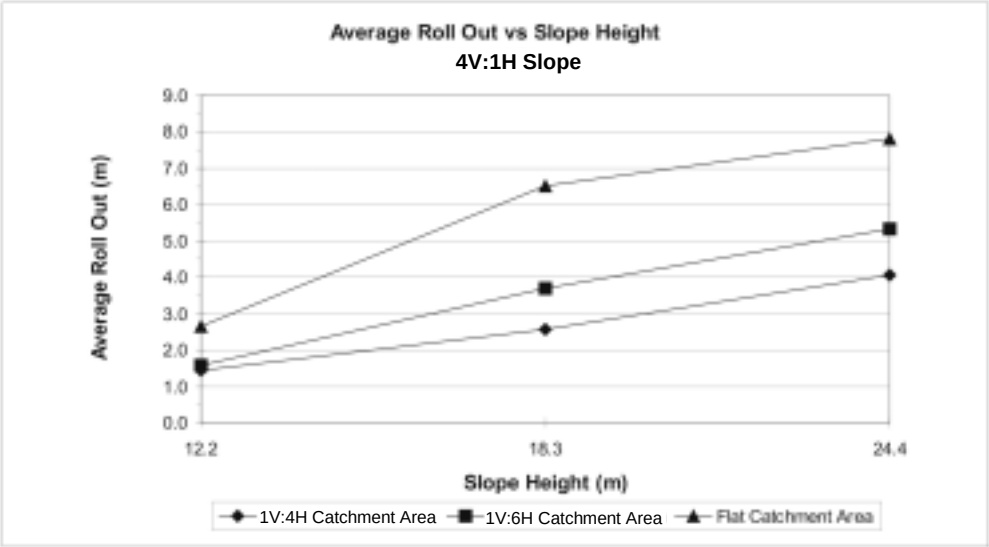


Figure 3.10: Average roll out distance vs. slope height (4V:1H slope)

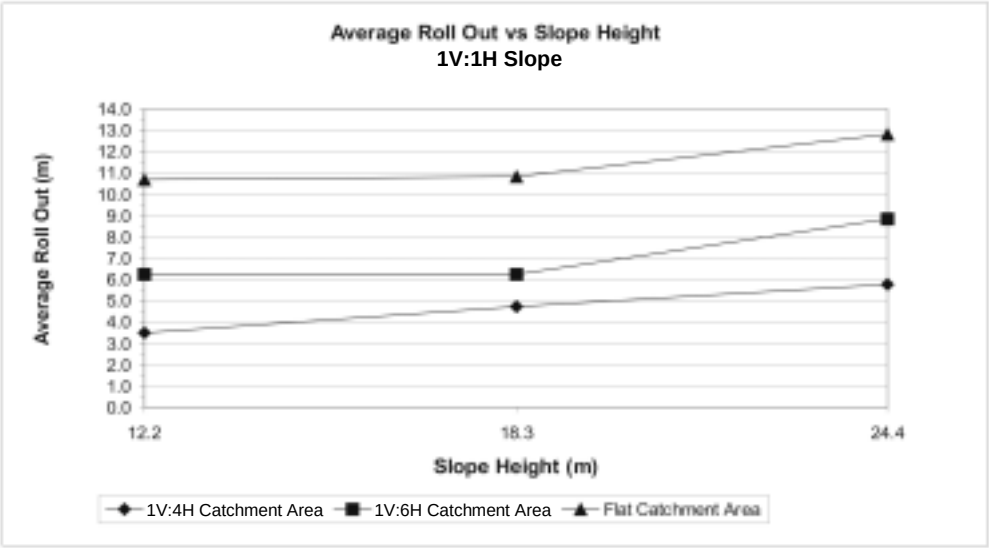


Figure 3.11: Average roll out distance vs. slope height (1V:1H slope)

Figures 3.12 through 3.14 show the roll out distance histograms for the 24.4-meter high, 4V:1H slope, and the three different catchment area slopes. When comparing the data trends for the different catchment areas, it is important to note that the maximum distances shown along the horizontal axes are different from one another. These histograms clearly demonstrate that steeper catchment areas restrict roll out considerably. For example, the average calculated roll out distances are 6.1, 4.9 and 3.7 meters for the flat-bottomed, 1V:6H and 1V:4H sloped catchment areas, respectively. Because the horizontal axis is not a scaled axis, these values can only be

estimated from the cumulative percentage curves. As with the impact distance histograms, the roll out distance histograms should not be used to establish design values. The complete set of Roll Out Distance histograms is included in Appendix D.

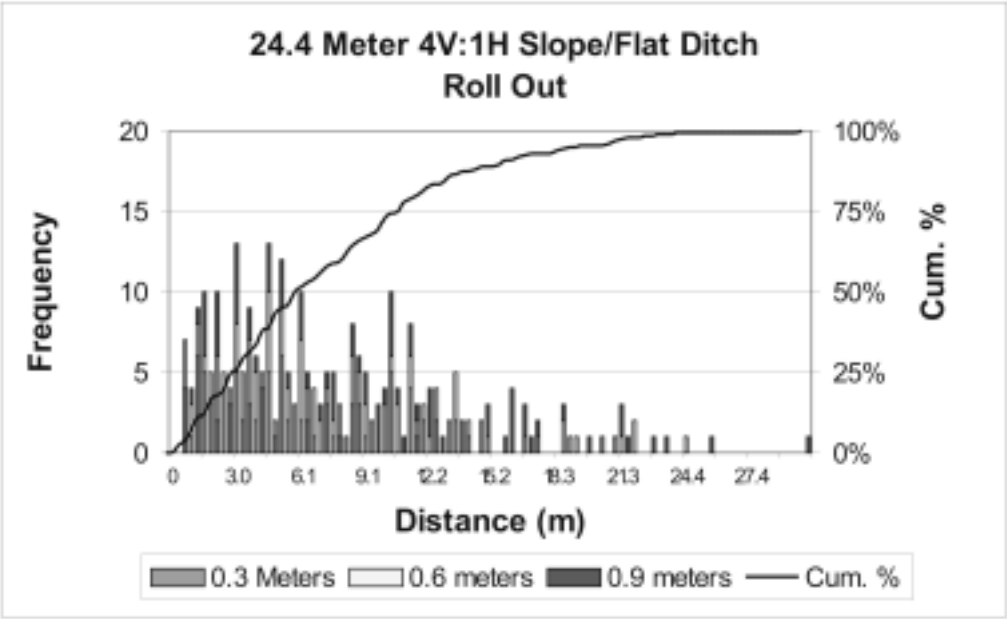


Figure 3.12: Roll out histogram, 24.4-meter slope – flat catchment area

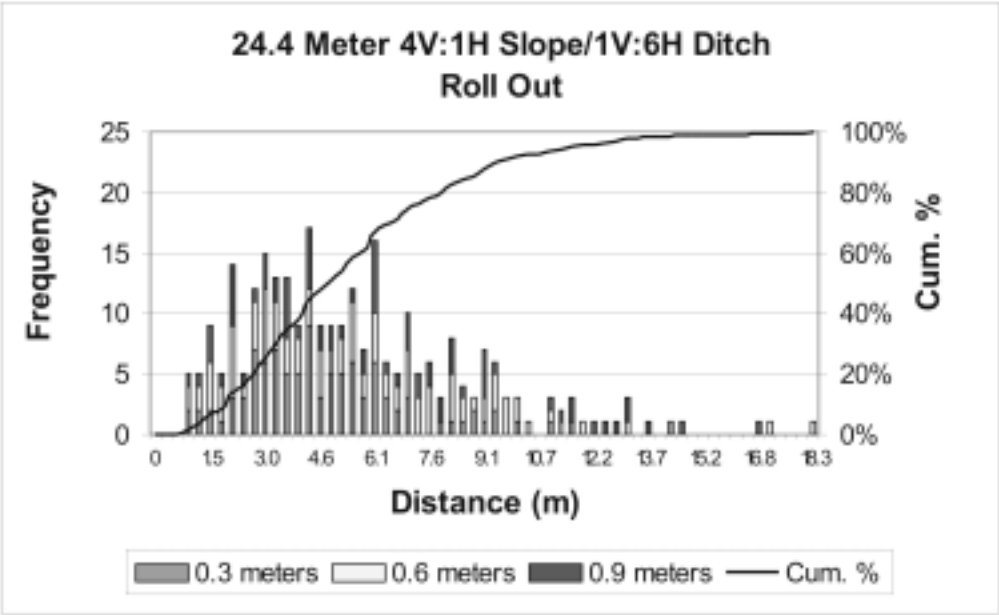


Figure 3.13: Roll out histogram, 24.4-meter slope – 1V:6H catchment area

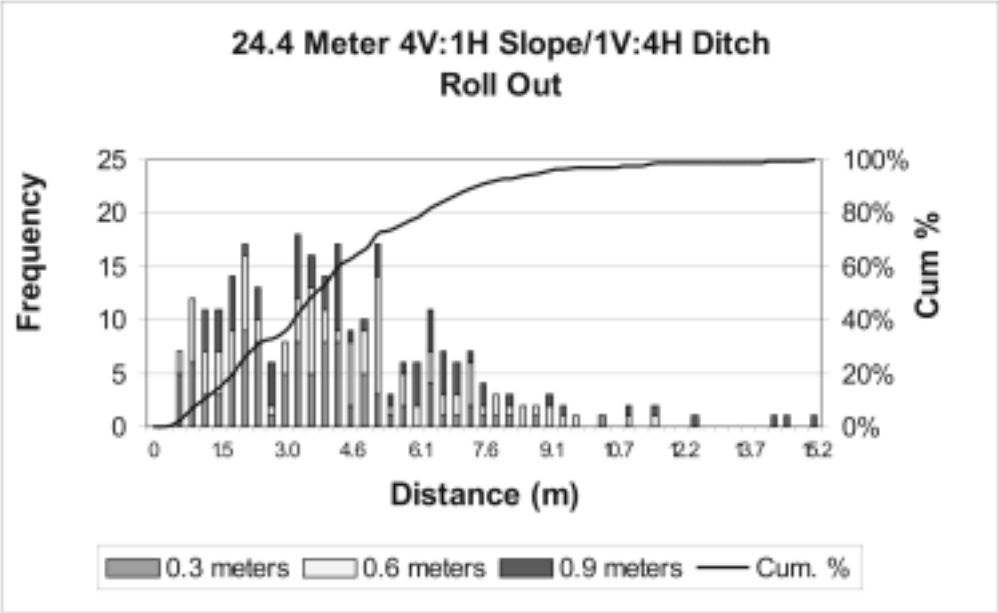


Figure 3.14: Roll out histogram, 24.4-meter slope – 1V:4H catchment area

3.4 IMPACT DISTANCE VERSUS ROLL OUT DISTANCE

Impact and roll out distances were recorded for each rock. Each cut slope angle exhibits a specific relationship with these data. The basic relationships of preferred path relative to the toe of the slope can be interpreted from these data, as discussed below. A comparison of impact versus roll out distances indicates that higher slopes and flatter catchment areas tend to have data that are more widely scattered or variable. The data show that the impact distances tend to be greatest for slopes between 4V:1H and 2V:1H where rockfall trajectories are significantly altered when the rocks strike the slope during falling. Striking the slope launches the rocks away from the slope, increasing impact distance. Large roll out values are also possible, especially if a rock strikes the cut slope near the base, which can result in most of the falling rock's translational momentum being changed into rotational momentum. The largest roll out value (30.2 meters) was recorded on a 24.4-meter high, 4V:1H slope.

On vertical slopes, falling rocks rarely strike the slope in trajectory. They typically drop undisturbed into the catchment area. Angular momentum is not imparted to the falling rocks, which results in small roll out values. This is demonstrated in the collected data for each rock, which include numerous measured impact and roll out values that are similar.

On flatter slopes (1.33V:1H and flatter), where rocks are rolling down the cut slope, the impact distances are lower, with most rocks entering the catchment area very near the base of the slope. Movement out into the catchment area is due primarily to roll out. Restricting these rockfalls from the roadway is accomplished by energy dissipation due to gravity and friction as the rock rolls through the flat bottom or up the inclined foreslope of a sloped catchment area.

An easier way to understand the variability in the rockfall data is to use a statistical quantity called standard deviation. Put simply, the standard deviation is a measure of data scatter. A small standard deviation means there is little scatter between measurements and most values are clustered around the average. A larger standard deviation means there are larger differences between measurements, and values are widely scattered about the average. Two sets of data may have the same average value but have very different standard deviations.

An examination of the standard deviation can help explain the relationship between impact and roll out. Figure 3.15 shows the standard deviation of impact distance plotted against slope height. All three catchment area slopes are shown. In each case, impact distance becomes more variable as the slope height increases. Since impact distance is independent of catchment area slope the curves cross each other at various points.

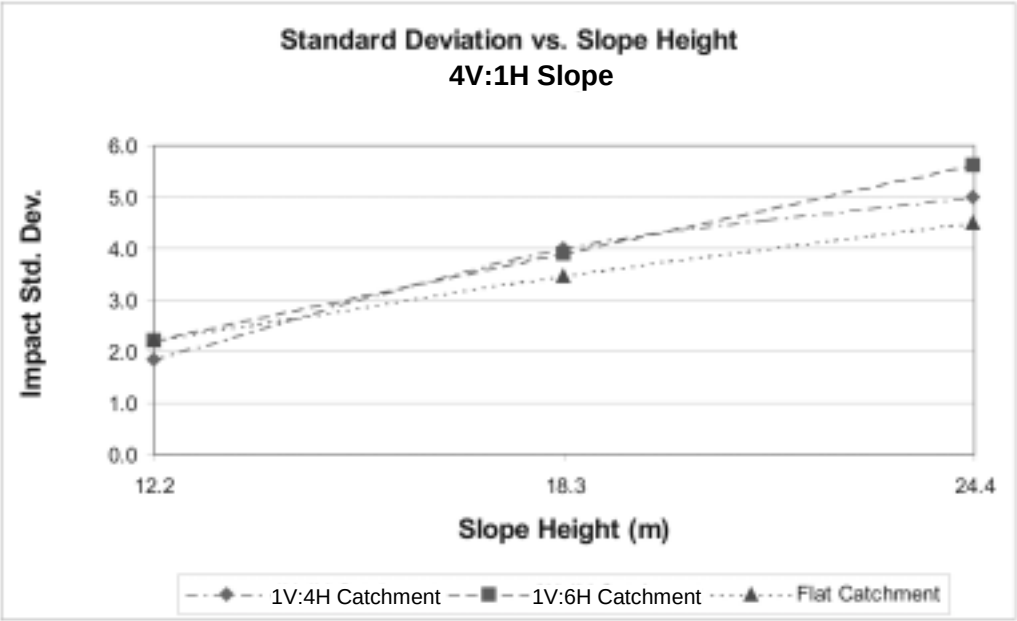


Figure 3.15: Standard deviation of impact distance (4V:1H slope)

Figure 3.16 shows the standard deviation of roll out distances plotted against slope height. In each case, roll out distance becomes more variable with both an increase in slope height and flattening of the catchment area. This relationship is particularly clear for flat catchment areas at greater slope heights.

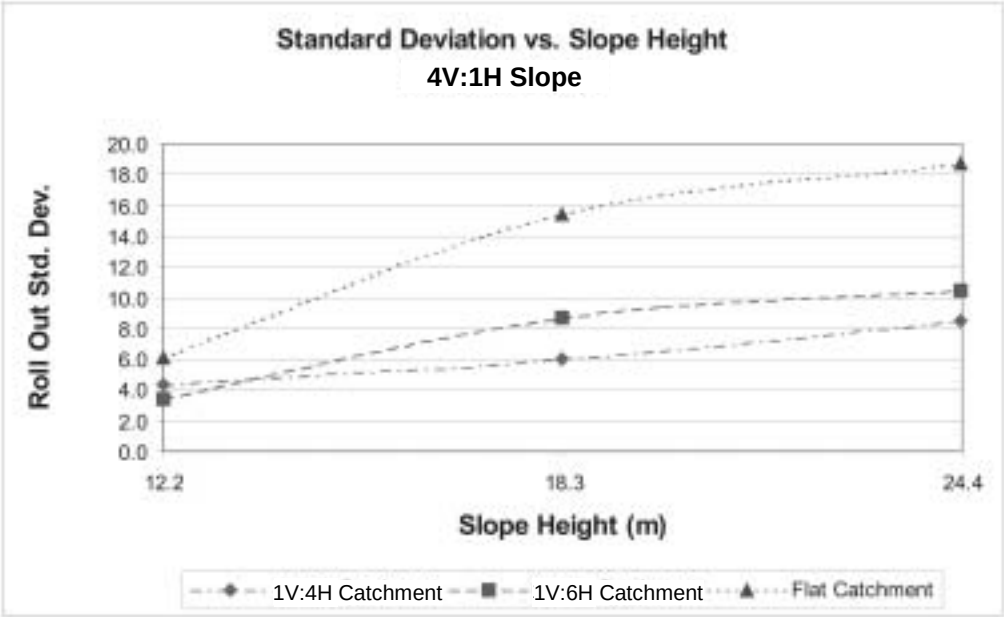


Figure 3.16: Standard deviation of roll out distance (4V:1H slope)

From these two graphs one can conclude that higher slopes produce impact distances that are more variable and that roll out distance is more variable in both higher slopes and flatter catchment areas. Because of these relationships, higher slopes typically require wider and/or steeper catchment areas in order to provide an equivalent degree of protection. However, because of the non-linear relationship between catchment area width and the percent of roll outs that can be contained, simply increasing catchment area width yields a diminishing return. This concept is clearly demonstrated by the percent retention graphs presented in Section 4.2 and Appendix F.

3.5 ROCKFALL ENERGY DATA

Further into the research project, an additional research item was added to collect rockfall energy data. The Technical Advisory Committee felt the information would be a valuable contribution to future research efforts such as testing various mitigation designs to failure and in comparing computer simulated results to real data. For example, rockfall mitigation measures such as catch fences or Jersey (GM) barriers could be instrumented, and the impact energies required to fail the systems could be determined. The rock rolling energy data would be useful in determining which slopes, slope heights and rockfall sizes would be appropriate candidates for these measures.

Selected rockfall energy data were recorded for the 2V:1H and 1.33V:1H slopes from the three heights tested. Sets of reference marks were placed on the slopes just above the base of the slope. Representative rocks within the 0.3-, 0.6- and 0.9-meter categories were weighed and video taped (VHS format at 30 frames/second) during rolling. By analyzing the video data, the

time it took the rolling rocks to pass through the reference marks was used to determine the rockfall velocity. The weight and velocity data were used to calculate the kinetic energy of the falling rocks upon entering the catchment area.

The energy information recorded represents a small population of data points. Because of the small numbers sampled, the results are limited. Still, the results show intuitive trends. The rockfall energy graphs are included in Appendix E. A sample graph is shown in Figure 3.17. As shown on the figure, the energies ranged from a low of 423 kilojoules to a high of 5,038 kilojoules. The difference is due primarily to the weights of the rocks that were tested. The weight of a rock increases exponentially by the third power of its radius. The rocks in this case varied in shape and were in the "0.3-meter" category, where rocks ranged in diameter from 0.15 to 0.45 meters.

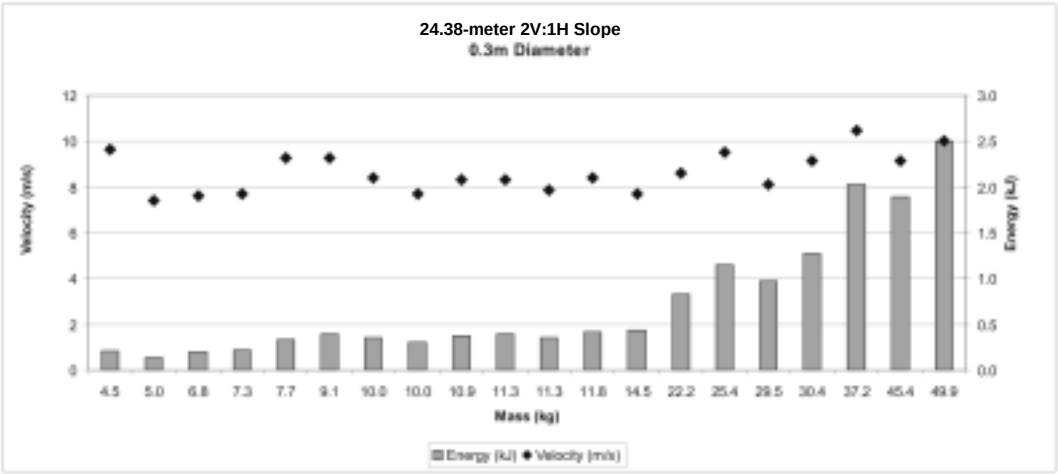


Figure 3.17: Energy data for 0.3-meter rocks (24.4-meter high, 2V:1H slope)

The rockfall velocities are a function of cut slope angle and height and the amount of time the rocks are in contact with the slope. Velocities tended to be within a narrow range of values for each of the two slope angles tested, with slight increases as the slope height increased. The variations are primarily attributable to the path taken by the rocks during descent.

In general, when in contact with the slope, friction slows the rocks and lowers the resulting energies. Because the rocks are less often in contact with the slope (bouncing not rolling) on the 2V:1H slopes, the resulting velocities and energies are higher than for the 1.33V:1H slopes. This relationship explains why rolling rocks can come to a complete stop on flatter slopes and not make it to the catchment area.

4.0 DESIGN GUIDELINES AND APPLICATION EXAMPLES

4.1 DESIGN GUIDELINES

Even though rockfall-related traffic accidents receive an inordinate amount of publicity relative to other types of traffic accidents, they are still a rare event. The probability of being involved in a rockfall accident is quite low. For a rockfall-related accident to occur, several conditions must be satisfied.

1. A rockfall event must take place.
2. The rockfall must enter the roadway by clearing or rolling through the catchment area.
3. The rockfall must strike, or be struck by, a vehicle, or cause an accident due to the vehicle maneuvering to avoid the rockfall.

A number of factors play a role in determining the rockfall hazard inherent to a particular slope. An accepted methodology for evaluating and quantifying the rockfall hazard potential is the Rockfall Hazard Rating System (RHRS) (*Pierson, et al 1989*). The system evaluates site conditions that include traffic density, geologic conditions, block size and rockfall history, among others. The RHRS provides a hazard rating of any number of sites relative to each other, enabling a transportation agency to prioritize how and where to spend their limited safety improvement and construction budget.

Because the likelihood of personal involvement in a rockfall event (and resulting injury) is low, the design goal of rockfall retention is normally less than 100%. The unreasonably high cost associated with 100% rockfall protection can not usually be justified by the risk to highway users. If rockfall mitigation includes the construction or improvement of a catchment area, its probable effectiveness must be considered. The rockfall retention guidance provided in this document is for a standalone catchment area mitigation measure. Commonly, a combination of mitigation measures may be applied. For example, if a barrier system is incorporated into the mitigation design, the full design criteria catchment area width may not be required. In such cases, the decision to reduce the catchment area width should be made by an experienced rock slope designer.

Through this research, design charts have been developed to evaluate catchment area effectiveness. Transportation agencies now have a quantitative tool with which to design catchment areas, based on a given design goal percentage of rockfall retention. They can use these tools to evaluate the economic feasibility of various cut slope and catchment area combinations that will maximize the benefit for a given investment.

The guidelines set forth in this report provide a means for designing catchment areas to varying percentage rockfall retention levels and for prioritizing of projects based on benefit/cost. As practitioners and state DOT policy officials consider the adoption of these guidelines, it is important to note that the application of such standards is not unique to design of rockfall catchment areas. Such an approach is analogous to numerous other programs administered by state and federal transportation agencies where program funding is limited. Examples include highway safety improvement projects; roadside hazard improvement projects; traffic safety improvement projects; bridge replacement projects; bridge seismic retrofit projects; and unstable slope correction projects. These programs are limited by available funding and involve prioritization and selection of projects based on use of ranking criteria, benefit/cost comparisons and professional judgment.

Legal counsel for both the Oregon DOT and Caltrans have advised that judges, juries and the public understand that due to limited funds and resources, public transportation agencies cannot be expected to correct every problem or deficiency immediately and cannot always design to 100% hazard reduction standards. They further advised that designing to less than 100% rockfall retention is legally defensible, when set as agency policy and done as part of a rational slope/rockfall assessment. Such catchment area design must be performed by experienced rock slope personnel using current state of the practice standards and within the economic constraints at the time of execution.

4.2 CATCHMENT AREA PERCENT RETENTION GRAPHS

Rockfall catchment area percent retention graphs have been prepared for vertical, 4V:1H, 2V:1H, 1.33V:1H, and 1V:1H cut slopes. The graphs are a compilation of the results from this latest research effort and the earlier 4V:1H slope pilot research project. The complete set of retention graphs is included in Appendix F. For each cut slope angle, the graphs show the rockfall impact and roll out retention widths compiled for all three slope heights, for all three catchment area configurations tested. The percent retention graphs were developed from the collected research data. Extrapolating beyond the graph limits – i.e., extending the curves below 12.2 meters or above 24.4 meters – is possible, but the decision to do so is left up to the discretion of the owner agency or the practitioner. Based on comparison of field test data to computer simulation results, computer simulation may be a viable method to evaluate the reasonableness of the values yielded from extended curves.

The percent retention graphs incorporate the maximum impact and roll out data points measured for the percentage indicated, converted from field measured slope distance to horizontal distance (1V:4H and 1V:6H foreslopes). In some cases, because of weather-related slope conditions, rockfall trajectory, or specific interaction with the catchment area, the maximum measurement shown on the retention graph may have occurred on any one of the three slope heights tested for each slope angle. In addition, this point may not be related to the larger rock size categories. Although the energy data indicated that the higher slopes and larger rocks tended to produce the highest rockfall energies, the higher energy rocks, depending on their trajectory, sometimes dissipated considerable energy by burrowing into the catchment area, reducing roll out distance.

The following sample percent retention graphs, included as Figures 4.1 and 4.2, are from the 1.33V:1H test slope. They represent 50% and 90% rockfall retention catchment area widths. Note that the horizontal scales are different. On the 50% chart for a 12.2-meter high slope the impact distance is zero. This means that at least 50% of the test rocks rolled into the catchment area at the toe of the slope, resulting in a zero value for impact distance.

On the 90% graph, the upper ends of the curves are becoming nearly vertical at the 24.4-meter slope height. This indicates that as slopes become higher, the need to continually increase the catchment area width diminishes. Although the curves do not extend below the 12.2-meter high slope value, for lower slopes where rockfall energies diminish, the trend of the impact and roll out curves will at some point reverse as they approach zero. At a minimum, the roll out values will be equal to the diameter of the rockfall.

Rockfalls can affect vehicles in three ways. They can impact a vehicle in trajectory, they can roll into a vehicle, or they can be in the way of a vehicle. The impact curves are included because they represent the minimum width needed to have the rockfalls land within the fallout area and not onto the roadway.

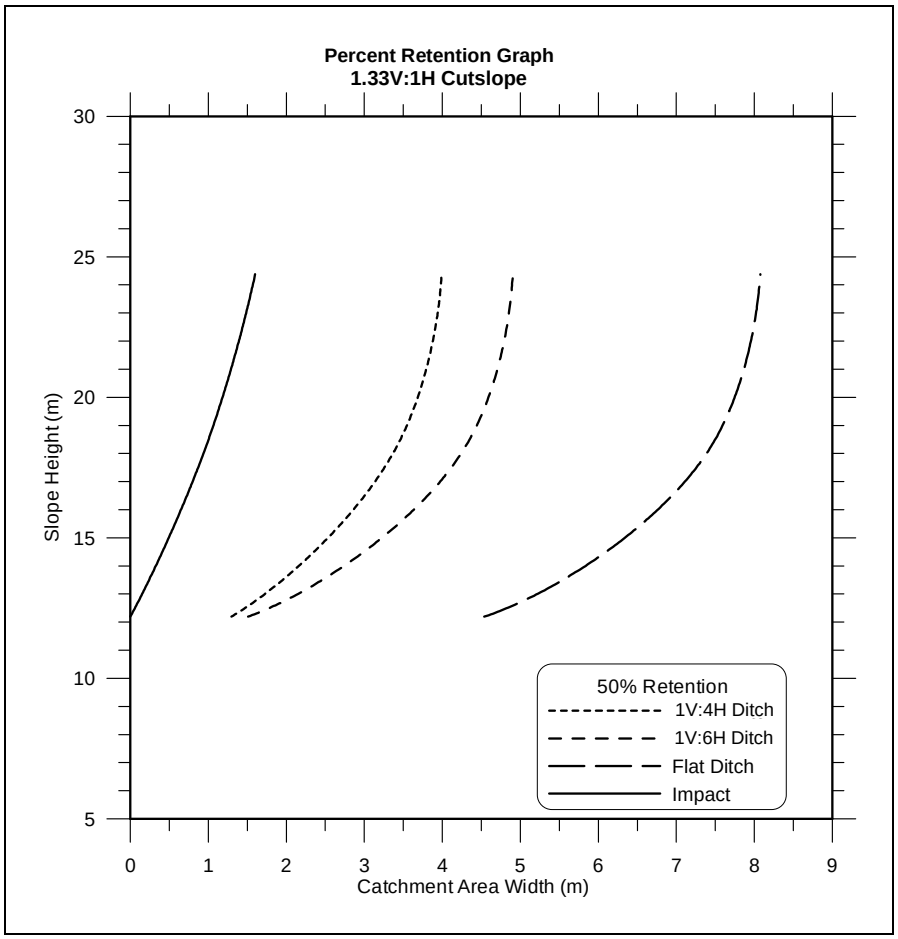


Figure 4.1: 50% Retention graph (1.33V:1H slope)

The complete suite of percent retention graphs, ranging from 30 to 99 percent retention, is included in Appendix F. If desired, the percent retention graphs can be used to design catchment area widths. The graphs allow easy interpolation of intermediate slope heights between the tested 12.2-, 18.3- and 24.4-meter heights.

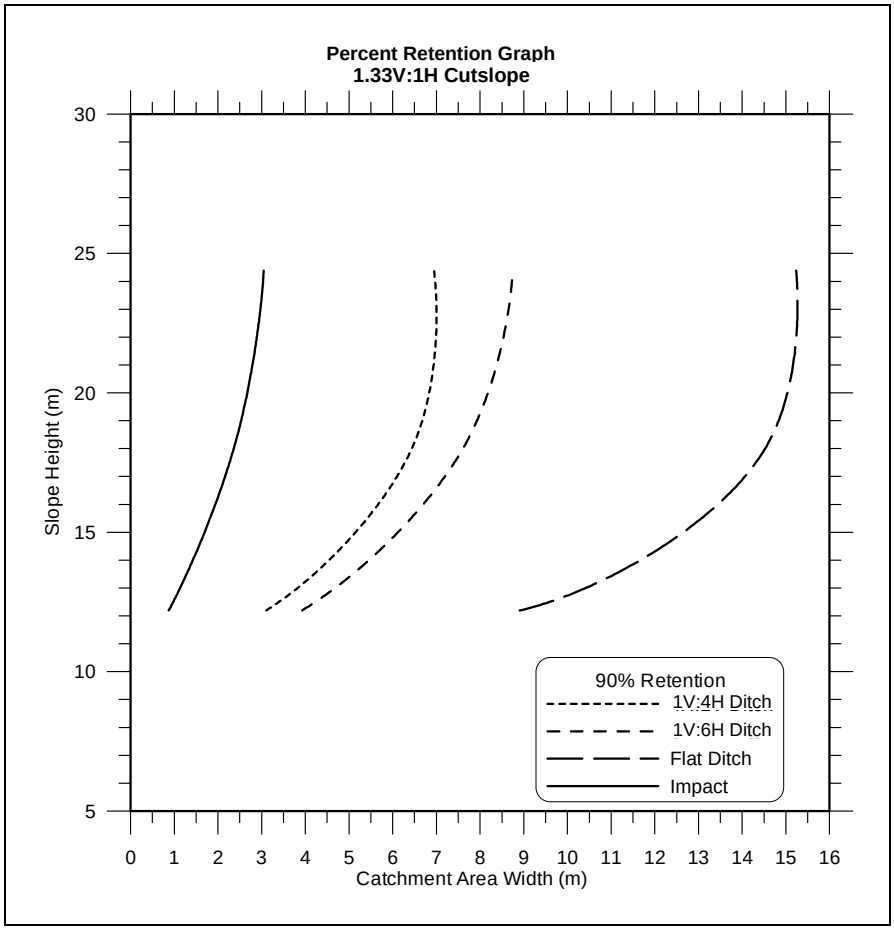


Figure 4.2: 90% Retention graph (1.33V:1H slope)

4.3 CUMULATIVE PERCENT RETAINED DESIGN CHARTS

Cumulative percent retained design charts have also been produced. These charts combine the data points from the percent retention graphs for a specific slope height. This is a “practitioner-friendly” format that allows rapid evaluation of catchment area widths as a comparison between the three catchment area slopes tested. They include all the percent retentions from 0 to 99%. Because the design charts have been created from a finite number of data points, the curves have been smoothed for practical use.

Figure 4.3 shows the cumulative percentage-retained curves for the 24.4-meter high, 4V:1H slope. The catchment area widths are plotted against the rockfall "cumulative percentages retained." In this example, a horizontal line is shown that denotes the 90th percentile. This line intersects the impact curve at a catchment area width of 4.3 meters. This means that 90% of the rocks impacted (initially hit the ground) within a 4.3-meter wide zone adjacent to the toe of the cut slope.

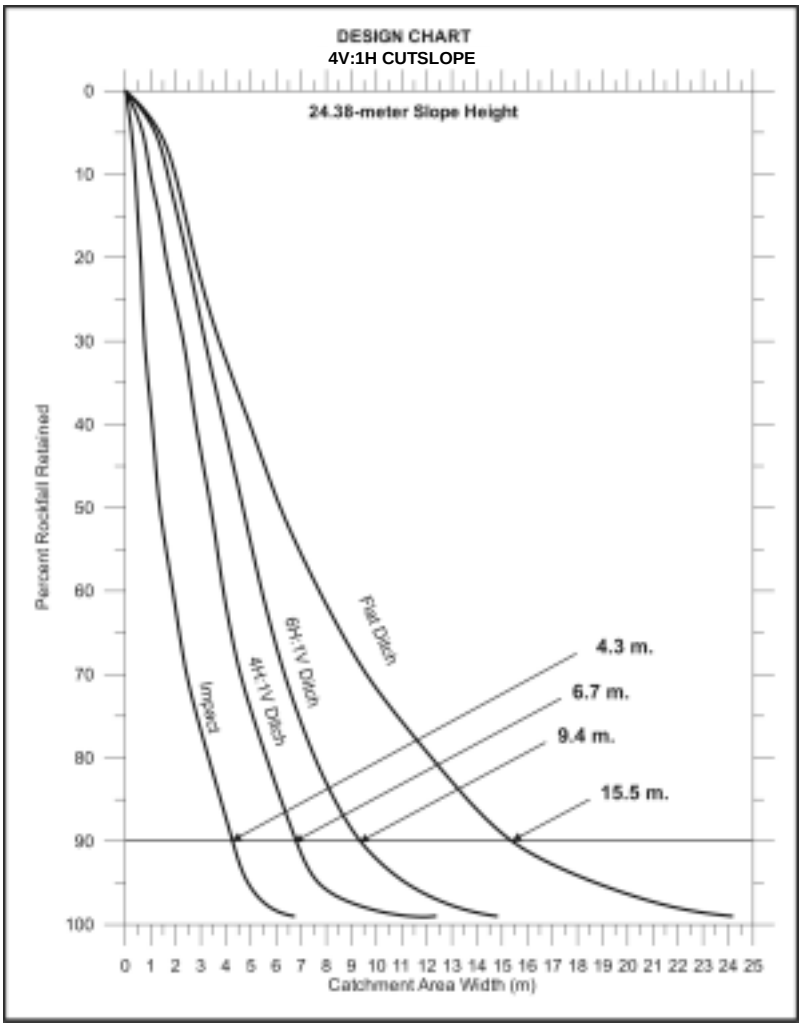


Figure 4.3: Cumulative percent retained for the 24.4 meter, 4V:1H slope

Following this 90th percentile line across, the intersection with the 1V:4H catchment area curve occurs at 6.7 meters; the intersection with the 1V:6H catchment area curve occurs at 9.4 meters; and the intersection with the flat bottom catchment area curve occurs at 15.5 meters – meaning 90% of all falling rocks had roll out distances less than or equal to these values. Using this approach, any combination of rockfall retained percentage and required catchment area width can be found for each of the catchment area configurations tested. The complete suite of design charts is presented in Chapter 5 (Figures 5.1 - 5.25).

4.4 STEP-BY-STEP DESIGN PROCEDURE

The following summarizes the step-by-step design procedure for dimensioning new rockfall catchment areas or evaluating existing catchment areas, using the developed design charts (Figures 5.1 - 5.25). Qualified, experienced rock slope engineering personnel should perform the overall rock slope design and catchment area dimensioning.

Step 1 - Establish overall design rock cut slope ratio based on overall rock slope stability.

Step 2 - Select critical rock cut slope design cross-section(s).

Step 3 - Select appropriate catchment area design chart, based on slope ratio and slope height.

Step 4 - When dimensioning new catchment areas, enter the appropriate slope design chart for a specified or desired percent rockfall retention and read off the required catchment area width, W, for the selected catchment area configuration(s), i.e., flat-bottom, 1V:6H or 1V:4H. This may need to be an iterative process, since wider catchment areas commonly result in higher rock cuts. It is also appropriate to perform a constructibility check to evaluate if the required catchment area width, W, will result in an overall rock excavation width sufficiently wide for excavation equipment to work the proposed cut slope to grade. Refer to Worked Example 1.

When evaluating the effectiveness of an existing catchment area, enter appropriate existing rock cut slope/catchment area slope design chart at existing catchment area width, W, and read off estimated percent rockfall retention. Refer to Worked Example 2.

Step 5 - When appropriate, perform benefit/cost comparison of alternate designs to select recommended final design. Refer to Worked Example 3.

The following worked examples illustrate the step-by-step design procedure and application of the design charts. See the Appendix G case study examples for more in-depth actual project application examples.

4.4.1 Worked Example 1 - Designing a New Catchment Area

Project Description: An existing section of highway in mountainous terrain is to be reconstructed as part of a safety improvement project. The project includes an approximate 1000-foot long rock slope consisting of basalt rock. The existing cut is 19.8 meters maximum height with slope ratio varying from near vertical to 3.33V:1H through the length of the cut. Natural ground slope behind the top of cut is approximately 1V:2H. The original construction was done in the 1950's when uncontrolled blasting was used, resulting in significant blast damage several feet into the slope, causing significant rockfall. Only a narrow 1.5-meter ditch width exists between the edge of pavement (EP) and base of rock slope. Two rockfall-caused accidents have occurred along the cut section during the past 5 years.

The design project manager has decided that construction of a rockfall catchment area is warranted. Agency policy on primary highways is to design catchment areas to provide 90% rockfall retention, whenever economically feasible.

Determine: Required catchment area width, W, to provide 90% rockfall retention.

Step 1 - Establish overall design rock cut slope ratio based on overall rock slope stability.

Agency geotechnical personnel recommend a design slope ratio of 4V:1H for overall slope stability. Agency policy is to use controlled blasting to improve overall stability and to minimize long-term rockfall.

Step 2 - Select critical rock cut slope design cross-section(s).

Plotting the 4V:1H slope on the roadway design cross-section, and assuming a cut widening in the 6.1 - 9.1 meter range to provide rockfall catchment, gives a maximum new cut slope height of approximately 24.4 meters.

Step 3 - Select the appropriate catchment area design chart based on slope ratio and slope height.

The Design Chart for 4V:1H Cut Slope, 24.4-meter Slope Height is selected. See Figure 4.4.

Step 4 - When dimensioning new catchment areas, enter appropriate slope design chart for a specified or desired percent rockfall retention and read off the required catchment area width, W, for desired catchment area slope(s), i.e., flat-bottom, 1V:6H or 1V:4H.

Entering the Figure 4.4 design chart at 90% rockfall retained and reading across to the various catchment area slope curves gives the following required catchment area widths, W:

Catchment Area Slope	Required Width W
Flat	15.5 meters
1V:6H	9.4 meters
1V:4H	6.7 meters

Agency policy is to use a 1V:6H sloped clear zone slope whenever possible. This gives a required catchment area width of 9.4 meters.

Perform the constructibility check. The Agency's controlled blasting specifications limit drilling lift heights to 12.2 meters. The 24.4-meter high cut excavation will require two excavation lifts. Examination of all cross-sections through the length of proposed cut shows that the 9.4-meter excavation width is wide enough to accommodate construction drilling and excavation equipment working the cut. Constructibility OK.

Design Recommendation: A rockfall catchment area width of 9.4 meters with a 1V:6H bottom slope is recommended for final design.

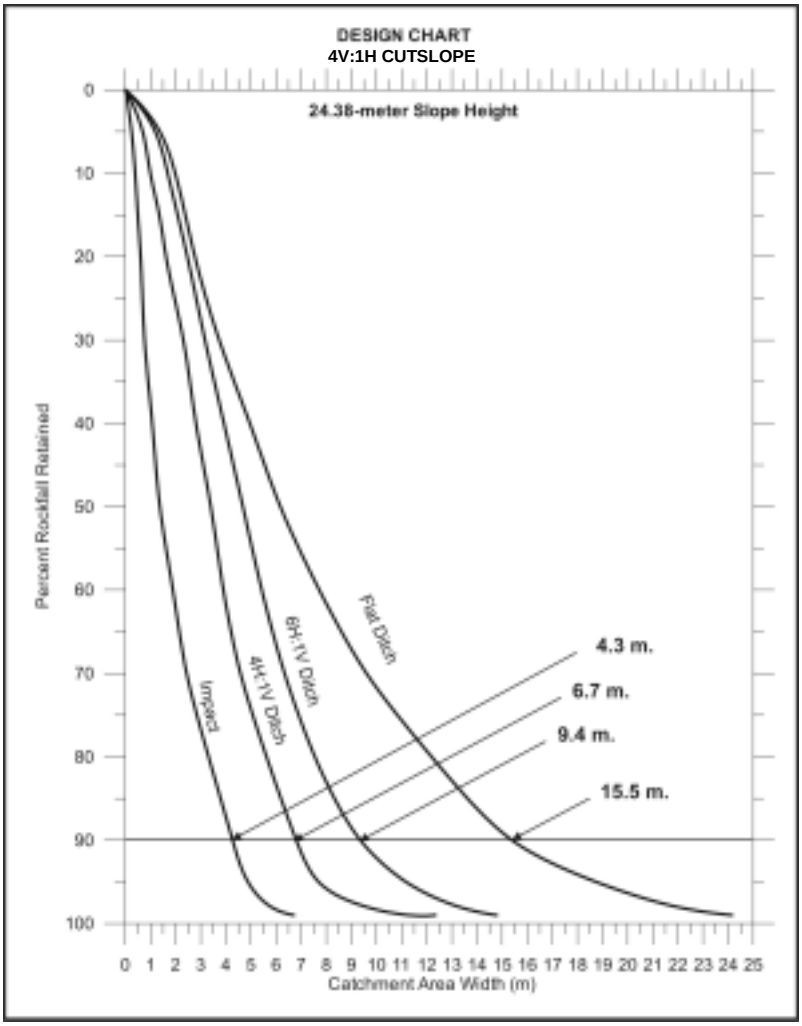


Figure 4.4: Design chart for 24.4-meter high, 4V:1H slope (Example 1)

4.4.2 Worked Example 2 - Evaluating an Existing Catchment Area

Using the cumulative percent retained design charts, the practitioner can also quickly evaluate the effectiveness of existing catchment areas adjacent to rock slopes. This is demonstrated in the following example.

Project Description: A 24.4-meter high, 152.4-meter long highway cut has a rockfall problem. The slope ratio is 4V:1H. A site visit reveals that a small portion of the cut length possesses the greatest hazard. Rockfalls appear to be generated primarily from the upper half of the cut. The existing catchment area width is constant at 7.6 meters, and most catchment area sections slope toward the toe of slope at approximately 1V:4H. However, the catchment area slope changes to 1V:6H or flatter in the problem area.

Determine: Estimate the percent rockfall retention provided by the existing catchment area and the most cost-effective way to increase the catchment area effectiveness.

Finding a catchment area width of 7.6 meters in the Figure 4.5 design chart. Following it up to the 1V:6H curve indicates that only 80% of the rocks falling into this section of the catchment area can be expected to be retained. Approximately 20% of rocks are allowed to reach the roadway. Alternately, 95% of rockfalls are retained in a catchment area of the same width with a 1V:4H catchment area slope, an increase in catchment of 15%.

Design Recommendation: Recommending a simple re-grading of the catchment area slope from the existing 1V:6H to 1V:4H significantly increases catchment area effectiveness and enhances public safety for a relatively small investment.

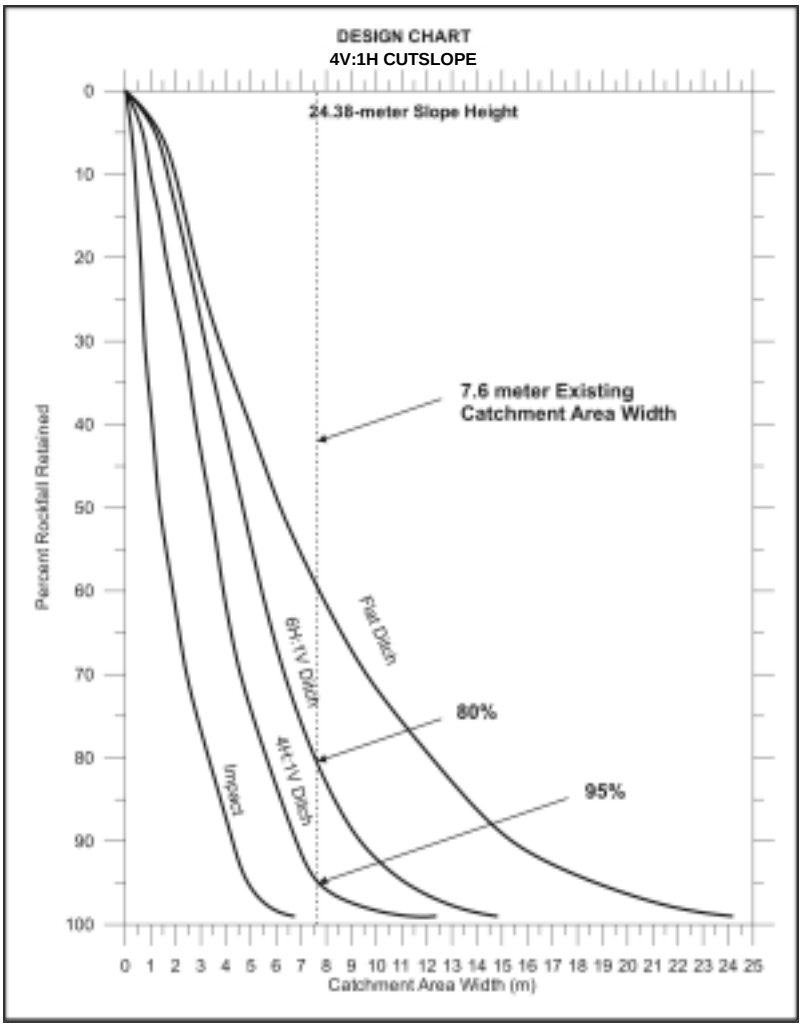


Figure 4.5: Design chart for 24.4-meter high, 4V:1H slope (Example 2)

Using the research data in this manner demonstrates a method for evaluating existing slopes. In a real highway cut, rocks could begin their fall from anywhere on the slope. Rockfalls may only initiate from one or two zones or from random locations scattered throughout the slope. In addition, catchment area geometry may vary appreciably throughout a cut section. Because of this, a higher or lower percentage of rocks may be retained than the design charts estimate. Obviously, an application of this sort requires the user to make a qualitative assessment of the slope. Site-specific characteristics must be considered if a realistic evaluation of catchment area effectiveness is to be obtained. Experienced rock slope engineering personnel should make these assessments.

4.4.3 Worked Example 3 - Benefit/Cost Comparison

On a national and international level, the problem of rockfall is significant, particularly in mountainous states/countries. Rockfall problems are typically dealt with using either a strategy of elimination or reduction. The goal of 100 % (zero tolerance) rockfall hazard elimination, while desirable, is difficult to attain. A limited budget, as well as a desire to limit the effects of highway construction on adjacent properties and the environment, usually precludes directing sufficient resources toward the total 100% elimination of a rockfall problem.

A more practical approach is to reduce the potential for rock on the road along as many miles of roadway as possible using the budget available. Hazard reduction along many miles of roadway provides a more consistent benefit than if only a short section of a given roadway had its entire rockfall problem eliminated for the same cost.

An informed decision must be made regarding hazard reduction relative to cost. The following generic example illustrates such a benefit/cost approach.

Project Description: Rockfall on the highway has been a serious problem along the high side of a 121.9-meter long through cut for many years. A design cross section of the site is shown in Figure 4.6. No catchment area was provided during the original construction. The agency would like to reduce the rockfall hazard but is unsure what level of improvement can be obtained for a reasonable investment.

Determine: Perform a benefit/cost comparison of alternate catchment area widths.

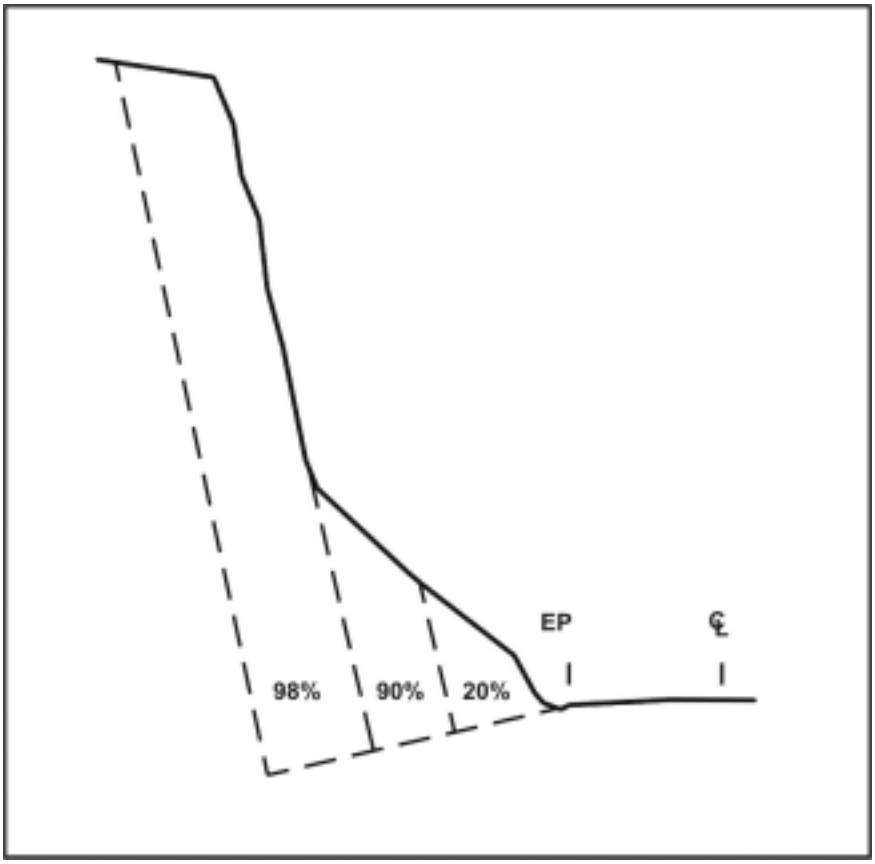
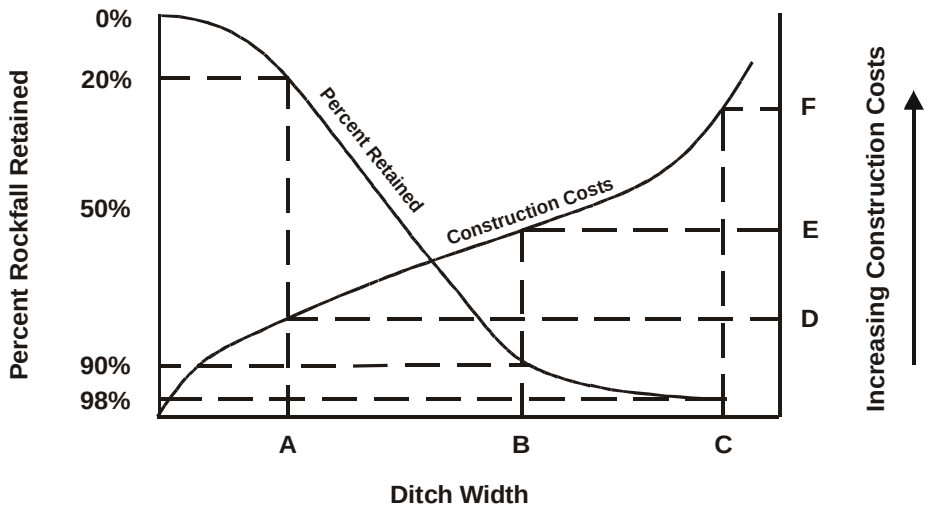


Figure 4.6: Slope cross-sections; benefit/cost comparison (Example 3)

Rockfall is possible from anywhere on the slope. Because of the shape of the slope (see Figure 4.6), excavation quantities will increase in a non-linear fashion as the catchment area width is increased. Therefore, the cost of a small amount of increased width is low initially, since the cut height would be low. As excavation of the entire slope is approached, the cost of each increment of catchment area width becomes higher due to the increasing cut height. For this example, the catchment area widths associated with providing 20%, 90% and 98 % rockfall retention are shown on Figure 4.6.

The results of this benefit/cost analysis can also be illustrated graphically as shown on Figure 4.7. Different excavation costs based on catchment area width are plotted against the percentage of rock that will be retained for a specific slope height and catchment area width. Using this method enables different options to be discussed in the decision making process. Both the benefits and costs can be clearly shown, and a prudent decision on the allocation of funds can be made. In this example, the cost of improvement between 20% and 90% rockfall retention is about the same as it is between 90% and 98%, i.e., increasing the percent retention the additional 8% from 90% to 98% nearly doubles the construction cost. Further, the additional catchment area width required to provide the additional 8% retention from 90% to 98% approximately triples the cut height, causing a far more severe impact to adjacent properties and the environment.



Construction Cost = f (Excavation Costs, R.O.W. Costs / Ft. of Width))

Increased Width from A to B increases Percent Rockfall Retained by 70% and increases cost from D to E.

For the same increase in Cost from E to F, Percent Rockfall Retained is increased by only 8%.

Figure 4.7: Example benefit/cost comparison (Example 3)

Design Recommendation: Based on this benefit/cost comparison, a catchment area width that provides 90% rockfall containment is selected.

4.4.4 Project Case Study Application Examples

Seven actual project case study examples are provided to further illustrate the practical application and ease of use of the rockfall catchment area design charts to dimension rockfall catchment areas. Several of the participating state and FHWA Technical Advisory Committee members provided case studies of actual projects where the new design criteria and design charts have been used, or where site specific rockfall testing was conducted to aid in the rockfall mitigation design. The case studies also illustrate the type of benefit/cost comparisons and experienced geotechnical judgment applied to arrive at final design recommendations.

Arizona, California, Federal Highway Administration - Central Federal Lands Highway

Division (FHWA-CFLHD), New York, Oregon, Washington, and Wyoming submitted project case study examples. These are included in Appendix G in their entirety.

The **Arizona** project involves highway widening of a portion of US 191 near the town of Morenci, AZ. Existing cutslopes generate substantial rockfall onto the road during rainstorms. Interesting features of this project include the use of actual rock rolling from one of the cutslopes during construction, combined with computer simulation using CRSP, to determine the extent of draped slope mesh required. This was necessitated by a roadway design decision to reduce the rockfall catchment area width and depth below that called for by the Ritchie criteria. ADOT also provides a comparison to the new design charts presented in this design guide.

The **California** project involves a curve correction along State Route 101 near the Monterey and San Benito county line by Caltrans District 5. The California project illustrates benefits of the new design charts to estimate percent rockfall retention and use of a flatter slope catchment versus a very deep Ritchie ditch.

The **New York** (Corning Bypass) project involves highway widening on State Route 17. This project utilized site specific rock rolling, combined with computer simulation, to determine the required height of a rockfall catchment fence, when roadway design changes reduced the available rockfall catchment area width.

The **Oregon** project is a cut widening being done as part of a roadway alignment improvement project on US 26 in the Mt. Hood National Forest.

The **FHWA-CFLHD** project includes a cut widening for a realignment of New Mexico Forest Highway, Route 45 near Sunspot, New Mexico.

The Oregon and FHWA-CFLHD examples are projects where the rockfall catchment areas had already been designed prior to the new design charts becoming available. These case studies illustrate “after the fact” catchment area width and cost comparisons of the as-designed catchment area widths, based on the Ritchie criteria, to the widths given by the new design charts.

The **Washington** project involves highway widening on a project on SR-243 in eastern Washington. The Washington case study compares use of the new design charts to current WSDOT rockfall ditch criteria (modified after Ritchie) for dimensioning new rockfall catchment areas and illustrates benefits of the new design charts. The Washington case study also illustrates the importance and benefit of paying attention to constructibility considerations as part of design.

The **Wyoming** project illustrates use of the new design charts to dimension a new rockfall catchment area constructed as part of a highway-widening project on US 26-89 in the Snake River Canyon.

Special thanks to Bill Hurguy and John Lawson (Arizona DOT), John Duffy (Caltrans), Barry Siel and Sam Holder (FHWA-CFLHD), Alex Yatsevitch (New York DOT) and Mike Vierling (New York Thruway Authority), Don Turner (Oregon DOT), Steve Lowell (Washington State DOT), and Mark Falk (Wyoming DOT) for their extra time and effort preparing these case study submittals.

5.0 COMPLETE SUITE OF DESIGN CHARTS

The Rockfall Catchment Area Design Guide is a current state of the practice reference for sizing rockfall catchment areas for 12.2 to 24.4 meter high rock cut slopes.

With the newly developed design charts, practitioners can more quickly and easily dimension new rockfall catchment areas or evaluate the effectiveness of existing catchment areas for rock cut slopes in the 12.2- to 24.4-meter height range. Practitioners will also be able to design and construct catchment areas that will have a predictable rockfall retention capacity.

5.1 USE OF DESIGN CHARTS

The Cumulative Percent Rockfall Retained Design Charts are included here for the vertical, 4V:1H, 2V:1H, 1.33V:1H, and 1V:1H cut slopes (Figures 5.1 - 5.25). These charts are derived from the data in the percent retention graphs for a specific slope height. The design charts are presented in a handy format that allows rapid evaluation of catchment area widths as a comparison between the three catchment area slopes tested.

To facilitate practical design usage, the field measured catchment area impact and roll out <u>slope</u> distances have been converted to <u>horizontal</u> catchment area width on the design charts.

The design charts are presented in a form that can be used to rapidly size rockfall catchment areas that satisfy specific rock catching/retention requirements. Based on slope angle, slope height and catchment area slope, the design charts estimate the required catchment area widths that will retain percentages of rockfall, ranging from 0 to 99 percent.

As a further design aid, the design charts include a handy “Quick Reference” table, listing the rockfall catchment width, W, required to provide 50%, 75%, 80%, 85%, 90%, 95% and 99% rockfall retention.

While the design charts have been developed for standard slope ratios (i.e., vertical, 4V:1H, 2V:1H, 1.33V:1H, 1V:1H) for practical design use, non-geotechnical users are cautioned that this should not be taken to imply that rock slopes are always designed to these standard slope ratios. Proper rock slope design requires designing the slope ratio (or angle) based upon the orientation of the predominant structural discontinuities that will control the slope’s overall stability. In many instances, this will be a slope ratio (or angle) different from those represented on the design charts. When this occurs, interpolation between charts can be used to determine the required catchment width. To facilitate this, the following table of slope ratio/slope angle equivalents is provided for easy reference:

Table 5.1: Slope ratio/slope angle equivalents

Decimal Slope Ratio	Fraction Slope Ratio	Slope Angle (Degrees)
Vertical	Vertical	90
4V:1H	4 to 1	76
2V:1H	2 to 1	63
1.33V:1H	$1^1/_3$ to 1	53
1V:1H	1 to 1	45

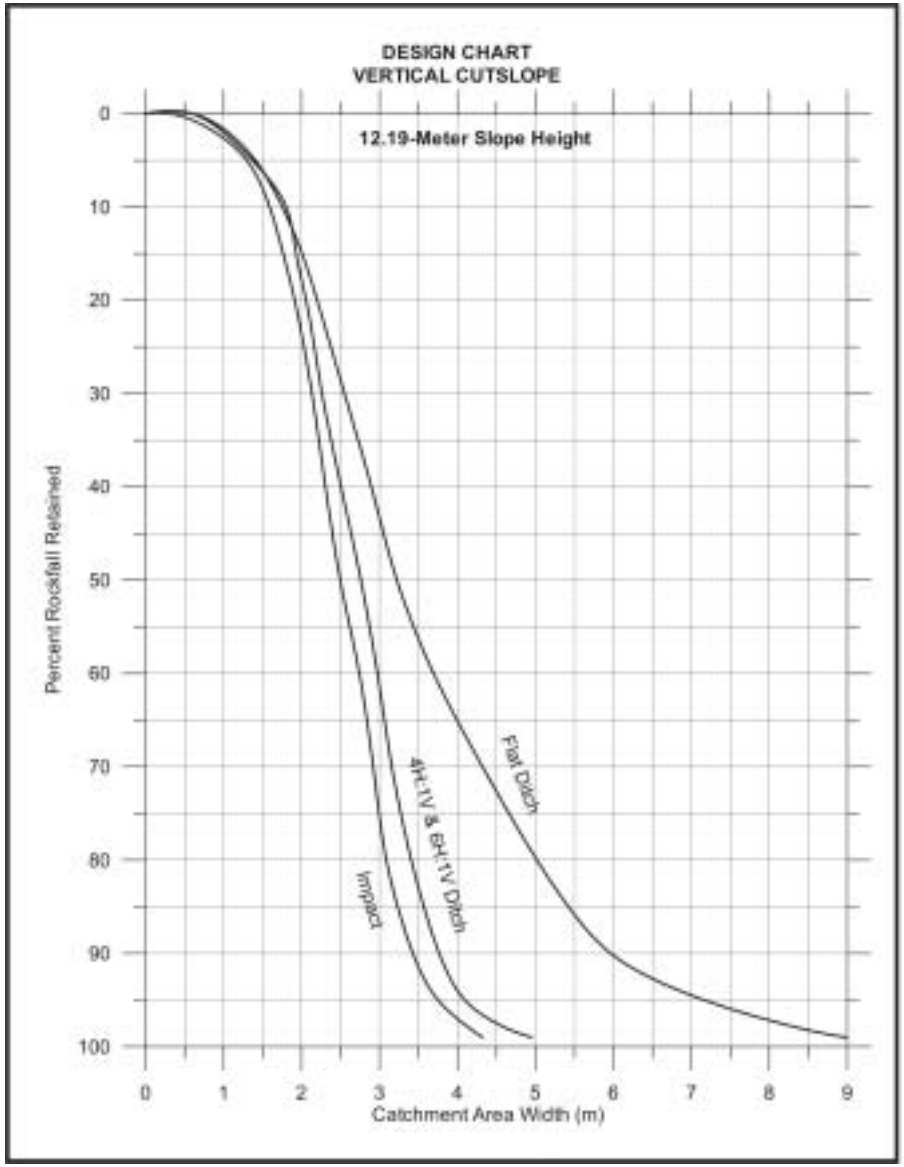
5.2 DESIGN CHART LIMITATIONS

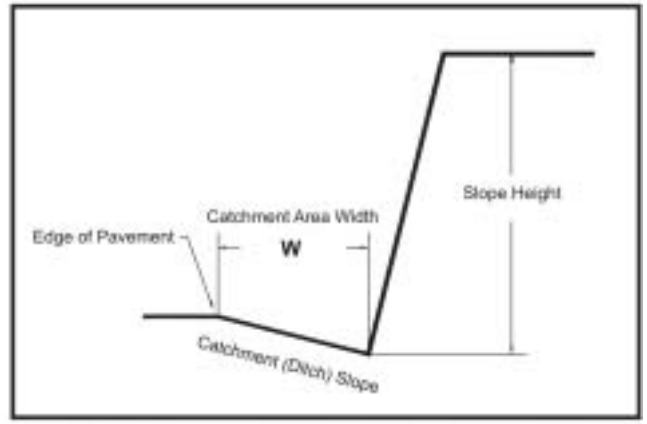
It is important to note that the design charts developed by this research effort are considered to be conservative. In general, the rock type at the Krueger Quarry test site is hard durable basalt that rebounds well after impact and rolls well. Slopes comprised of softer rocks would tend to have lesser impact and roll out distances. In addition, all the rocks started at the top of the slope for each slope height tested. In reality, rocks can and do fall from all portions of a slope. The result is that rocks that initiate from heights less than the maximum possible may not require the entire catchment area width to achieve the specified containment.

Although this was an extensive research effort, it should be kept in mind that different weather, slope and catchment area conditions, rock qualities and rockfall generation sources that vary significantly from those present at the research site may result in different behavior. **It is important to have experienced rock slope engineering personnel (engineering geologists/ geotechnical engineers) involved in designing rock slope catchment areas. They should evaluate and decide when it is appropriate to directly use the figures in the enclosed design charts or to modify the catchment area dimensions shown.**

Because there are many different combinations of slopes, catchment areas, rock types and maintenance practices, it is possible for rockfall to occur where the result exceeds the maximum-recorded value documented in this report. With any data set, outliers are possible. For that reason, the highest retention design chart represents 99% retention, not 100%.

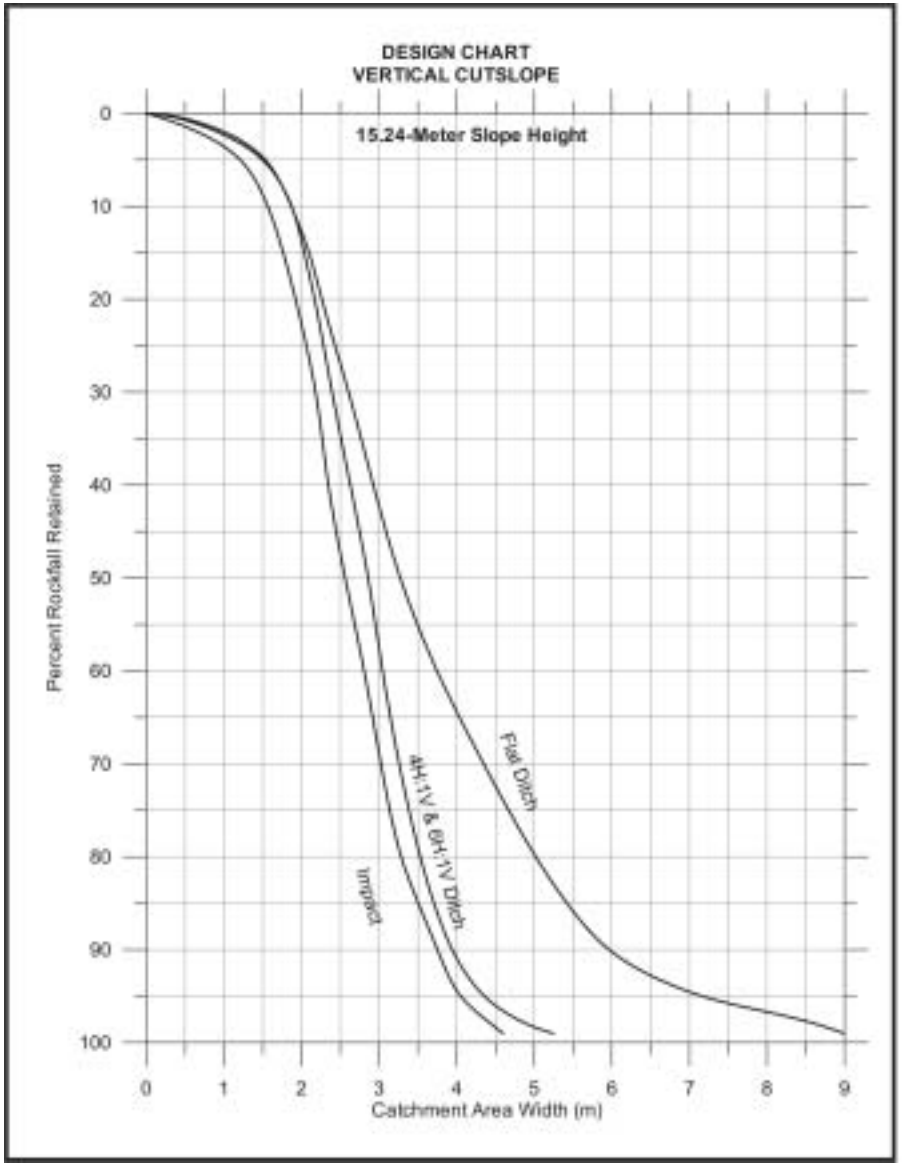
In a real highway cut, rocks could begin their fall from anywhere on the slope. Rockfalls may initiate from one or two zones or from random locations scattered throughout the slope. In addition, catchment area geometry may vary appreciably throughout a cut section. Because of these factors, a higher or lower percentage of rocks may be retained than the design charts estimate. Obviously, an application of this sort requires the user to make a qualitative assessment of the slope. Site-specific characteristics must be considered if a realistic evaluation of catchment area effectiveness is to be obtained. **Experienced rock slope engineering personnel should make these assessments.**

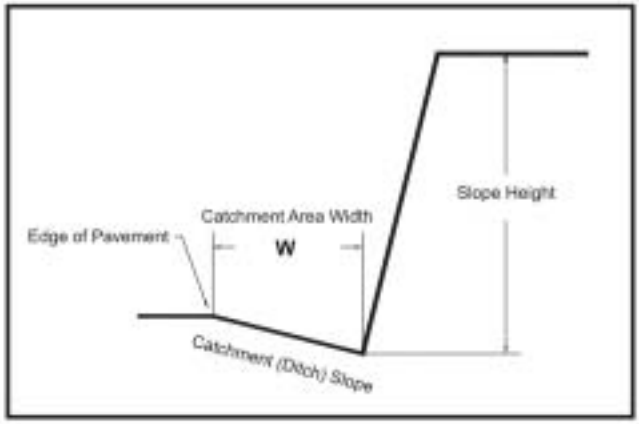




Quick Reference - 12-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	2.5	2.8	2.8	3.2
75%	3.0	3.3	3.3	4.6
80%	3.1	3.5	3.5	5.0
85%	3.3	3.5	3.5	5.5
90%	3.6	3.8	3.8	6.0
95%	3.7	4.1	4.1	7.2
99%	4.3	5.0	5.1	9.0

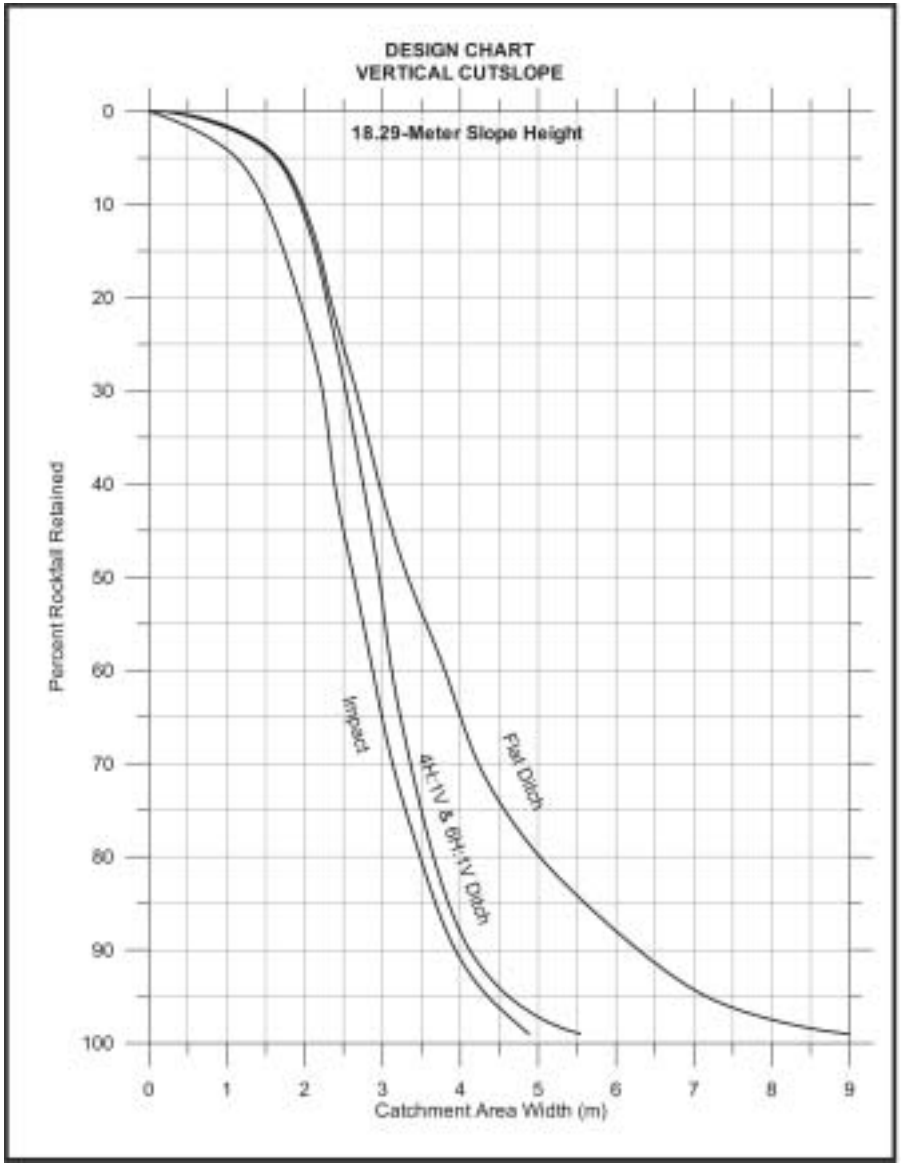
Figure 5.1: Design chart for 12.2-meter high vertical cutslopes

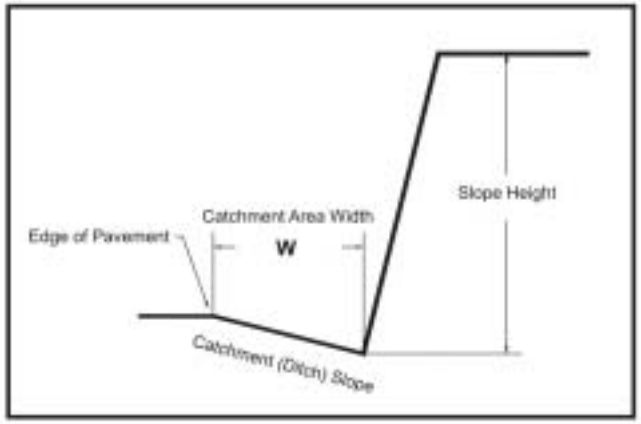




Quick Reference - 15-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	2.6	2.9	2.9	3.3
75%	3.2	3.4	3.4	4.6
80%	3.3	3.6	3.6	5.0
85%	3.5	3.8	3.8	5.5
90%	3.8	3.9	3.9	6.1
95%	4.1	4.4	4.4	7.2
99%	4.6	5.2	5.4	9.0

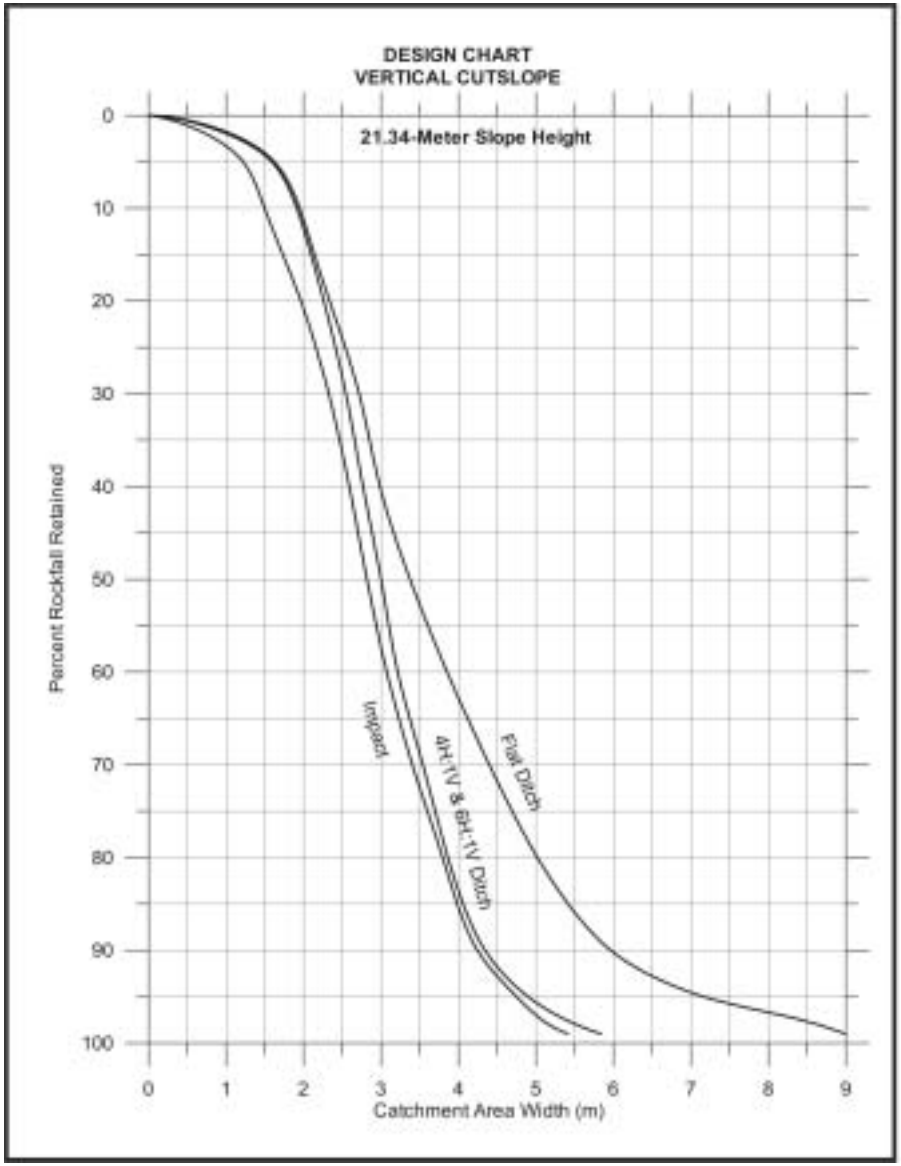
Figure 5.2: Design chart for 15.2-meter high vertical cutslopes

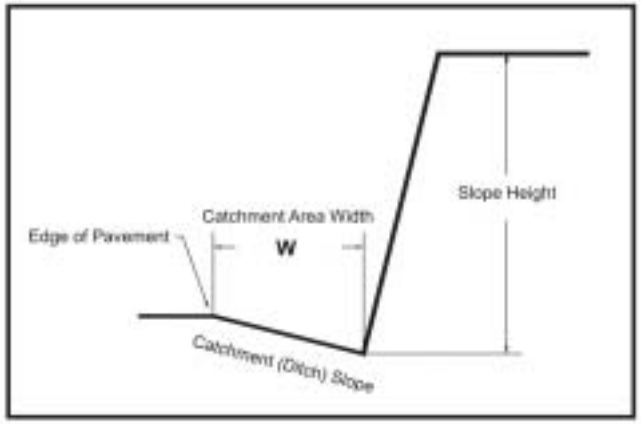




Quick Reference - 18-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	2.6	3.0	3.0	3.3
75%	3.3	3.5	3.5	4.6
80%	3.5	3.7	3.7	5.0
85%	3.7	3.8	3.8	5.6
90%	3.9	4.1	4.1	6.3
95%	4.4	4.6	4.6	7.2
99%	4.9	5.5	5.7	9.0

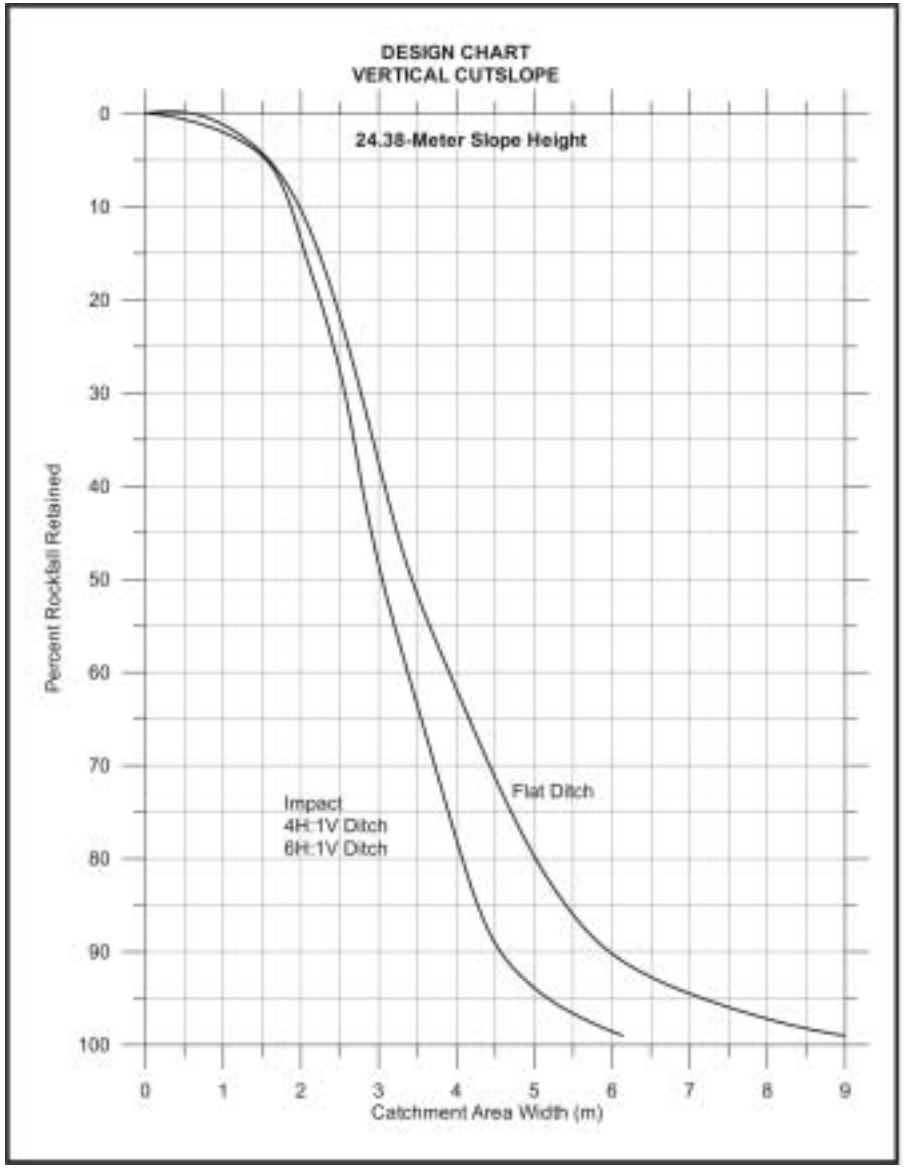
Figure 5.3: Design chart for 18.3-meter high vertical cutslopes

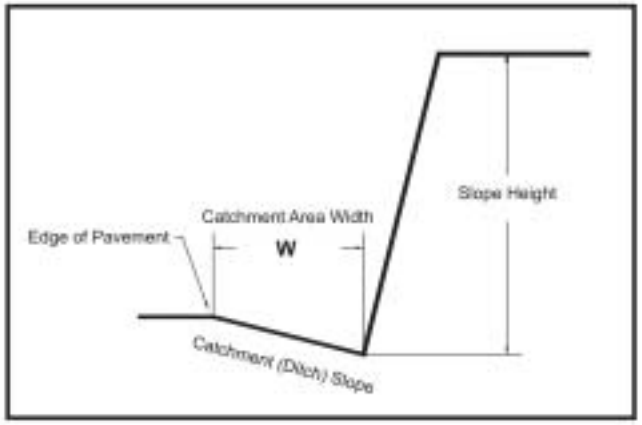




Quick Reference - 21-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	2.8	3.0	3.0	3.4
75%	3.6	3.7	3.7	4.6
80%	3.8	3.9	3.9	5.0
85%	4.0	4.1	4.1	5.4
90%	4.2	4.3	4.3	6.0
95%	4.8	4.9	4.9	7.2
99%	5.5	5.8	5.9	9.0

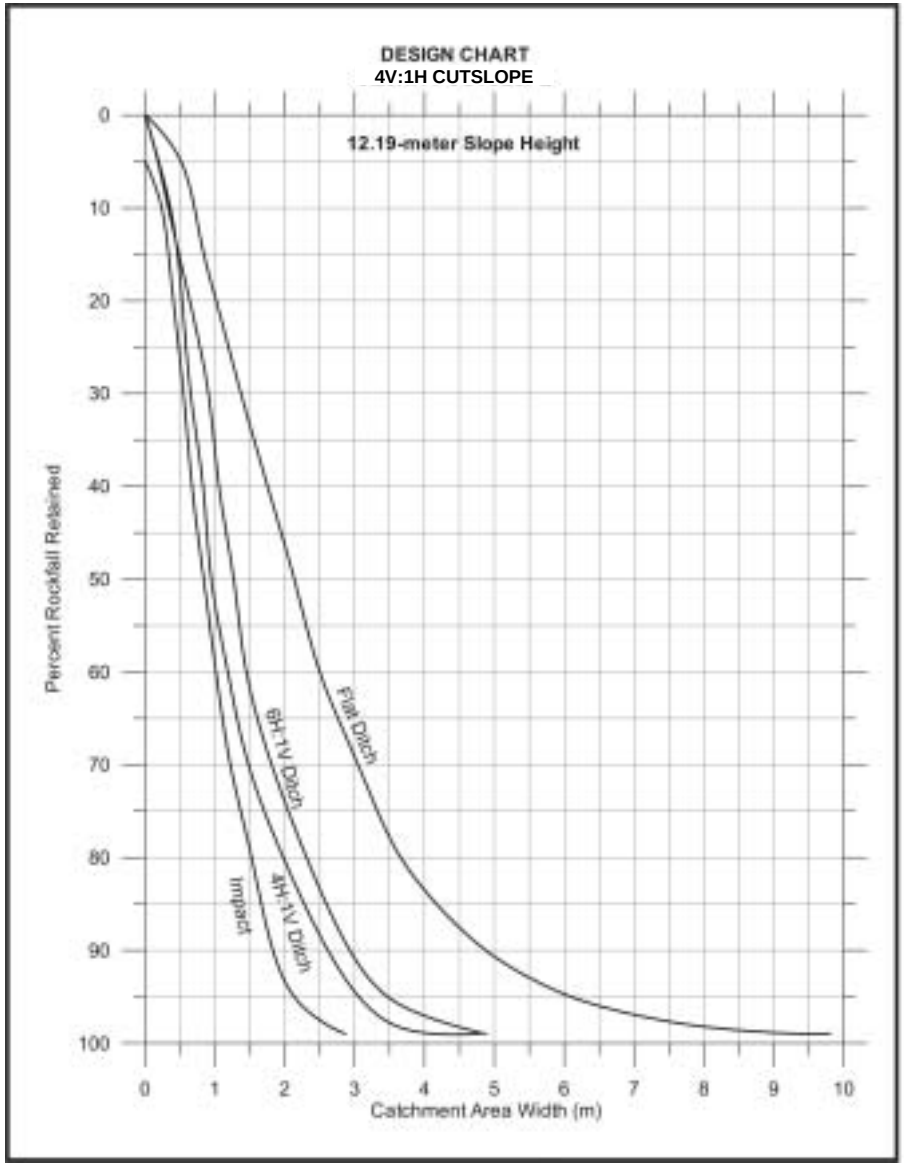
Figure 5.4: Design chart for 21.3-meter high vertical cutslopes

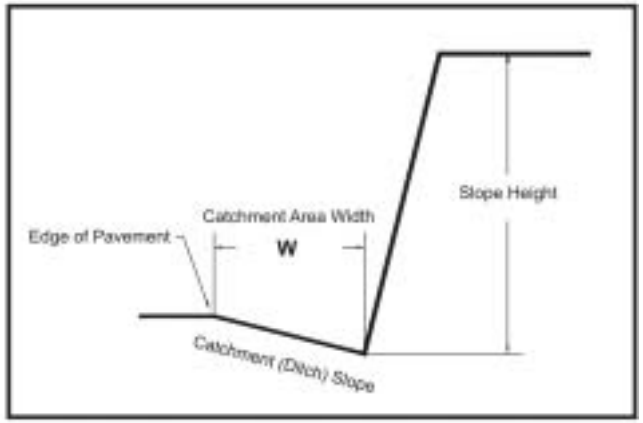




Quick Reference - 24-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	3.0	3.0	3.0	3.4
75%	3.9	3.9	3.9	4.7
80%	4.1	4.1	4.1	5.0
85%	4.3	4.3	4.3	5.4
90%	4.6	4.6	4.6	6.0
95%	5.2	5.2	5.2	7.2
99%	6.1	6.1	6.1	9.0

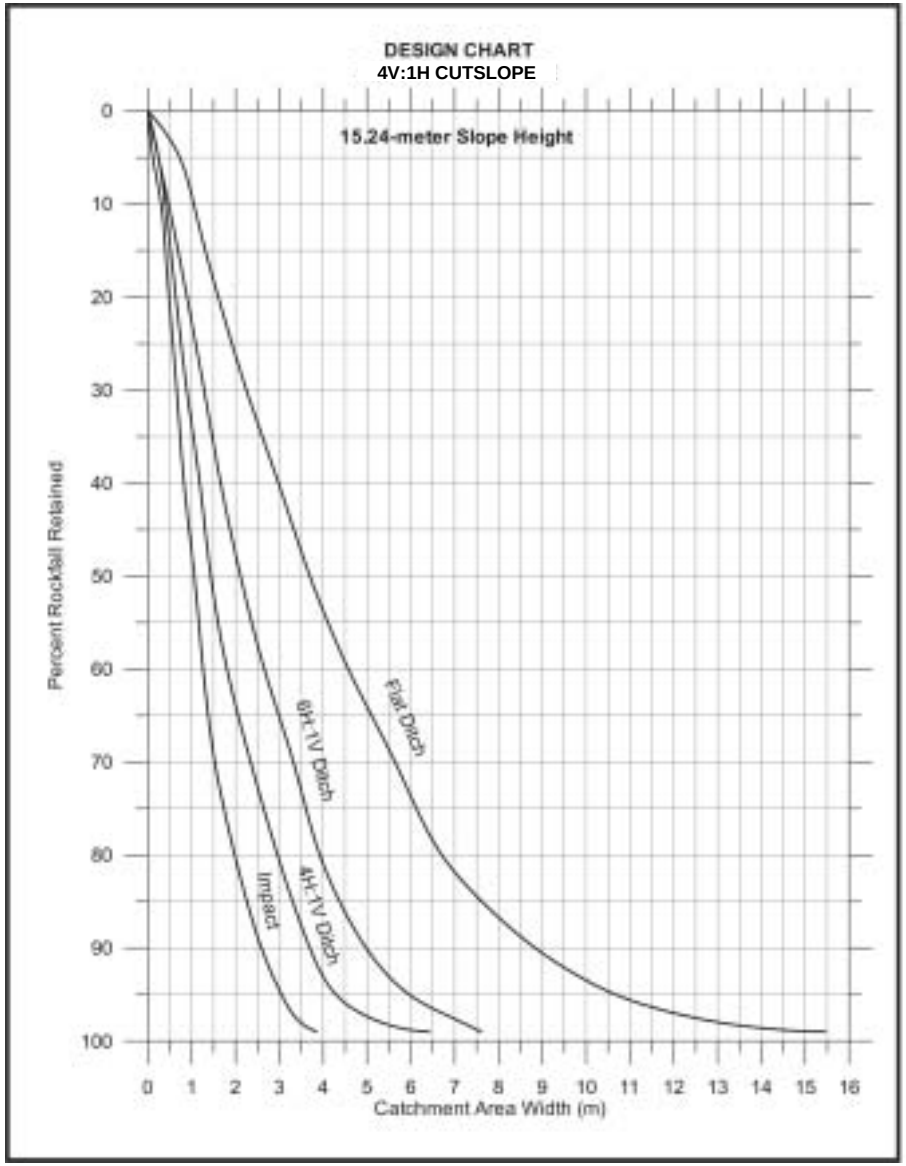
Figure 5.5: Design chart for 24.4-meter high vertical cutslopes

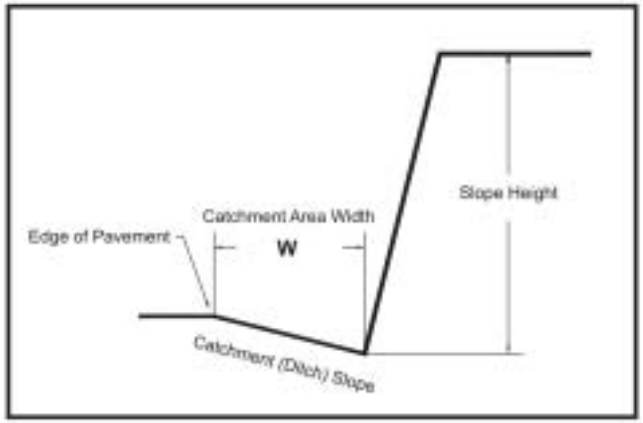




Quick Reference - 12-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.8	0.9	1.3	2.1
75%	1.4	1.8	2.0	3.4
80%	1.5	2.1	2.3	3.7
85%	1.8	2.3	2.5	4.3
90%	1.8	2.7	2.9	4.9
95%	2.1	3.1	3.5	6.1
99%	2.9	4.8	4.9	9.8

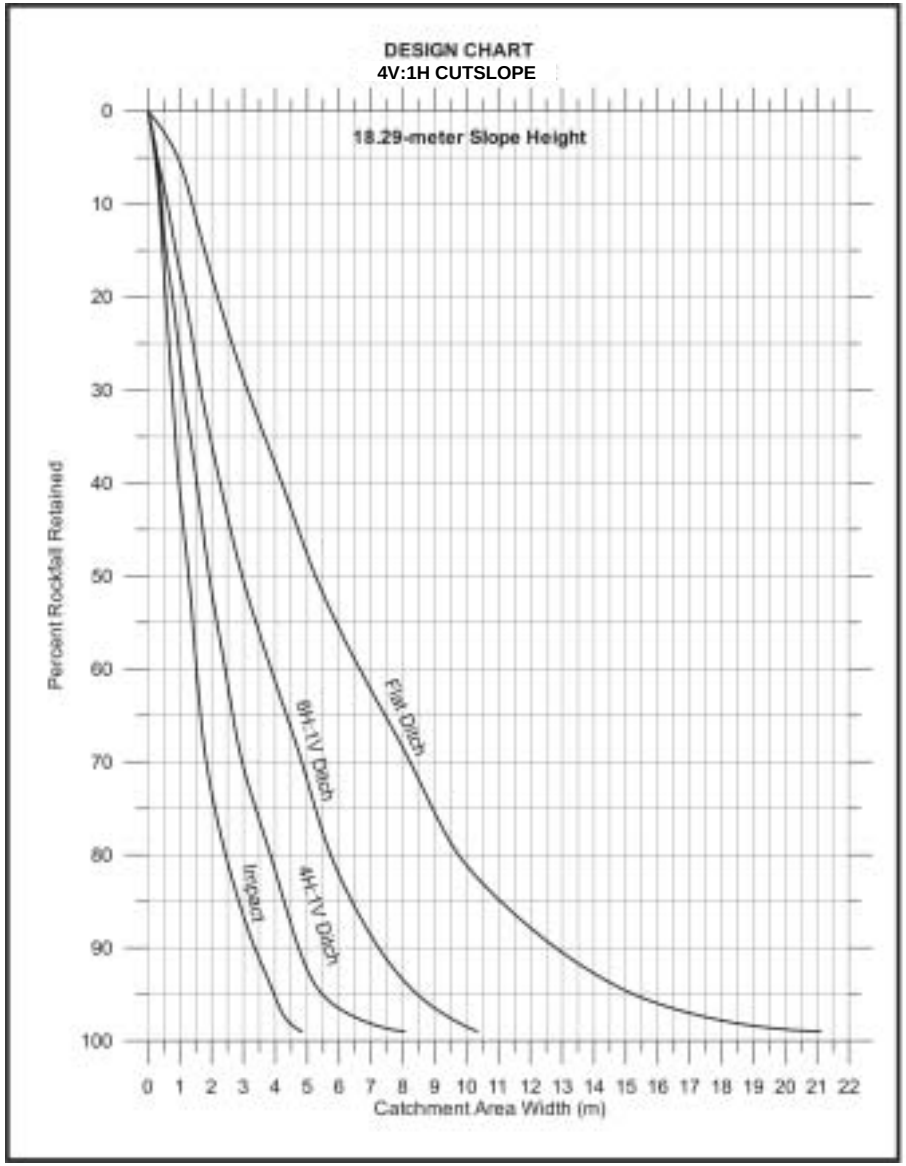
Figure 5.6: Design chart for 12.2-meter high 4V:1H cutslopes

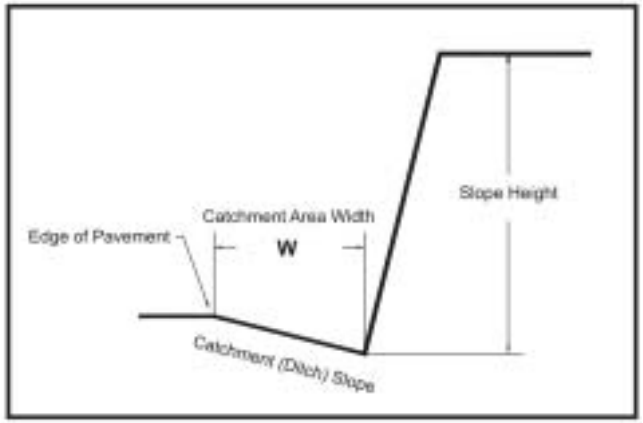




Quick Reference - 15-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.1	1.4	2.1	3.7
75%	1.8	2.6	3.6	6.2
80%	2.0	3.0	4.0	6.7
85%	2.3	3.3	4.5	7.5
90%	2.5	3.7	5.1	8.8
95%	3.0	4.3	6.0	10.7
99%	3.8	6.4	7.6	15.5

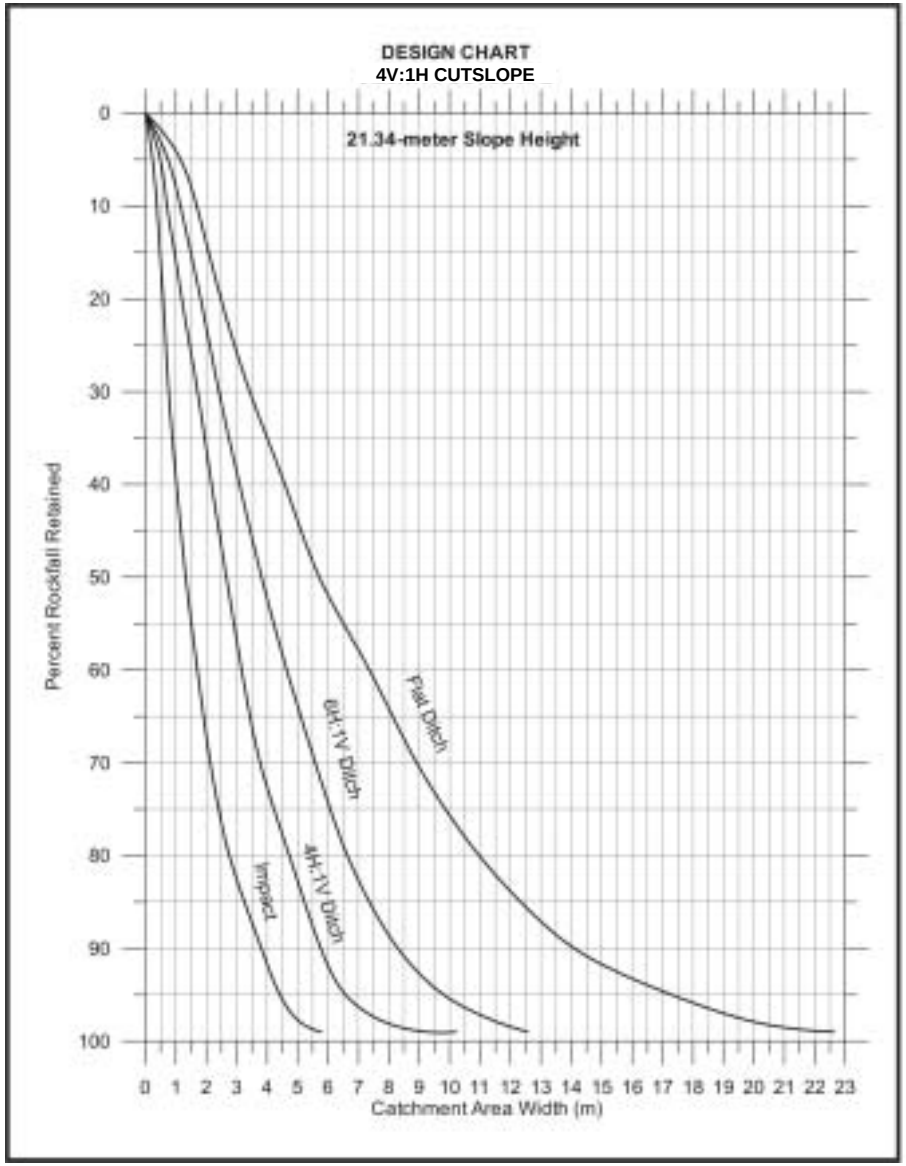
Figure 5.7: Design chart for 15.2-meter high 4V:1H cutslopes

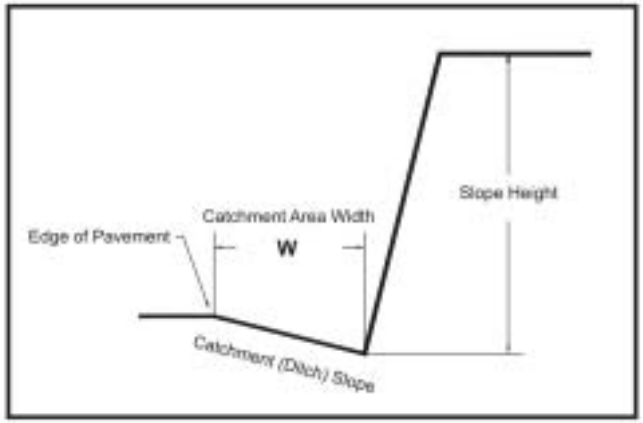




Quick Reference - 18-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.3	1.9	3.0	5.3
75%	2.1	3.4	5.3	9.0
80%	2.4	3.8	5.7	9.8
85%	2.8	4.3	6.5	11.0
90%	3.4	4.7	7.2	12.8
95%	4.0	5.5	8.4	15.2
99%	4.8	8.1	10.3	21.1

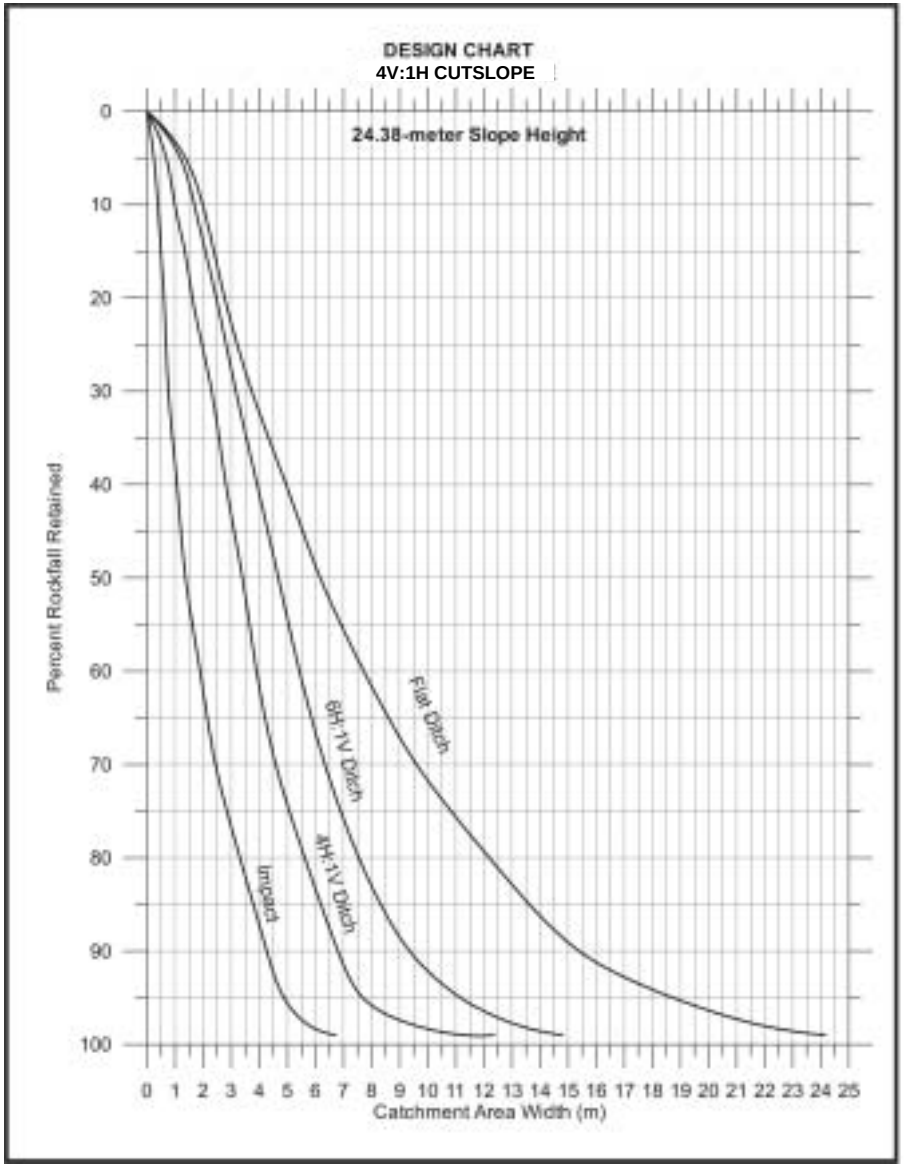
Figure 5.8: Design chart for 18.3-meter high 4V:1H cutslopes

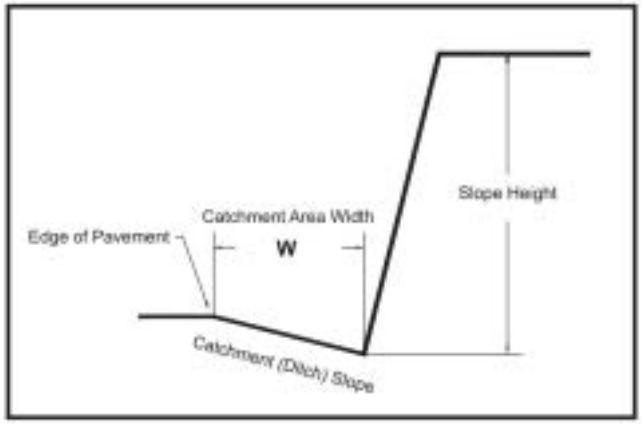




Quick Reference - 21-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.3	2.7	3.8	5.7
75%	2.5	4.3	6.1	9.9
80%	2.8	4.7	6.6	11.0
85%	3.3	5.3	7.3	12.3
90%	3.8	5.8	8.3	14.1
95%	4.5	6.6	9.8	17.0
99%	5.8	10.2	12.6	22.6

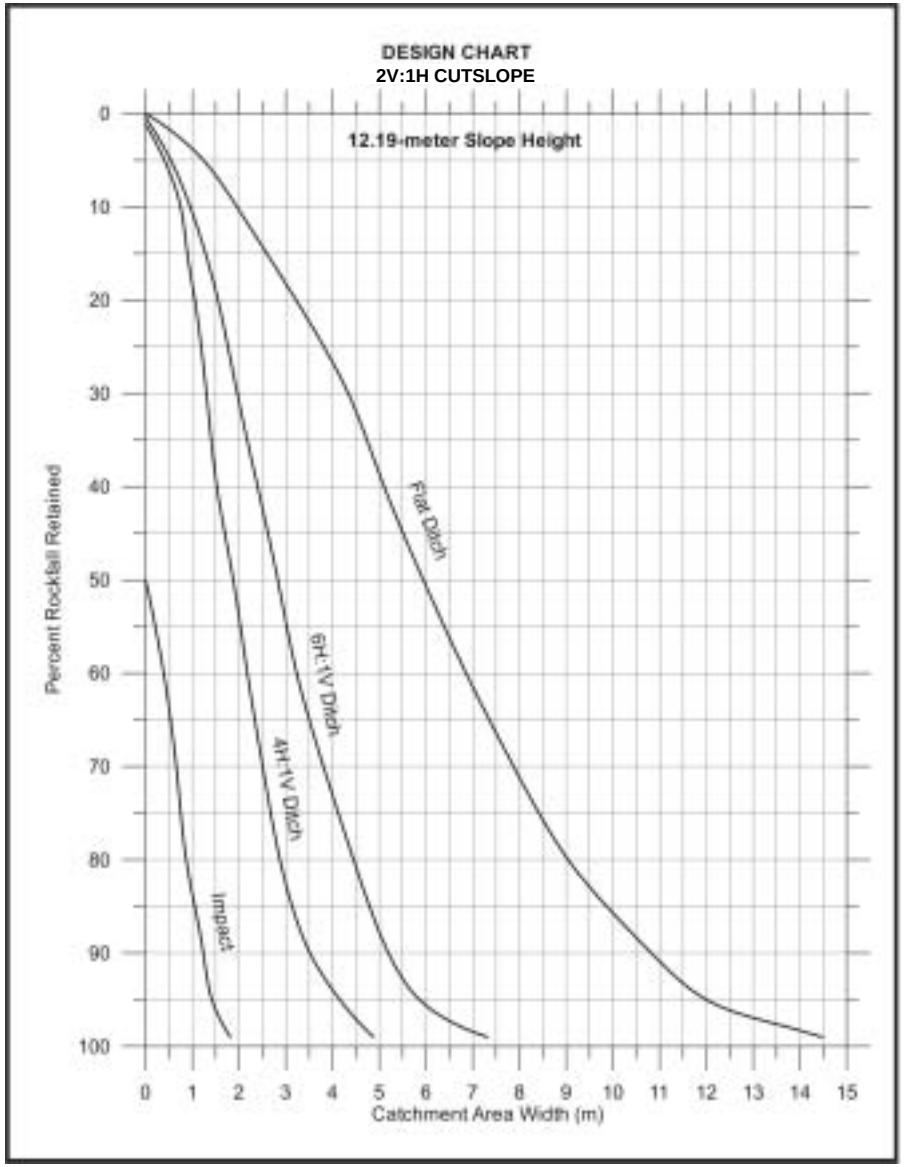
Figure 5.9: Design chart for 21.3-meter high 4V:1H cutslopes

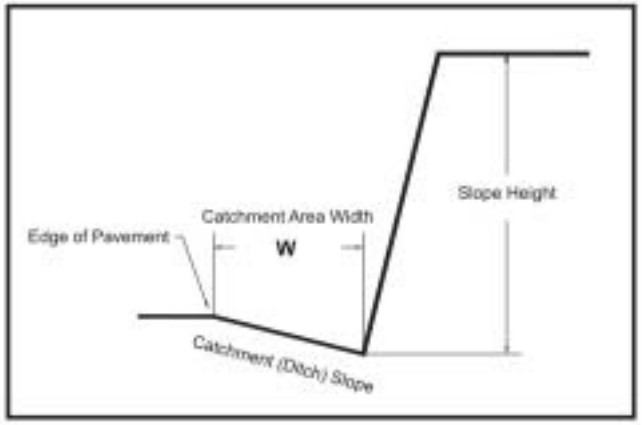




Quick Reference - 24-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.4	3.4	4.7	6.2
75%	2.7	5.1	6.9	10.9
80%	3.0	5.6	7.5	12.2
85%	3.8	6.3	8.3	13.5
90%	4.3	6.8	9.4	15.4
95%	4.9	7.7	11.2	18.8
99%	6.7	12.3	14.8	24.2

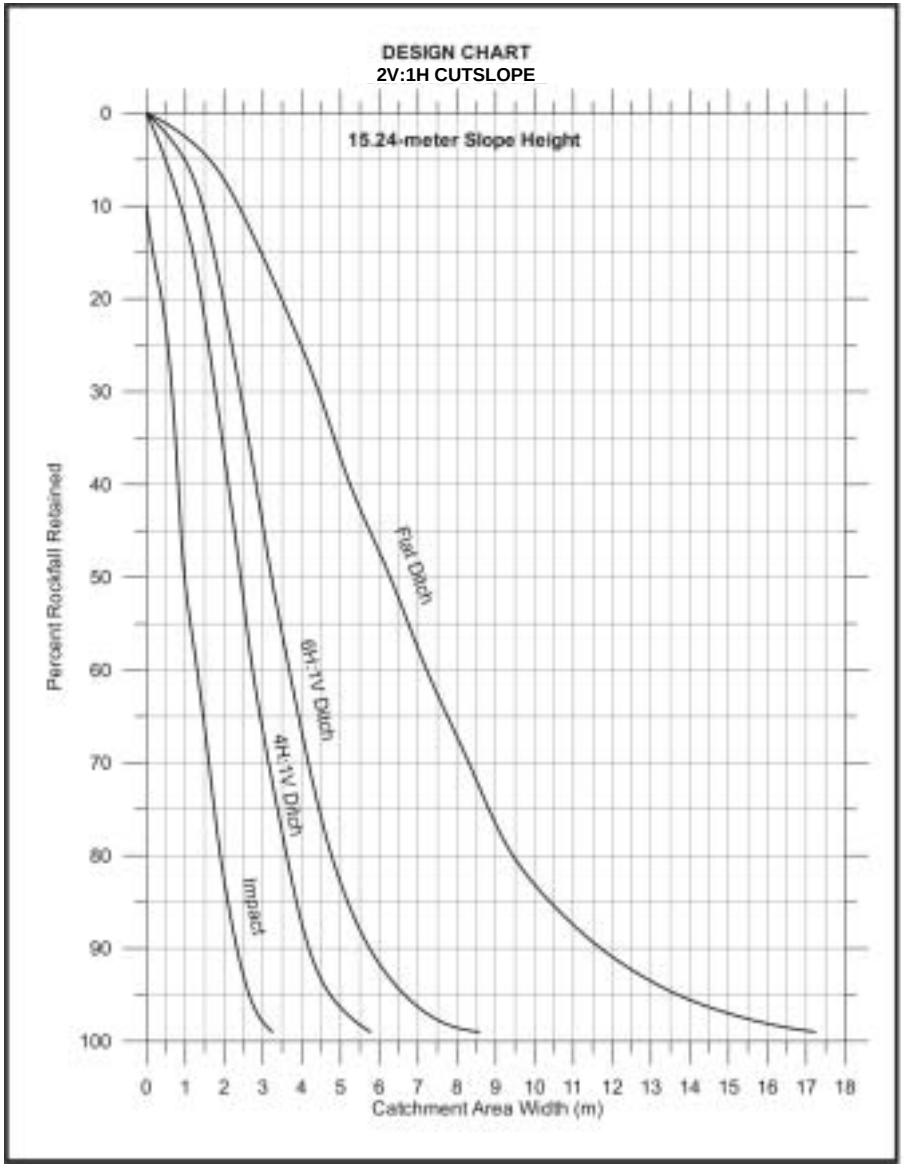
Figure 5.10: Design chart for 24.4-meter high 4V:1H cutslopes

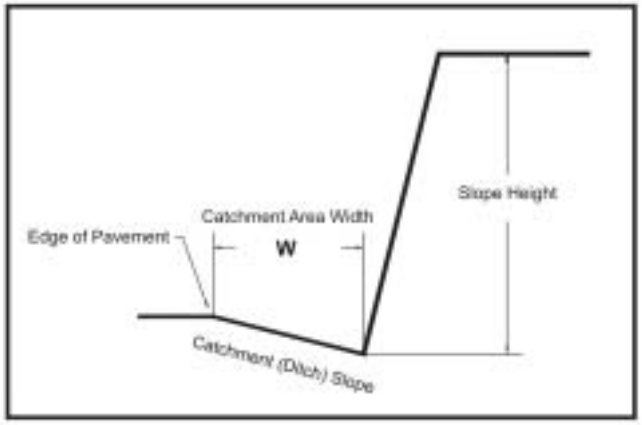




Quick Reference - 12-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	W (m)	W (m)	W (m)
50%	0.0	1.9	2.8	5.9
75%	0.8	2.7	4.1	8.5
80%	0.9	2.9	4.5	9.0
85%	1.0	3.3	4.8	9.8
90%	1.2	3.5	5.2	10.8
95%	1.4	4.3	5.9	12.0
99%	1.8	4.9	7.3	14.5

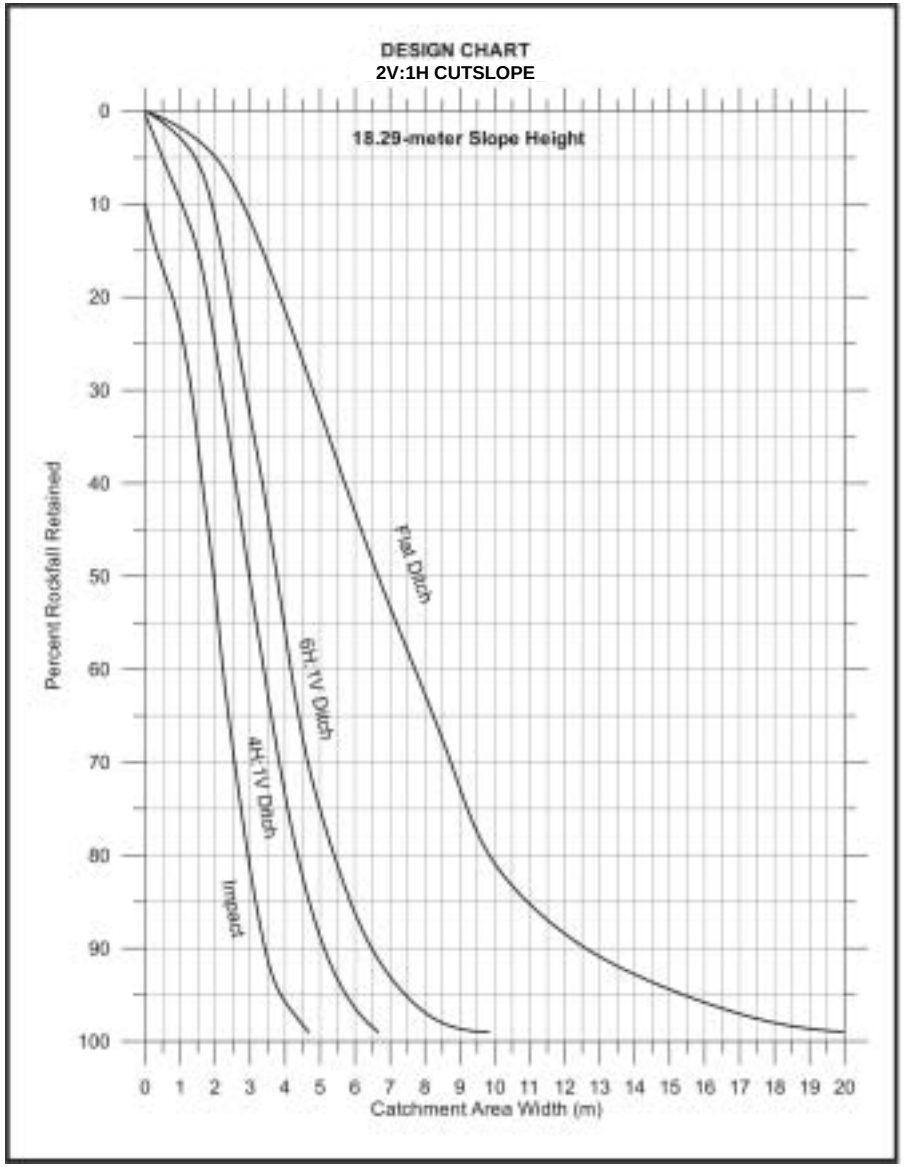
Figure 5.11: Design chart for 12.2-meter high 2V:1H cutslopes

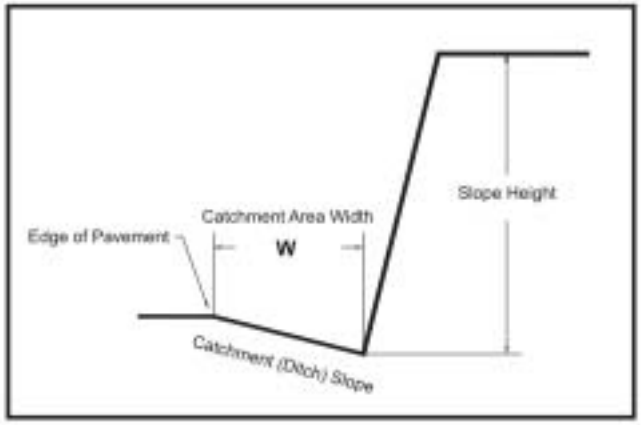




Quick Reference - 15-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.0	2.4	3.2	6.3
75%	1.8	3.3	4.5	8.9
80%	1.9	3.6	4.9	9.4
85%	2.1	3.8	5.3	10.3
90%	2.3	4.2	5.8	11.7
95%	2.6	5.0	6.6	13.7
99%	3.2	5.8	8.6	17.2

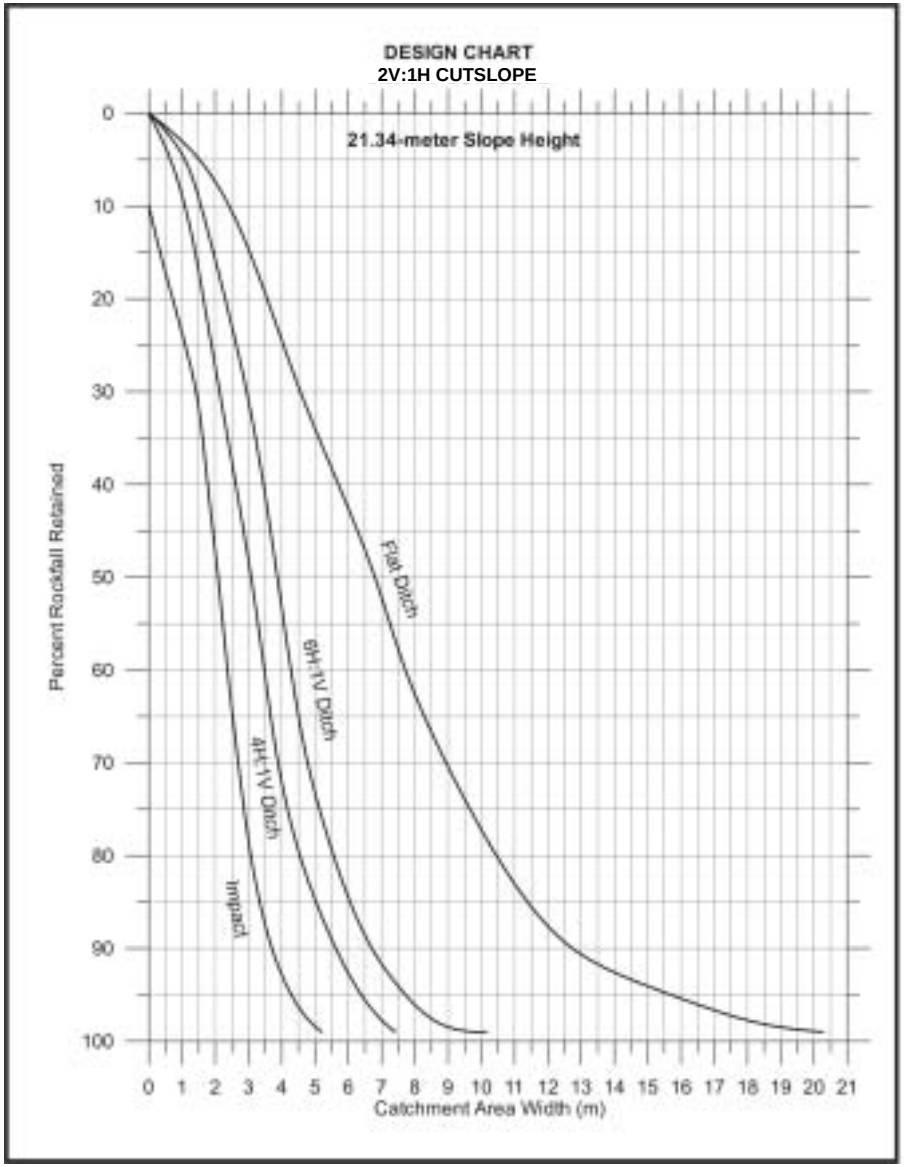
Figure 5.12: Design chart for 15.2-meter high 2V:1H cutslopes

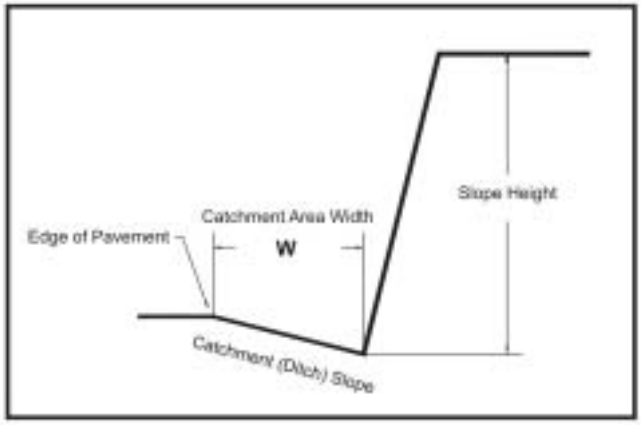




Quick Reference - 18-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	2.0	3.0	3.6	6.7
75%	2.7	4.0	4.9	9.3
80%	2.9	4.4	5.4	9.8
85%	3.3	4.8	5.8	11.0
90%	3.4	4.9	6.5	12.6
95%	3.9	5.8	7.4	15.4
99%	4.7	6.7	9.8	20.0

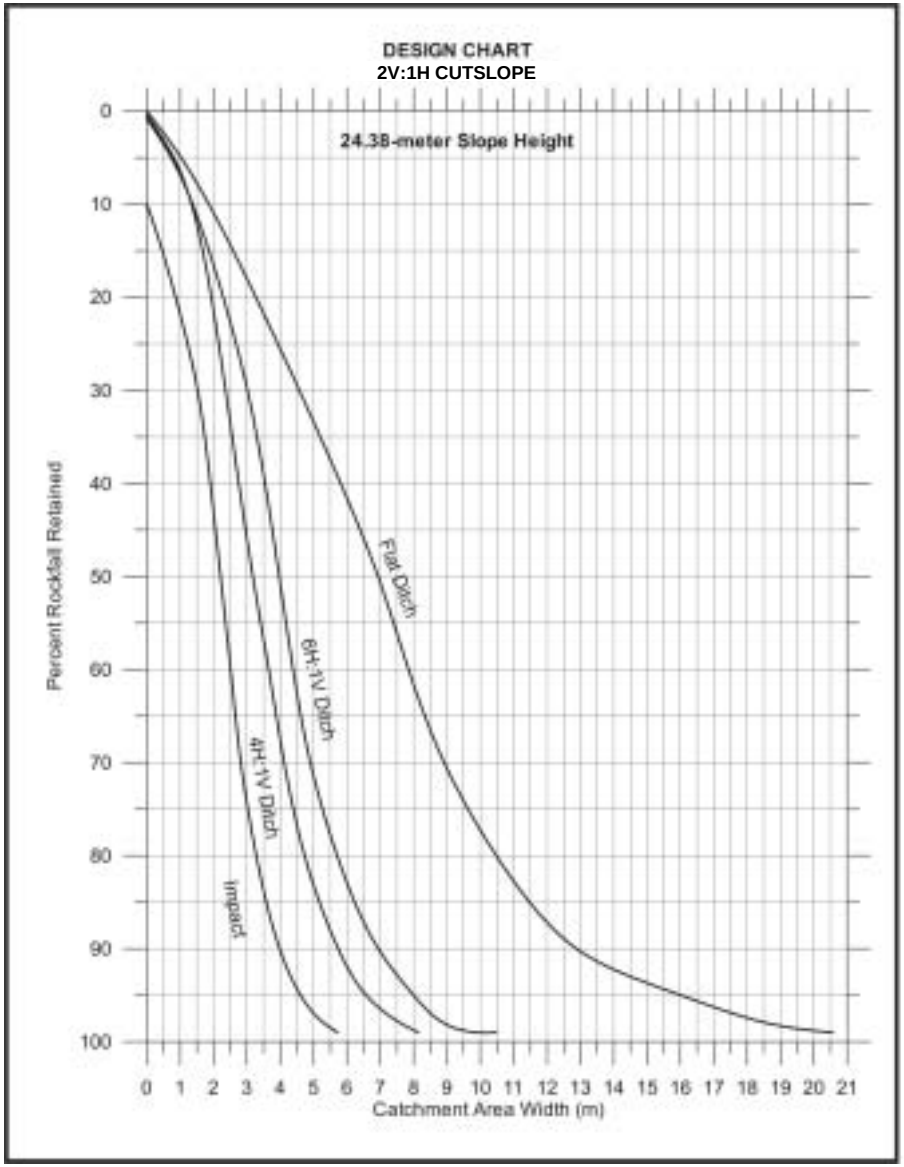
Figure 5.13: Design chart for 18.3-meter high 2V:1H cutslopes

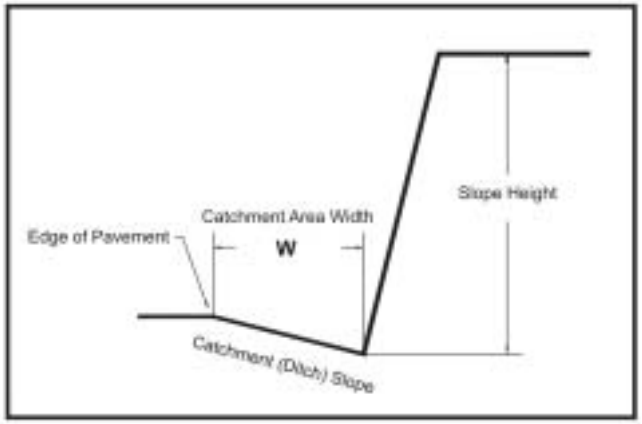




Quick Reference - 21-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	2.1	3.1	3.8	6.8
75%	2.9	4.2	5.0	9.6
80%	3.1	4.5	5.6	10.4
85%	3.3	5.0	6.0	11.3
90%	3.7	5.6	6.7	12.7
95%	4.2	6.2	7.7	15.7
99%	5.2	7.4	10.2	20.3

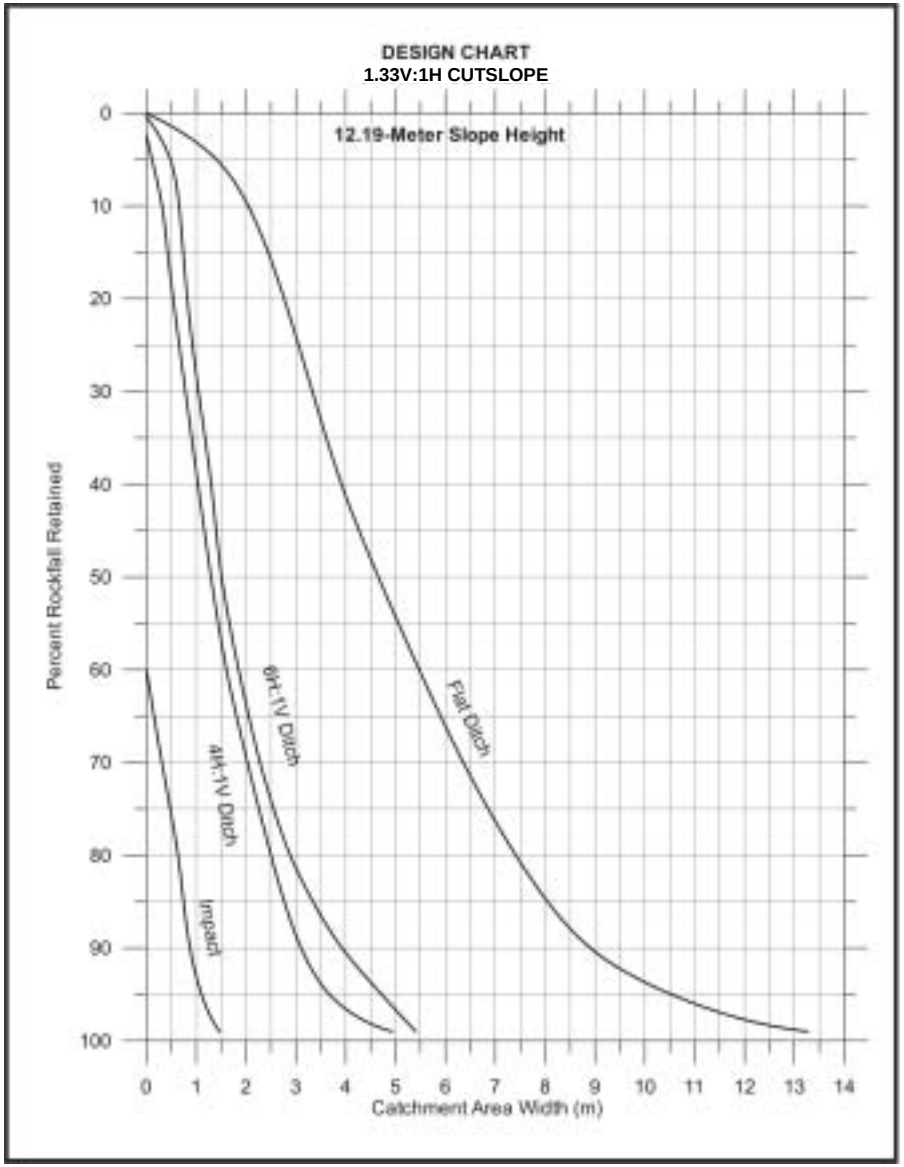
Figure 5.14: Design chart for 21.3-meter high 2V:1H cutslopes

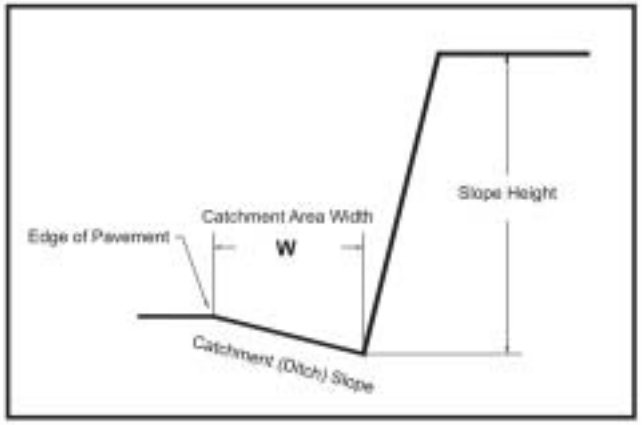




Quick Reference - 24-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	2.2	3.2	4.0	6.9
75%	3.0	4.4	5.1	9.6
80%	3.2	4.7	5.7	10.5
85%	3.5	5.3	6.3	11.5
90%	4.0	5.7	6.9	12.9
95%	4.5	6.6	8.0	16.0
99%	5.7	8.1	10.5	20.6

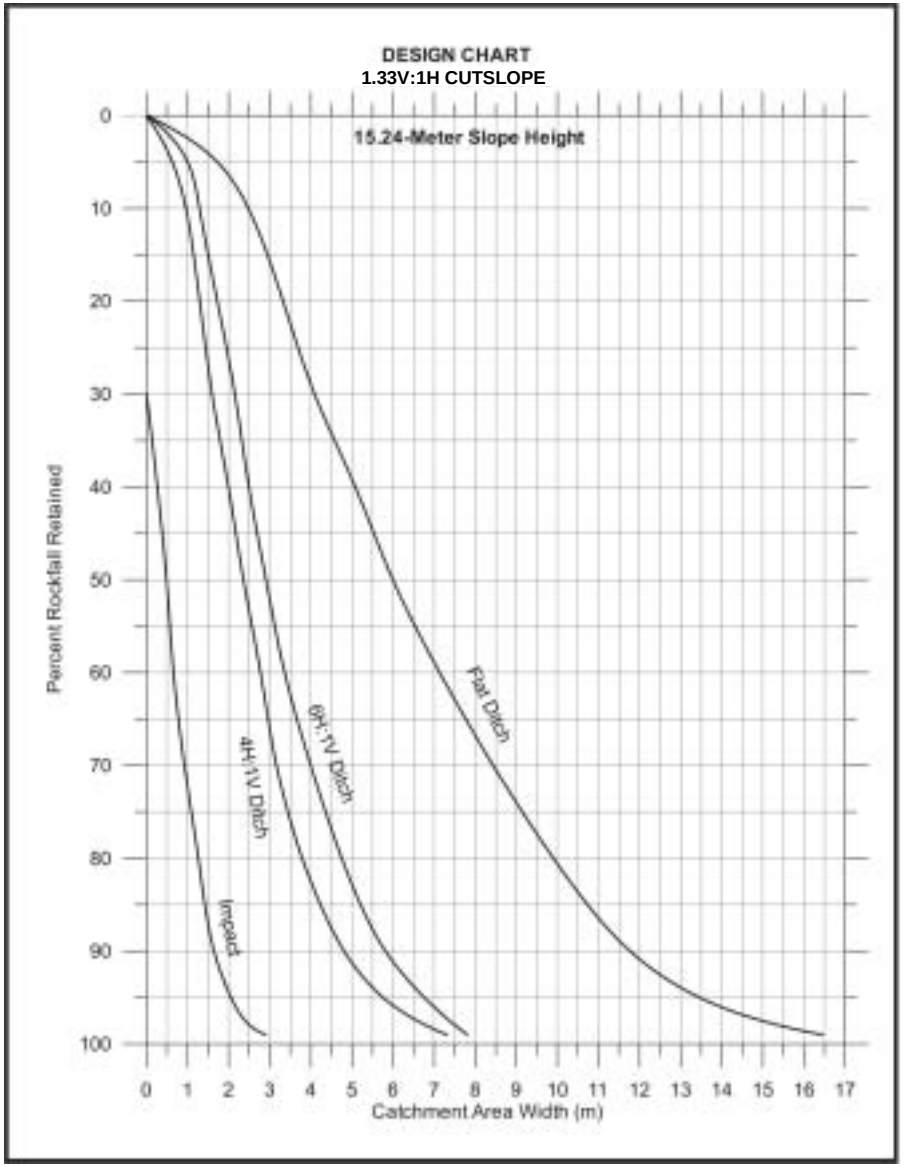
Figure 5.15: Design chart for 24.4-meter high 2V:1H cutslopes

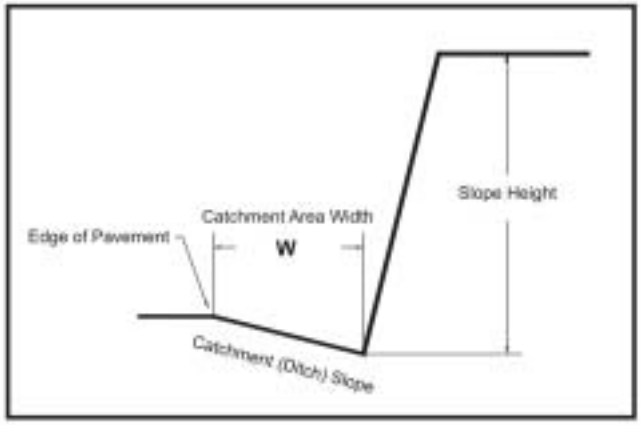




Quick Reference - 12-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	1.3	1.5	4.7
75%	0.5	2.3	2.6	6.9
80%	0.6	2.5	2.9	7.4
85%	0.8	2.8	3.3	8.0
90%	0.9	3.1	3.9	8.9
95%	1.1	3.7	4.7	10.5
99%	1.5	4.9	5.4	13.3

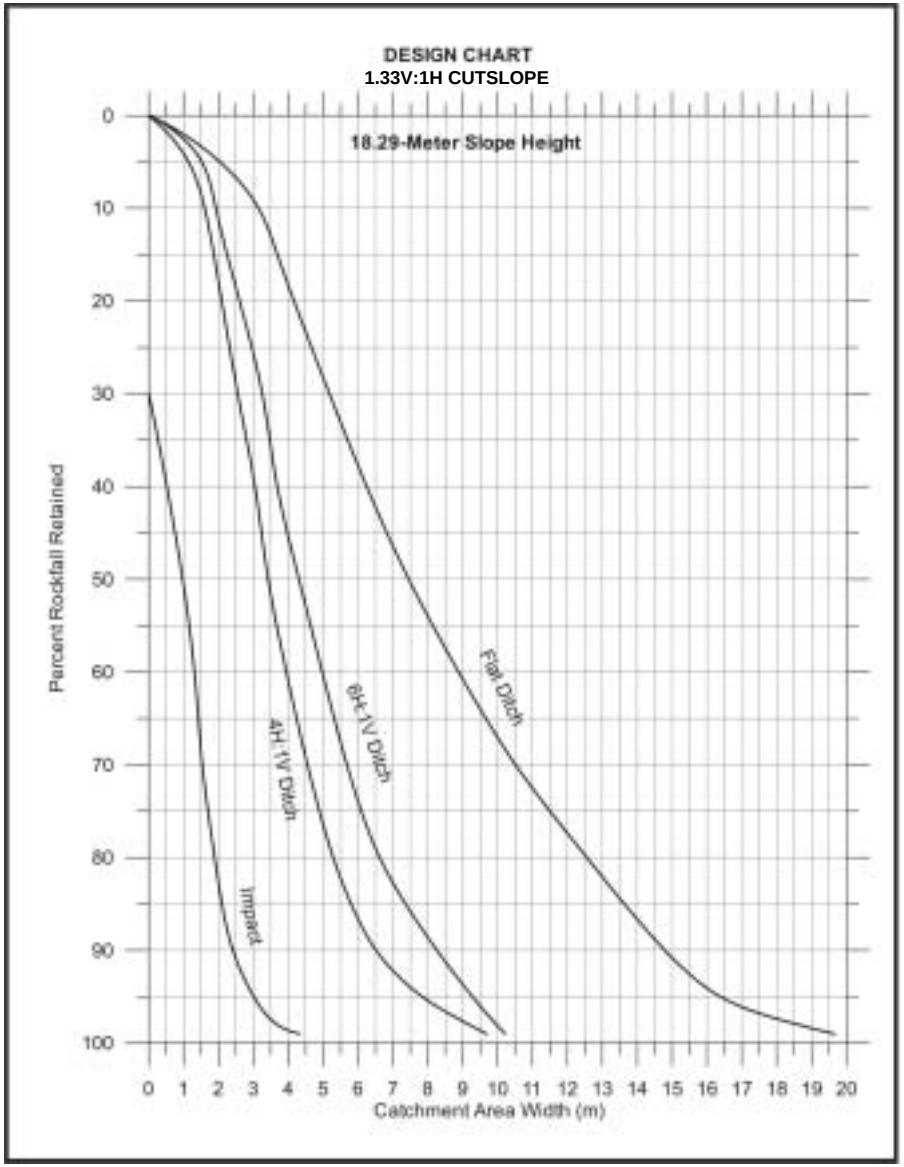
Figure 5.16: Design chart for 12.2-meter high 1.33V:1H cutslopes

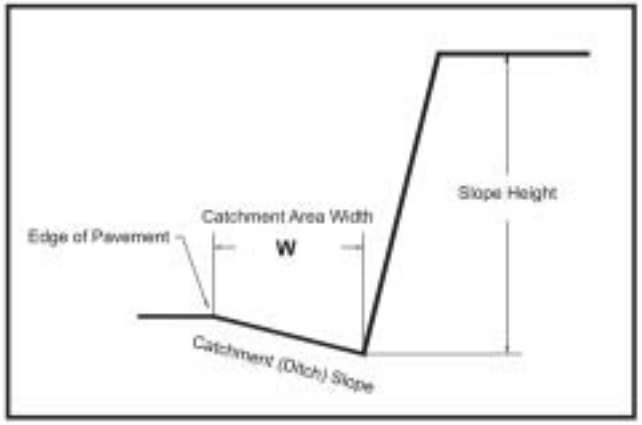




Quick Reference - 15-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.5	2.4	2.9	6.1
75%	1.1	3.6	4.3	9.2
80%	1.3	3.9	4.8	9.9
85%	1.4	4.3	5.3	10.8
90%	1.6	4.8	6.1	11.8
95%	2.1	5.8	7.0	13.5
99%	2.9	7.3	7.8	16.5

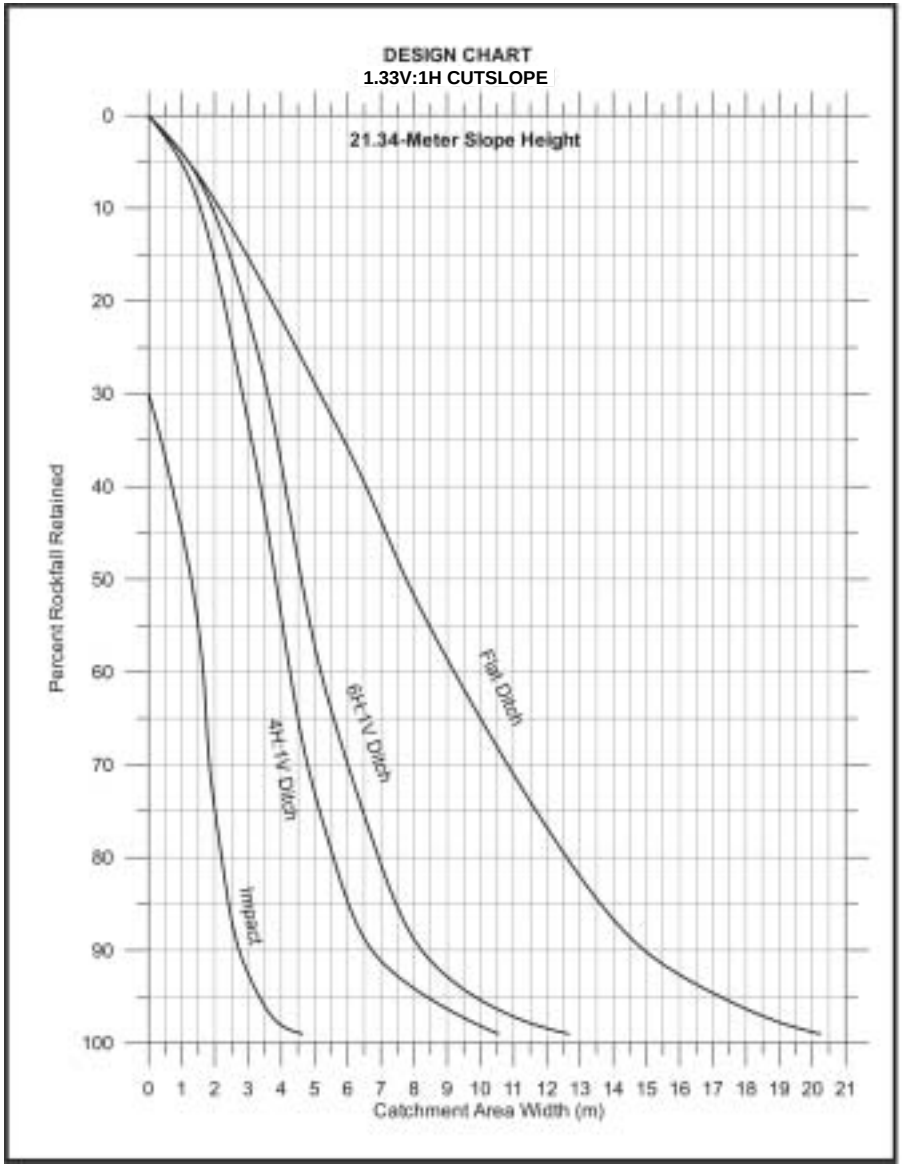
Figure 5.17: Design chart for 15.2-meter high 1.33V:1H cutslopes

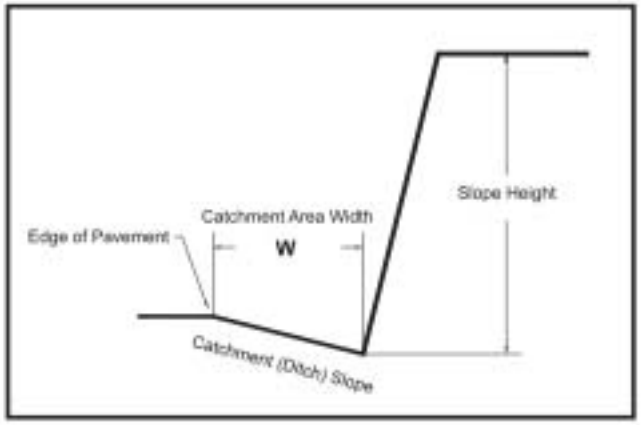




Quick Reference - 18-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.0	3.4	4.3	7.5
75%	1.7	4.9	6.0	11.5
80%	1.9	5.3	6.6	12.6
85%	2.3	5.8	7.3	13.8
90%	2.4	6.5	8.3	14.6
95%	3.0	7.8	9.3	16.4
99%	4.3	9.7	10.2	19.7

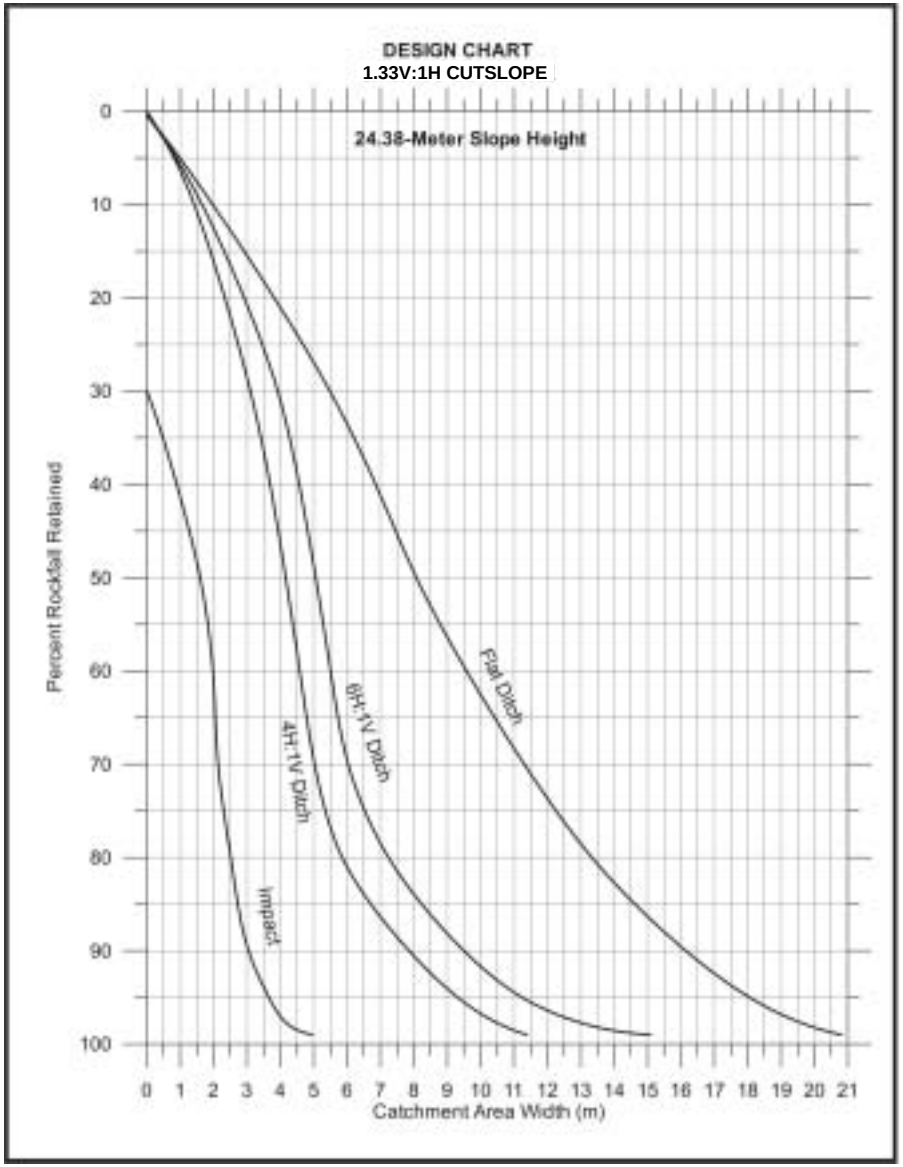
Figure 5.18: Design chart for 18.3-meter high 1.33V:1H cutslopes

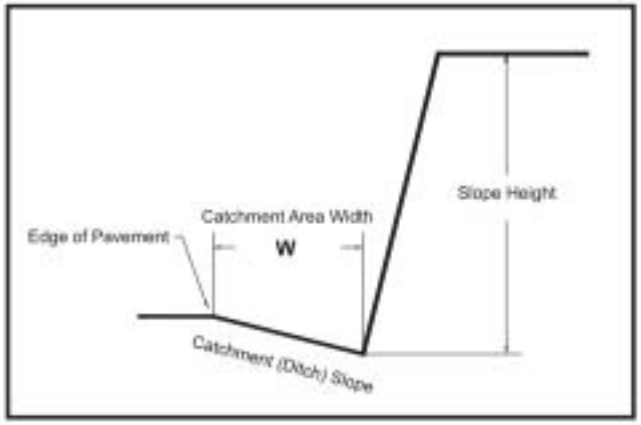




Quick Reference - 21-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.3	3.8	4.6	7.8
75%	2.0	5.2	6.3	11.7
80%	2.2	5.6	6.9	12.7
85%	2.5	6.0	7.5	13.5
90%	2.7	7.2	8.3	15.4
95%	3.3	8.4	9.8	17.2
99%	4.6	10.5	12.6	20.2

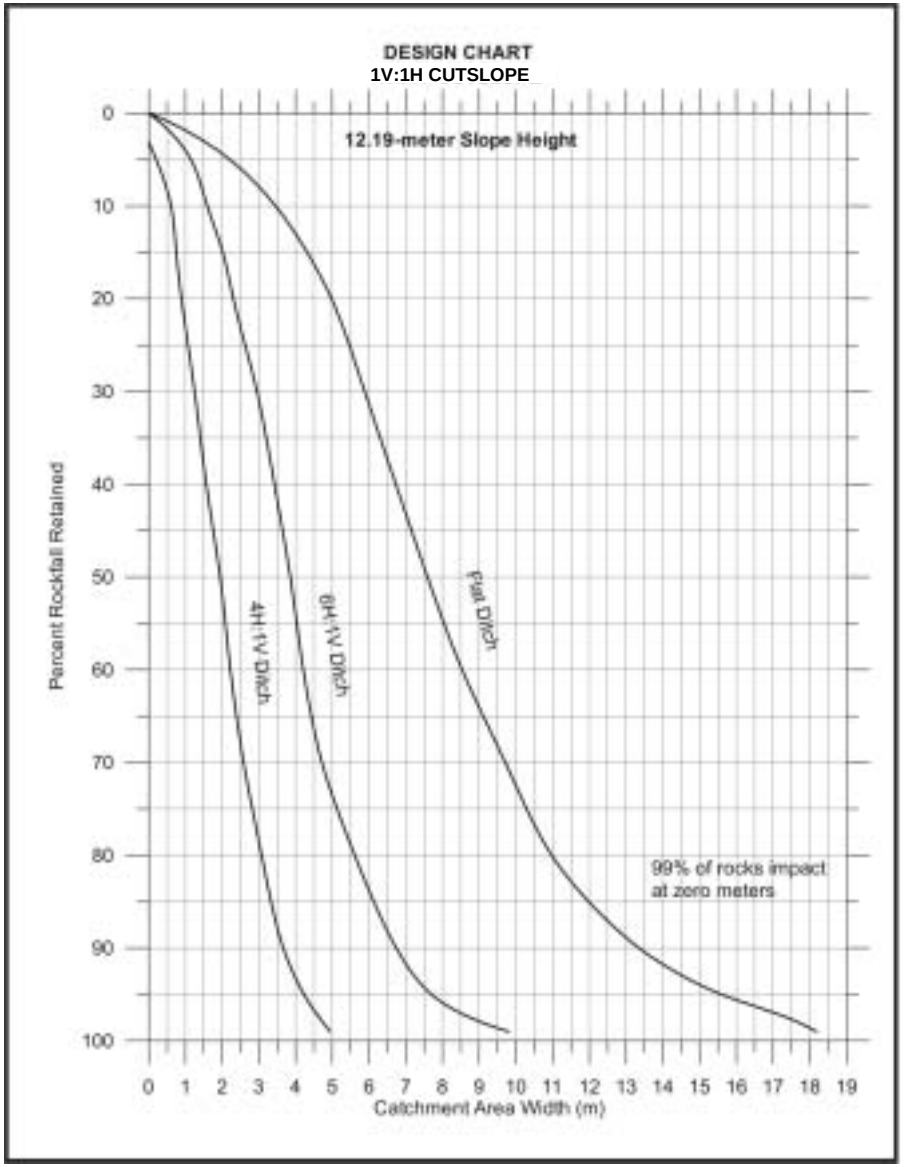
Figure 5.19: Design chart for 21.3-meter high 1.33V:1H cutslopes

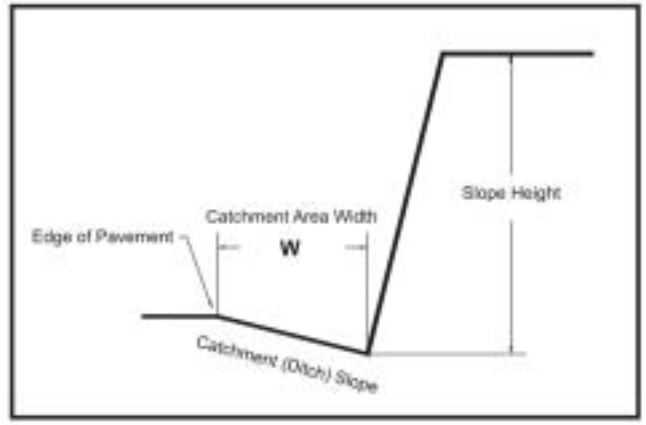




Quick Reference - 24-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	1.6	4.2	4.9	8.1
75%	2.3	5.4	6.6	12.2
80%	2.5	5.9	7.2	13.3
85%	2.8	6.8	8.3	14.8
90%	3.0	7.8	9.5	16.3
95%	3.7	9.3	11.2	18.1
99%	5.0	11.4	15.1	20.8

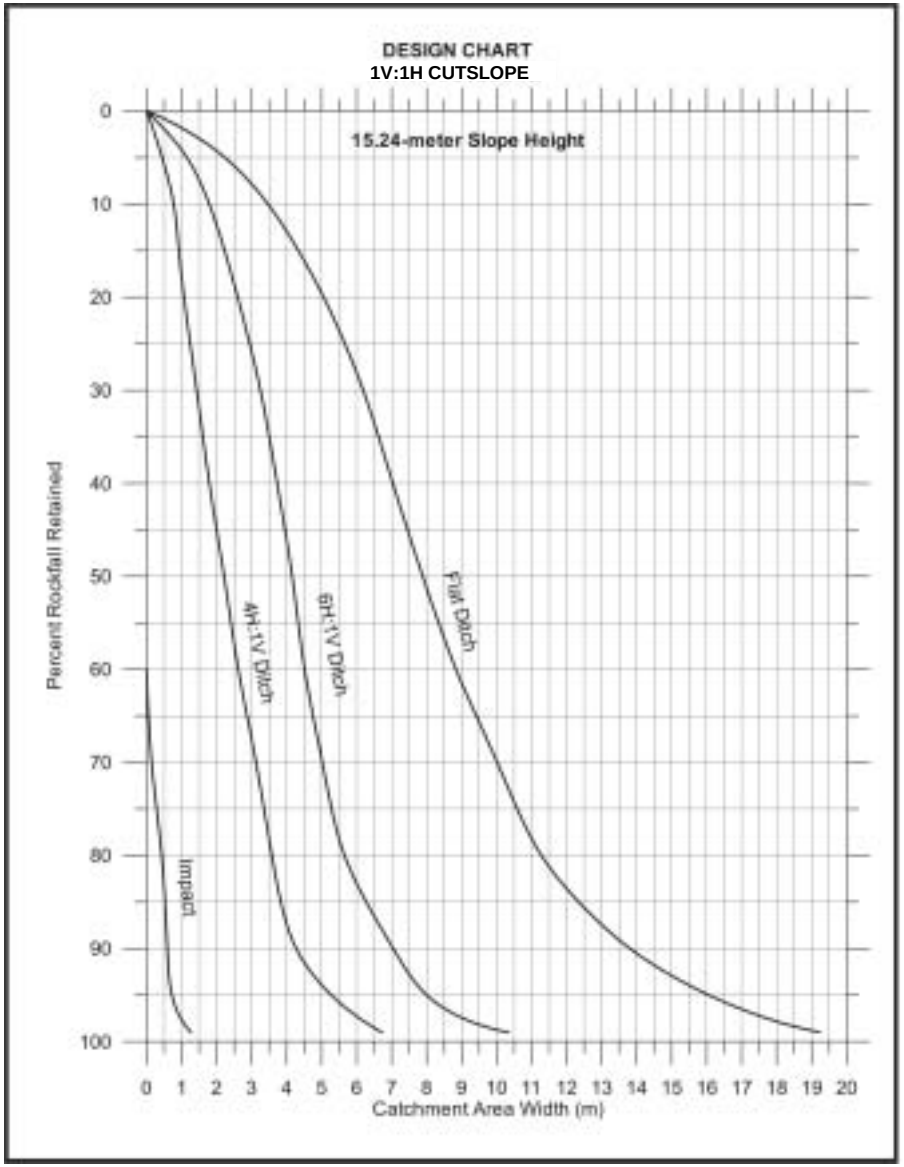
Figure 5.20: Design chart for 24.4-meter high 1.33V:1H cutslopes

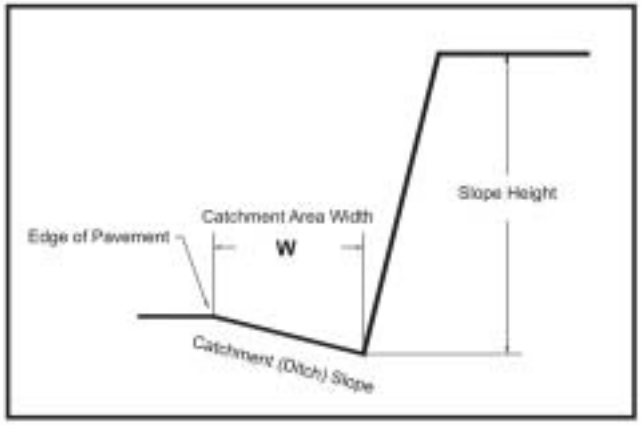




Quick Reference - 12-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	1.9	3.9	7.4
75%	0.0	2.8	5.2	10.3
80%	0.0	3.1	5.8	11.0
85%	0.0	3.3	6.3	12.0
90%	0.0	3.7	6.7	13.4
95%	0.0	4.2	7.7	15.6
99%	0.0	4.9	9.8	18.2

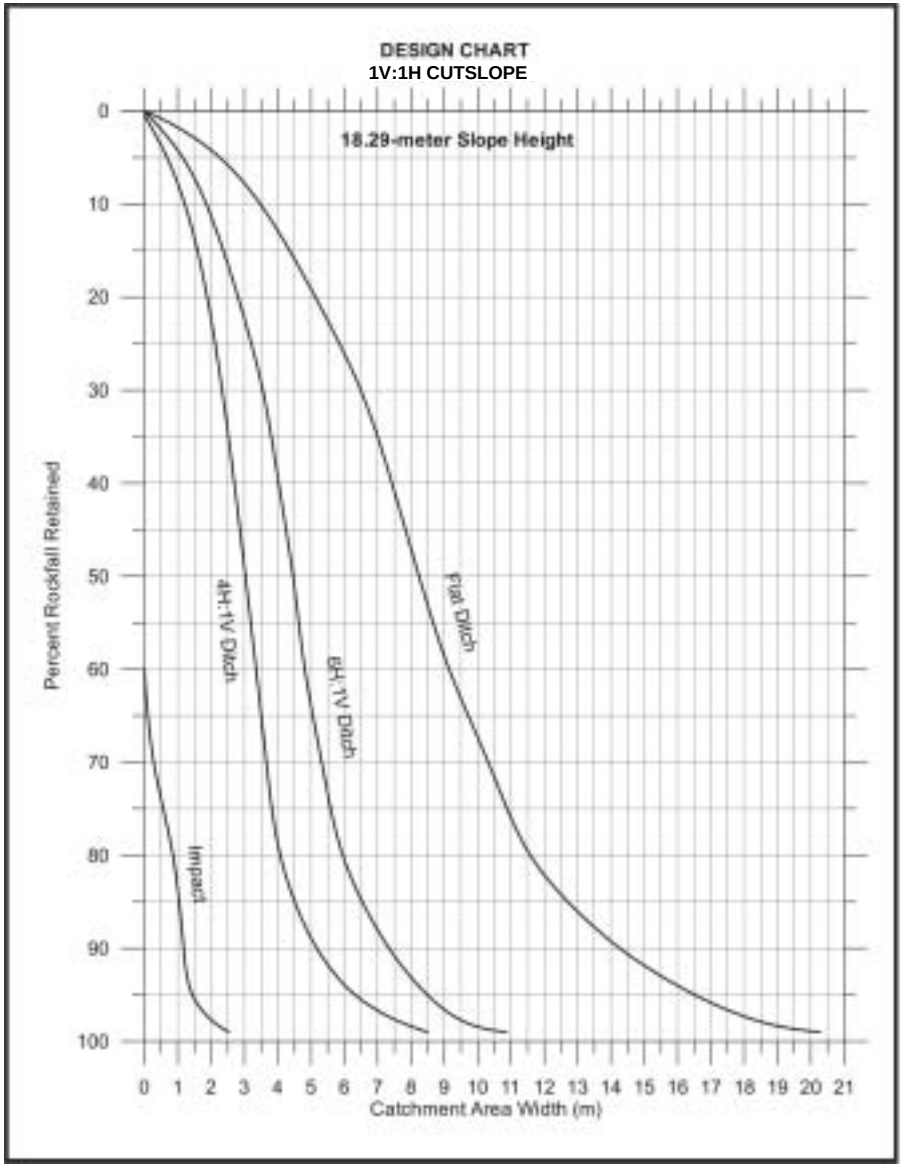
Figure 5.21: Design chart for 12.2-meter high 1V:1H cutslopes

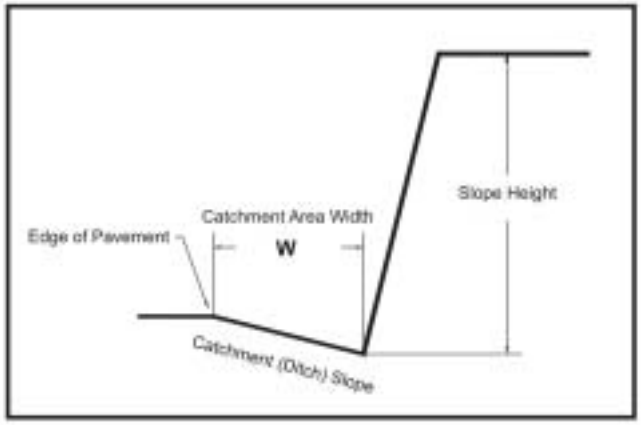




Quick Reference - 15-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	2.5	4.2	7.9
75%	0.3	3.3	5.4	10.6
80%	0.4	3.6	5.9	11.3
85%	0.5	3.8	6.3	12.3
90%	0.6	4.5	7.0	13.8
95%	0.7	5.3	8.1	16.1
99%	1.3	6.7	10.3	19.2

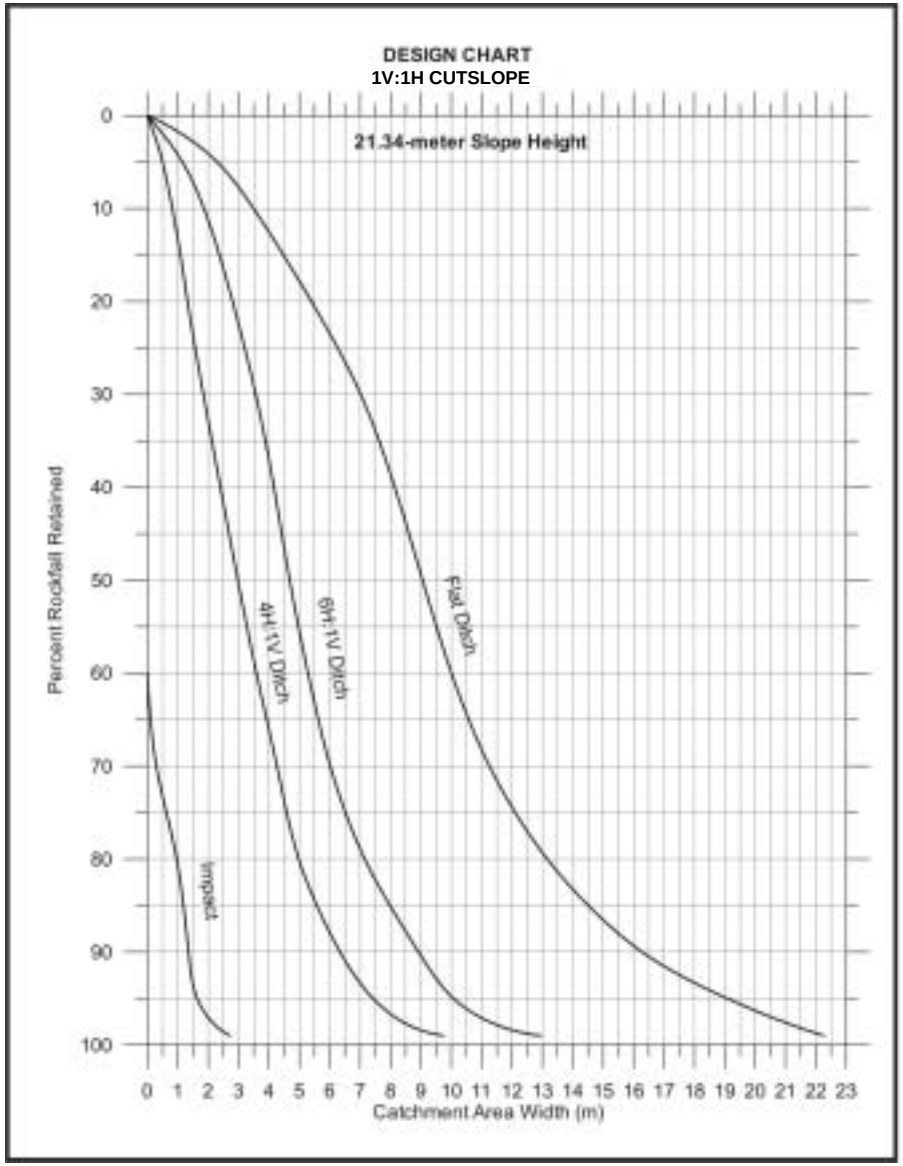
Figure 5.22: Design chart for 15.2-meter high 1V:1H cutslopes

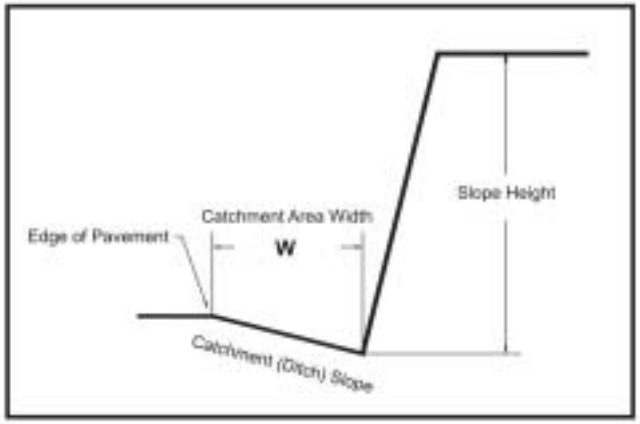




Quick Reference - 18-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	3.0	4.5	8.3
75%	0.6	3.9	5.6	10.9
80%	0.9	4.1	6.0	11.6
85%	1.0	4.5	6.5	12.8
90%	1.2	5.3	7.3	14.3
95%	1.4	6.3	8.5	16.5
99%	2.5	8.5	10.9	20.3

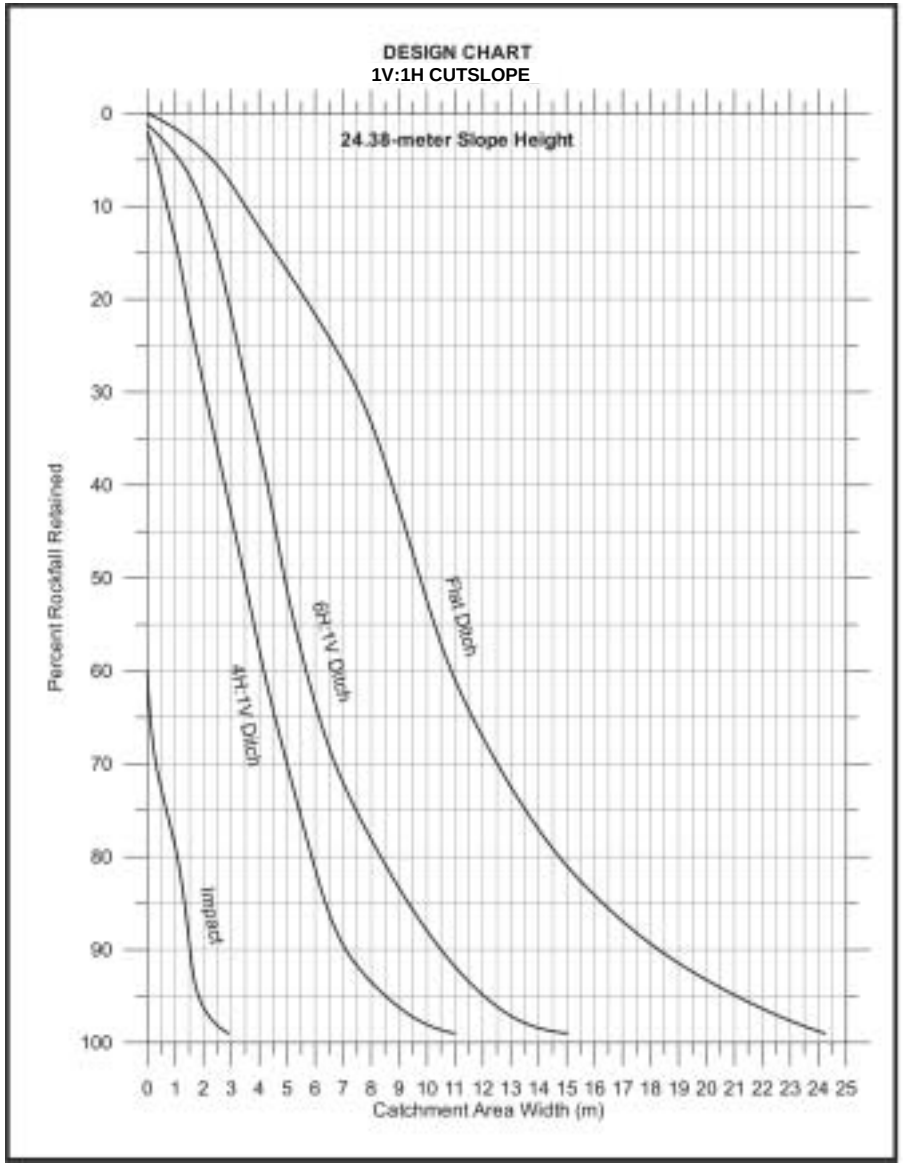
Figure 5.23: Design chart for 18.3-meter high 1V:1H cutslopes

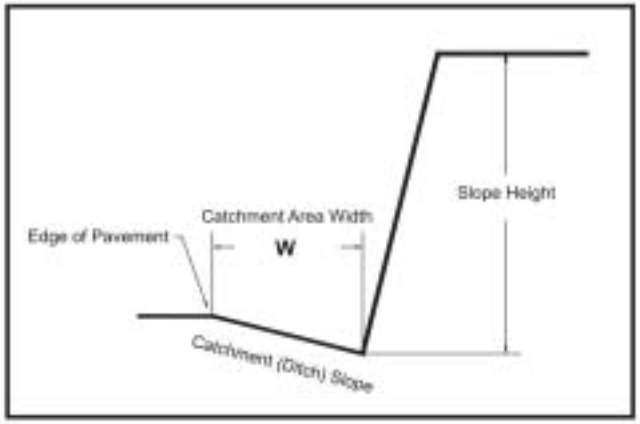




Quick Reference - 21-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	3.2	4.7	9.0
75%	0.6	4.6	6.6	12.2
80%	1.0	5.0	7.2	13.2
85%	1.3	5.5	8.0	14.5
90%	1.4	6.2	8.9	16.3
95%	1.6	7.4	10.3	19.0
99%	2.7	9.7	12.9	22.3

Figure 5.24: Design chart for 21.3-meter high 1V:1H cutslopes





Quick Reference - 24-meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		1V:4H	1V:6H	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	3.5	4.9	9.8
75%	0.7	5.4	7.5	13.5
80%	1.1	5.9	8.3	14.7
85%	1.3	6.3	9.3	16.3
90%	1.5	7.1	10.5	18.3
95%	1.8	8.5	12.0	21.0
99%	2.9	11.0	15.0	24.2

Figure 5.25: Design chart for 24.4-meter high 1V:1H cutslopes

6.0 CONCLUSIONS

6.1 SUMMARY OBSERVATIONS AND CONCLUSIONS

The following general observations and conclusions may be drawn from the research. Some items may seem intuitively obvious but are worth summarizing here, especially for those who have had limited experience with rockfall behavior. The extensive number of rockfalls observed in this study provides a comprehensive basis for these observations.

- A catchment area's slope, whether flat-bottom or inclined, has insignificant influence on where a falling rock will first impact the catchment area.
- Steeper catchment area slopes dramatically reduce roll out distances.
- Cut slope irregularities, commonly referred to as "launch features," strongly influence a rockfall's point of impact when struck by the falling rock.
- Factors such as the presence of launch features and increasing slope height are key to the development of preferred rockfall paths.
- "Launched" rocks tend to have greater impact distances, increasing the spread or dispersion of recorded impacts, compared to rocks that do not strike launch features.
- Launch features change a rock's vertical drop to horizontal displacement. Typically, the higher the rock velocity when it strikes a launch feature, the greater the horizontal displacement.
- Higher slopes and flatter catchment areas produce rockfall roll out distances that are more widely scattered or variable.
- Higher slopes typically produce larger average roll out and impact distances.
- Higher slopes produce impact distances that are more variable.
- Large roll out distances are possible when a falling rock's translational momentum is changed into rotational momentum by impacting the slope, especially if the rock strikes near the base of the cut slope.
- On vertical slopes, falling rocks rarely strike the slope in trajectory. They typically drop undisturbed into the catchment area. Angular momentum is not imparted to the falling rocks, which results in smaller roll out values.

- On flatter slopes (1.33V:1H and flatter) where rocks are rolling down the cut slope, the impact distances are lower, with most rocks entering the catchment area very near the base of the slope.

- On flatter slopes, movement out into the catchment area is due primarily to roll out.

- Rockfall velocities are a function of cut slope angle and height and the amount of time the rocks are in contact with the slope.

- When in contact with the slope, friction decelerates a rockfall, which lowers the resulting energies.

- Because rocks are less often in contact with steeper slopes (free falling or bouncing not rolling), the resulting velocities and energies are higher than for flatter slopes (1.33V:1H or flatter).

- Field testing of a Ritchie catchment area sized to meet the modified FHWA chart for a 24.4-meter high, 4V:1H slope provided a rockfall retention value of 85 percent.

- Compared to field testing results, the computer simulations for 4V:1H slopes tended to under-predict the rockfall roll out distances for 24.4-meter high slopes and over-predict the roll out distances for the 12.2-meter high slopes, but the simulations still gave reasonable results. Computer simulations produced distributions similar to field testing, and the effects of rock size and catchment area slope were also similar.

- **It is important to have experienced rock slope engineering personnel (engineering geologists/ geotechnical engineers) involved in designing rock slope catchment areas. They should evaluate and decide when it is appropriate to directly use the figures in this report's design charts or to modify the catchment area dimensions shown.**

6.2 FURTHER RESEARCH NEEDS

The research project Technical Advisory Committee members jointly developed the following list of future research needs to further improve rockfall catchment area designs. TAC members are listed in the Acknowledgments section at the beginning of this report.

- Test other rock slope heights (less than 12.2 meters and greater than 24.4 meters).

- Compile case studies of in-service existing rock cut slopes to document the performance history of rockfall catchment area design and/or other rockfall mitigation elements.

- Perform some abbreviated testing on existing highway rock cut slopes to check the sensitivity of different catchment area (ditch) shapes and/or different bedding materials.

- Determine the effect on rockfall roll out distance if a portion of catchment area width is pavement.

- Compile and digitize the available rock rolling video footage from ODOT testing and other available sources for use in future rockfall energy research.

- Document more rock rolling energy data – similar to that presented in Appendix E – for use in structural design of different rockfall mitigation elements (barriers, fences, slope mesh, etc.).

- Test to the point of failure commonly used rockfall mitigation measures, such as conventional concrete guardrail, timber-backed conventional concrete guardrail, metal guardrail, and rockfall catch fences, to determine their ultimate structural/rockfall energy absorbing capacity.

- Use ODOT-generated rockfall energy data to help refine computer simulations provided by Colorado Rockfall Simulation Program (CRSP) or other rockfall computer programs.

7.0 REFERENCES

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APPENDICES

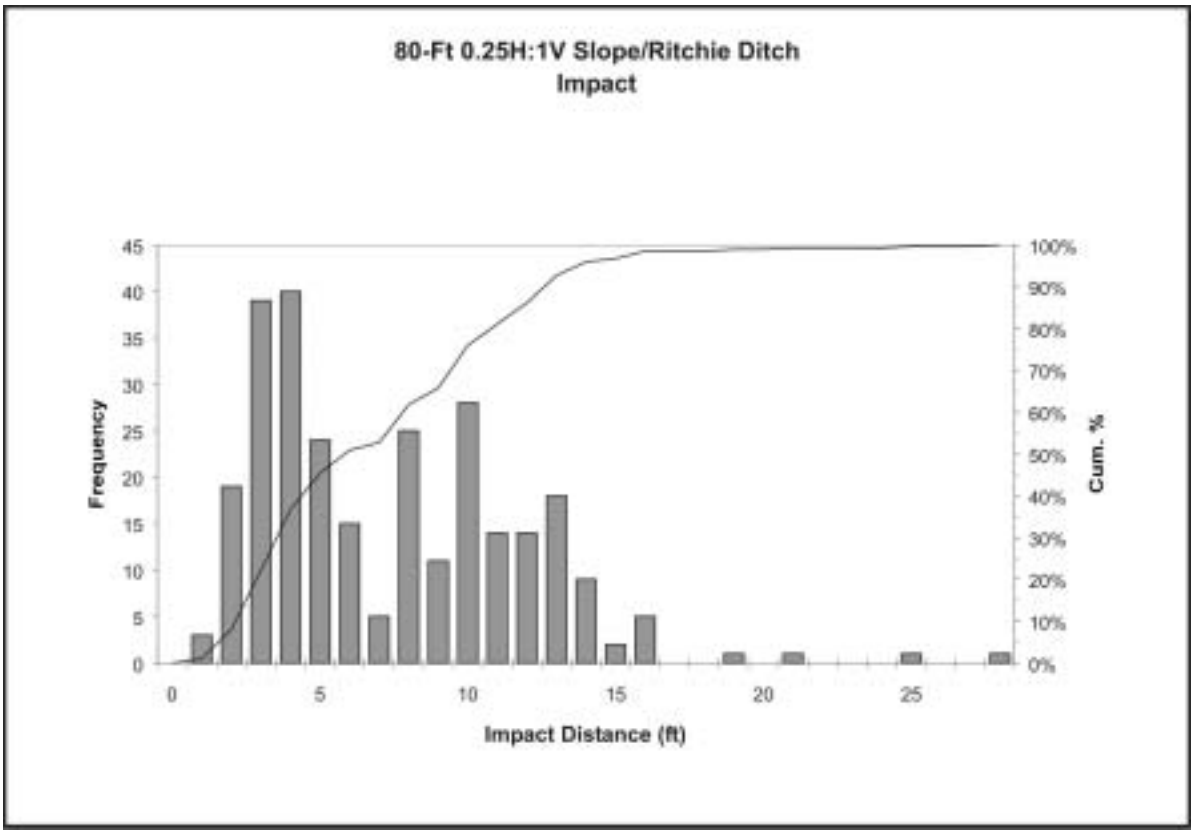
APPENDIX A: RITCHIE TEST CATCHMENT AREA COMPARISON

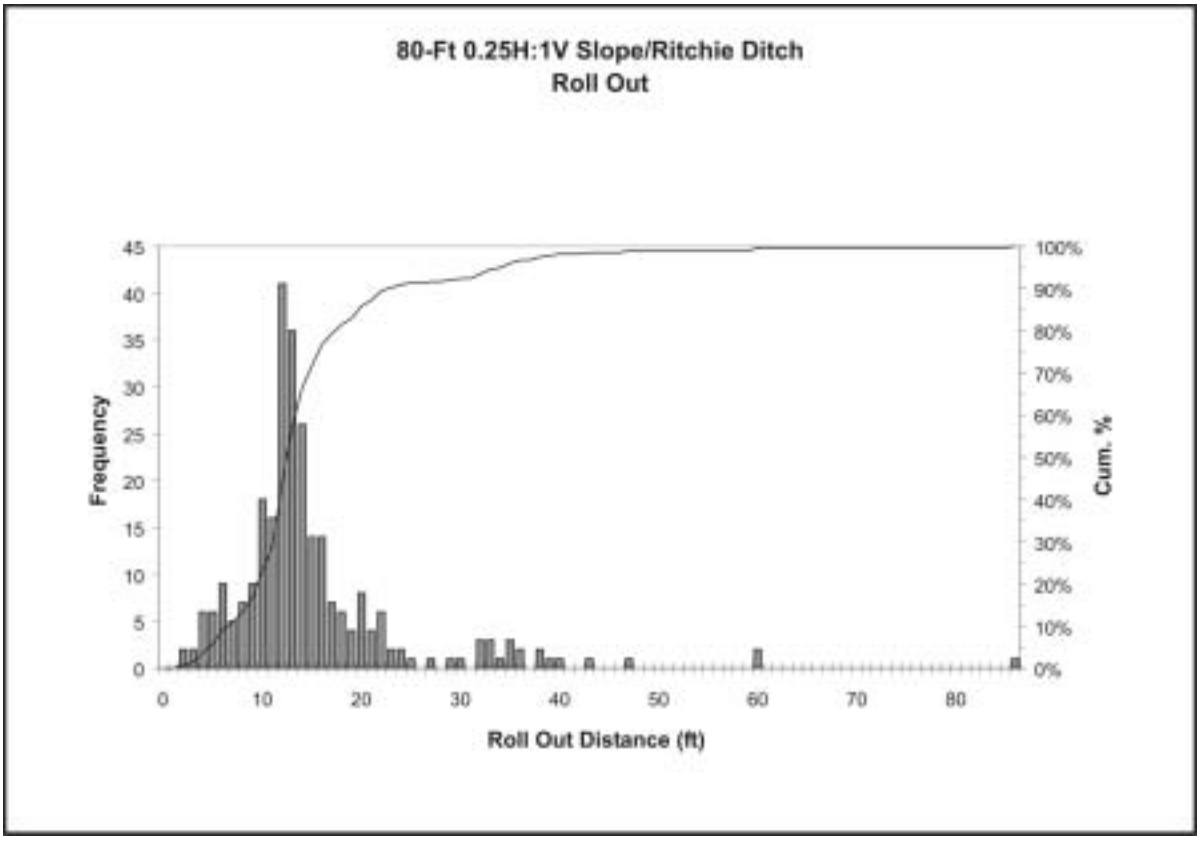
RITCHIE TEST CATCHMENT AREA COMPARISON

During the initial pilot research effort, a full suite of 250 rocks were rolled into a Ritchie catchment area from the 80-foot high, 0.25H:1V cutslope. For comparison purposes, the tested "Ritchie" catchment area was sloped and sized for an 80-foot high slope according to the Ritchie design chart contained in the FHWA Rock Slopes Manual (*FHWA 1989*), (see Figure 2.2). The Ritchie chart contained in the FHWA manual is slightly more conservative for higher slopes than is the original Ritchie criteria. The width of the tested Ritchie catchment area was 24 feet, with 6-foot depth and 1H:1V foreslope.

The most effective features of the tested Ritchie catchment area are its 6-foot depth and steep 1H:1V foreslope. Eight percent of the rocks (22 out of 275) escaped the limits of the tested catchment area; i.e., 92 percent of the rocks were retained. A catchment area designed to an exact Ritchie width would have been 20 feet wide, which would have allowed 41 rocks or about 15 percent of the total to roll through the catchment area; i.e., it would have retained 85 percent of the rocks. Of the 41 rocks, three would have landed (impacted) beyond the catchment area and the remaining 38 would have rolled through.

Refer to Section 2.3.2 of this report for further details and discussion of the tested Ritchie catchment area comparison.


80-Ft 0.25H:1V Slope/Ritchie Ditch
Impact
Frequency
Cum. %
Impact Distance (ft)
0
5
10
15
20
25
30
35
40
45
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


80-Ft 0.25H:1V Slope/Ritchie Ditch
Roll Out
Frequency
Cum. %
Roll Out Distance (ft)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
30
35
40
45
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

APPENDIX B: ROCK ROLLING FIELD DATA

ROCK ROLLING FIELD DATA

This appendix contains the field data from the 11,250 rocks that were rolled off the five slope angles tested. The slopes were vertical, 0.25H:1V, 0.5H:1V, 0.75H:1V, and 1H:1V rock cutslopes. Each slope was tested from three heights at 40, 60 and 80 feet. Three catchment area slopes were compared for each slope height tested. The catchment area slopes included a flat catchment area and two inclined catchment areas that sloped downward toward the toe of the cutslope at a 6H:1V and 4H:1V. A standard suite of 250 rocks were rolled into each catchment area. This number included 100 rocks averaging one foot in diameter, 75 rocks averaging two feet in diameter and 75 rocks averaging three feet in diameter. The diameter dimension was measured along the longest axis. The actual diameter dimensions for each size category ranged within plus or minus 6 inches. For example, the two-foot rocks varied from 1.5 to 2.5 feet in diameter along the longest axis.

The impact and roll out distances in the following tables are the field measured slope distances. Field data was measured to the nearest foot.

NOTE: Also included at the end of Appendix B is a limited set of data gathered from a 40-foot high, 1.25H:1V slope. The rocks rolled from this slope fell into a 4H:1V catchment area. The results were recorded but not compiled into catchment area percent retention graphs or design charts, because there were not sufficient funds to test the full suite of slope heights and catchment area inclinations for the 1.25H:1V test slope.

Field Data for Vertical Slopes

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	4	11	11	8	8
6	10	12	12	8	8
5	5	15	15	11	11
5	5	9	9	11	11
14	17	7	7	13	13
9	9	10	10	11	11
9	11	10	10	12	12
9	9	10	11	7	7
11	11	11	14	11	11
5	5	5	9	14	14
9	9	9	9	12	12
12	13	9	9	9	9
7	7	8	8	11	11
8	8	9	9	11	11
8	10	15	15	13	13
9	9	11	11	13	13
11	11	7	7	11	11
9	9	11	11	14	15
7	7	7	7	13	14
8	8	12	12	13	13
10	10	8	8	12	12
9	9	8	8	10	10
8	8	11	11	17	17
10	10	13	13	15	15
6	6	10	10	11	11
9	9	8	8	16	16
9	9	10	10	11	13
8	8	7	7	9	9
5	5	10	10	13	15
11	11	11	11	12	12
5	5	7	7	7	7
8	8	12	12	11	11
10	10	11	11	10	10
10	10	12	12	7	7
7	8	12	12	12	12
2	3	10	10	14	14
8	8	10	10	12	12
5	7	8	8	12	13
7	8	8	8	9	10
5	5	8	8	13	13
6	7	11	13	11	11
9	9	7	7	9	9
8	8	9	11	14	14
5	6	12	12	10	10
7	7	10	10	11	11
11	11	10	10	13	13
5	5	12	12	13	13
5	5	10	10	11	11
17	17	11	11	10	10
4	4	12	12	12	12

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
8	8				
6	7	10	10		
8	9	9	9		
8	9	10	13		
5	5	12	12		
7	7	10	10		
3	3	13	13		
7	7	15	15		
6	8	10	10		
11	14	14	14		
9	9	8	8		
5	7	11	11		
4	4	11	11		
8	8	13	13		
6	6	8	8		
11	11	12	12		
7	7	11	11		
6	6	10	10		
10	10	11	11		
11	11	9	9		
11	11	10	10		
11	11	10	10		
10	10	12	12		
6	6	11	11		
6	7	7	7		
6	8				
8	8				
11	12				
5	5				
11	11				
8	10				
13	13				
6	8				
12	12				
8	8				
7	7				
12	12				
9	9				
7	8				
7	7				
13	13				
8	8				
8	8				
7	8				
7	7				
8	8				
5	7				
7	7				
14	14				
10	10				

Field Data for Vertical Slopes

40-Foot Slope with a 6H:1V Catchment Area					
1-foot	1-foot	2-foot	2-foot	3-foot	3-foot
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	9	11	11	8	8
9	10	13	13	10	10
8	8	13	16	3	8
11	11	7	7	3	3
10	10	13	13	15	15
8	8	10	10	10	13
6	8	5	5	13	13
7	8	4	4	12	12
6	6	8	8	5	8
11	12	11	11	10	11
6	6	11	11	9	10
10	10	9	9	9	11
9	9	10	10	12	12
6	6	3	3	8	8
8	8	11	11	12	12
11	11	10	10	7	9
9	12	8	8	11	11
8	8	11	11	7	7
3	3	4	4	7	7
7	7	11	14	3	6
2	3	10	10	5	5
7	7	11	16	8	13
7	7	10	12	11	11
11	11	10	10	8	8
8	8	6	6	9	9
14	17	8	12	13	13
9	14	6	6	8	11
7	7	5	8	8	8
7	7	10	10	8	13
4	4	9	9	11	11
10	12	7	11	10	13
6	6	11	11	5	5
8	8	7	7	7	7
10	11	13	18	7	7
10	11	8	10	5	7
5	5	11	11	7	9
7	7	7	7	10	10
5	5	11	13	12	12
8	10	10	10	9	9
8	8	11	11	13	13
10	10	7	7	7	7
10	14	11	11	10	10
10	13	8	8	9	10
6	6	5	5	8	10
8	9	9	9	7	8
5	5	11	11	6	8
6	8	12	12	9	9
4	7	12	12	7	9
8	8	15	15	8	8
4	4	7	7	14	14

40-Foot Slope with a 6H:1V Catchment Area					
1-foot	1-foot	2-foot	2-foot	3-foot	3-foot
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	9	10	11	10	10
3	3	15	15	7	7
10	10	10	10	13	15
5	6	7	8	10	10
5	5	8	8	7	7
9	9	8	8	7	7
6	6	5	5	4	5
8	8	3	3	7	7
9	9	5	5	11	11
7	7	6	6	9	13
7	9	11	11	11	11
8	10	9	9	11	11
12	12	7	7	8	8
12	14	9	9	14	14
8	10	12	12	9	9
6	6	10	10	9	9
5	5	10	11	7	10
4	4	13	18	5	5
14	14	7	7	7	7
14	17	11	11	7	7
7	8	9	9	10	10
12	12	10	10	11	16
8	8	10	10	8	8
7	7	8	8	11	11
7	7	5	5	13	13
9	9			9	9
7	7			10	10
4	8			8	8
8	8			8	8
6	6			12	12
9	9				
11	11				
6	6				
8	8				
8	8				
9	9				
6	6				
4	4				
7	7				
9	12				
8	11				
7	8				
10	10				
9	9				
12	12				
12	12				
10	10				
10	10				
7	7				
6	6				

Field Data for Vertical Slopes

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
6	8	10	20	14	14
8	10	12	20	13	13
8	8	10	13	7	29
11	18	10	18	10	28
5	5	7	7	9	25
10	20	11	17	9	25
9	10	10	20	8	20
7	7	8	8	13	17
9	12	9	14	10	19
6	6	10	30	6	12
7	7	9	13	7	7
9	9	8	12	9	22
9	17	10	10	13	23
5	5	8	18	11	17
8	18	9	18	10	11
10	17	6	9	11	16
5	5	9	9	10	16
9	17	8	13	8	8
3	3	8	15	9	9
5	5	9	9	5	10
5	5	8	11	8	17
8	8	7	15	9	11
14	14	9	9	8	14
8	8	7	10	9	14
8	10	8	8	10	29
8	8	10	10	10	19
6	6	7	7	5	11
8	11	9	12	8	8
3	7	12	15	11	11
8	11	12	12	12	17
7	7	9	12	10	10
12	12	10	10	7	14
5	6	8	8	9	16
8	11	8	9	6	10
10	13	10	15	5	5
13	13	8	18	13	13
8	8	10	18	11	29
5	5	8	17	14	14
9	17	7	18	10	10
5	5	7	7	13	16
7	11	7	10	6	16
7	9	7	7	9	14
8	10	11	11	8	11
5	5	12	12	7	14
9	9	7	10	13	22
6	6	12	17	13	13
7	7	8	8	8	17
5	5	5	9	10	10
5	5	4	11	10	20
11	12	6	6	11	11

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
8	21	10	25	8	18
8	22	8	12	10	16
10	17	10	10	11	11
5	5	9	9	7	15
5	8	7	7	13	13
5	6	14	16	8	13
5	5	9	31	13	13
10	19	7	9	11	11
9	10	11	14	10	18
6	6	9	9	7	7
10	10	12	12	8	25
8	9	6	8	10	10
8	8	6	10	8	8
8	28	7	11	9	9
8	14	7	7	8	8
11	11	9	11	13	31
6	6	10	16	8	23
5	5	11	14	11	11
7	7	8	8	9	9
3	3	7	25	8	10
5	5	10	20	5	5
7	7	6	10	7	13
12	25	6	13	5	10
8	8	9	13	8	13
12	23	7	7	8	22
8	8				
8	10				
12	12				
9	17				
10	10				
8	8				
14	14				
5	8				
5	5				
9	9				
3	13				
7	7				
11	17				
10	13				
9	9				
7	10				
8	8				
7	9				
9	16				
12	12				
8	12				
11	14				
7	7				
8	11				
8	11				

Field Data for Vertical Slopes

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
6	6	11	11	9	9
12	12	10	10	8	8
7	7	13	13	11	11
11	11	10	10	9	9
7	7	13	13	6	6
11	11	14	14	8	8
4	4	10	10	14	14
11	11	5	5	10	10
10	10	13	13	11	11
15	15	8	8	11	11
10	10	13	13	16	16
15	15	10	10	14	14
11	11	12	12	10	10
8	8	12	12	11	11
13	14	9	9	12	12
8	8	9	9	8	11
12	12	7	7	19	19
11	11	13	13	10	10
9	9	14	14	14	14
8	8	9	9	8	8
7	7	8	9	7	7
10	10	13	13	8	8
10	10	10	10	15	15
6	6	8	8	11	11
8	8	8	8	12	12
12	12	9	9	15	15
12	12	9	9	13	13
12	12	12	12	11	11
10	10	18	18	11	11
9	9	11	11	13	13
11	11	9	9	10	10
12	12	9	9	13	13
14	14	14	14	6	14
13	13	12	12	13	13
10	10	12	12	11	11
11	11	11	11	14	14
11	11	9	9	18	18
16	16	12	12	10	10
10	11	7	7	13	13
10	10	9	9	13	13
8	8	6	9	7	11
10	10	6	10	10	10
6	6	11	11	13	13
5	5	15	15	8	8
5	5	13	13	9	9
4	4	12	12	11	11
10	10	14	14	6	11
16	16	8	8	14	14
11	11	13	13	14	14
4	4	10	10	12	12

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
11	11	5	19	11	11
8	8	9	9	6	11
6	6	9	9	9	9
15	15	8	8	9	9
6	6	12	12	9	9
13	13	11	11	13	13
9	9	9	11	13	13
11	11	8	8	13	13
10	10	9	9	14	14
9	9	9	9	13	13
8	8	5	5	10	10
9	9	11	11	11	11
8	8	9	9	7	7
13	13	14	14	7	7
8	8	11	11	13	13
6	6	6	6	8	16
8	8	10	10	7	9
11	11	11	11	8	8
11	11	7	7	11	11
12	12	9	9	10	10
19	19	10	10	13	13
10	10	7	7	9	9
10	10	10	10	14	14
8	8	14	14	8	18
9	9	11	11	6	6
8	8				
10	10				
7	7				
7	7				
11	11				
10	10				
5	11				
8	11				
5	5				
8	8				
10	10				
9	11				
13	13				
8	8				
16	16				
10	10				
8	8				
11	11				
7	7				
10	10				
12	12				
12	12				
7	7				
10	10				
11	11				

Field Data for Vertical Slopes

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
7	7	10	10	12	12
4	4	8	8	14	14
4	4	12	12	13	13
3	3	11	14	8	8
6	6	8	8	10	10
4	4	7	7	9	9
9	9	6	6	7	7
4	4	9	9	7	7
8	8	9	9	9	9
4	4	11	11	9	9
7	7	10	10	10	10
5	5	13	13	13	13
5	5	9	9	9	9
8	10	9	9	11	11
6	6	15	15	10	10
3	3	15	15	8	8
4	4	8	8	8	8
7	7	12	12	5	5
2	2	9	9	11	11
4	4	5	5	11	11
3	3	16	16	16	16
2	2	7	7	15	15
5	5	6	6	10	10
12	15	11	11	15	15
7	7	8	8	12	12
2	2	12	14	5	5
6	6	10	10	15	15
5	5	8	8	6	6
1	1	10	10	11	11
5	5	7	7	9	9
9	9	8	8	8	8
4	4	8	8	9	9
3	3	5	7	11	11
5	5	8	8	16	16
7	7	11	11	10	10
2	2	8	8	5	11
2	2	5	5	11	11
6	6	11	11	7	7
6	6	6	6	10	10
6	6	11	11	10	10
5	5	13	13	13	13
6	9	8	8	7	7
5	5	9	9	7	7
14	14	9	9	11	11
2	2	5	5	16	16
2	2	9	9	13	13
3	3	5	5	8	8
5	5	8	8	10	10
5	5	10	10	13	13
6	6	9	9	6	6

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
6	6	11	11	11	11
2	2	8	8	11	11
4	4	11	11	12	12
5	5	11	11	16	16
11	13	12	12	7	7
5	5	11	11	16	16
11	11	10	10	8	8
8	8	5	5	12	12
16	16	5	5	5	5
6	6	7	7	10	10
9	9	5	5	7	7
5	5	9	9	7	7
5	5	14	17	8	8
5	5	11	11	8	8
7	7	6	6	7	7
9	9	9	9	5	5
7	7	13	13	9	9
8	8	10	10	10	10
16	16	5	5	4	4
5	5	8	8	9	9
7	7	11	11	8	11
9	9	6	8	11	11
8	8	13	13	8	8
6	6	6	6	9	9
6	6	7	7	9	9
5	5				
9	9				
5	5				
9	9				
13	13				
14	16				
5	5				
7	7				
9	11				
6	6				
6	6				
9	9				
4	4				
12	12				
5	5				
5	5				
6	6				
7	7				
7	8				
3	3				
10	10				
9	9				
3	3				
3	3				
8	8				

Field Data for Vertical Slopes

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	10	10	10	10	10
10	10	10	10	8	8
9	10	14	15	5	5
7	8	5	5	12	12
8	9	9	9	10	14
10	10	6	6	10	10
7	7	11	13	6	10
10	10	14	24	8	11
17	18	10	10	13	13
6	6	6	7	10	10
5	5	5	6	10	10
12	12	10	13	9	11
9	9	8	12	5	5
4	4	9	9	6	6
5	5	10	10	11	12
4	5	9	9	12	13
6	6	13	13	10	10
8	8	10	10	11	13
7	10	9	11	8	10
10	10	10	10	5	5
16	18	11	11	11	11
11	11	14	15	13	13
4	4	10	10	16	16
4	4	9	9	8	12
6	6	10	10	11	11
10	11	1	1	10	10
5	5	10	10	5	14
7	7	9	9	9	9
10	10	8	8	12	14
18	18	7	7	13	13
7	7	6	6	13	13
13	13	9	13	13	13
7	7	11	11	9	15
9	9	13	13	12	12
4	4	11	11	9	9
6	6	16	20	9	9
10	10	10	10	13	13
8	8	15	15	13	13
3	3	16	20	15	16
10	10	6	8	10	10
10	10	7	7	9	9
11	11	7	7	5	5
8	8	10	10	13	13
15	15	4	4	15	15
6	6	8	8	12	12
4	4	13	14	8	8
13	13	8	8	10	10
4	6	14	14	10	10
13	13	9	9	9	9
3	3	10	10	8	10

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
7	7	7	7	11	11
4	5	16	21	11	11
15	15	12	12	13	13
9	9	13	17	8	8
3	5	13	13	9	9
8	8	15	15	6	9
9	9	10	14	14	16
6	6	8	8	12	12
8	8	8	8	16	21
3	3	11	11	8	14
5	5	9	9	9	12
7	7	9	9	8	8
18	20	14	14	18	18
6	6	10	10	9	9
9	9	7	8	8	8
8	8	12	14	6	6
5	5	11	11	13	13
5	5	14	22	15	15
8	8	8	9	13	14
14	14	7	10	9	9
5	5	9	9	15	15
6	7	7	9	11	11
14	18	8	8	15	19
10	10	11	15	11	11
10	10	11	13	12	12
6	6				
7	7				
5	5				
5	5				
9	9				
9	10				
10	11				
9	9				
6	7				
8	8				
8	8				
5	5				
3	3				
5	5				
8	8				
5	8				
7	7				
10	10				
4	5				
8	8				
5	5				
3	3				
12	12				
9	9				
7	7				

Field Data for Vertical Slopes

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
3	3	10	10	10	10
12	12	10	10	8	8
11	11	14	15	5	5
11	11	5	5	12	12
10	10	9	9	10	14
13	13	6	6	10	10
11	11	11	13	6	10
20	20	14	24	8	11
11	11	10	10	13	13
15	15	6	7	10	10
11	11	5	6	10	10
10	10	10	13	9	11
15	15	8	12	5	5
11	11	9	9	6	6
17	17	10	10	11	12
10	10	9	9	12	13
11	11	13	13	10	10
19	19	10	10	11	13
13	13	9	11	8	10
8	8	10	10	5	5
3	3	11	11	11	11
14	14	14	15	13	13
2	2	10	10	16	16
10	10	9	9	8	12
10	10	10	10	11	11
12	12	1	1	10	10
5	5	10	10	5	14
5	5	9	9	9	9
9	9	8	8	12	14
8	8	7	7	13	13
10	10	6	6	13	13
6	6	9	13	13	13
17	17	11	11	9	15
11	11	13	13	12	12
14	14	11	11	9	9
10	10	16	20	9	9
5	5	10	10	13	13
11	11	15	15	13	13
11	11	16	20	15	16
16	16	6	8	10	10
9	9	7	7	9	9
11	11	7	7	5	5
10	10	10	10	13	13
10	10	4	4	15	15
20	20	8	8	12	12
5	5	13	14	8	8
8	8	8	8	10	10
10	11	14	14	10	10
18	18	9	9	9	9
16	16	10	10	8	10

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
8	8	7	7	11	11
12	12	16	21	11	11
8	8	12	12	13	13
9	9	13	17	8	8
3	3	13	13	9	9
7	7	15	15	6	9
13	13	10	14	14	16
12	12	8	8	12	12
5	5	8	8	16	21
7	7	11	11	8	14
8	8	9	9	9	12
6	6	9	9	8	8
14	14	14	14	18	18
15	15	10	10	9	9
11	11	7	8	8	8
11	11	12	14	6	6
11	11	11	11	13	13
15	15	14	22	15	15
17	17	8	9	13	14
9	9	7	10	9	9
14	14	9	9	15	15
10	10	7	9	11	11
15	15	8	8	15	19
15	15	11	15	11	11
10	10	11	13	12	12
7	7				
11	11				
10	10				
14	14				
14	14				
13	13				
7	7				
6	6				
3	3				
5	5				
15	15				
13	13				
8	8				
3	3				
16	16				
9	9				
11	11				
10	10				
10	10				
4	4				
12	12				
11	11				
16	16				
17	17				
6	6				

Field Data for Vertical Slopes

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
21	21	8	8	14	14
13	15	6	6	11	11
15	15	6	6	11	11
11	11	8	8	10	10
14	14	14	14	12	12
10	11	9	9	10	10
8	8	15	15	9	9
14	14	8	8	12	12
13	13	10	10	13	13
8	8	12	12	10	10
9	9	12	12	6	6
14	14	5	5	8	8
6	6	8	8	10	10
12	12	11	11	9	9
5	5	7	7	18	18
15	15	11	11	10	10
8	8	13	13	15	15
11	11	11	11	8	8
16	16	22	22	10	10
8	8	8	8	6	6
6	6	15	15	14	14
6	6	18	18	8	8
9	9	13	13	12	12
9	9	8	8	10	10
15	15	9	9	13	13
18	18	3	6	15	15
18	18	8	8	15	15
14	14	9	12	11	11
8	8	13	13	13	13
11	11	11	11	8	8
9	9	15	18	11	11
11	11	5	5	7	7
13	13	8	8	7	7
8	8	6	6	7	7
10	10	16	16	12	12
10	10	12	12	8	8
16	16	14	14	5	8
11	11	7	7	14	14
14	14	6	6	19	21
10	10	15	15	14	14
11	11	10	10	10	10
13	13	5	5	11	11
14	14	4	7	7	7
11	11	8	8	10	10
18	18	8	8	6	6
10	10	9	9	10	10
6	6	11	11	10	10
11	11	12	12	11	11
5	6	9	9	9	9
8	8	5	5	13	13

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
12	12	11	11	11	15
6	6	11	14	13	13
8	8	8	8	10	10
14	14	14	14	14	14
10	10	6	6	11	11
10	10	6	6	7	7
6	6	4	6	7	7
18	18	11	11	13	13
19	21	6	6	10	10
11	11	11	11	13	13
15	16	3	3	13	13
7	7	1	34	16	16
12	12	11	11	17	17
10	10	16	16	2	7
10	10	12	12	7	7
11	11	6	6	7	7
15	15	8	8	12	12
12	12	12	12	15	15
21	21	9	9	10	13
14	14	14	14	15	15
9	11	7	7	17	17
18	18	12	12	16	16
9	9	6	6	9	9
14	14	10	10	7	7
8	8	10	10	10	10
19	19				
8	8				
16	16				
18	18				
11	11				
8	8				
11	14				
11	11				
15	15				
10	10				
14	14				
18	18				
12	12				
7	7				
18	18				
14	14				
5	5				
12	12				
13	13				
14	14				
8	10				
15	15				
13	13				
8	8				
16	16				

Field Data for Vertical Slopes

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
15	17	7	7	9	11
15	15	8	8	15	15
8	8	3	3	13	13
10	12	4	4	13	13
8	8	6	6	15	17
10	10	5	5	7	7
3	3	13	13	8	9
3	3	15	15	6	6
5	5	12	12	6	14
5	5	11	11	11	15
7	7	8	8	10	10
16	16	5	5	9	10
6	6	6	6	15	20
8	8	10	10	13	16
10	10	18	18	9	9
13	13	10	10	12	12
5	5	4	4	12	12
7	7	10	10	9	11
5	5	18	18	14	15
8	10	8	12	7	7
8	8	14	14	12	22
11	11	11	11	10	10
12	15	13	13	6	6
12	12	14	14	8	8
11	11	11	14	7	7
13	13	8	8	8	11
11	11	7	7	8	8
15	22	3	4	8	8
14	15	8	12	14	14
19	22	5	5	9	9
10	11	5	5	20	20
11	12	6	6	12	13
10	10	10	10	8	19
10	12	12	12	10	12
14	18	15	15	12	12
12	12	15	15	15	17
8	8	20	25	14	21
10	15	7	7	17	18
13	14	17	17	10	10
11	17	10	10	8	14
20	24	8	8	8	12
12	14	7	7	8	15
17	19	16	17	12	15
15	19	9	14	11	11
16	18	2	2	18	18
10	13	8	11	15	16
10	15	11	11	8	8
10	10	10	11	7	7
13	16	10	10	10	10
14	14	14	15	7	8

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
19	20	15	15	11	12
13	14	15	18	15	15
18	18	7	9	13	14
12	13	8	8	20	20
20	21	15	15	15	16
13	21	6	6	7	7
10	12	10	14	10	10
4	4	11	11	8	10
6	6	10	10	14	14
3	3	10	10	8	8
17	17	7	10	14	14
17	21	11	13	8	8
23	25	14	14	14	19
5	8	13	15	16	22
7	14	11	11	8	10
10	12	11	11	7	9
10	10	11	15	10	10
5	5	6	6	10	10
9	9	10	10	10	10
10	14	5	5	12	12
13	16	10	10	17	17
10	16	12	12	10	10
18	19	16	17	5	5
4	4	12	12	9	9
18	18	6	6	5	19
15	30				
14	15				
8	8				
14	14				
15	15				
15	16				
10	10				
15	15				
16	18				
16	18				
14	17				
14	14				
13	13				
10	11				
9	10				
8	8				
12	14				
12	20				
14	14				
12	12				
18	19				
5	8				
13	17				
4	4				
8	8				

Field Data for 0.25H:1V Slopes

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
1	4	5	6	2	2
3	4	3	1	7	8
9	11	7	9	2	2
2	4	2	3	4	3
7	12	3	1	5	7
2	2	5	7	3	5
1	3	1	3	7	3
7	20	1	19	3	4
1	4	1	3	1	10
5	6	4	5	1	10
2	5	2	3	6	5
4	7	3	2	2	5
2	2	4	4	3	4
2	2	2	5	2	6
1	3	2	3	2	12
1	5	1	2	3	3
5	5	5	3	2	3
3	4	1	8	3	2
1	2	1	14	6	6
3	1	1	14	2	10
2	2	7	5	1	17
3	3	1	9	1	13
3	2	7	6	7	7
3	8	1	13	3	3
4	5	1	14	3	2
2	3	2	2	2	3
3	7	5	7	7	3
1	11	1	12	5	9
2	1	4	3	1	20
2	10	4	2	7	6
1	23	2	2	1	18
6	6	6	3	7	4
1	3	2	2	2	2
8	4	2	5	7	8
7	8	3	3	2	2
6	7	3	1	4	3
2	3	5	5	2	4
5	2	2	2	4	6
4	12	7	9	5	5
4	3	5	12	3	5
3	3	1	8	2	16
2	1	2	11	4	4
1	2	2	2	1	5
1	3	2	4	3	7
3	13	1	9	1	17
2	6	5	3	1	1
4	4	3	2	2	1
3	3	5	3	2	2
3	3	2	4	2	14
2	2	4	4	1	13

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	7	5	6	2	1
2	3	2	2	2	2
2	4	4	4	1	21
3	3	4	3	3	1
5	5	2	2	4	4
2	2	9	14	1	1
1	2	3	3	9	9
2	2	1	11	2	9
4	1	1	12	2	2
5	10	7	6	2	2
3	3	1	7	4	3
5	5	3	2	3	5
4	4	3	5	3	3
2	3	2	3	2	7
1	4	2	8	3	3
3	5	1	13	3	2
4	1	4	2	2	1
3	9	3	4	3	3
2	8	3	6	2	1
3	3	2	2	4	5
2	1	3	2	3	3
1	16	5	2	2	1
1	15	3	2	2	3
1	1	4	8	2	3
2	1	1	12	2	7
2	2	1	13		
5	7	7	9		
1	2	2	7		
1	6	2	13		
2	3	6	5		
3	4	2	5		
1	14	4	6		
7	10	3	3		
1	5	2	4		
7	9	3	5		
7	9	1	22		
1	1	5	10		
1	8	2	4		
1	3	4	4		
3	4	3	4		
5	5	2	10		
6	10	1	9		
3	4	2	5		
4	1	5	3		
6	6	2	7		
2	4	4	6		
4	9	4	2		
2	9	4	4		
4	4	2	2		
2	2	5	7		

Field Data for 0.25H:1V Slopes

40-Foot Slope with a 6H:1V Catchment Area					
1-foot	1-foot	2-foot	2-foot	3-foot	3-foot
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
5	6	3	3	7	7
5	6	7	4	2	8
1	6	1	1	4	2
5	5	2	14	7	4
4	4	3	7	7	7
1	12	3	5	7	7
3	6	1	5	2	16
5	6	1	6	7	7
4	9	3	3	5	6
4	4	1	5	2	8
1	4	4	1	3	3
9	10	5	5	1	10
4	4	5	5	5	5
5	3	4	4	6	4
1	1	3	1	2	7
4	2	2	8	2	1
1	5	2	14	2	5
2	2	4	4	5	3
2	1	3	3	3	5
1	4	5	8	2	2
1	6	4	2	5	3
1	2	3	2	3	6
1	1	2	11	3	5
2	2	1	1	2	3
4	4	3	5	1	16
3	3	4	6	2	3
1	6	4	9	3	4
1	3	4	4	3	7
1	1	5	6	3	3
1	4	5	5	4	4
5	2	4	3	3	3
2	2	5	5	6	7
1	4	8	9	4	2
1	2	3	4	5	12
6	2	2	4	3	14
4	7	1	2	3	9
1	1	1	6	3	3
4	9	3	3	6	6
15	16	5	1	4	9
3	4	4	5	6	8
1	3	3	7	2	1
2	3	2	4	4	4
3	4	7	7	4	6
1	3	4	3	3	2
3	4	3	5	3	7
3	1	7	7	8	11
3	6	6	7	5	6
8	5	3	7	6	5
5	7	5	8	4	4
1	1	3	4	5	5

40-Foot Slope with a 6H:1V Catchment Area					
1-foot	1-foot	2-foot	2-foot	3-foot	3-foot
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	13	2	5	4	3
2	11	1	1	1	10
2	3	3	7	7	6
6	5	4	7	5	6
8	7	8	13	6	2
6	4	2	7	1	3
8	17	1	7	4	4
2	2	5	2	4	4
10	13	5	5	4	10
5	5	5	5	2	2
1	2	10	15	5	3
3	4	4	4	7	2
1	4	5	5	8	15
1	4	3	8	3	3
1	8	5	8	4	3
7	8	5	17	4	4
1	1	3	4	3	3
2	1	5	5	3	3
11	12	2	2	2	6
5	3	3	8	4	11
6	6	5	5	3	8
3	3	4	2	4	3
10	17	2	4	2	2
1	8	1	12	3	5
7	8	4	5	8	2
3	9				
1	2				
2	4				
1	6				
4	5				
3	5				
2	6				
1	5				
3	6				
1	7				
3	4				
2	7				
1	1				
2	1				
2	3				
3	4				
4	4				
2	11				
4	8				
6	5				
2	4				
4	3				
1	3				
2	4				
1	5				

Field Data for 0.25H:1V Slopes

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
5	11	2	10	7	12
3	5	4	8	1	20
1	3	2	18	4	11
8	18	1	3	5	9
2	5	1	7	5	7
3	7	1	30	3	6
3	3	3	6	6	22
1	1	2	26	12	25
3	10	3	13	5	6
5	8	6	13	5	5
3	8	1	8	3	11
5	8	1	19	7	7
3	7	2	7	5	5
3	3	3	6	3	6
2	2	5	9	8	12
4	9	3	3	7	15
3	3	6	10	1	15
1	4	3	7	2	8
6	13	1	5	1	3
5	12	6	9	1	19
4	13	2	13	3	13
5	6	4	10	4	9
1	4	3	20	8	14
2	3	3	12	3	3
4	6	8	11	9	22
8	13	2	8	5	5
6	7	7	11	3	5
2	3	7	7	3	6
3	4	7	9	3	18
13	17	7	14	4	9
3	8	2	2	5	14
2	6	4	4	2	2
5	11	6	11	4	6
2	5	2	8	3	21
4	7	6	6	6	6
2	6	3	3	3	8
3	3	1	2	2	6
5	7	3	6	9	11
2	2	3	3	4	4
1	1	5	21	7	7
4	4	3	4	1	13
4	16	8	11	2	12
5	5	4	4	3	8
7	7	2	15	8	28
10	10	4	7	4	4
10	16	5	8	5	18
5	6	3	9	1	11
3	3	1	2	3	7
2	3	3	10	3	3
3	3	5	13	8	33

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	4	4	16	3	3
3	3	7	8	4	10
7	17	7	13	4	17
2	6	1	13	2	5
3	12	7	8	2	11
4	4	5	6	2	13
6	9	3	3	2	6
4	4	5	10	3	9
8	8	2	6	2	2
6	10	6	9	4	4
5	5	2	5	5	7
4	4	4	29	8	11
5	10	3	8	4	6
6	8	2	7	3	3
5	5	3	3	2	2
1	3	5	4	6	7
6	6	3	3	7	8
8	12	4	5	6	7
4	5	3	8	4	24
7	7	2	2	3	3
4	10	7	21	3	3
4	4	5	14	7	7
5	8	5	5	1	21
1	6	5	20	3	13
1	4	6	19	3	20
3	8	3	3		
4	10	3	14		
3	13	4	14		
3	13	3	17		
6	7	8	6		
1	3	3	10		
5	8	5	12		
2	2	3	8		
2	3	4	7		
5	11	4	11		
9	10	2	14		
3	7	4	13		
7	8	2	4		
5	7	2	8		
1	3	2	12		
1	18	2	13		
3	5	5	7		
1	1	3	8		
4	11	1	5		
1	1	1	33		
7	10	4	14		
10	11	2	5		
7	17	2	2		
1	1	2	34		
2	2	5	18		

Field Data for 0.25H:1V Slopes

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
5	4	6	3	3	7
3	4	12	15	9	6
2	2	1	9	3	3
4	8	18	19	8	1
5	3	6	10	4	3
15	17	11	12	13	21
15	20	3	5	2	11
15	12	1	1	4	3
1	1	2	28	7	10
5	7	11	11	12	19
1	1	2	5	2	10
15	27	8	8	5	5
2	2	12	13	6	15
5	7	3	5	6	7
8	5	7	1	7	12
7	12	1	7	8	5
2	7	2	2	5	4
2	3	5	2	11	11
7	11	5	5	3	2
6	6	10	7	9	8
1	6	4	15	12	9
10	15	3	2	3	2
1	2	2	8	4	5
1	1	5	2	3	3
5	1	2	8	10	10
2	1	2	14	8	5
5	10	10	17	6	4
3	2	1	8	4	17
7	5	6	11	2	4
9	9	2	8	13	17
14	16	4	3	5	10
14	22	11	11	5	3
5	4	4	6	5	2
10	10	2	2	11	13
10	15	2	7	5	9
17	17	2	4	6	4
6	4	6	4	6	4
10	10	13	30	3	18
3	2	1	10	5	2
5	7	9	7	6	4
2	2	5	2	3	18
1	6	7	2	5	2
2	8	14	21	3	4
5	6	3	4	3	9
6	6	2	6	9	13
4	4	12	12	12	16
3	4	7	7	4	6
2	2	11	19	4	5
5	7	3	4	4	7
2	2	11	17	3	14

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	3	7	15	2	6
12	13	5	5	5	10
10	10	9	17	2	2
10	15	4	9	3	11
14	14	7	7	7	8
3	6	2	2	8	5
12	19	5	4	9	14
4	7	1	6	3	5
17	30	2	4	5	15
1	7	13	28	5	5
7	7	2	13	8	10
5	11	9	8	6	14
5	5	2	3	8	10
2	3	2	1	4	2
6	5	10	14	3	13
6	4	8	10	7	5
8	11	3	9	2	15
4	7	4	7	2	2
4	5	1	13	9	9
14	14	5	5	5	10
12	16	5	3	3	20
4	3	3	8	3	23
14	21	3	2	13	15
2	1	10	12	5	6
6	8	16	28	7	7
6	16	9	8		
8	15	3	8		
5	10	4	17		
2	2	3	3		
4	4	1	9		
5	5	5	1		
9	16	6	7		
3	5	5	3		
15	17	2	4		
9	14	4	10		
12	11	5	12		
15	15	2	2		
3	7	14	20		
2	1	5	12		
10	12	1	2		
1	6	1	6		
2	2	10	10		
4	7	3	1		
6	7	2	3		
1	1	2	3		
16	16	5	5		
7	9	2	15		
4	4	13	14		
1	6	2	8		
2	10	2	2		

Field Data for 0.25H:1V Slopes

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
6	7	2	2	5	4
6	9	3	4	2	4
1	6	14	24	2	3
8	10	2	10	8	12
10	15	5	21	2	15
5	8	7	15	6	15
1	4	7	7	2	19
3	4	7	21	5	19
12	12	7	10	2	7
2	5	2	2	4	26
5	5	2	15	6	5
4	12	6	7	7	7
2	1	6	12	4	4
8	8	6	12	8	11
5	10	2	17	11	17
4	5	2	8	5	18
2	22	2	11	3	43
1	5	2	2	25	30
1	3	14	22	2	7
15	16	2	3	2	16
5	8	10	17	2	7
1	1	10	22	1	28
13	16	10	8	2	16
9	9	3	9	4	10
5	12	3	1	2	5
5	5	1	2	6	12
5	6	8	8	4	9
5	6	3	3	3	5
3	5	2	2	2	3
1	1	2	3	1	35
12	28	6	17	1	30
12	15	2	2	5	12
16	18	3	6	2	3
10	16	3	3	11	22
9	11	4	6	6	4
11	17	2	2	2	17
7	10	8	7	2	6
2	2	5	8	2	19
13	26	7	14	2	10
4	5	9	15	2	16
4	5	7	18	2	17
13	14	8	10	1	19
5	10	12	21	1	14
5	14	1	14	4	4
2	1	1	24	1	19
6	7	6	7	9	21
7	20	1	26	2	20
1	1	2	12	4	24
7	1	4	4	9	17
6	10	1	1	4	5

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
12	15	6	6	8	8
1	9	4	2	1	49
7	7	2	8	8	8
6	8	5	5	1	32
12	30	10	13	3	15
12	19	5	1	2	20
5	4	1	28	7	9
12	17	4	23	6	20
2	1	4	17	3	2
12	17	12	33	3	10
7	12	7	25	3	15
7	7	3	6	3	3
12	20	6	10	12	33
2	7	4	15	4	5
1	1	7	9	4	20
3	3	3	21	6	7
10	7	13	23	2	34
3	6	20	34	7	5
4	15	8	22	3	28
2	3	9	21	7	7
2	2	12	28	12	19
12	26	3	9	3	23
3	1	2	6	9	7
3	10	1	7	9	8
4	12	6	25	7	11
1	24	3	17	2	15
6	6	9	27		
2	3	1	21		
16	19	8	8		
2	4	11	31		
3	3	7	14		
6	5	3	3		
8	8	1	15		
3	2	1	13		
6	8	3	12		
4	1	5	24		
4	9	1	16		
3	10	9	17		
3	2	3	3		
12	17	6	23		
7	15	5	5		
11	16	14	28		
10	19	8	23		
2	1	7	15		
7	23	3	4		
1	4	6	6		
1	5	7	7		
14	17	4	7		
3	9	1	3		
7	18	1	4		

Field Data for 0.25H:1V Slopes

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	40	3	16	4	15
6	7	16	36	3	24
3	20	4	50	3	35
3	9	11	15	4	2
2	30	4	15	10	35
1	22	4	23	3	37
10	34	4	14	7	7
3	8	8	11	7	8
2	6	4	15	15	71
9	4	6	14	3	8
9	14	6	44	10	32
3	4	2	3	4	4
8	8	7	24	4	36
2	5	12	49	5	22
7	14	14	27	6	65
2	13	6	31	3	1
4	21	12	45	10	31
15	29	2	8	4	24
7	26	3	18	6	37
7	24	5	40	4	70
2	14	3	25	5	21
2	7	13	37	6	47
5	6	2	20	6	55
3	7	15	45	5	19
9	14	3	12	3	36
7	9	5	5	12	20
7	8	2	34	2	18
7	7	10	15	14	46
2	2	2	3	5	76
2	3	11	30	5	4
2	10	4	8	7	65
3	3	11	53	6	6
2	16	4	27	3	29
2	3	5	5	10	10
4	16	7	37	3	37
9	36	11	20	6	8
11	15	4	5	7	48
12	39	7	14	8	12
13	21	2	20	3	8
3	4	5	35	5	4
5	5	5	17	9	14
3	3	4	25	4	42
3	7	3	5	3	8
7	14	3	5	6	36
3	25	5	8	4	4
3	20	5	7	3	13
2	5	7	24	5	22
4	13	4	11	4	32
2	9	15	37	3	26
10	31	2	9	6	1

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	14	9	45	3	17
2	21	3	16	3	44
5	8	4	4	16	35
4	23	4	9	6	10
2	2	7	55	7	17
14	32	6	23	4	32
6	22	3	20	3	25
7	16	7	38	3	49
3	17	10	17	4	16
6	6	7	27	5	7
3	13	15	28	9	35
1	22	7	8	7	8
15	37	4	9	6	50
6	28	4	5	6	14
2	23	8	22	3	15
11	13	5	49	2	51
10	27	10	27	2	54
6	4	6	10	2	15
7	12	4	28	6	2
19	21	5	19	14	58
2	14	5	34	2	7
2	11	7	28	5	9
6	28	3	17	4	31
10	27	7	65	3	23
5	31	5	24	9	27
5	14	9	16		
5	9	7	67		
4	12	4	17		
10	35	4	6		
6	6	9	18		
2	6	3	17		
6	11	7	41		
3	8	3	27		
6	18	7	41		
2	14	3	27		
2	19	5	21		
4	4	5	35		
4	16	10	16		
8	8	6	54		
4	9	2	32		
6	13	10	43		
17	38	10	14		
3	5	3	24		
10	10	9	40		
5	12	3	21		
5	6	5	16		
9	27	3	6		
3	2	7	13		
10	41	3	7		
3	5	5	40		

Field Data for 0.25H:1V Slopes

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
1	14	3	6	5	22
12	14	3	6	3	16
8	8	19	17	4	22
1	16	3	28	6	41
12	15	2	24	9	27
7	24	14	13	9	9
5	8	4	12	6	14
11	12	10	7	5	13
7	7	4	18	4	5
12	14	3	3	3	12
8	17	2	7	10	14
7	7	1	21	18	18
14	19	1	28	12	20
7	3	12	16	19	19
16	17	1	6	3	12
5	3	15	21	4	48
3	3	5	7	7	7
6	11	7	17	9	9
1	16	6	19	3	31
7	7	3	7	5	17
8	10	3	12	3	36
7	7	3	13	3	47
2	27	4	17	10	11
4	7	18	12	8	8
2	29	2	8	10	17
4	4	15	17	9	21
15	12	2	2	5	24
4	6	13	11	6	22
4	5	6	2	3	14
4	5	4	15	4	21
2	2	2	7	6	6
2	25	1	22	11	11
3	7	17	21	5	5
7	5	2	3	3	11
5	4	2	19	9	13
8	12	5	17	14	14
7	3	2	24	3	11
14	16	4	16	9	11
22	34	2	11	9	9
3	7	6	12	3	23
9	10	3	4	2	6
5	3	5	15	4	4
10	11	4	3	2	30
2	2	14	22	6	15
14	12	3	11	5	6
10	12	3	7	12	22
14	14	5	14	5	5
9	8	1	3	14	14
10	8	2	25	2	12
20	9	2	32	2	23

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
12	13	6	9	2	20
2	15	10	8	9	9
7	7	9	13	2	23
6	17	3	4	10	14
7	6	3	17	6	6
16	18	4	5	3	8
7	6	14	10	8	8
1	21	4	31	5	17
4	19	14	10	2	20
7	10	3	3	11	25
2	11	2	4	3	4
4	3	2	23	1	50
11	11	2	7	4	4
9	8	8	12	17	21
12	14	1	24	9	14
11	13	7	11	4	4
4	13	12	17	2	20
17	11	17	23	2	11
19	24	2	38	5	5
7	21	6	12	2	21
7	6	16	24	2	38
21	26	4	17	3	13
10	13	7	12	11	14
10	10	2	19	6	25
10	8	6	20	3	6
6	23	17	26		
2	11	2	4		
8	8	3	16		
13	13	3	16		
13	14	3	17		
10	11	2	36		
1	2	10	10		
13	13	22	30		
13	14	2	29		
10	11	1	30		
1	14	10	26		
2	2	10	12		
17	13	1	5		
8	16	17	15		
14	21	14	15		
20	21	3	27		
6	10	3	20		
2	4	12	17		
9	7	7	6		
1	16	2	17		
9	8	14	5		
15	22	10	5		
4	2	11	15		
2	6	5	3		
6	13	15	15		

Field Data for 0.25H:1V Slopes

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	4	19	20	3	26
16	23	7	7	11	20
16	29	7	9	6	19
1	28	11	13	3	23
3	9	4	15	9	11
14	19	8	16	5	10
7	14	9	9	9	23
3	3	4	34	7	18
5	5	2	56	3	7
6	6	7	11	5	10
1	17	5	10	1	43
4	18	5	11	10	15
1	21	4	4	20	20
9	9	12	32	5	27
5	7	4	9	5	7
1	11	18	27	1	8
25	38	2	24	2	43
3	4	8	10	10	23
6	20	2	23	4	7
10	11	10	10	10	20
17	18	12	18	4	42
20	22	14	18	9	24
3	3	4	7	11	11
1	15	11	30	5	6
23	47	10	27	18	37
13	16	2	21	7	14
10	12	1	5	2	30
16	21	1	5	2	27
17	18	14	14	12	12
7	13	9	15	5	5
10	10	7	7	2	27
25	26	5	6	6	30
1	17	3	7	3	14
12	12	23	23	4	25
1	17	2	13	10	12
5	5	3	14	5	5
9	17	23	28	4	36
1	30	7	11	12	26
3	16	4	5	10	12
2	8	10	27	7	7
4	10	8	9	8	28
14	18	5	7	2	45
10	12	9	27	9	16
17	19	2	31	5	7
8	8	2	22	3	55
10	12	3	18	6	10
1	17	2	33	3	40
8	8	4	14	7	25
6	18	3	16	3	30
4	14	3	11	4	38

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	18	10	23	14	17
3	14	3	3	13	19
2	16	2	60	2	13
1	36	17	18	10	14
4	20	5	10	10	15
11	11	2	12	5	9
17	21	3	21	2	31
18	20	5	22	17	30
16	16	5	30	4	14
3	27	1	15	3	3
5	14	4	10	3	41
10	23	11	17	12	22
16	19	15	39	15	20
4	10	2	31	3	5
20	20	24	24	14	14
3	33	2	20	10	12
3	13	2	24	2	38
7	9	5	10	5	20
3	7	2	7	14	24
19	29	2	29	15	21
10	15	23	43	4	12
3	14	2	25	4	16
3	11	11	19	3	20
1	10	2	28	4	48
4	13	10	13	4	4
2	22	3	3		
3	20	2	6		
16	20	3	12		
10	14	3	8		
10	23	10	20		
1	14	9	36		
13	13	14	17		
3	9	5	6		
7	7	3	37		
2	10	4	5		
11	12	4	18		
3	13	11	25		
10	11	2	23		
7	9	15	20		
7	11	4	33		
7	11	10	12		
22	31	3	32		
4	16	10	25		
7	10	9	19		
24	31	15	31		
12	15	4	4		
8	9	6	15		
4	14	2	32		
14	14	10	25		
9	9	15	17		

Field Data for 0.25H:1V Slopes

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	2	7	61	10	37
4	34	14	69	3	99
1	41	1	48	5	34
4	4	16	20	2	53
1	41	2	31	11	32
4	4	1	10	4	25
7	14	8	11	4	32
5	14	2	20	5	35
1	37	9	28	3	20
1	29	2	18	3	25
20	27	2	17	3	12
5	24	2	43	7	15
6	14	7	29	7	15
15	67	2	44	12	65
3	6	6	33	3	77
15	17	2	70	3	32
14	24	2	7	3	53
5	17	21	33	8	24
9	10	11	33	4	4
2	9	2	2	4	10
2	29	6	13	6	37
4	4	7	26	17	61
5	17	2	6	14	71
2	7	1	13	3	3
3	12	2	10	5	17
6	20	6	30	5	5
4	10	3	44	2	33
2	14	4	3	7	7
5	5	1	26	5	20
1	18	1	72	15	42
2	2	16	43	2	36
1	49	5	22	9	18
1	8	8	12	3	84
6	28	2	18	9	57
10	37	6	15	6	15
7	15	7	11	6	34
8	25	1	80	3	21
1	34	5	19	2	38
14	39	4	28	5	34
4	4	6	15	7	7
2	8	3	4	5	30
12	20	2	15	7	10
3	6	3	3	3	56
17	21	11	15	3	25
4	15	5	5	15	28
7	16	4	20	4	20
3	7	7	11	3	23
16	37	7	34	3	5
2	3	15	19	11	40
2	2	15	22	15	53

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	4	14	72	7	10
10	45	10	17	3	28
3	9	2	23	3	53
4	8	3	21	7	30
9	37	7	23	3	40
6	38	7	38	7	7
4	5	3	2	6	70
3	10	4	19	11	49
5	34	11	29	9	10
15	44	4	35	10	17
18	28	11	21	5	5
16	30	5	24	9	29
5	5	14	37	6	13
3	9	1	48	2	55
4	13	5	17	4	75
3	5	3	12	10	12
1	34	3	4	6	49
10	11	2	39	3	55
2	26	9	35	3	70
1	5	3	7	4	5
5	39	10	28	3	17
9	29	5	12	3	34
15	18	3	9	5	40
14	52	10	41	5	10
2	15	5	14	3	7
2	17	9	7		
6	8	2	7		
1	17	2	44		
15	57	3	13		
14	21	5	16		
2	28	2	6		
7	10	10	10		
7	12	15	63		
8	22	15	37		
1	46	4	22		
8	13	5	40		
5	44	3	46		
5	10	5	20		
2	2	5	31		
12	15	11	15		
15	34	5	25		
20	45	5	8		
1	6	2	2		
11	17	10	12		
7	12	2	62		
4	4	2	61		
7	24	11	30		
15	15	12	41		
6	11	2	20		
18	55	6	35		

Field Data for 0.5H:1V Slopes

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	5	0	17	7	7
0	5	3	10	5	5
0	4	2	4	2	12
0	5	0	11	3	11
0	7	0	17	4	7
0	10	0	13	2	17
3	3	3	3	3	4
0	3	0	6	1	4
2	4	3	3	3	8
0	3	0	9	2	14
5	7	4	12	3	5
3	5	0	6	4	4
0	5	0	15	4	7
0	5	0	6	1	9
0	5	5	8	2	9
0	7	6	6	2	13
0	4	4	9	3	9
0	6	5	8	3	3
0	9	0	16	2	11
0	5	0	9	5	5
3	3	1	5	2	10
0	0	2	9	3	6
0	3	0	5	3	3
0	8	0	10	2	16
0	4	5	5	2	9
0	9	0	7	4	12
0	5	0	12	1	4
0	8	0	7	3	3
1	3	3	10	5	5
0	8	0	8	2	6
0	7	0	5	3	8
4	4	0	6	6	11
0	5	2	6	3	3
0	4	1	8	3	8
0	5	4	7	2	9
3	3	1	1	1	10
6	6	4	6	5	9
3	3	4	10	3	15
4	4	0	11	4	6
0	1	0	13	4	15
0	0	5	5	3	8
4	7	5	5	6	6
0	4	2	6	5	5
5	8	0	7	3	14
0	7	0	14	4	12
0	5	0	9	2	9
0	3	0	15	2	9
0	4	0	16	4	10
0	9	0	12	5	5
0	7	5	10	2	15
0	3	0	9	2	10

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	4	0	15	3	7
2	2	3	7	2	2
0	9	5	9	5	5
0	3	3	3	3	7
0	9	3	11	3	10
8	8	0	7	1	10
3	3	5	5	1	6
0	2	0	14	4	8
0	5	6	6	4	8
2	2	0	11	4	4
7	7	0	10	2	16
0	4	1	4	2	3
0	3	0	12	4	7
0	11	2	7	4	11
4	9	0	8	6	11
0	5	0	14	6	11
0	7	0	9	7	7
0	5	0	16	4	4
0	5	0	8	3	3
0	10	0	8	3	7
0	11	0	12	5	13
4	4	0	8	2	10
0	3	0	10	3	7
0	5	0	20	5	6
0	12				
5	5				
3	3				
0	3				
0	5				
0	6				
5	8				
0	4				
0	5				
0	9				
0	7				
0	4				
5	5				
0	8				
4	10				
0	0				
5	5				
3	3				
0	2				
0	5				
0	6				
4	4				
2	2				
4	8				
0	10				

Field Data for 0.5H:1V Slopes

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	3	4	6	0	16
3	5	3	11	0	18
0	11	2	8	0	12
0	9	0	10	0	10
0	8	0	26	0	15
0	8	0	20	0	12
1	6	1	12	0	17
1	6	0	16	1	3
0	16	1	4	0	25
0	7	3	6	0	13
0	3	4	13	0	17
0	12	0	8	0	3
0	10	2	10	0	11
0	8	0	10	0	10
0	16	0	12	0	15
4	7	0	10	0	8
0	8	0	10	0	13
0	16	0	8	3	5
0	5	0	20	0	16
0	12	1	1	0	10
4	7	0	12	0	5
2	2	0	7	0	12
3	9	0	14	0	12
1	1	0	11	0	25
0	5	2	8	1	2
1	3	0	15	0	10
3	3	0	16	1	6
1	3	0	20	0	16
1	3	2	6	0	20
0	12	0	10	0	12
0	9	0	16	0	16
2	2	0	22	0	17
0	3	0	13	0	5
4	16	3	7	1	11
0	9	0	17	1	6
4	6	0	10	1	5
7	15	0	17	0	8
4	7	0	8	3	6
0	11	0	13	0	5
0	12	0	5	4	10
0	9	1	4	0	12
0	16	0	19	0	5
2	2	0	15	0	10
0	4	0	10	0	17
0	7	3	3	0	20
0	21	0	7	4	8
0	4	0	23	0	18
0	8	0	17	0	7
1	7	0	17	0	13
0	7	4	8	0	13
0	3	0	23	0	13

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	7	0	7	0	11
0	5	0	7	0	10
0	8	0	9	0	10
0	10	0	19	0	12
0	13	0	7	0	17
0	7	0	8	0	20
0	13	0	17	0	7
0	7	0	13	2	7
0	15	0	13	0	22
3	5	0	7	0	15
0	13	5	9	3	8
0	7	0	15	0	15
0	9	0	11	0	18
3	7	0	6	0	10
0	5	0	15	0	15
0	14	0	17	0	11
2	3	1	1	3	3
0	0	0	10	0	7
0	13	0	11	5	24
0	10	0	17	0	17
0	5	0	10	0	17
0	11	0	15	0	12
0	16	0	11	0	7
0	8	0	6	0	12
0	8				
2	11				
0	10				
1	1				
2	2				
2	4				
2	6				
0	10				
0	6				
0	14				
0	13				
0	8				
2	2				
3	13				
2	2				
0	12				
5	11				
0	6				
1	4				
0	8				
3	14				
0	6				
1	1				
1	1				
1	4				

Field Data for 0.5H:1V Slopes

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	12	3	23	0	25
0	2	0	16	0	35
0	10	0	6	3	35
0	17	4	9	0	40
1	26	3	30	0	3
5	15	3	20	0	17
5	10	3	38	0	16
5	7	4	35	0	25
0	8	3	25	0	12
3	30	0	28	5	21
2	12	0	20	0	30
2	18	5	21	5	35
4	8	5	27	4	40
0	18	3	44	3	28
0	7	0	33	0	45
0	8	3	28	5	22
3	18	3	26	4	23
2	18	3	7	3	20
4	22	5	26	0	23
1	10	0	23	2	12
4	15	0	17	2	15
3	18	0	23	3	3
5	21	3	14	2	35
4	10	2	15	0	35
5	19	0	20	0	40
2	13	3	22	0	47
0	17	5	20	3	34
3	7	3	17	0	28
4	9	2	5	5	12
10	22	5	15	3	28
2	8	0	18	7	18
3	7	3	10	0	8
3	3	3	19	2	13
3	8	5	6	0	35
5	8	4	17	2	20
0	8	3	48	1	20
3	11	5	14	3	30
2	16	4	23	0	34
0	8	5	34	0	27
3	5	0	23	2	27
3	3	3	13	5	34
3	6	0	20	4	37
2	25	3	18	2	30
0	23	0	15	0	15
1	35	0	20	0	23
3	20	0	16	3	16
2	20	5	38	0	57
3	8	2	7	0	35
0	30	0	17	2	42
0	29	0	25	0	15
0	16	0	20	5	18

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
3	6	0	17	6	45
2	19	1	40	2	18
0	25	4	35	0	24
2	20	3	40	0	30
5	15	3	33	0	15
6	27	0	29	2	8
2	5	0	24	3	20
0	23	0	25	0	25
3	11	2	40	5	23
4	8	3	19	0	48
3	3	0	41	2	15
0	30	5	6	0	30
3	17	3	20	5	30
1	4	3	38	2	17
5	28	3	31	5	17
5	16	2	25	0	36
3	37	2	37	2	30
2	27	2	25	3	33
1	10	3	14	0	25
1	22	5	34	5	48
5	25	0	40	2	25
3	3			3	30
2	8				
2	28				
4	18				
1	4				
0	8				
0	6				
0	4				
5	23				
5	18				
3	5				
3	20				
2	14				
5	17				
0	10				
0	4				
0	11				
0	28				
4	8				
0	12				
5	27				
4	10				
2	10				
0	4				
5	24				
0	37				
0	13				
1	34				

Field Data for 0.5H:1V Slopes

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	5	10	12	6	9
9	10	0	5	11	17
11	16	12	17	6	6
12	13	7	11	8	8
10	10	0	15	6	14
7	7	0	8	11	15
5	7	5	6	11	16
8	17	4	7	8	8
1	1	6	8	11	18
8	16	0	11	8	15
8	10	1	5	8	12
3	3	14	14	0	15
8	8	5	9	10	17
9	11	8	8	5	9
13	21	8	15	8	8
10	13	8	8	7	16
9	13	5	18	8	17
1	1	10	16	10	13
7	10	5	15	8	8
10	16	7	17	7	11
3	9	7	11	8	8
7	9	12	12	12	16
7	8	7	7	8	12
0	13	5	5	4	4
0	7	13	25	8	11
0	6	9	14	7	13
0	6	8	8	15	25
7	7	9	12	3	10
7	7	10	12	11	11
0	1	6	8	10	10
10	14	7	13	0	12
3	4	10	13	8	17
2	3	10	17	0	13
2	5	7	7	12	18
1	1	12	22	0	10
5	7	0	10	8	9
6	7	10	12	7	16
7	7	10	12	6	11
6	8	8	14	0	16
1	2	0	12	0	12
2	2	5	9	12	17
4	5	9	10	0	17
5	16	6	12	5	18
3	6	9	16	8	11
5	6	8	11	5	5
0	6	0	7	18	23
0	1	5	12	0	11
3	5	7	13	0	12
14	20	5	7	10	16
8	10	6	11	5	17
10	12	5	11	8	18

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
12	15	5	11	3	7
0	7	10	17	1	11
5	5	0	15	1	1
8	10	0	22	13	16
4	4	7	8	10	17
14	20	11	11	7	12
0	2	7	12	7	7
9	13	6	13	4	7
0	3	10	12	0	8
8	8	11	12	6	11
4	6	5	9	8	11
6	7	7	15	0	14
6	11	7	8	5	22
2	2	7	22	8	10
6	6	11	11	0	8
5	6	8	10	10	16
0	5	5	15	10	12
3	3	5	8	6	10
5	7	6	13	10	12
8	11	0	8	11	15
7	11	5	15	8	14
10	10	7	7		
0	1	15	17		
2	2	10	12		
0	3				
5	6				
6	7				
10	11				
6	13				
13	18				
5	7				
7	7				
9	12				
3	5				
5	7				
0	5				
7	7				
6	6				
9	10				
0	0				
12	16				
7	10				
8	8				
0	1				
4	5				
15	17				
4	7				
5	5				
6	6				

Field Data for 0.5H:1V Slopes

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
11	14	5	9	7	17
10	15	7	9	5	8
3	10	6	12	7	10
4	10	0	21	10	18
9	22	0	12	12	20
4	8	12	17	0	18
2	9	10	17	10	20
10	10	0	8	5	12
10	12	11	16	10	13
2	8	8	12	10	28
2	4	10	13	7	7
8	15	0	12	12	23
10	10	0	8	4	4
4	8	5	10	12	17
11	13	11	14	0	10
15	17	10	14	12	28
14	18	13	23	7	14
3	13	0	12	8	13
3	8	4	10	5	17
6	6	4	7	13	23
13	18	0	4	10	21
12	12	8	15	5	8
14	14	12	17	11	11
9	9	6	16	7	13
5	5	8	14	10	17
0	7	7	16	10	12
8	12	11	13	10	10
8	13	15	37	9	12
14	16	12	12	12	35
8	8	12	21	7	10
8	13	0	11	10	20
8	13	6	10	0	6
5	6	6	10	6	10
9	11	7	17	6	15
7	8	11	14	5	13
6	19	5	12	7	11
7	13	6	17	8	8
15	15	7	13	7	12
4	8	5	7	8	8
16	22	8	19	5	12
11	13	6	12	7	14
9	13	6	16	6	10
11	23	4	8	7	11
5	22	8	16	0	23
2	6	8	26	12	17
3	4	8	16	0	12
12	17	12	25	0	33
8	8	11	11	0	13
0	16	7	13	7	10
11	15	6	8	15	32
0	13	9	16	7	24

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	15	12	19	7	26
6	8	7	7	11	27
3	6	7	13	7	16
3	5	7	12	7	16
0	1	6	13	10	10
11	12	8	27	10	22
0	8	12	18	10	10
0	18	0	26	8	8
0	13	4	10	7	16
0	10	8	30	8	8
0	17	13	19	8	17
3	8	8	22	5	20
0	10	8	14	9	11
3	16	6	12	8	17
11	16	0	5	0	7
12	12	0	8	8	10
8	12	10	17	10	21
6	9	13	20	6	6
3	3	9	12	5	7
2	3	0	23	0	8
0	4	5	12	12	24
10	10	10	24	10	16
5	5			6	11
6	18				
10	12				
0	15				
10	10				
10	16				
12	12				
7	15				
9	13				
0	17				
0	7				
12	12				
3	10				
8	15				
5	8				
5	6				
8	12				
4	6				
5	5				
9	16				
7	10				
8	11				
0	13				
9	10				
0	7				
5	5				
0	9				

Field Data for 0.5H:1V Slopes

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	11	3	42	9	26
7	7	9	30	0	21
3	14	6	16	8	27
12	27	9	30	7	32
10	22	2	34	6	46
9	16	14	39	0	16
5	8	8	12	7	7
5	8	2	50	0	38
2	12	10	25	12	15
11	15	7	23	7	25
10	30	15	22	0	50
13	32	10	24	5	26
5	10	14	52	5	26
12	15	12	30	0	32
4	16	16	31	7	12
16	41	6	31	4	15
8	15	6	14	6	21
8	15	7	35	10	16
11	15	7	7	7	43
7	27	6	17	11	39
17	23	5	15	12	30
12	22	10	14	8	31
5	10	14	34	8	28
10	15	9	31	4	37
12	22	15	30	7	23
10	14	9	28	15	26
10	40	7	37	15	32
6	28	3	23	0	52
5	18	7	31	4	10
0	11	5	14	9	23
9	21	10	14	10	22
3	5	10	26	3	45
5	15	4	19	0	16
5	15	8	20	3	25
4	10	7	7	10	21
8	38	3	16	8	22
5	17	14	34	22	32
5	6	0	29	5	32
6	11	10	17	4	15
7	38	5	15	8	54
9	15	2	10	0	10
5	7	5	26	0	8
8	15	3	5	10	16
5	10	4	25	12	34
4	10	5	25	5	34
11	15	9	26	0	5
7	22	10	16	10	42
5	9	11	42	7	27
0	25	7	28	0	32
4	21	8	10	17	43
7	21	11	23	0	56

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
12	16	11	34	15	60
9	20	7	24	0	23
4	7	7	48	2	7
7	15	11	24	0	74
10	20	5	37	10	30
5	9	12	28	11	37
6	13	10	32	0	34
1	5	6	14	0	29
11	11	9	18	0	40
2	11	9	29	2	27
6	12	16	39	2	50
10	25	11	14	3	27
11	18	10	19	4	9
5	5	6	17	3	59
9	24	13	26	9	23
7	12	4	4	0	53
2	17	15	30	6	66
5	9	9	57	2	25
8	21	3	41	8	65
2	16	7	26	5	28
9	16	5	21	4	26
10	47	3	20	7	19
4	16	10	55	0	15
6	7	8	35	9	69
10	16				
8	21				
8	11				
16	37				
4	10				
15	23				
5	24				
6	14				
10	30				
6	7				
7	15				
11	20				
7	24				
7	10				
8	47				
3	40				
8	15				
0	10				
9	24				
7	23				
15	31				
0	16				
4	16				
6	20				
7	13				

Field Data for 0.5H:1V Slopes

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
6	7	7	7	2	16
6	6	7	11	2	19
16	16	13	13	12	12
4	6	6	12	13	13
15	21	11	20	5	11
7	8	4	4	11	11
0	28	6	22	7	7
12	13	13	13	6	6
11	11	5	17	9	9
0	7	18	24	2	22
4	4	10	10	18	18
3	4	13	13	15	15
6	9	5	9	16	16
5	11	5	7	9	10
5	6	5	10	5	6
3	10	13	13	5	10
6	6	13	13	5	8
1	2	0	20	12	26
9	10	6	8	10	10
7	7	5	15	11	17
9	9	7	16	20	24
11	18	5	6	19	27
15	15	4	13	14	20
3	3	6	7	4	9
9	13	6	9	8	8
14	17	3	12	10	16
18	21	4	20	2	29
7	7	2	4	3	14
0	6	1	3	0	36
1	7	3	20	14	16
3	3	21	22	14	14
0	16	3	5	10	18
5	5	4	4	5	15
3	6	6	6	5	8
3	4	10	13	8	8
6	8	5	18	10	10
5	7	9	17	9	12
4	15	0	16	6	18
0	6	19	19	7	22
4	4	8	8	10	12
13	13	4	6	10	15
13	13	3	3	9	14
12	13	0	0	2	16
9	14	7	7	1	3
11	11	10	15	15	22
2	4	11	17	10	11
4	5	7	9	10	20
3	5	10	16	3	27
3	3	8	10	7	7
0	8	9	14	15	25
12	15	7	16	11	11

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
3	3	3	4	3	22
3	3	4	10	13	17
3	6	0	6	9	17
11	14	13	13	13	13
6	6	3	7	5	5
6	6	0	12	3	11
14	14	15	27	10	16
13	13	17	17	9	17
13	13	2	3	13	17
7	7	11	16	3	16
5	10	5	6	0	23
3	4	1	9	2	18
3	5	3	5	0	6
5	5	11	16	6	6
9	9	14	23	10	15
11	11	0	4	14	14
13	13	11	12	3	13
5	14	20	23	0	15
3	5	10	10	4	4
7	7	4	4	7	7
3	3	11	11	5	11
3	5			3	13
3	3			9	13
3	5			18	18
3	5				
11	11				
5	7				
1	3				
3	4				
5	8				
4	5				
11	11				
5	6				
4	5				
0	16				
10	14				
4	7				
2	3				
0	14				
3	3				
11	11				
10	14				
15	15				
3	5				
3	9				
4	10				
3	5				
4	4				

Field Data for 0.5H:1V Slopes

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	11	15	30	17	23
5	5	10	15	0	2
4	4	9	20	7	9
5	10	13	13	11	29
7	7	8	10	7	7
0	5	10	17	11	12
0	30	10	23	0	34
2	4	3	8	11	13
14	24	9	9	10	21
0	18	5	7	20	27
8	11	0	14	6	8
3	3	4	23	14	18
0	18	10	15	11	20
0	2	13	17	3	5
3	3	16	20	13	14
0	10	7	7	9	9
0	26	9	9	8	8
2	3	0	30	9	13
13	17	8	19	5	8
10	27	12	16	7	7
7	7	0	16	7	17
0	14	0	19	10	13
4	4	0	15	6	11
4	4	0	0	9	14
3	3	12	25	7	7
7	7	2	2	15	27
5	9	3	3	2	11
7	8	0	0	0	8
8	13	2	23	4	6
10	18	2	5	11	27
3	3	14	17	9	21
6	6	9	12	10	13
4	6	17	22	0	50
4	4	0	25	10	19
4	9	0	32	4	10
11	13	9	11	8	30
6	6	8	8	8	15
5	5	7	10	0	10
9	11	8	8	10	10
0	17	9	9	5	8
0	13	0	19	10	19
4	4	4	10	11	16
6	8	9	9	5	10
0	3	6	12	7	7
8	8	8	11	10	13
10	14	7	9	5	5
6	13	10	17	0	28
0	12	8	8	12	12
12	13	6	9	11	26
8	8	4	8	8	14
2	9	7	11	5	8

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
15	15	6	12	4	10
9	12	12	18	12	12
11	12	14	17	11	19
10	10	8	8	7	10
1	16	0	16	4	12
9	10	6	7	15	15
5	12	5	5	7	7
3	6	15	20	5	6
7	11	0	24	8	9
0	11	0	13	0	29
8	8	2	12	5	24
15	18	3	6	5	10
2	2	0	14	7	17
0	19	18	21	5	10
1	1	6	10	5	11
7	7	12	24	4	7
0	13	9	9	21	21
5	5	0	13	15	23
6	6	7	7	0	17
15	26	6	9	7	9
10	16	8	11	8	10
6	6	3	10	0	27
10	14	5	9	5	9
10	18	6	9	15	22
4	5				
3	3				
15	24				
0	13				
11	14				
2	16				
1	5				
8	10				
0	22				
5	7				
2	2				
11	11				
2	4				
14	18				
8	9				
13	16				
6	14				
8	12				
1	1				
4	6				
7	11				
2	7				
9	14				
7	7				
0	9				

Field Data for 0.5H:1V Slopes

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
11	17	0	30	11	19
10	14	0	14	12	17
2	2	12	12	8	20
1	1	20	52	5	14
3	18	10	32	10	18
1	14	10	15	0	43
0	11	5	20	10	33
13	13	14	22	13	17
9	16	11	24	18	28
9	17	14	15	4	12
8	16	5	14	10	21
5	19	0	5	0	6
3	3	4	4	0	21
4	11	0	28	8	10
15	19	3	13	11	58
9	12	8	14	4	14
0	11	0	2	4	4
0	37	5	15	5	10
3	6	0	16	5	39
3	6	0	39	6	11
3	18	3	20	18	43
2	8	5	10	5	14
3	4	6	13	10	17
11	14	3	12	11	11
8	9	0	10	7	23
4	17	5	13	3	4
14	16	4	9	6	21
9	9	9	34	10	20
15	17	15	35	8	14
6	7	2	10	8	9
10	12	0	5	7	8
5	8	7	29	8	8
11	16	5	32	0	28
4	7	10	24	14	19
4	18	4	13	12	21
9	32	8	14	15	17
5	10	0	9	8	8
9	9	4	8	12	12
7	8	9	31	3	55
9	28	20	36	18	38
10	18	4	10	7	22
14	26	5	5	18	41
0	16	10	16	4	4
3	5	5	11	5	23
5	7	8	16	12	17
10	11	3	6	6	22
5	9	10	30	5	18
0	21	10	20	7	10
1	1	7	7	5	9
2	13	3	7	0	60
5	15	10	12	7	22

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	9	8	23	15	17
2	12	10	45	8	20
3	11	5	5	3	3
5	30	10	10	5	28
17	36	10	41	7	21
3	8	0	15	10	12
12	12	15	27	5	25
0	6	3	3	0	30
0	5	3	26	7	16
10	13	3	7	3	14
3	12	16	43	5	23
14	19	14	14	4	20
12	18	8	8	9	27
6	8	10	14	7	13
16	22	10	16	14	27
5	8	4	9	15	32
3	13	18	30	5	15
2	3	9	9	3	32
0	11	0	18	10	38
4	16	0	19	15	24
0	4	11	11	5	13
11	15	6	22	7	35
13	25	3	16	10	15
5	7	10	21	13	48
17	26				
6	10				
9	17				
5	9				
1	10				
2	9				
6	9				
9	10				
4	4				
10	16				
5	6				
8	17				
10	11				
0	5				
0	13				
4	9				
16	36				
0	7				
10	19				
3	3				
0	8				
7	7				
14	14				
2	3				
9	12				

Field Data for 0.75H:1V Slopes

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	1	0	13	0	10
0	2	0	4	0	5
0	4	2	11	2	2
1	1	2	2	3	13
0	2	1	4	0	10
0	4	0	3	0	12
0	3	0	6	0	3
0	5	0	10	0	11
0	4	2	2	0	12
0	2	2	2	0	12
1	6	0	4	0	9
0	5	0	8	0	6
1	1	0	5	2	4
0	0	0	7	2	4
0	2	0	7	0	5
0	3	0	4	0	6
1	1	0	5	3	3
0	3	3	7	0	11
0	0	0	5	0	19
0	4	3	3	0	3
0	3	4	4	2	4
0	1	2	6	0	13
0	0	0	11	2	5
0	0	3	3	2	4
0	1	2	4	0	17
0	2	1	3	2	11
0	3	0	13	2	6
0	4	0	4	0	14
0	6	0	7	0	9
0	7	0	7	0	17
0	1	1	4	0	7
4	5	0	5	0	8
1	4	0	5	3	7
0	2	0	6	2	9
0	2	0	8	3	3
1	2	0	15	3	3
0	2	4	12	0	9
0	2	3	7	0	7
0	3	0	23	1	5
0	2	1	6	3	3
0	10	3	3	0	14
0	3	0	8	0	9
2	2	2	2	4	8
0	3	0	4	3	7
0	5	0	5	0	7
0	2	1	6	1	4
0	2	0	6	0	17
0	1	1	1	0	4
0	1	2	6	0	11
0	3	1	3	2	6
0	2	0	7	0	10

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	4	0	6	0	10
0	5	0	6	2	4
0	3	0	4	3	3
0	2	0	6	0	11
0	4	0	7	3	3
0	5	0	14	0	13
0	8	0	7	1	1
0	3	0	9	0	9
0	4	0	5	2	2
0	1	1	4	2	5
0	5	2	2	0	12
0	2	0	7	4	4
0	0	0	6	0	7
0	4	0	6	2	5
1	1	0	10	0	7
0	2	0	10	0	7
0	3	0	12	0	5
1	1	0	9	1	4
0	8	0	6	4	4
0	3	3	3	3	3
0	3	2	4	2	5
1	3	0	8	0	13
0	5	0	10	4	4
0	6	0	9	1	3
0	6				
0	4				
0	0				
0	2				
0	2				
0	2				
2	2				
0	2				
0	1				
0	2				
0	3				
0	5				
0	6				
3	5				
0	3				
1	1				
0	10				
0	11				
0	2				
0	3				
0	2				
0	3				
0	1				
0	3				
0	3				

Field Data for 0.75H:1V Slopes

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	2	2	8	3	16
0	4	0	19	0	10
3	4	0	3	0	5
2	3	1	6	0	12
0	4	0	7	0	18
3	16	1	4	2	4
0	3	0	9	0	6
0	3	0	4	0	7
0	2	0	4	4	4
0	5	0	10	0	13
0	3	0	10	0	8
0	2	0	7	0	6
0	6	0	13	0	8
0	9	0	18	0	16
1	3	0	8	4	4
0	6	0	14	0	16
0	3	0	7	0	5
0	4	1	3	0	5
0	4	0	4	1	11
0	3	0	3	3	7
3	5	0	4	0	11
0	9	0	5	0	9
2	7	0	15	0	5
0	7	0	8	0	5
0	3	0	12	0	16
0	6	0	18	0	5
0	4	0	14	0	8
0	2	0	10	3	17
0	5	0	9	4	4
0	3	0	4	0	5
0	9	0	6	0	10
0	3	3	3	0	5
0	2	0	4	0	12
0	3	0	14	1	4
0	6	0	13	0	14
0	3	1	11	0	5
2	3	0	6	1	5
2	3	0	7	1	5
1	1	0	0	1	5
0	5	1	6	0	17
0	5	0	5	0	6
0	5	0	6	3	3
0	3	3	3	0	13
0	5	3	10	0	12
0	3	0	16	0	17
0	6	0	12	0	10
0	3	0	9	0	9
0	9	3	5	7	7
0	5	0	7	0	7
0	3	0	11	0	6
0	3	0	3	0	7

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	2	3	5	4	12
2	3	0	7	0	10
0	3	0	7	0	15
0	9	0	12	0	18
3	3	3	13	2	5
0	1	3	7	0	12
0	6	3	13	0	9
3	5	1	3	3	3
2	6	3	5	4	4
2	3	0	10	4	10
1	4	0	18	5	5
0	6	1	10	0	14
0	4	0	9	3	5
0	5	2	4	0	10
0	10	0	6	4	16
0	3	0	7	0	7
2	2	0	10	0	15
0	3	1	4	0	7
1	1	0	5	0	7
0	3	2	6	0	5
0	8	0	5	0	7
0	3	0	6	4	4
0	5	0	20	0	10
0	2	4	8	0	8
1	1				
3	3				
0	3				
0	7				
0	2				
0	2				
3	3				
0	3				
0	5				
3	3				
0	3				
0	3				
0	7				
0	4				
0	3				
0	7				
0	4				
0	3				
0	3				
0	2				
0	1				
0	5				
0	6				
0	10				
0	6				

Field Data for 0.75H:1V Slopes

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
3	17	3	13	3	42
3	9	5	25	3	24
0	10	1	6	5	22
0	4	2	17	0	38
0	7	6	18	0	5
0	6	3	8	0	14
3	22	2	13	0	16
3	12	4	15	5	25
0	5	4	18	0	22
0	15	4	35	0	5
3	16	2	18	0	29
0	11	0	7	0	45
0	13	3	17	3	13
3	17	3	6	2	13
0	4	0	40	5	22
0	14	0	21	3	20
3	8	4	15	0	11
2	10	4	21	4	43
0	16	0	4	3	27
0	13	3	7	3	28
2	6	0	38	3	32
2	7	0	38	3	20
3	14	2	23	5	19
3	14	4	22	4	15
4	20	0	28	0	30
0	17	0	27	2	12
3	16	0	1	5	33
2	6	0	21	2	19
3	14	0	30	3	30
0	3	0	15	3	25
2	14	0	5	3	22
0	6	4	19	2	25
0	13	0	40	3	33
6	17	3	23	0	25
0	14	0	23	0	12
0	7	0	22	0	23
2	6	0	48	2	28
0	14	0	27	0	17
3	13	0	22	4	24
5	14	0	17	3	28
5	22	0	21	0	12
0	7	5	14	3	25
0	10	0	20	4	19
0	10	0	7	5	28
0	20	0	37	0	26
0	13	0	27	0	13
0	6	0	25	2	30
2	16	0	23	0	22
3	16	4	23	0	27
0	8	0	15	0	29
3	15	0	5	3	18

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
1	10	0	36	3	9
0	16	0	23	5	32
3	13	0	27	3	11
2	16	0	6	3	18
2	18	0	20	4	10
5	26	1	34	3	19
3	13	1	3	2	12
0	5	0	34	3	10
5	18	0	19	3	5
3	24	0	7	0	21
4	20	0	11	2	32
4	4	5	22	3	13
0	12	2	8	0	26
0	8	2	12	0	10
0	15	0	7	5	8
0	17	0	17	1	7
4	15	0	7	3	9
0	8	0	12	0	20
0	5	0	17	0	27
4	15	6	12	5	45
3	13	0	6	0	5
0	10	0	12	4	33
4	12	0	26		
0	15	2	10		
3	7	0	10		
0	15				
5	15				
0	4				
3	10				
4	7				
0	20				
0	6				
0	7				
3	8				
0	10				
3	13				
3	8				
2	12				
3	17				
0	10				
4	20				
3	6				
2	8				
3	23				
4	7				
5	30				
2	15				
2	27				
2	16				

Field Data for 0.75H:1V Slopes

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
9	10	0	29	12	33
7	13	10	17	6	10
7	9	0	21	0	21
6	7	0	12	6	14
6	10	0	11	0	15
8	8	5	8	0	15
7	10	0	16	0	19
7	7	5	6	0	18
9	15	0	17	0	17
0	10	0	11	0	24
0	12	2	10	3	17
0	18	0	12	5	12
0	7	5	7	0	24
6	7	6	18	0	12
11	13	0	17	4	7
10	16	10	11	8	24
6	13	0	13	0	10
0	8	0	22	5	15
7	7	0	12	5	20
0	8	5	8	0	10
8	16	0	16	0	27
11	12	5	9	0	24
3	12	0	12	0	21
0	19	0	12	0	22
6	11	0	11	2	17
0	6	3	12	5	8
4	5	5	13	0	35
5	7	0	15	0	31
4	12	4	9	8	20
0	12	0	17	0	27
7	11	0	14	5	7
4	4	8	10	0	20
1	6	0	19	0	7
7	7	0	5	4	12
6	8	5	11	0	17
7	12	0	12	0	43
9	11	7	12	5	8
0	7	7	12	5	16
5	12	7	8	0	15
0	26	5	7	0	32
7	11	10	17	0	20
0	9	5	13	6	19
15	15	5	15	9	11
6	11	7	13	5	16
7	9	5	7	0	14
7	14	5	10	0	30
0	8	0	33	0	29
6	17	12	14	5	26
5	9	10	18	0	20
0	7	4	19	5	5
3	3	5	10	0	16

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	6	4	16	0	26
0	4	9	12	0	15
0	9	7	25	0	25
0	8	0	15	0	15
4	7	0	11	8	14
5	7	0	17	4	16
3	4	0	24	0	13
10	12	0	28	0	15
0	13	0	12	8	12
0	6	0	27	0	25
8	11	0	20	0	20
6	10	10	18	0	20
5	5	15	16	0	20
6	18	7	11	0	10
0	7	0	15	0	17
6	6	0	12	0	16
3	5	4	29	5	12
8	9	11	13	0	20
0	10	4	20	0	7
0	7	0	21	5	14
0	18	0	22	5	10
7	10	4	15	0	15
0	2	5	13	0	20
3	7			0	15
8	8				
0	8				
0	5				
0	5				
0	8				
2	3				
5	6				
0	7				
0	13				
7	8				
0	9				
5	7				
3	4				
7	11				
0	1				
0	1				
0	8				
6	6				
1	2				
0	1				
0	6				
5	5				
2	2				
0	1				
7	10				

Field Data for 0.75H:1V Slopes

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
7	12	5	12	0	24
0	9	0	12	11	16
0	25	5	25	6	13
0	12	0	8	0	15
0	18	6	11	0	15
13	18	0	25	0	24
0	27	0	20	0	10
5	15	1	2	7	21
2	5	5	25	0	27
5	13	0	13	0	22
1	13	5	29	6	30
7	16	6	6	7	22
6	15	0	12	0	13
0	14	0	25	0	11
0	13	4	20	0	16
12	29	0	34	0	56
5	15	0	17	6	25
0	16	0	15	5	34
6	11	0	10	7	13
0	7	5	17	4	9
12	12	0	13	9	22
7	13	0	12	0	19
8	12	0	15	0	26
2	2	5	17	0	18
9	15	5	15	0	10
8	16	0	18	6	6
8	9	0	7	7	7
0	21	0	12	0	9
0	22	5	7	0	16
5	8	0	21	0	9
6	13	0	18	0	17
0	26	5	11	0	10
5	12	5	10	0	8
10	18	5	5	5	11
7	10	0	5	10	27
10	13	5	12	5	24
0	17	0	32	5	7
0	11	0	33	7	13
2	4	6	16	5	12
0	24	5	8	0	7
0	25	7	7	0	16
0	7	5	5	0	13
0	21	4	8	0	10
10	12	0	19	5	5
0	19	0	32	14	26
1	8	6	6	0	18
0	22	10	19	0	13
7	17	0	10	0	22
3	8	0	7	10	14
5	6	17	25	0	27
5	23	8	19	5	15

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	14	5	26	5	14
9	23	5	13	0	8
6	14	0	24	0	9
6	15	6	8	0	22
7	13	5	34	0	17
6	11	7	13	0	28
4	17	0	15	6	20
0	23	0	25	0	32
1	5	3	24	0	16
4	8	6	18	8	12
6	19	3	10	8	18
5	18	0	5	6	12
11	20	8	24	0	15
0	25	7	16	5	13
0	28	5	27	5	26
6	7	5	26	6	16
12	27	0	9	5	7
0	7	5	7	6	37
0	6	5	16	0	17
3	18	0	17	0	20
0	12	5	17	5	8
5	12	0	8	5	8
9	18	0	14		
0	27				
1	2				
0	11				
7	7				
0	7				
4	8				
0	18				
4	17				
8	18				
3	10				
6	9				
6	6				
0	16				
6	14				
9	23				
7	12				
0	5				
3	6				
0	28				
6	12				
7	17				
0	19				
0	21				
6	9				
5	17				
6	11				

Field Data for 0.75H:1V Slopes

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	25	7	57	0	47
6	15	2	18	0	52
2	4	10	32	7	15
4	19	2	33	3	31
10	20	3	12	5	33
7	30	0	48	0	37
6	21	6	37	0	20
3	28	4	15	0	36
0	1	4	52	5	23
6	23	11	44	0	26
7	27	3	15	0	15
5	8	5	41	4	41
5	10	6	18	9	46
4	20	1	17	0	36
8	28	0	26	0	28
0	36	3	18	0	16
8	10	6	37	0	48
6	14	11	43	0	46
6	21	5	42	0	51
1	14	6	14	2	70
8	23	7	43	0	32
9	12	5	73	8	33
4	7	1	46	0	56
0	16	5	42	0	15
16	42	6	40	0	30
3	15	4	44	5	26
4	6	10	33	0	27
0	7	5	25	0	46
0	10	0	21	0	28
7	24	0	10	0	22
4	13	7	40	8	61
1	22	2	28	0	37
4	16	5	55	1	17
0	16	5	25	1	20
2	26	9	15	0	52
3	33	1	25	0	62
8	13	4	47	1	16
1	11	3	10	0	32
6	27	8	15	0	36
9	17	7	28	0	15
0	16	5	49	8	16
0	1	4	21	0	54
10	16	4	16	0	37
1	1	4	41	0	23
3	10	6	28	0	25
4	12	5	46	2	25
3	12	2	16	0	15
11	30	3	21	0	52
0	8	6	27	0	40
6	13	2	26	0	49
7	11	7	65	8	31

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	22	5	42	16	29
7	16	2	30	6	23
8	14	2	55	7	15
7	12	2	12	4	7
5	22	4	15	12	14
7	23	3	50	1	5
6	9	7	56	13	50
1	5	7	25	8	21
4	24	7	22	8	17
4	11	5	31	14	42
6	9	7	47	11	45
7	7	5	48	14	35
4	15	1	29	4	13
21	59	0	53	15	19
4	7	3	40	9	27
14	43	3	19	2	64
7	27	3	16	5	17
2	4	4	38	3	5
6	15	2	12	11	39
4	25	10	54	4	31
9	22	7	31	11	34
5	17	5	48	17	46
2	13	4	40	11	46
5	14	6	22	14	23
6	29				
4	27				
5	25				
2	41				
9	12				
1	21				
2	53				
4	28				
3	48				
0	36				
6	20				
10	35				
4	27				
4	25				
11	20				
2	17				
9	25				
2	21				
3	19				
5	29				
4	12				
11	41				
1	41				
4	14				
0	12				

Field Data for 0.75H:1V Slopes

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	14	0	36	5	16
5	5	5	5	2	2
1	1	1	25	10	13
5	7	5	35	10	30
7	13	2	17	3	12
0	5	6	6	4	8
0	9	5	37	5	20
0	7	4	16	3	34
0	3	3	11	6	6
0	14	5	32	5	36
4	5	2	9	4	42
0	3	4	18	3	3
0	11	3	8	5	39
2	11	4	18	4	45
0	6	4	4	4	4
6	6	2	22	2	12
4	4	3	17	14	18
2	30	3	5	8	8
1	3	3	16	3	23
0	17	5	14	4	36
0	4	4	19	5	8
2	8	6	15	5	5
5	20	4	12	5	28
13	13	6	18	2	23
3	6	3	18	5	14
0	26	3	22	15	23
3	22	1	18	2	3
4	5	2	11	2	4
4	4	0	24	4	5
3	11	4	9	2	18
4	10	2	3	6	14
0	3	3	17	2	4
1	4	4	16	2	6
0	9	1	13	4	25
0	8	2	11	4	16
6	14	5	20	3	20
4	4	7	21	2	35
0	13	6	22	8	18
3	3	4	18	1	19
1	7	7	12	7	10
1	3	2	10	2	19
2	6	3	16	5	10
7	13	3	24	3	18
1	5	5	9	5	5
5	5	5	34	3	3
11	13	6	16	5	24
5	11	0	23	4	15
2	6	5	5	0	15
0	16	13	17	6	21
0	13	4	12	7	7
0	10	3	12	0	5

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
4	4	0	22	2	7
1	21	2	14	5	14
2	12	0	30	2	15
4	9	5	7	2	39
8	14	1	13	3	17
4	4	5	12	13	15
0	7	0	32	7	24
3	19	2	4	3	20
2	12	5	16	4	14
0	8	4	4	4	14
3	5	3	13	7	7
3	11	4	4	3	9
0	8	3	10	2	20
0	5	3	14	6	15
3	18	4	10	0	12
2	9	3	5	6	12
5	5	7	7	4	27
4	16	0	14	0	10
3	12	4	5	6	14
7	7	5	6	2	15
0	8	6	7	3	13
5	12	4	21	5	23
10	11	3	5	4	20
5	18	1	2	3	27
3	3				
6	6				
3	8				
0	2				
1	13				
4	8				
6	12				
8	8				
14	17				
4	9				
8	20				
4	4				
12	18				
0	19				
6	6				
5	16				
3	5				
0	17				
4	16				
0	8				
5	5				
7	7				
4	10				
3	14				
7	8				

Field Data for 0.75H:1V Slopes

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
2	32	0	4	5	20
4	12	11	14	5	23
3	17	0	38	2	29
9	10	4	11	0	42
2	7	2	22	3	8
3	11	6	8	5	11
4	13	0	15	0	13
5	17	3	3	0	7
3	11	0	24	3	22
3	10	0	7	1	39
5	16	0	14	3	9
2	10	5	13	5	10
4	9	5	42	3	11
1	5	0	33	0	12
1	7	0	8	3	49
5	10	4	12	0	36
1	10	6	18	0	21
9	26	1	26	4	11
2	11	0	4	0	12
2	5	2	3	0	11
3	15	0	4	6	20
5	27	0	14	0	3
7	9	10	23	0	37
1	6	0	9	0	6
7	10	0	37	4	8
4	9	0	12	3	17
2	4	7	62	5	17
9	22	3	5	0	38
4	13	0	49	0	17
4	8	0	15	5	9
4	8	9	14	6	23
3	9	5	13	3	16
4	20	0	5	0	25
6	12	6	11	5	33
0	11	5	17	0	26
0	12	5	24	0	16
0	17	2	2	5	20
0	5	8	8	0	36
0	2	0	7	3	19
0	22	0	60	3	25
3	3	5	29	10	22
5	19	0	24	0	14
7	29	0	28	0	23
2	12	3	9	8	16
3	17	2	2	0	21
1	3	3	22	0	19
0	7	0	10	0	22
3	9	0	39	0	37
10	19	0	23	2	14
0	4	0	10	0	15
3	7	5	9	2	22

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
1	1	0	14	3	43
4	5	3	18	0	22
8	8	2	14	0	17
2	4	0	9	0	27
7	13	6	26	0	27
2	9	0	30	0	30
0	7	0	18	0	21
0	11	2	12	2	12
2	13	4	10	5	7
4	15	1	1	7	10
3	18	10	13	0	51
0	24	0	29	0	28
0	10	2	15	0	23
5	5	0	9	3	44
3	10	0	18	0	24
0	0	0	11	5	17
0	17	2	6	4	4
0	31	3	7	0	24
2	4	0	4	4	4
0	3	6	17	2	17
12	16	5	8	0	32
0	5	0	16	0	23
5	23	3	13	0	20
4	13	4	4	10	14
0	21				
5	8				
0	7				
10	16				
3	14				
4	7				
0	6				
0	4				
3	27				
2	19				
0	15				
5	11				
2	24				
2	10				
5	15				
5	5				
4	6				
0	18				
0	6				
3	12				
3	6				
2	2				
3	10				
3	7				
0	13				

Field Data for 0.75H:1V Slopes

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
5	7	5	47	5	52
4	12	5	69	0	25
0	17	5	15	0	65
0	10	0	27	0	52
6	6	5	23	5	18
0	22	7	16	5	46
5	19	0	52	3	14
4	32	5	35	1	16
0	19	0	33	4	37
2	21	0	42	3	42
0	2	0	26	1	23
1	46	5	5	0	69
15	26	5	45	9	12
0	6	0	18	0	33
4	11	0	27	9	25
10	20	0	16	0	33
2	10	0	40	0	19
6	7	10	44	2	8
11	25	5	19	1	26
6	8	0	60	1	2
0	7	0	38	5	21
0	24	0	39	0	26
4	9	4	35	5	22
1	1	6	35	11	52
0	4	12	36	0	63
0	14	0	23	0	27
0	30	5	6	0	24
0	8	10	28	10	37
4	13	5	18	9	28
5	38	0	0	0	18
0	3	4	46	5	38
0	15	0	36	9	15
0	4	0	62	0	58
0	48	5	27	9	29
0	19	4	30	0	21
0	26	3	22	0	52
15	30	3	14	4	29
0	14	4	30	0	37
0	26	0	48	0	45
0	13	8	29	0	37
0	1	0	19	5	9
5	18	3	24	0	15
0	3	0	45	0	14
9	27	0	60	4	8
0	14	4	15	0	30
3	16	4	6	2	16
0	3	6	15	3	10
0	6	0	32	0	65
0	17	0	20	13	34
3	16	5	23	5	28
0	20	3	22	5	26

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	8	0	14	3	23
15	19	0	19	4	28
0	23	0	4	0	39
0	3	0	57	2	27
0	2	0	12	5	37
0	17	0	11	5	68
4	11	5	20	0	4
0	23	5	32	0	33
0	7	0	10	0	11
3	6	0	10	2	20
3	4	5	31	0	17
0	17	10	10	0	13
4	7	5	23	0	2
0	6	5	10	0	68
3	11	5	20	0	6
3	17	10	28	0	55
2	20	3	19	0	61
3	13	4	10	3	3
0	27	5	15	6	59
3	3	0	45	4	38
0	9	10	24	3	75
5	24	3	27	6	65
0	8	10	22	4	13
5	29	6	42	3	34
0	2				
0	42				
0	11				
4	22				
1	1				
1	1				
4	4				
1	8				
6	34				
4	23				
0	19				
0	36				
3	24				
0	13				
3	45				
7	30				
0	33				
0	18				
0	26				
0	13				
0	4				
0	12				
15	19				
9	58				
5	26				

Field Data for 1H:1V Slopes

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	3	0	12	0	13
0	4	0	10	0	11
0	7	0	13	0	16
0	6	0	7	0	8
0	5	0	15	0	12
0	6	0	8	0	9
0	5	0	5	0	3
0	0	0	3	0	15
0	8	0	7	0	13
0	4	0	8	0	11
0	3	0	7	0	9
0	10	0	4	0	5
0	5	0	5	0	6
0	8	0	9	0	8
0	10	0	7	2	10
0	6	0	16	0	5
0	7	0	21	0	10
0	8	0	14	0	12
0	5	0	8	0	13
0	8	0	13	0	6
0	6	0	10	0	11
0	7	0	11	0	7
0	8	0	11	0	6
0	5	0	17	0	8
0	6	0	15	0	8
0	3	0	7	0	7
0	3	0	13	0	5
0	5	0	6	0	11
0	7	0	10	0	4
3	2	0	12	0	8
0	3	0	16	0	10
0	3	0	10	0	12
0	6	0	0	0	3
0	5	0	17	0	11
0	3	0	8	0	9
0	7	0	15	0	9
0	4	0	7	0	16
3	4	0	8	0	15
0	5	0	9	0	12
0	3	0	7	0	9
0	7	0	5	0	8
0	6	0	11	0	12
0	3	0	8	0	5
0	1	0	12	0	8
0	4	0	13	0	9
0	1	0	12	0	23
0	0	0	9	0	7
0	0	0	11	0	10
0	5	0	4	0	11
0	4	0	8	0	3
0	1	0	8	0	12

40-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	4	0	7	0	6
0	2	0	6	0	13
0	4	0	8	0	10
0	0	0	7	0	8
0	5	0	11	0	15
0	3	0	7	0	10
0	3	0	8	0	9
0	1	0	7	0	8
0	2	0	10	0	10
0	2	0	6	0	9
0	0	0	14	0	8
0	4	0	12	0	5
0	2	0	3	0	8
0	1	0	7	0	13
0	2	0	9	0	10
0	6	0	8	0	5
0	5	0	11	0	13
0	8	0	9	0	12
0	3	0	13	0	11
0	6	0	7	0	0
0	3	0	9	0	5
0	2	0	12	0	7
0	4	0	7	0	11
0	3	0	5	0	15
0	1			0	10
0	5			0	4
0	1			0	9
0	5			0	8
0	3			0	14
0	4			0	7
0	3			0	14
0	5				
0	2				
0	9				
0	4				
0	3				
0	4				
0	3				
0	4				
0	0				
0	3				
0	4				
0	3				
0	5				
0	2				
0	3				
0	4				
0	3				
0	5				

Field Data for 1H:1V Slopes

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	10	0	26	0	25
0	14	0	13	0	38
0	4	0	32	0	12
0	8	0	22	0	19
0	13	0	27	0	9
0	18	0	18	0	8
0	19	0	6	0	6
0	17	0	19	0	30
0	14	0	20	0	18
0	13	0	24	0	16
0	12	0	17	0	22
0	14	0	12	0	21
0	9	0	13	0	23
0	3	0	9	0	14
0	5	0	23	0	19
0	24	0	14	0	8
0	11	0	19	0	18
0	13	0	17	0	16
0	12	0	11	0	14
0	13	2	16	0	10
0	23	0	23	0	11
0	5	0	3	0	16
0	11	0	22	0	22
0	12	0	19	0	9
0	13	0	9	0	8
0	13	0	16	0	29
0	14	0	22	0	24
0	7	0	15	0	18
0	27	0	17	0	11
0	15	0	11	0	16
0	14	0	14	0	19
0	13	0	7	0	13
0	14	0	12	0	18
0	16	0	5	0	16
0	16	0	7	0	22
0	5	0	13	0	23
0	13	0	20	0	13
0	4	0	29	0	16
0	6	0	15	0	24
0	5	0	15	0	18
0	5	0	7	0	7
0	7	0	12	0	33
0	5	0	23	0	14
0	8	0	15	0	14
0	11	0	18	0	15
0	19	0	12	0	10
0	16	0	8	0	12
0	9	0	16	0	16
0	10	0	10	0	13
0	10	0	14	0	14

40-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	9	0	14	0	17
0	11	0	16	0	9
0	16	0	13	0	8
0	8	0	18	0	10
0	12	0	8	0	24
0	13	0	17	0	32
0	16	0	9	0	30
0	11	0	21	0	37
0	12	0	17	0	29
0	4	0	22	0	24
0	15	0	11	0	12
0	13	0	14	0	25
0	12	0	7	0	10
0	8	0	17	0	15
0	6	0	14	0	19
0	17	0	16	0	10
0	8	0	18	0	18
0	6	0	15	0	9
0	5	0	4	0	11
0	10	0	16	0	14
0	4	0	17	0	14
0	12	0	15	0	16
0	10	0	6	0	15
0	12	0	11	0	12
0	11	0	10	0	13
0	4				
0	3				
0	7				
0	10				
0	8				
0	14				
0	3				
0	7				
0	8				
0	11				
0	5				
0	7				
0	4				
0	3				
0	4				
0	6				
0	12				
0	14				
0	11				
0	15				
0	8				
0	3				
0	11				
0	7				
0	14				

Field Data for 1H:1V Slopes

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	27	0	56	0	70
0	33	0	61	0	52
0	16	0	52	0	35
0	16	0	43	0	60
0	33	0	42	0	45
0	20	0	58	0	34
0	5	0	26	0	38
0	23	0	18	0	24
0	33	0	54	0	13
0	3	0	32	0	15
0	29	0	34	0	27
0	22	0	60	0	40
0	8	0	53	0	19
0	33	0	16	0	51
0	38	0	35	0	22
0	26	0	20	0	18
0	38	0	39	0	3
0	22	0	44	0	3
0	48	0	33	0	32
0	27	2	35	0	22
0	24	0	45	0	40
0	20	0	24	0	44
0	26	0	21	0	22
0	44	0	27	0	28
0	19	0	22	0	8
0	13	0	20	0	20
0	2	0	42	0	27
0	7	0	23	0	9
0	10	0	45	0	17
0	23	0	25	0	52
0	32	0	31	0	18
0	24	0	50	0	17
0	7	0	26	0	32
0	12	0	11	0	14
0	29	0	12	0	28
0	13	0	17	0	29
0	9	0	37	0	19
0	30	0	19	0	25
0	17	0	33	0	23
0	16	0	42	0	0
0	38	0	43	0	60
0	8	0	51	0	23
0	31	0	37	0	30
0	23	0	48	0	35
0	24	0	20	0	37
0	41	0	23	0	30
0	29	0	23	0	18
0	34	0	11	0	30
0	11	0	13	0	20
0	21	0	29	0	58
0	18	0	25	0	34

40-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	50	0	46	0	51
0	22	0	30	0	36
0	21	0	17	0	32
0	15	0	38	0	29
0	25	0	16	0	22
0	6	0	32	0	15
0	13	0	37	0	36
0	21	0	20	0	22
0	33	0	33	0	38
0	23	0	29	0	23
0	29	0	36	0	20
0	24	0	21	0	29
0	23	0	19	0	14
0	22	0	33	0	21
0	26	0	35	0	22
0	25	0	27	0	44
0	14	0	38	0	18
0	39	0	33	0	28
0	23	0	12	0	32
0	5	0	24	0	30
0	20	0	8	0	28
0	28	0	31	0	27
0	19	0	12	0	33
0	27	0	44	0	18
0	19				
0	26				
0	5				
0	18				
0	13				
0	23				
0	25				
0	18				
0	24				
0	30				
0	24				
0	19				
0	8				
0	17				
0	16				
0	26				
0	8				
0	12				
0	36				
0	24				
0	12				
0	27				
0	16				
0	18				
0	24				

Field Data for 1H:1V Slopes

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	5	0	10	0	10
0	6	0	9	0	5
0	8	3	3	0	15
0	4	0	25	0	14
0	6	0	14	0	22
4	4	0	13	0	13
1	4	0	11	0	14
0	5	2	4	0	9
0	7	0	16	0	5
3	4	0	11	0	10
0	11	0	5	0	3
0	9	0	6	0	4
0	7	0	8	0	15
0	2	0	9	0	14
0	10	0	15	0	13
0	4	0	10	0	14
0	7	0	22	0	4
0	3	0	17	0	15
3	5	0	11	0	14
0	3	0	12	0	8
1	3	3	5	4	9
2	4	0	7	0	13
0	5	0	14	4	9
0	1	0	13	3	10
0	5	0	12	2	10
0	7	0	15	0	11
0	6	0	14	1	13
0	5	0	14	0	17
0	5	4	4	0	14
0	8	0	12	0	10
0	2	0	8	2	6
0	8	0	12	0	21
0	1	0	18	0	11
0	4	0	11	0	7
0	6	0	16	0	20
0	11	0	24	0	13
0	8	0	14	0	28
0	2	0	17	0	14
0	6	0	29	0	8
0	6	0	10	0	12
1	2	0	11	0	9
0	3	0	6	0	25
2	4	0	16	0	13
1	7	0	21	0	8
3	5	0	12	0	7
2	4	0	13	0	8
1	8	0	11	5	5
1	10	0	4	0	16
0	8	0	10	4	4
4	4	0	8	0	13
0	7	0	1	0	11

60-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	7	0	7	2	5
0	6	0	22	0	14
0	5	0	13	0	16
2	3	0	15	0	31
0	7	0	19	0	14
0	5	0	13	0	14
1	6	0	13	0	17
0	3	0	5	0	15
2	4	0	11	0	12
1	3	0	29	0	22
1	5	0	15	0	15
0	5	0	14	0	14
0	3	0	10	0	19
0	2	0	15	0	17
0	0	5	10	0	16
0	4	0	8	0	18
0	9	0	13	0	14
0	3	0	12	0	13
0	7	0	10	0	10
0	8	0	24	0	14
0	4	0	31	0	16
0	6	0	23	0	11
0	7	4	4	0	14
0	6	0	9	0	17
0	8	0	20		
1	5				
0	4				
0	7				
0	5				
0	4				
0	6				
0	8				
0	9				
0	6				
0	9				
0	4				
0	7				
0	9				
0	7				
0	16				
0	4				
0	3				
0	5				
0	6				
4	4				
0	11				
0	7				
0	7				
0	6				

Field Data for 1H:1V Slopes

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	27	4	11	4	16
0	11	5	12	3	22
0	19	0	12	3	8
0	9	0	9	7	13
3	3	0	12	5	5
3	5	3	9	5	16
0	9	0	8	3	15
0	6	7	16	0	17
2	3	0	3	1	22
0	18	0	24	3	11
0	7	0	27	0	11
0	15	0	21	0	15
3	3	0	16	4	8
0	6	0	14	2	3
0	9	0	14	3	12
9	11	0	10	1	23
4	8	0	22	4	4
4	7	4	6	0	18
3	5	4	23	2	4
0	8	2	11	4	7
0	7	4	28	0	19
5	5	5	17	0	21
5	8	0	16	0	35
0	11	0	19	4	13
3	4	0	17	3	10
3	11	0	22	0	12
4	6	0	17	0	21
3	5	0	16	5	13
4	11	3	19	0	12
4	10	4	13	2	15
0	9	3	17	3	18
2	3	0	24	5	9
4	6	0	27	0	9
0	11	0	40	0	17
3	7	5	22	3	14
4	7	0	21	5	9
2	9	0	9	8	8
3	6	0	8	4	11
0	10	0	29	5	12
4	12	0	21	0	6
0	8	0	17	0	9
0	5	0	20	0	18
7	16	5	10	6	6
0	10	5	12	0	14
1	8	0	22	0	19
4	6	0	11	0	16
0	10	0	15	0	5
0	12	0	14	0	12
0	7	0	17	4	4
4	9	0	7	0	8
0	15	4	9	2	22

60-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	18	3	12	0	6
3	5	0	31	0	14
3	4	0	12	0	20
0	13	0	38	0	17
0	11	5	9	0	12
0	15	0	17	0	11
0	11	3	11	0	22
10	14	4	16	4	6
4	9	0	24	0	15
8	8	0	14	4	4
0	24	1	13	0	22
0	5	0	14	7	12
0	11	0	15	0	13
0	17	0	15	3	11
0	5	2	19	0	25
0	1	0	17	4	11
0	11	5	14	3	20
0	8	0	13	3	24
0	15	0	17	0	16
5	7	0	18	0	21
0	6	0	13	5	13
4	12	4	8	0	7
0	13	5	10	0	9
0	14	0	24	0	37
0	13				
4	10				
0	13				
0	12				
0	5				
0	11				
0	13				
0	12				
7	10				
4	5				
5	5				
0	8				
4	12				
0	9				
0	10				
0	8				
0	7				
0	13				
0	11				
0	9				
0	4				
0	23				
0	25				
0	13				
0	7				

Field Data for 1H:1V Slopes

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
1	24	3	38	0	68
3	15	4	37	0	40
0	14	1	35	4	34
0	4	0	55	0	23
9	30	0	14	0	19
0	19	0	32	4	20
0	41	0	31	6	41
4	14	0	30	7	19
0	12	0	37	0	17
0	23	0	40	0	40
0	24	0	12	0	23
3	14	0	33	0	37
0	45	3	33	3	13
0	45	0	52	0	36
0	21	0	36	0	22
0	15	0	12	0	35
0	15	0	25	0	16
3	5	0	13	0	46
1	2	5	17	0	24
5	8	0	27	5	15
4	28	0	24	0	24
0	22	3	17	0	25
0	9	0	43	0	19
3	18	0	31	0	13
0	14	0	28	4	13
6	20	4	36	4	14
0	21	2	37	0	27
0	14	0	53	0	24
2	3	9	19	0	15
1	15	0	32	5	20
0	3	0	24	0	39
0	40	0	29	5	9
3	28	0	18	0	17
0	20	0	17	4	70
0	28	4	26	5	57
1	1	0	33	0	18
1	25	5	11	0	31
3	14	0	11	3	22
0	19	7	47	3	24
4	12	0	56	4	17
0	14	3	33	3	35
4	17	0	33	5	25
10	34	0	60	0	16
0	21	4	37	0	50
3	3	0	44	5	21
9	32	0	41	4	36
3	5	0	32	7	23
7	16	5	27	5	42
0	8	3	20	8	12
1	22	0	44	0	33
3	17	0	26	0	33

60-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	4	0	53	0	14
0	13	5	11	0	42
0	9	4	23	0	58
0	35	4	38	0	33
0	14	0	70	0	29
0	13	0	41	0	22
4	30	2	32	8	13
0	20	0	40	4	20
0	21	0	48	3	8
1	16	0	33	4	46
0	54	0	42	8	23
0	8	0	11	0	23
4	22	0	26	0	18
3	26	0	24	3	15
4	22	0	18	4	41
0	32	0	19	4	65
0	18	0	14	1	58
1	7	0	25	3	47
6	16	0	18	5	18
4	13	3	23	0	26
3	22	0	26	11	60
0	7	0	28	9	25
2	12	5	25	0	36
12	17	0	34	4	53
5	8				
4	11				
0	28				
4	31				
3	6				
0	23				
1	22				
5	6				
4	10				
4	12				
0	13				
0	22				
4	10				
4	12				
1	17				
3	22				
3	25				
0	27				
3	18				
0	22				
3	5				
0	25				
0	19				
3	18				
5	19				

Field Data for 1H:1V Slopes

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	8	0	5	0	7
0	5	0	22	4	20
0	2	4	20	0	10
0	1	0	26	6	6
0	4	4	22	3	8
0	7	0	8	1	2
0	7	0	21	0	5
0	5	4	10	4	17
0	12	3	14	0	18
0	1	0	12	0	23
0	10	5	15	0	17
0	6	0	29	0	37
0	3	0	28	0	38
0	5	3	10	0	14
5	13	4	8	0	13
0	4	3	29	0	20
0	2	5	34	5	8
6	10	0	18	3	6
1	10	4	6	0	14
0	4	0	17	0	17
1	21	0	13	0	21
0	15	0	19	0	13
0	11	0	14	0	15
0	8	0	21	0	16
0	2	0	0	0	5
1	3	0	12	0	24
0	0	0	4	0	24
0	6	0	22	0	6
1	1	0	21	0	33
0	7	4	23	2	28
1	0	3	19	0	24
0	0	0	13	5	16
0	4	3	16	0	14
0	3	0	18	0	21
0	3	5	15	0	15
0	7	4	17	0	5
0	5	0	15	0	22
0	9	3	27	0	20
0	13	4	8	0	30
0	6	0	24	0	5
0	6	0	16	0	20
0	3	0	18	5	13
0	8	4	38	0	13
0	15	2	5	2	11
5	8	0	17	2	25
2	6	5	14	0	30
0	7	4	20	0	15
0	4	0	23	0	21
0	10	0	19	2	28
0	1	0	7	5	15
0	7	0	21	0	28

80-Foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	9	0	13	0	38
0	19	5	16	2	6
0	7	0	17	0	25
0	8	0	12	0	16
0	6	0	9	0	22
0	6	0	10	0	12
0	6	0	15	5	15
0	2	0	11	0	14
0	8	0	13	0	18
1	1	0	19	0	13
0	4	0	34	0	25
5	5	0	21	0	23
1	22	0	15	0	16
0	9	0	13	5	20
3	3	0	17	4	32
0	9	0	18	0	34
1	11	3	12	0	33
0	16	4	9	0	29
0	2	3	18	0	9
0	12	4	7	0	27
0	5	4	14	0	24
0	14	6	16	0	17
1	2	0	11	0	20
2	3	0	12	0	18
0	1				
0	6				
0	7				
0	0				
2	7				
0	6				
0	7				
0	8				
0	9				
1	2				
0	3				
0	7				
0	16				
0	5				
1	3				
1	13				
0	3				
0	7				
1	1				
0	6				
4	5				
0	4				
0	2				
3	3				
2	9				

Field Data for 1H:1V Slopes

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	16	3	16	0	33
3	3	0	33	0	18
0	12	0	18	0	32
0	11	3	22	0	11
1	5	5	9	0	50
0	8	3	34	0	32
0	22	3	21	0	45
3	4	0	18	0	23
0	14	0	22	0	20
2	4	0	17	0	50
0	4	0	30	0	37
0	17	0	32	0	38
4	15	0	23	0	19
0	4	0	28	0	24
4	5	3	8	0	13
0	18	0	26	0	30
0	13	4	13	3	34
0	12	0	19	6	15
0	17	0	17	0	42
3	18	4	23	0	42
0	25	0	31	2	35
0	19	0	30	0	45
5	6	3	25	3	18
0	39	0	17	3	17
0	0	0	15	2	23
1	5	0	24	0	12
0	14	7	11	0	52
0	30	0	11	0	28
4	6	5	21	0	13
3	9	0	15	4	9
5	5	0	36	0	16
3	21	0	12	0	23
3	13	0	18	0	35
0	10	0	16	5	20
0	28	0	17	0	58
1	3	5	17	0	24
0	16	12	14	0	8
0	14	3	27	0	18
0	13	0	11	0	26
0	15	0	28	0	36
0	22	0	12	0	21
0	37	0	37	0	16
4	16	4	16	0	31
3	10	3	15	0	37
0	42	0	17	0	38
0	13	0	33	0	49
0	15	0	23	0	42
0	8	5	14	0	33
7	10	0	25	4	23
0	9	4	18	0	35
0	28	0	19	0	39

80-Foot Slope with a 6H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	8	3	9	4	24
0	14	2	14	0	26
0	7	0	19	0	28
0	0	4	8	3	17
0	4	4	6	0	31
0	5	0	15	0	20
0	15	5	11	3	40
0	16	0	23	4	30
2	3	7	22	2	32
2	7	0	16	0	14
0	11	0	15	4	17
3	5	0	22	4	4
6	10	0	14	8	22
0	7	0	9	0	22
0	0	0	14	4	13
3	3	0	18	3	24
3	8	5	10	0	27
0	3	5	19	0	38
0	22	0	18	0	32
0	5	0	24	0	19
1	4	0	13	8	8
0	10	0	16	0	40
1	5	0	5	0	21
0	18	0	35	0	35
0	26				
0	19				
0	12				
0	15				
4	5				
5	15				
0	16				
2	3				
4	11				
0	19				
0	17				
0	14				
3	9				
0	8				
0	3				
3	4				
0	8				
0	9				
0	19				
0	6				
0	15				
0	4				
1	2				
0	13				
4	12				

Field Data for 1H:1V Slopes

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	4	0	22	0	43
0	33	0	26	4	69
0	52	0	25	0	80
0	13	0	46	0	68
0	40	0	42	0	41
0	14	0	38	5	70
0	29	0	28	5	62
0	12	0	25	0	76
4	32	0	37	0	49
0	12	0	30	4	33
5	17	0	39	0	24
3	12	0	51	0	38
0	6	0	57	0	33
4	35	0	44	0	28
3	26	0	31	0	50
5	28	0	33	0	57
5	28	0	32	0	80
2	34	0	31	0	53
2	15	0	48	0	57
3	42	0	46	0	43
0	8	0	20	0	44
0	16	3	35	6	23
0	8	0	32	6	31
0	35	0	49	0	30
1	4	0	23	0	47
0	16	0	33	0	80
2	13	0	37	0	38
0	14	0	44	0	42
0	33	0	28	0	32
5	32	0	29	8	52
0	33	0	39	0	31
0	18	0	32	0	80
5	33	0	37	0	78
0	33	2	29	0	80
3	30	0	36	0	70
4	54	0	51	0	38
0	27	5	49	0	44
0	32	5	26	0	66
3	28	8	24	0	80
0	8	0	12	0	29
4	31	0	32	0	36
0	34	5	5	0	52
4	10	0	35	0	56
0	10	0	29	0	75
0	38	0	13	6	31
0	14	0	25	5	30
0	40	0	30	5	40
7	28	0	50	0	22
4	31	0	8	0	44
3	20	0	51	0	36
6	34	0	23	0	40

80-Foot Slope with a Flat Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	33	0	19	0	35
5	45	0	11	0	25
0	32	0	58	0	16
0	14	0	22	0	28
0	43	0	47	0	21
0	37	0	34	0	39
0	33	0	39	0	60
0	50	0	44	5	38
0	46	0	37	5	37
0	37	0	27	0	63
1	32	0	38	0	58
0	27	0	64	0	72
11	22	0	30	0	80
0	21	0	31	0	80
6	24	0	15	0	58
0	42	0	21	0	78
0	5	0	8	0	80
0	16	0	2	0	78
3	15	0	34	0	18
0	19	0	55	0	48
4	39	0	34	0	55
4	17	0	35	0	72
3	8	0	14	0	80
0	17	0	50	0	60
0	10				
3	10				
0	41				
5	14				
0	27				
0	10				
0	31				
0	28				
4	11				
4	8				
2	14				
0	20				
0	8				
0	32				
0	14				
0	11				
0	15				
0	31				
0	39				
0	28				
0	21				
0	9				
0	18				
3	41				
0	22				

Field Data for 1.25H:1V Slopes

40-foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	5	0	12	3	5
0	7	0	8	0	8
0	8	0	15	3	7
0	7	0	15	0	10
0	6	0	13	0	0
0	0	0	12	0	4
0	4	0	6	6	8
0	7	4	6	0	8
0	3	0	14	0	9
0	7	0	12	0	5
0	4	0	8	0	4
0	0	0	7	0	11
0	5	0	9	0	14
0	0	0	7	0	13
0	6	0	5	0	6
0	5	4	10	0	16
0	0	4	10	0	14
0	0	3	6	0	17
0	4	0	8	0	13
0	8	0	7	0	14
0	6	0	12	0	10
0	4	0	9	0	6
0	7	0	7	0	16
0	0	0	11	0	8
0	8	0	12	0	0
3	7	0	6	0	10
0	6	0	10	0	4
0	8	3	3	0	4
0	6	2	4	0	6
3	5	0	6	0	5
0	3	0	8	0	5
0	7	0	12	0	22
0	0	0	15	0	15
0	6	0	12	0	10
0	5	0	13	0	18
0	2	0	6	0	13
0	7	0	9	0	11
2	6	0	6	0	16
0	4	0	7	0	13
0	3	0	6	0	12
0	0	0	0	0	9
0	3	0	14	0	9
0	1	0	8	0	11
0	5	0	7	0	7
0	4	0	10	0	11
0	6	0	9	0	7
0	5	0	8	0	12
0	7	0	13	0	8
0	6	0	4	0	14
0	5	0	12	0	13
0	0	0	13	0	12

40-foot Slope with a 4H:1V Catchment Area					
1-foot		2-foot		3-foot	
Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)	Impact (ft)	Roll Out (ft)
0	6	0	15	0	17
0	5	0	6	0	15
0	5	0	12	0	11
0	4	0	14	0	0
0	9	0	14	0	10
0	5	0	13	0	14
0	4	0	3	0	8
0	4	0	9	0	16
0	5	0	12	0	12
0	8	0	5	0	13
0	7	0	9	0	14
0	8	0	12	0	9
0	3	0	0	0	11
0	5	0	12	0	8
0	7	0	18	0	4
0	3	0	12	0	11
0	7	0	8	0	9
0	6	0	11	0	16
0	0	0	11	0	20
0	3	0	9	0	6
0	5	0	4	0	8
0	4	0	14	0	4
0	0			0	6
0	6			0	4
0	4				
0	8				
0	2				
0	7				
0	3				
0	9				
0	6				
0	7				
0	5				
0	6				
0	4				
0	4				
0	8				
2	2				
0	5				
0	9				
0	8				
0	6				
0	9				
0	7				
0	3				
0	6				
0	3				
0	0				
0	3				

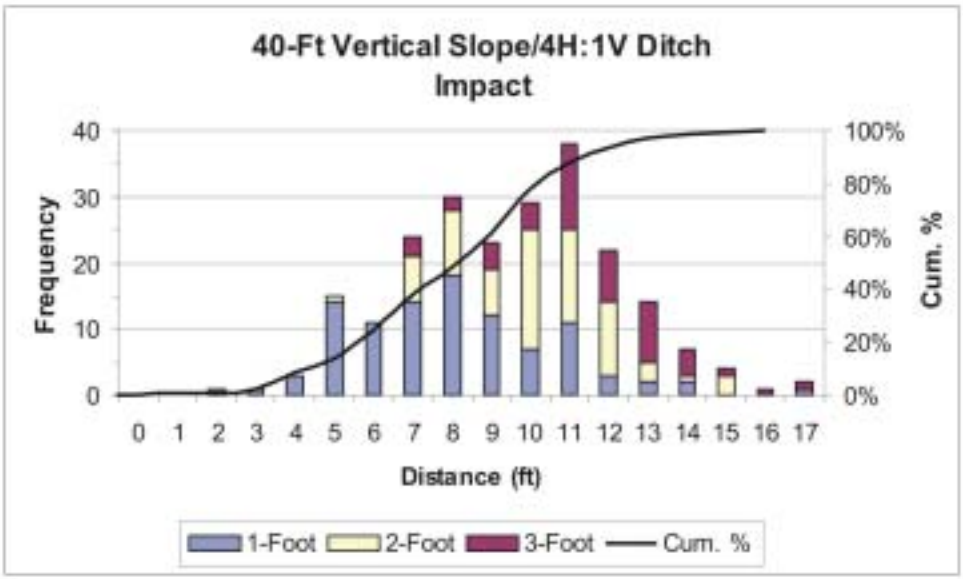
Note: This was the only 1.25H:1V slope tested. Insufficient funds were available to test additional slopes.

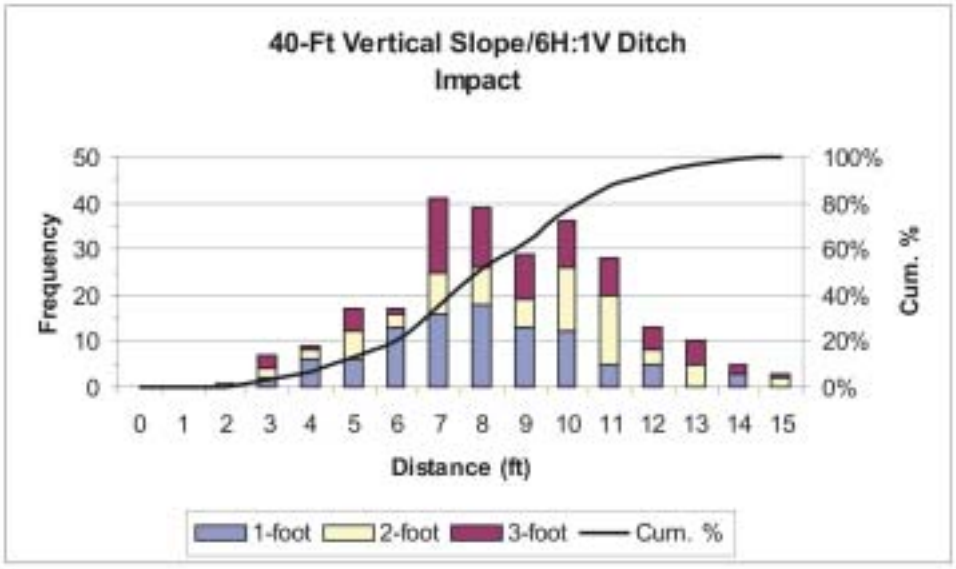
APPENDIX C: ROCKFALL IMPACT DISTANCE HISTOGRAMS

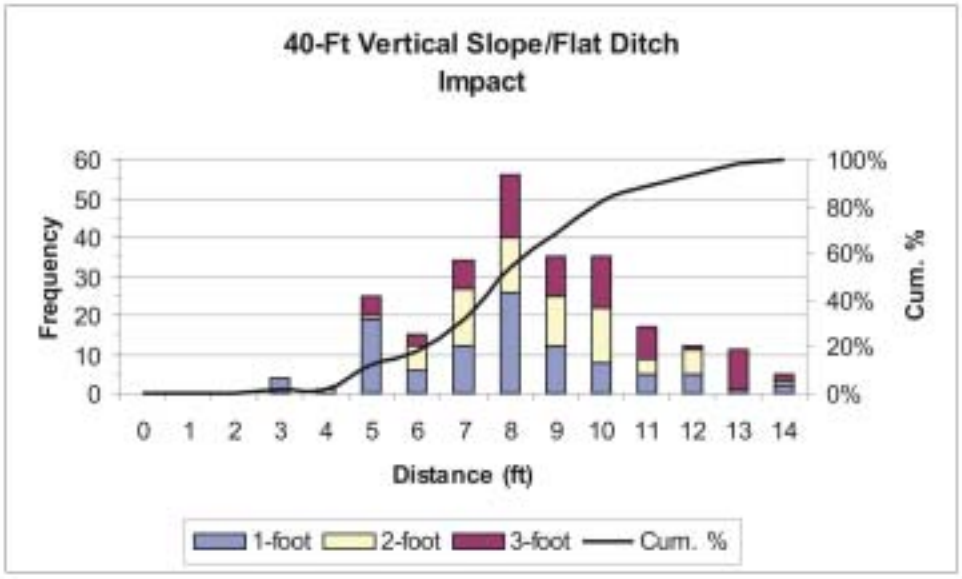
ROCKFALL IMPACT DISTANCE HISTOGRAMS

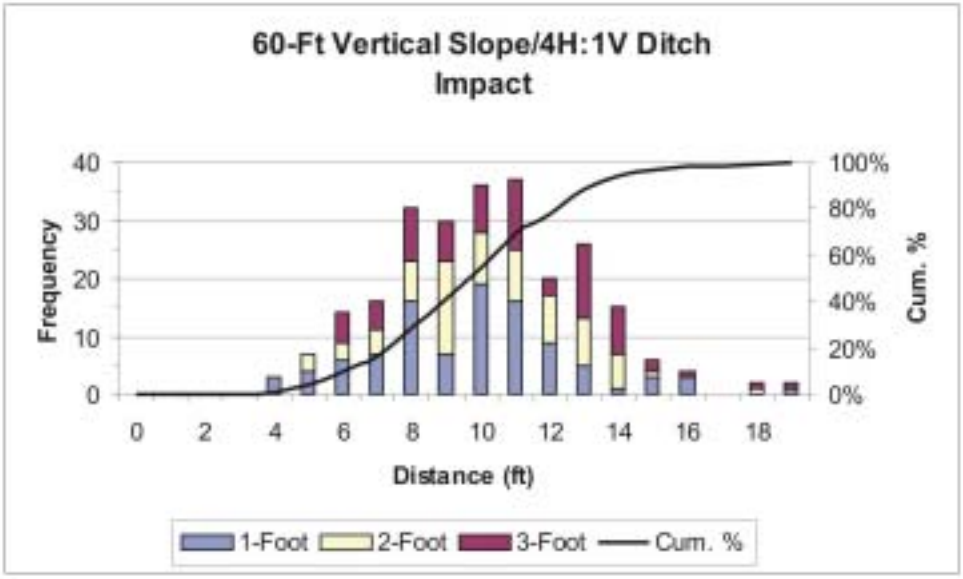
Impact histograms show the tabulated rockfall impact data from Appendix B in a graphical manner. The frequency bars show the relative number of one-, two-, and three-foot rocks that comprise them. The histograms include a cumulative frequency line. This line provides a quick reference for determining the percentage of rocks rolled that landed within a specific width. On steep slopes the rocks rarely impacted (first contacted the catchment area) near the toe of the slope. Conversely, rockfalls on the flatter slopes commonly entered the catchment area in a rolling manner, resulting in many recorded impact distances of zero feet. The impact distances are the field measured slope distances. Field data was recorded to the nearest foot.

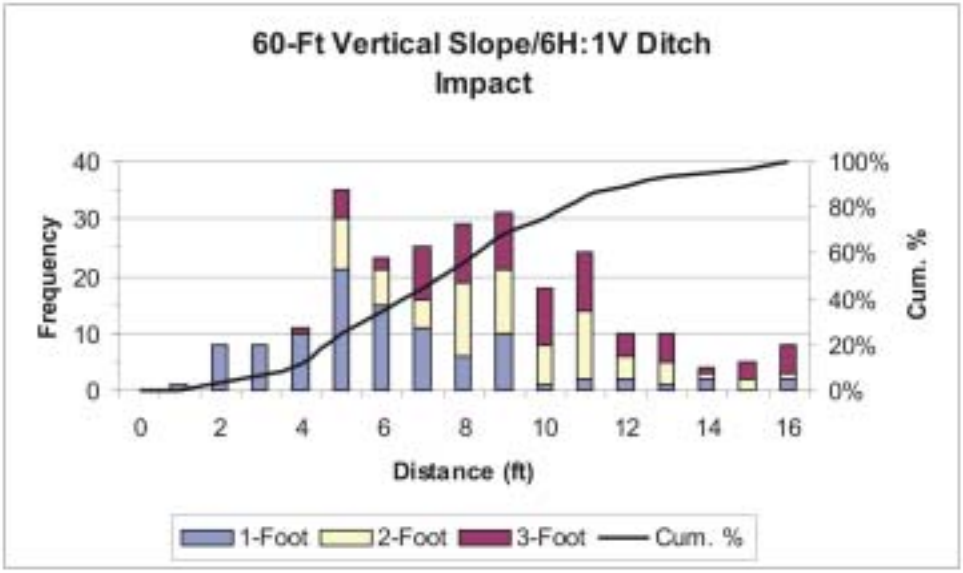
NOTE: Also included at the end of Appendix C is a limited set of data gathered from a 40-foot high, 1.25H:1V slope. The rocks rolled from this slope fell into a 4H:1V catchment area. The results were recorded but not compiled into catchment area percent retention graphs or design charts, because there were not sufficient funds to test the full suite of slope heights and catchment area inclinations for the 1.25H:1V test slope.

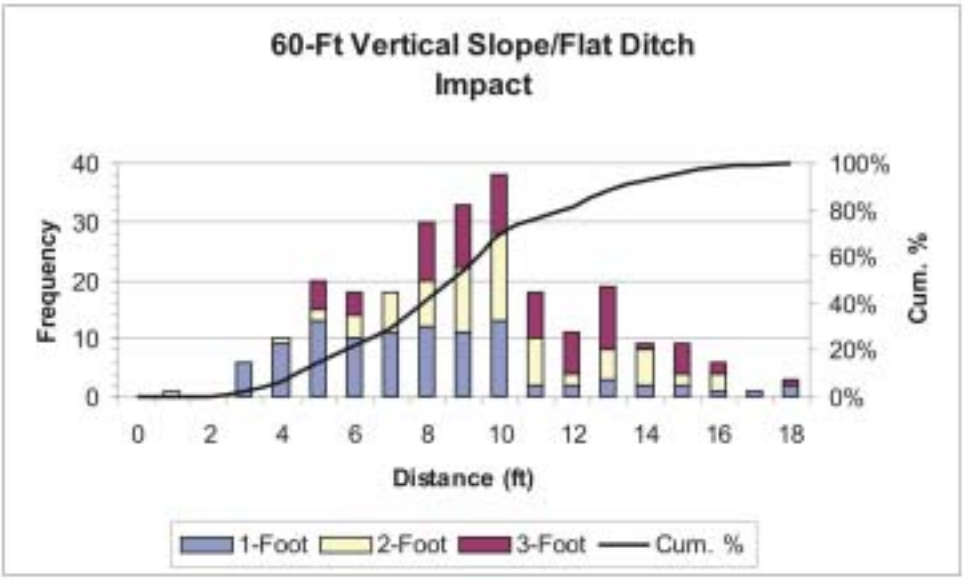

40-Ft Vertical Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

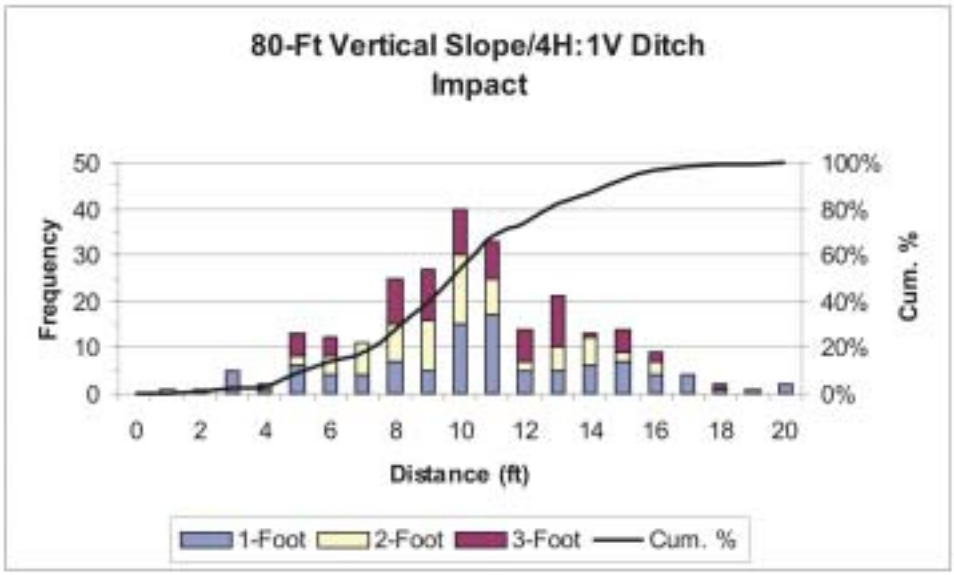

40-Ft Vertical Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-foot
2-foot
3-foot
Cum. %

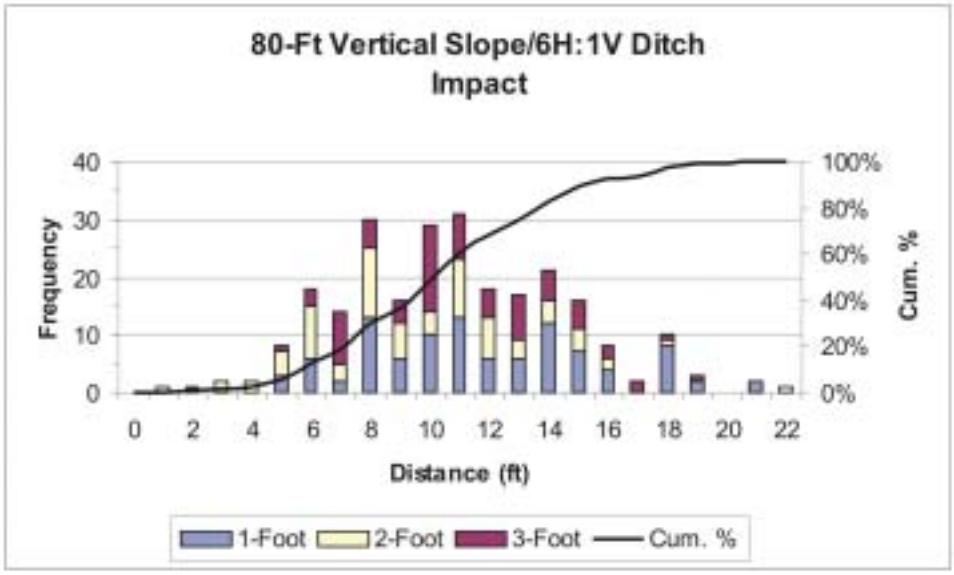

40-Ft Vertical Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-foot
2-foot
3-foot
Cum. %

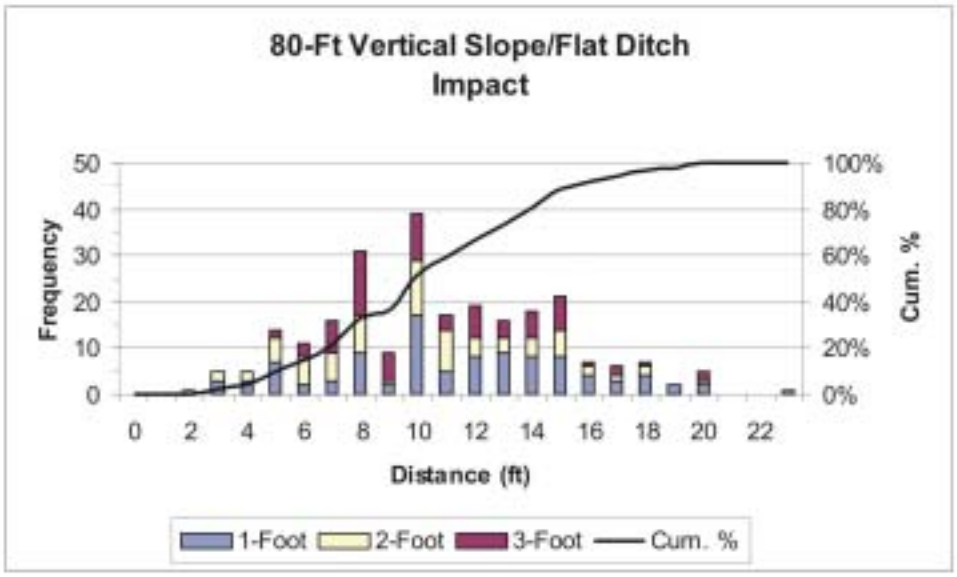

60-Ft Vertical Slope/4H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

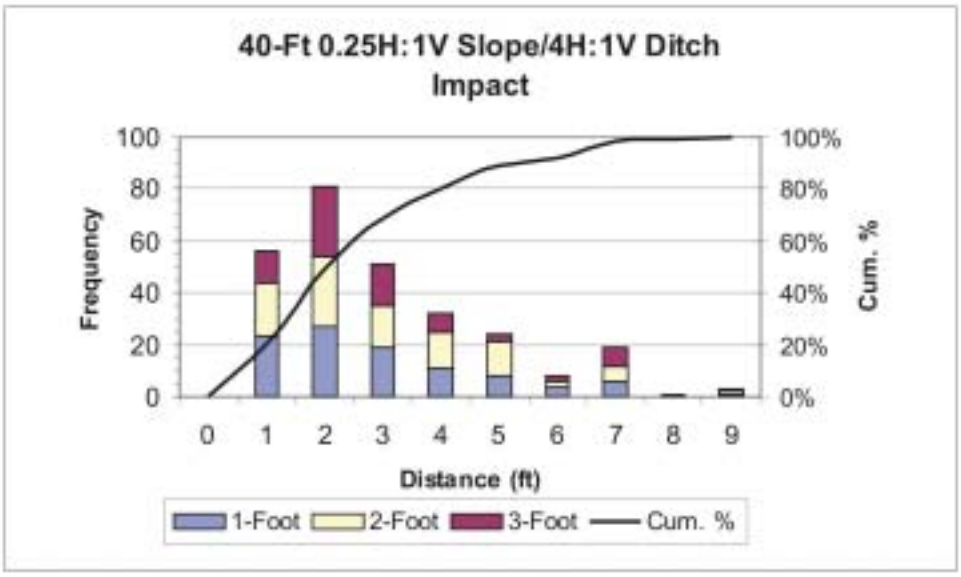

60-Ft Vertical Slope/6H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

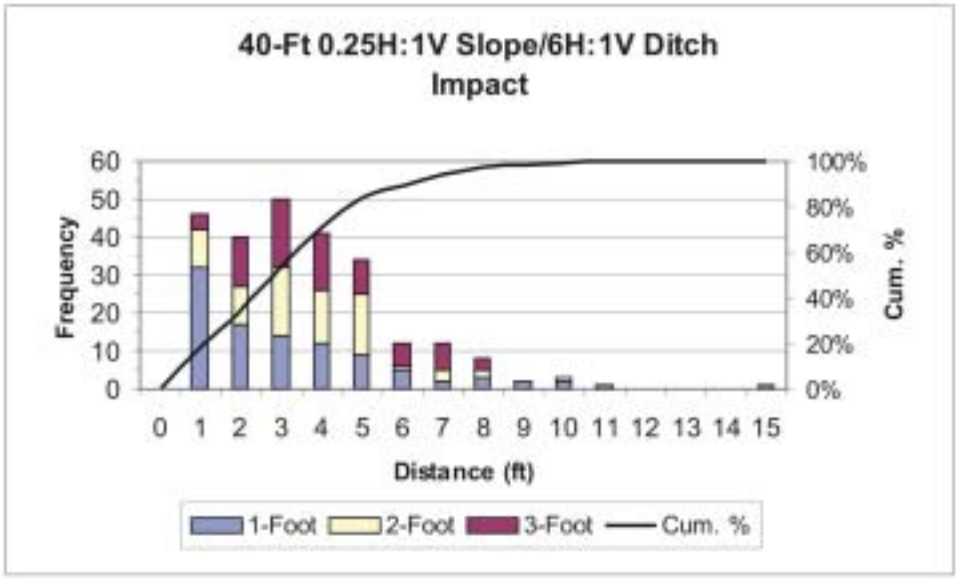

60-Ft Vertical Slope/Flat Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

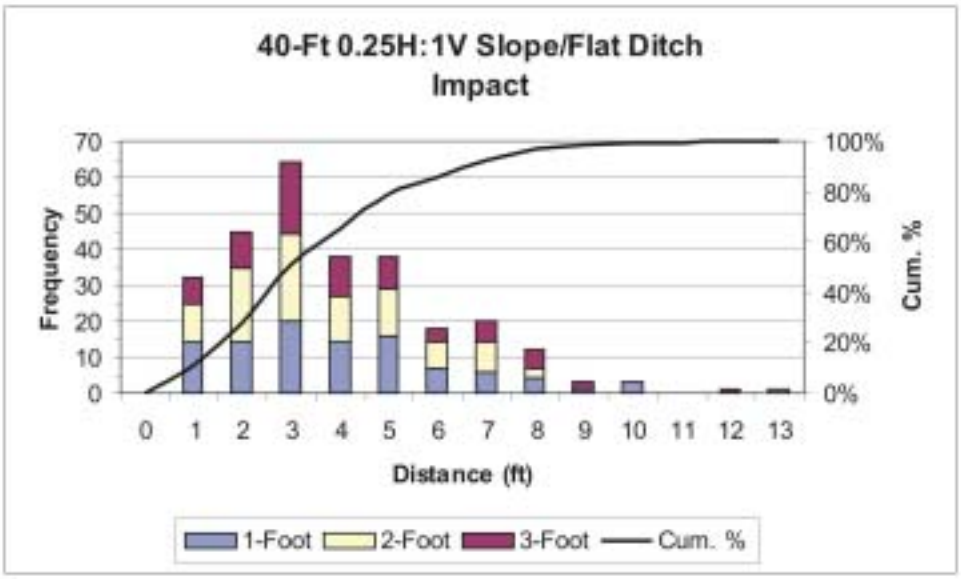

80-Ft Vertical Slope/4H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

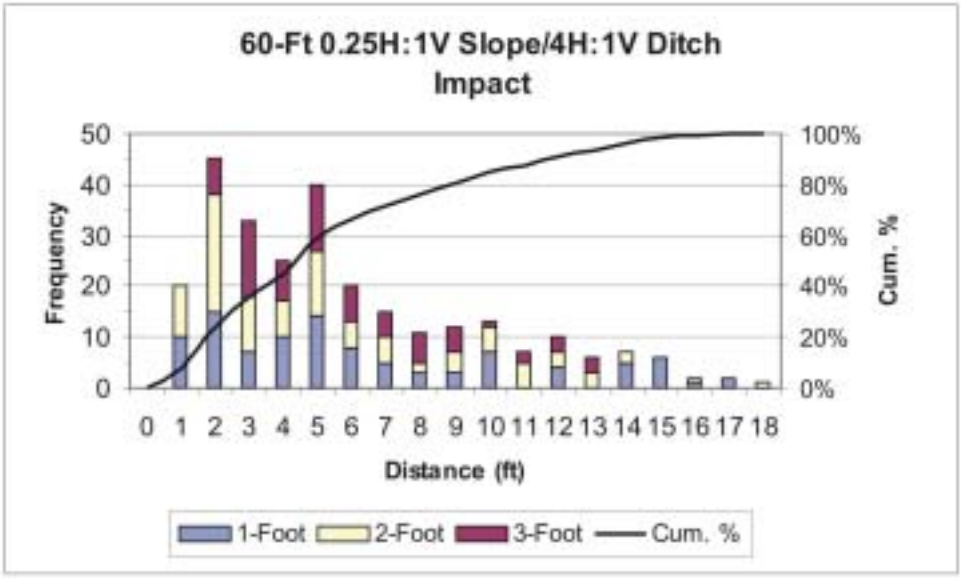

80-Ft Vertical Slope/6H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

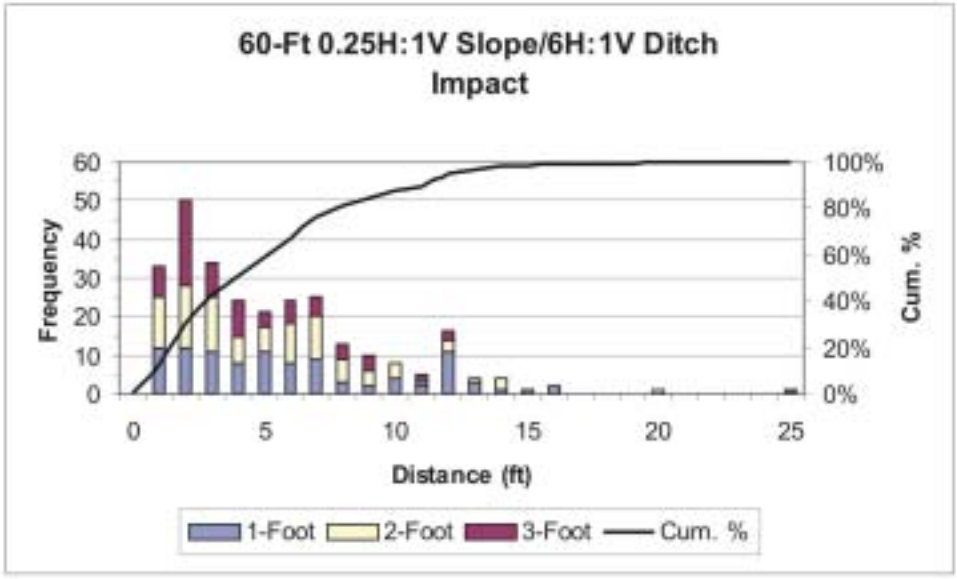

80-Ft Vertical Slope/Flat Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

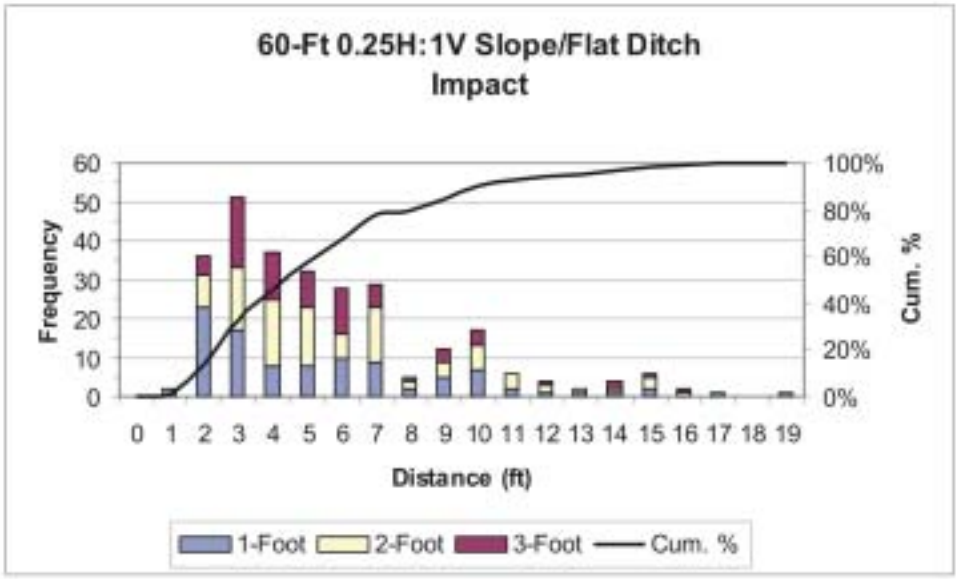

40-Ft 0.25H:1V Slope/4H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

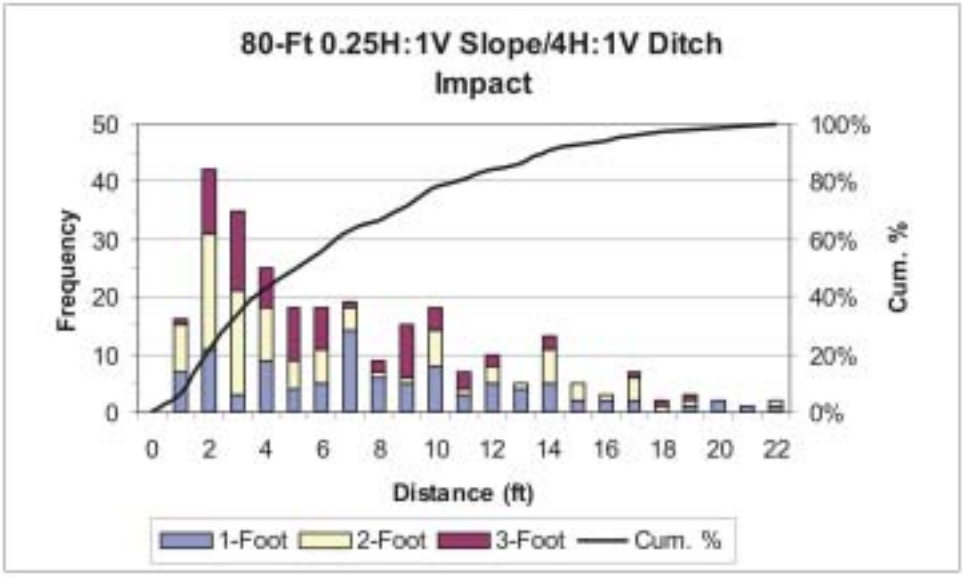

40-Ft 0.25H:1V Slope/6H:1V Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

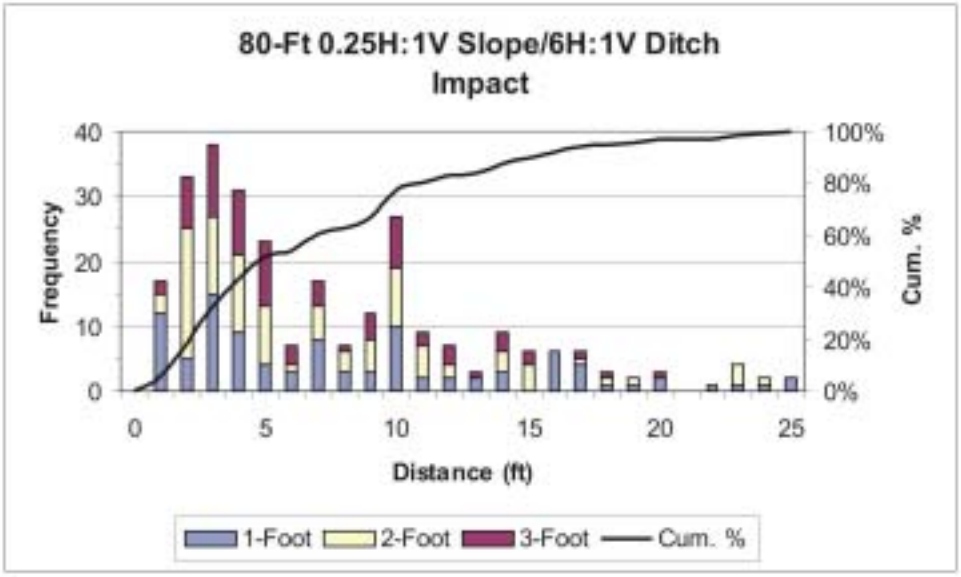

40-Ft 0.25H:1V Slope/Flat Ditch Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

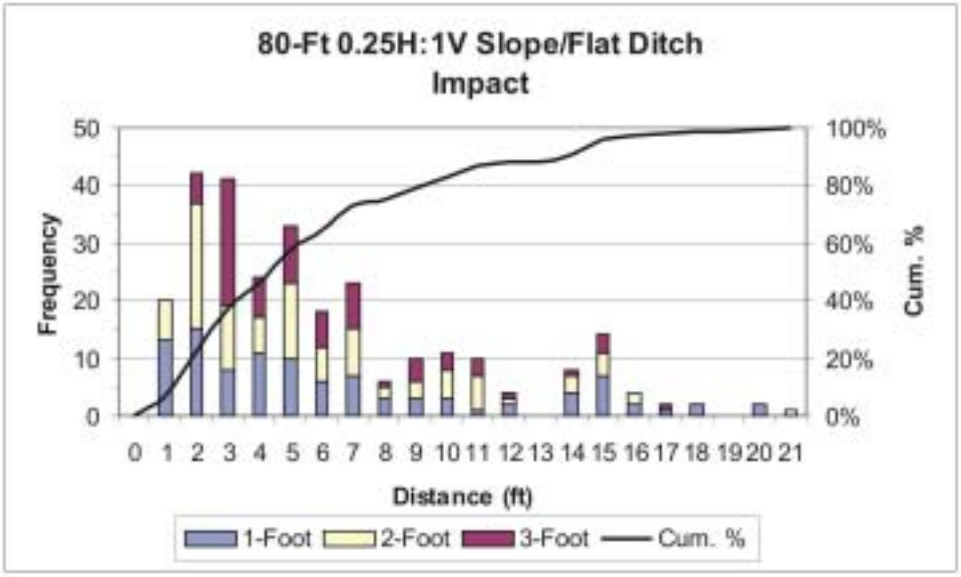

60-Ft 0.25H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

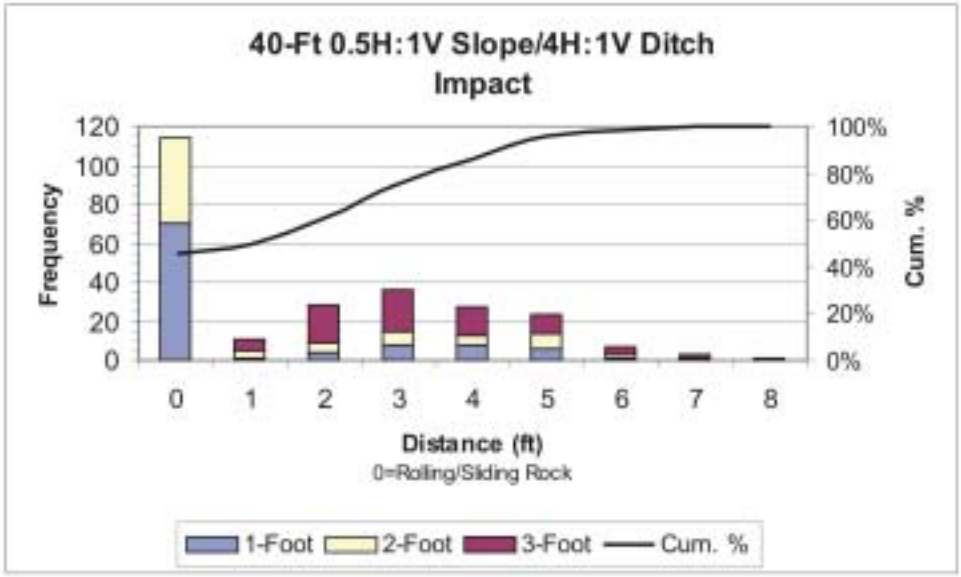

60-Ft 0.25H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

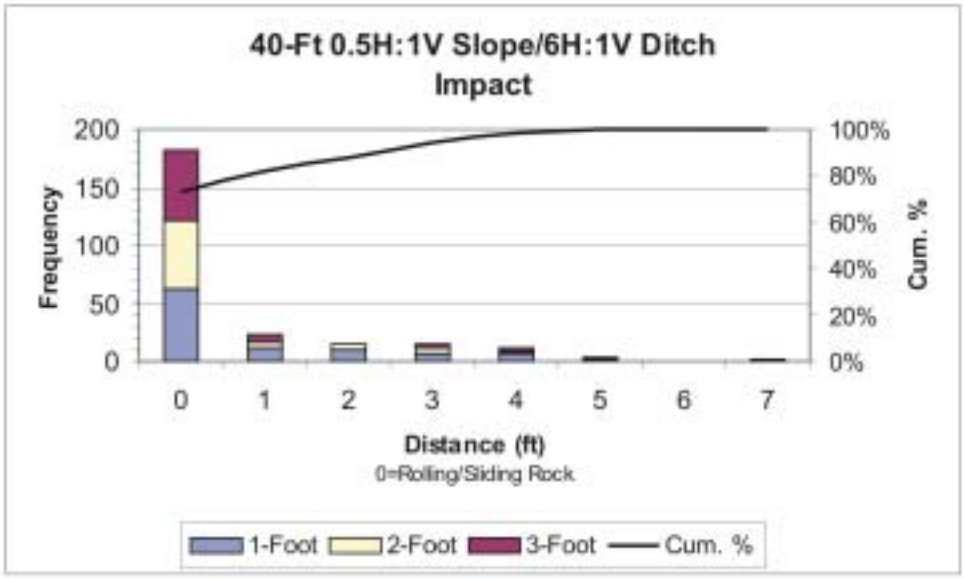

60-Ft 0.25H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

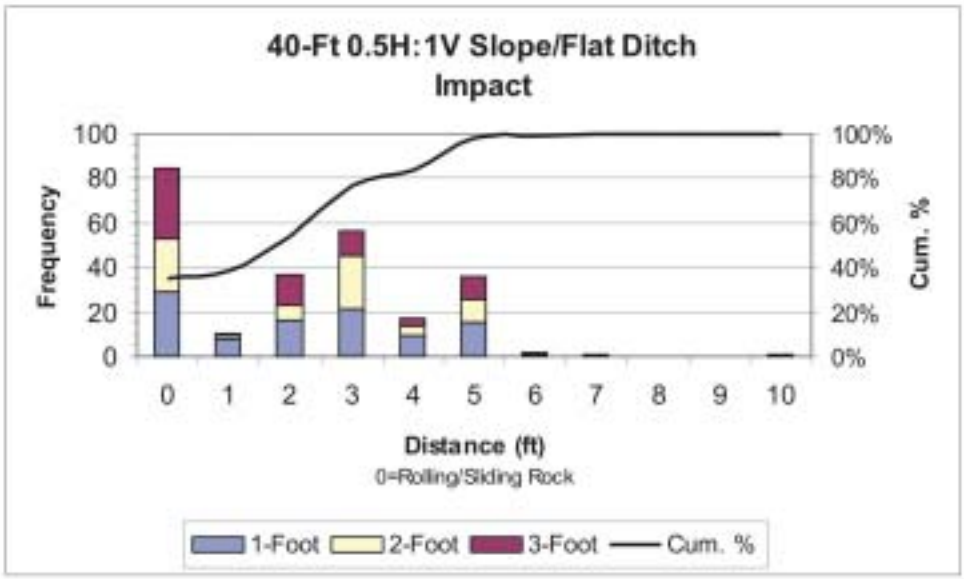

80-Ft 0.25H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

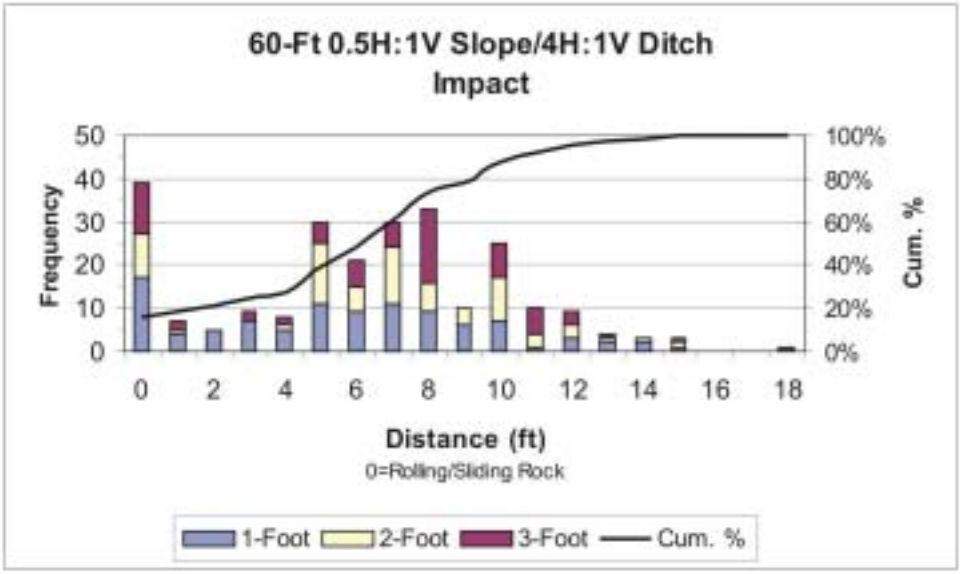

80-Ft 0.25H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

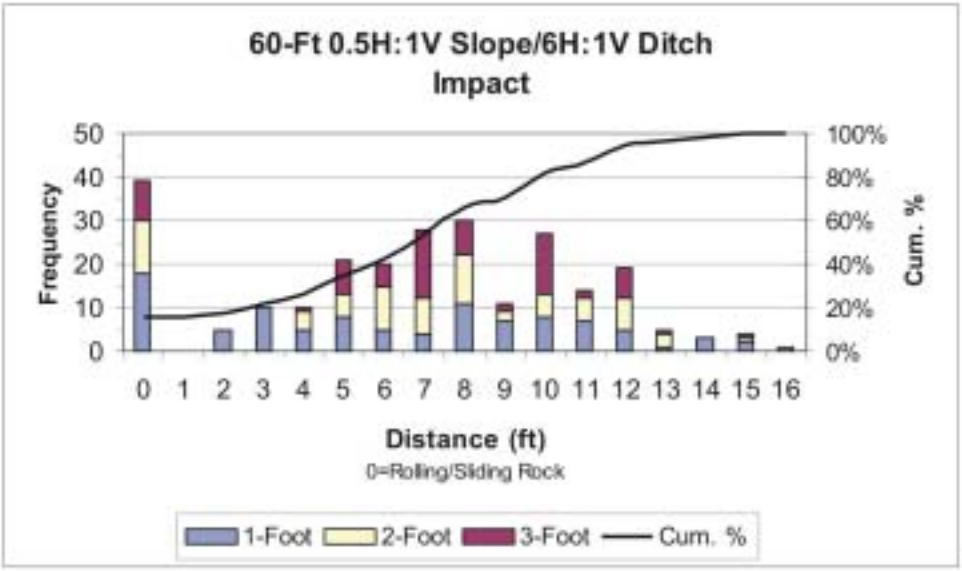

80-Ft 0.25H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

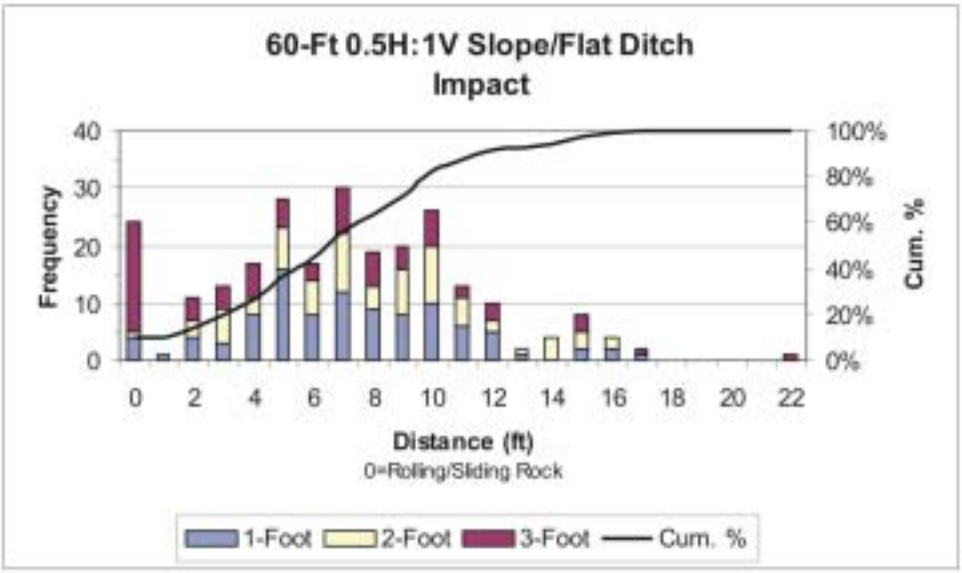

40-Ft 0.5H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

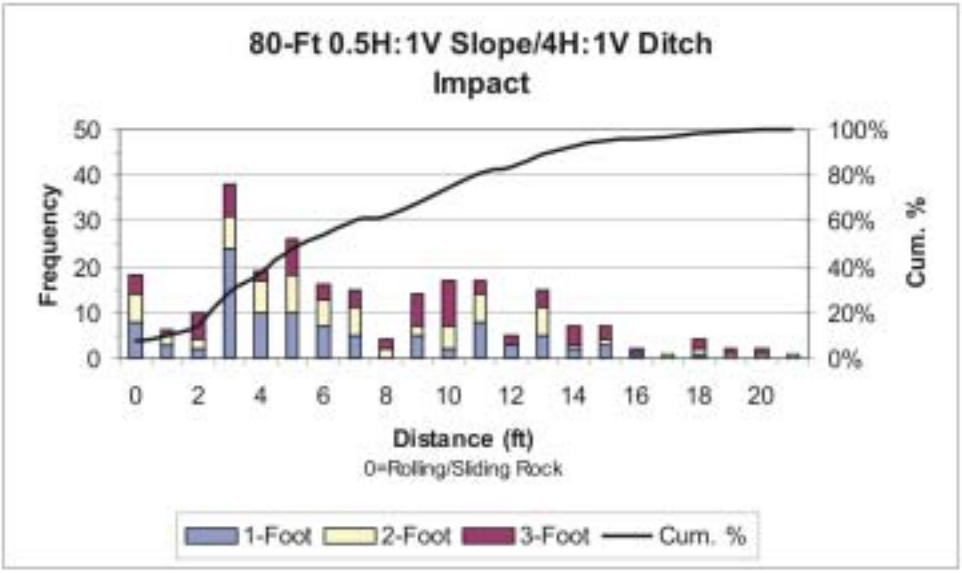

40-Ft 0.5H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

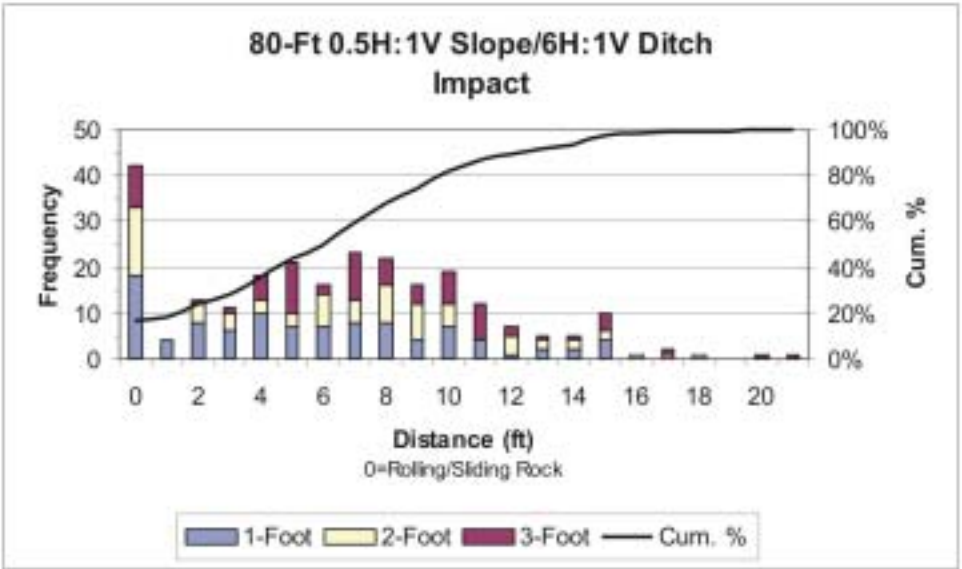

40-Ft 0.5H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

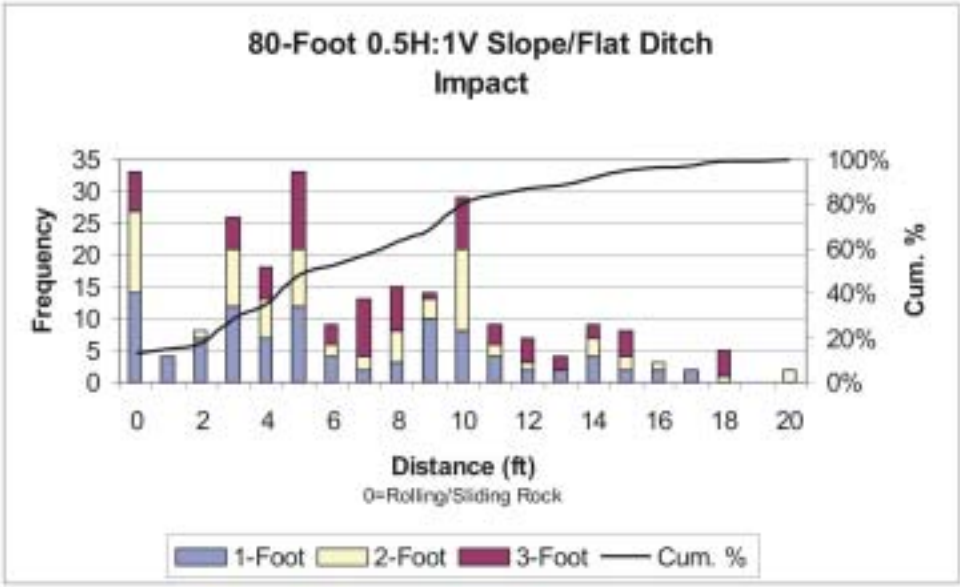

60-Ft 0.5H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

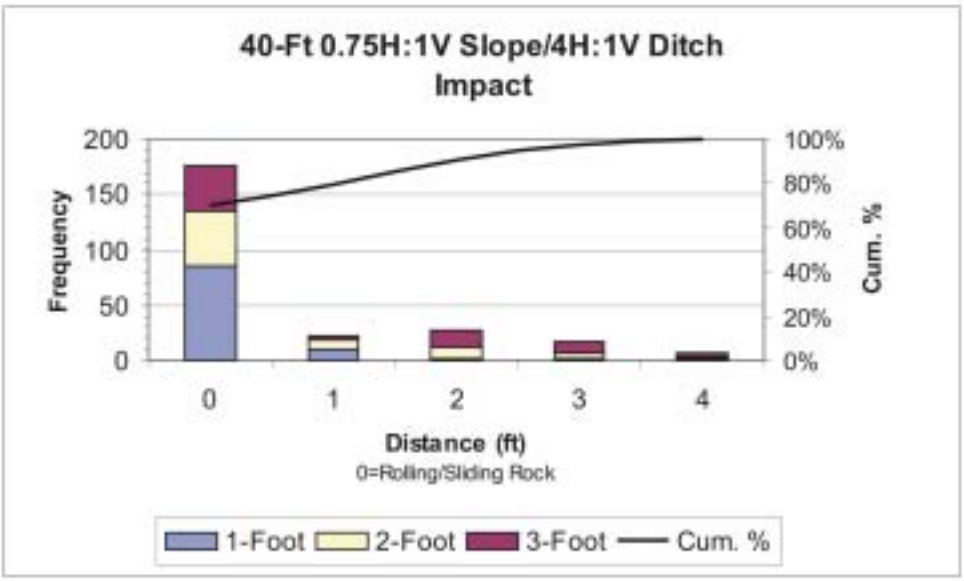

60-Ft 0.5H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

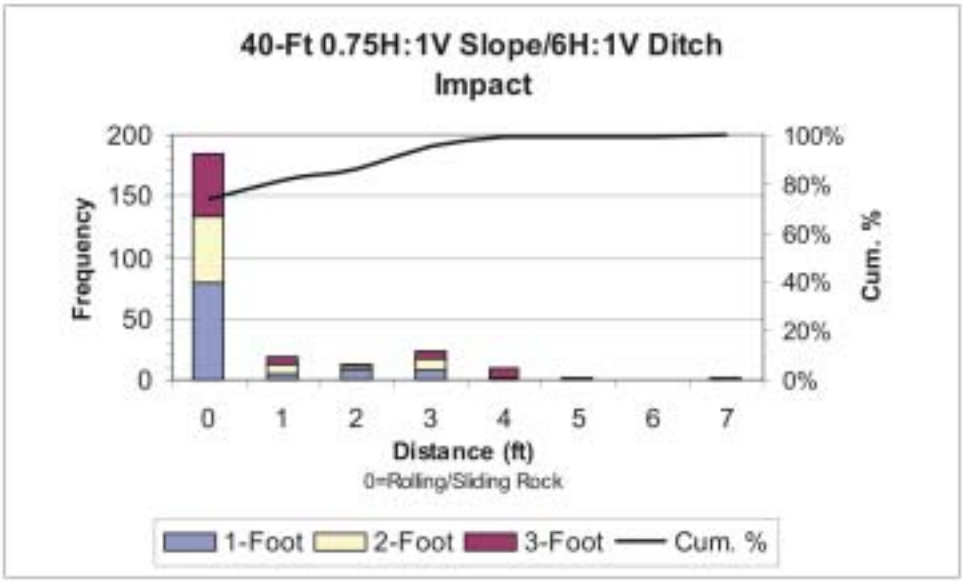

60-Ft 0.5H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

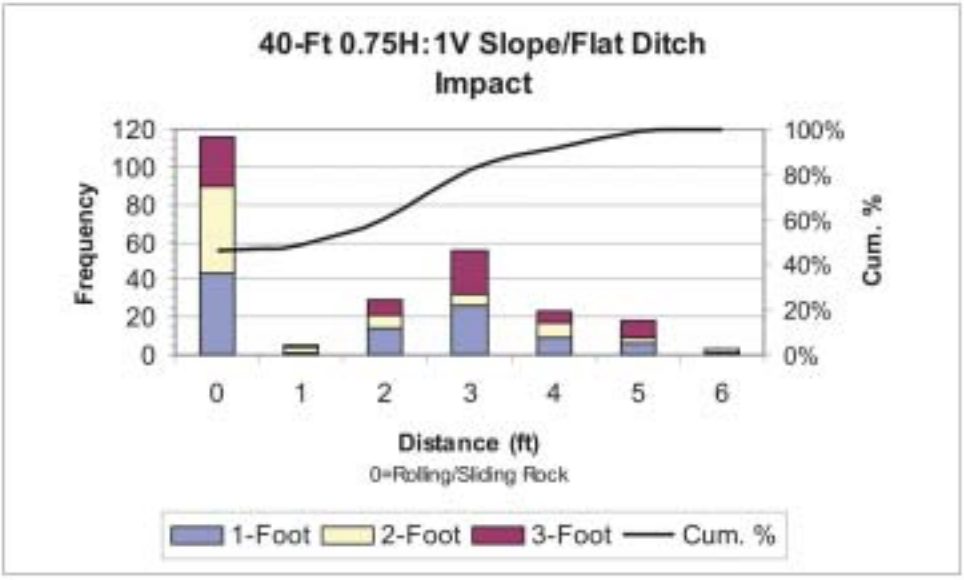

80-Ft 0.5H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

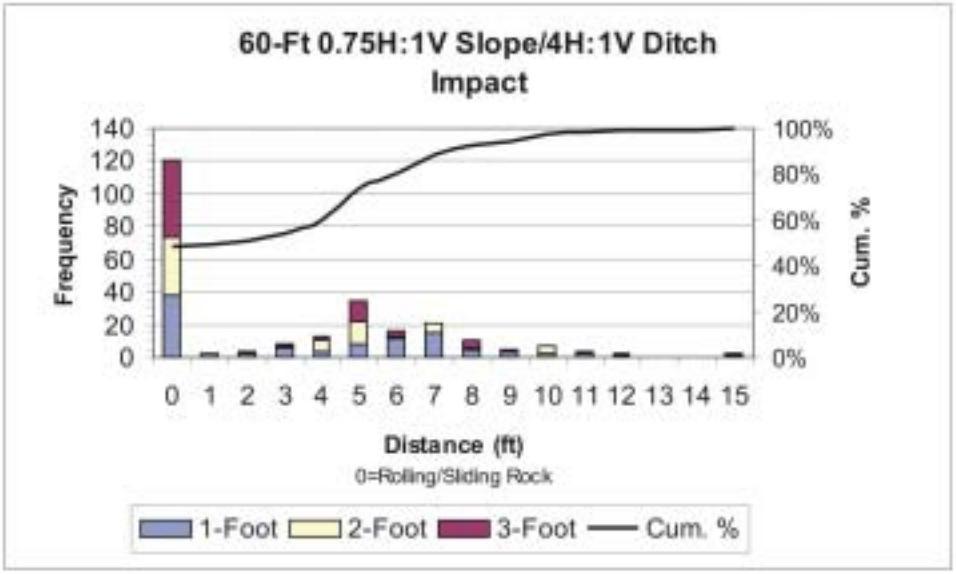

80-Ft 0.5H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

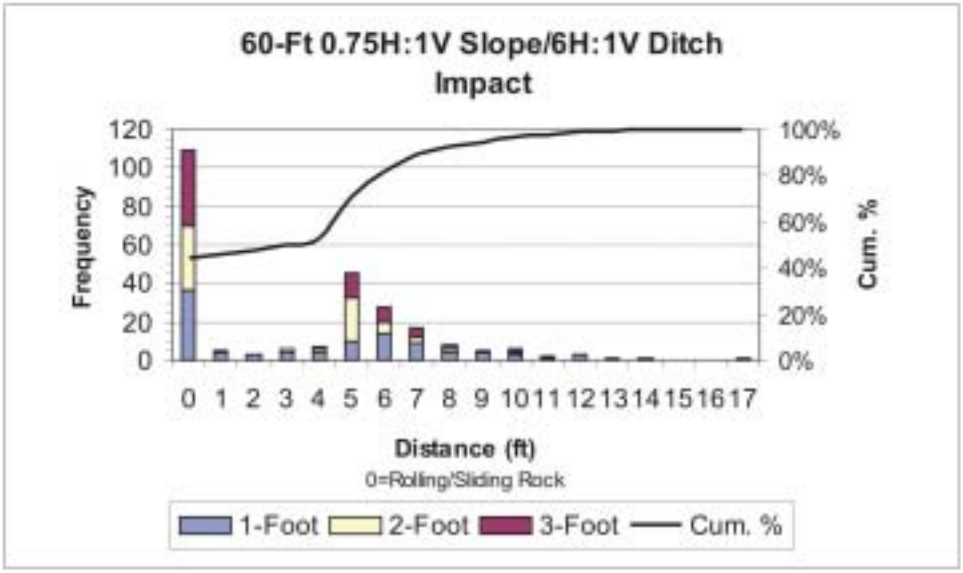

80-Foot 0.5H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

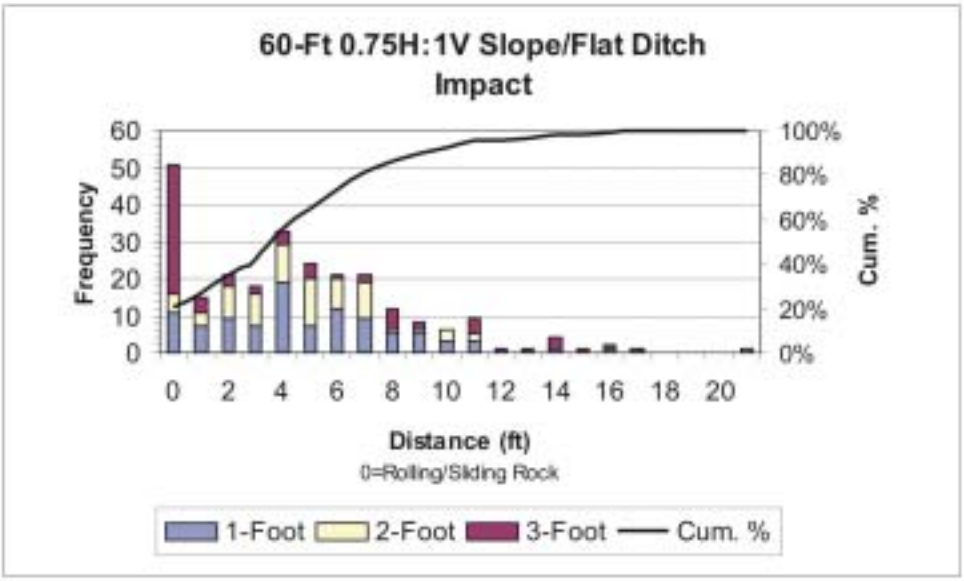

40-Ft 0.75H:1V Slope/4H:1V Ditch Impact
Frequency
Cum. %
200
150
100
50
0
100%
80%
60%
40%
20%
0%
0
1
2
3
4
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

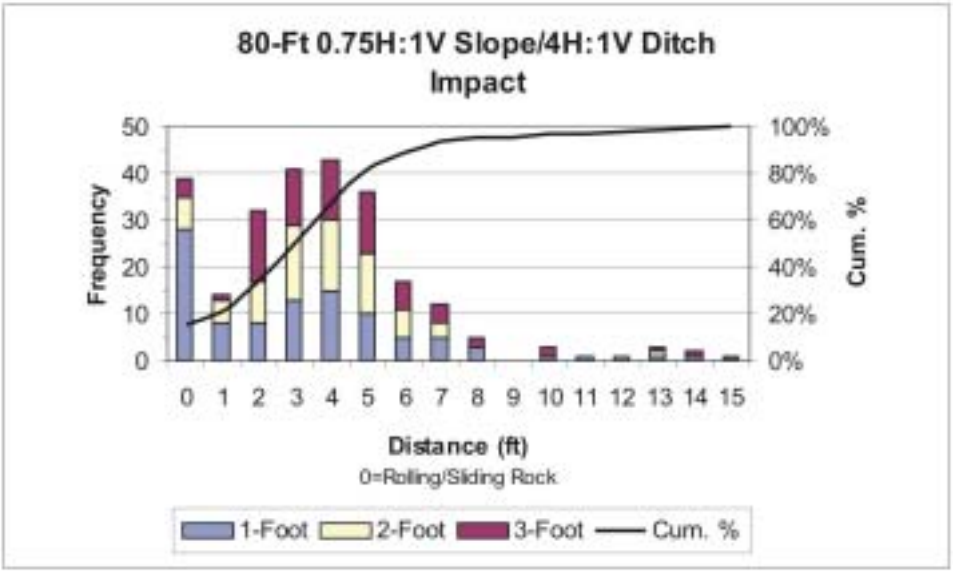

40-Ft 0.75H:1V Slope/6H:1V Ditch Impact
Frequency
Cum. %
200
150
100
50
0
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
7
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

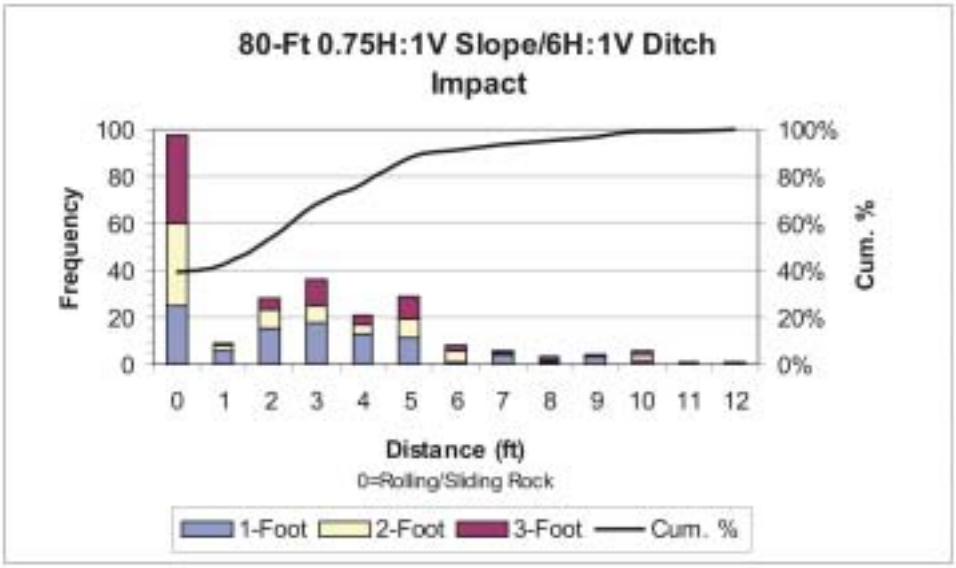

40-Ft 0.75H:1V Slope/Flat Ditch Impact
Frequency
Cum. %
120
100
80
60
40
20
0
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

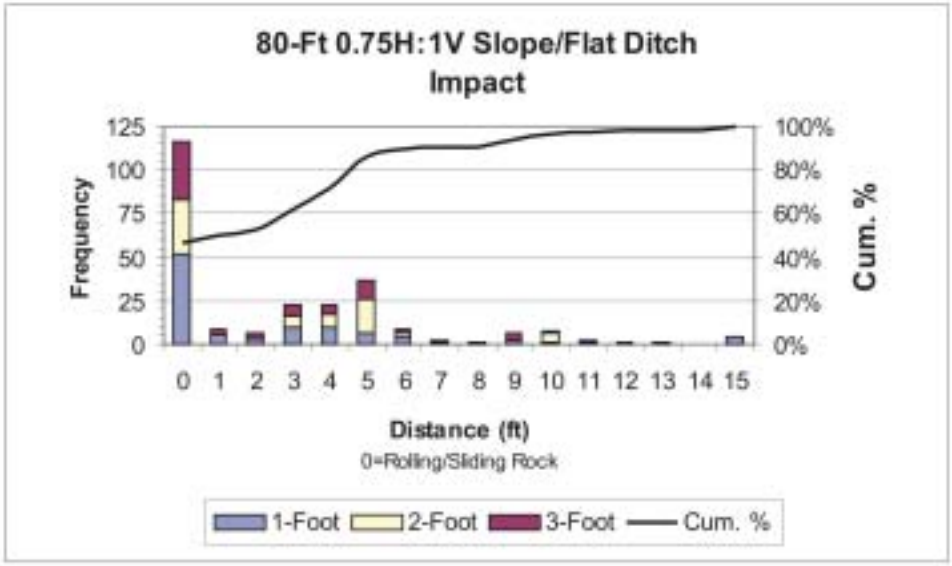

60-Ft 0.75H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

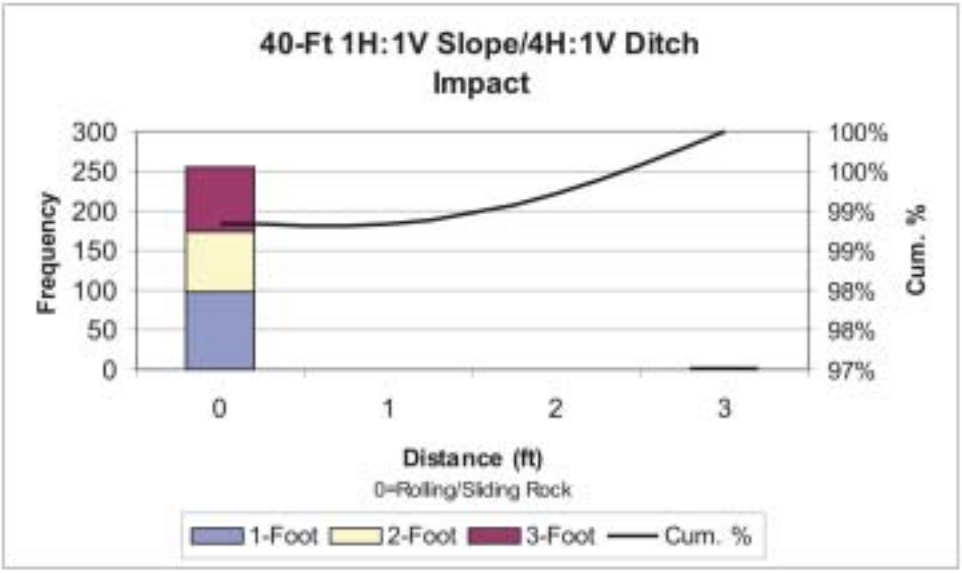

60-Ft 0.75H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

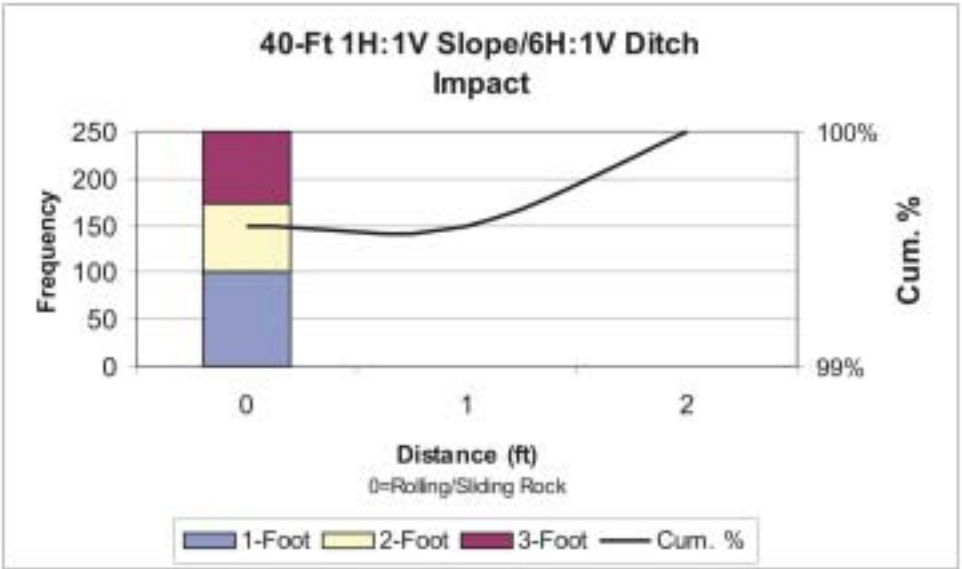

60-Ft 0.75H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

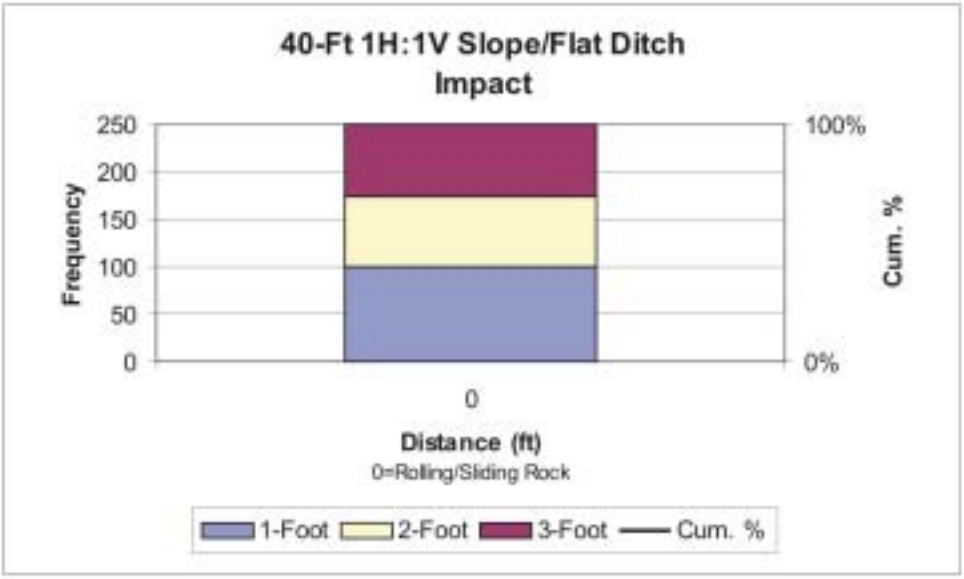

80-Ft 0.75H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

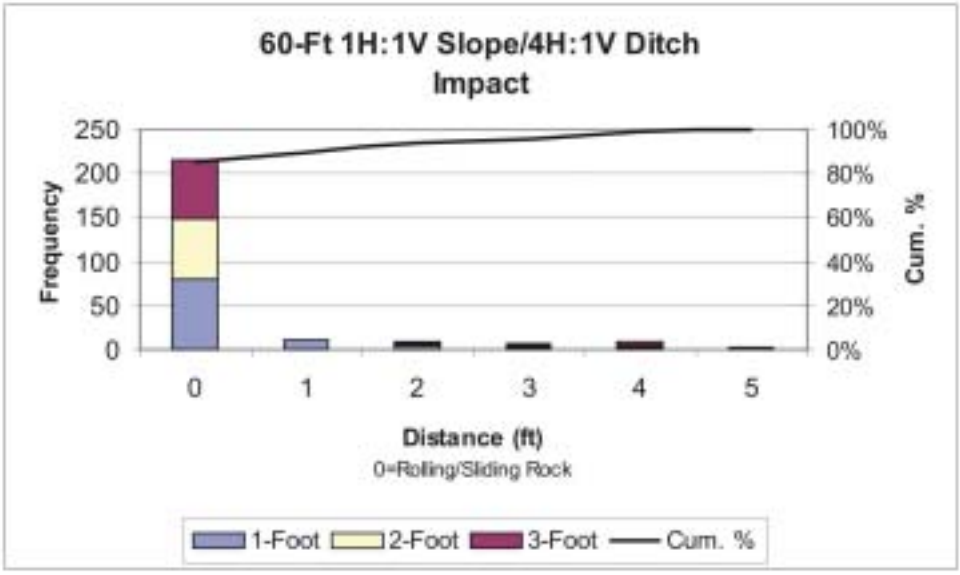

80-Ft 0.75H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

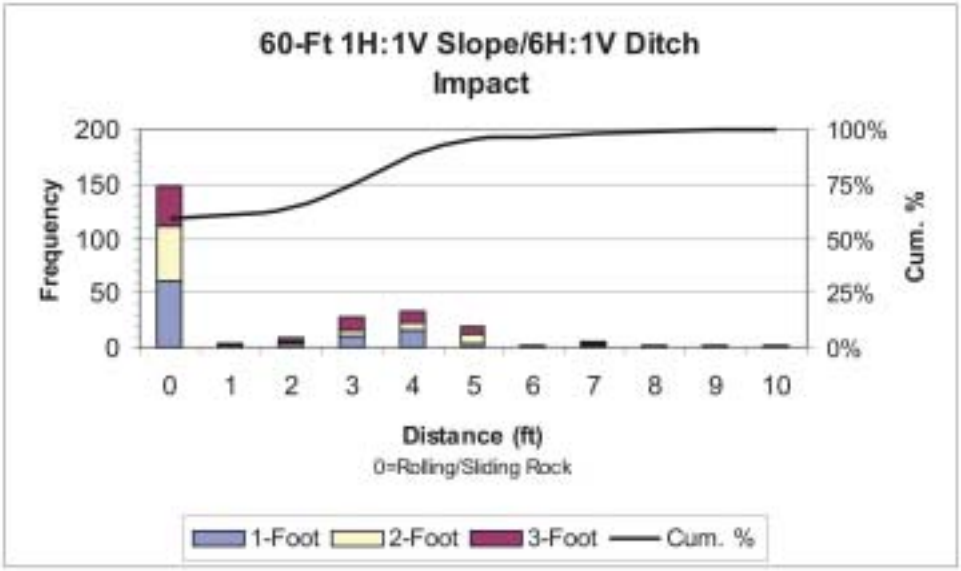

80-Ft 0.75H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

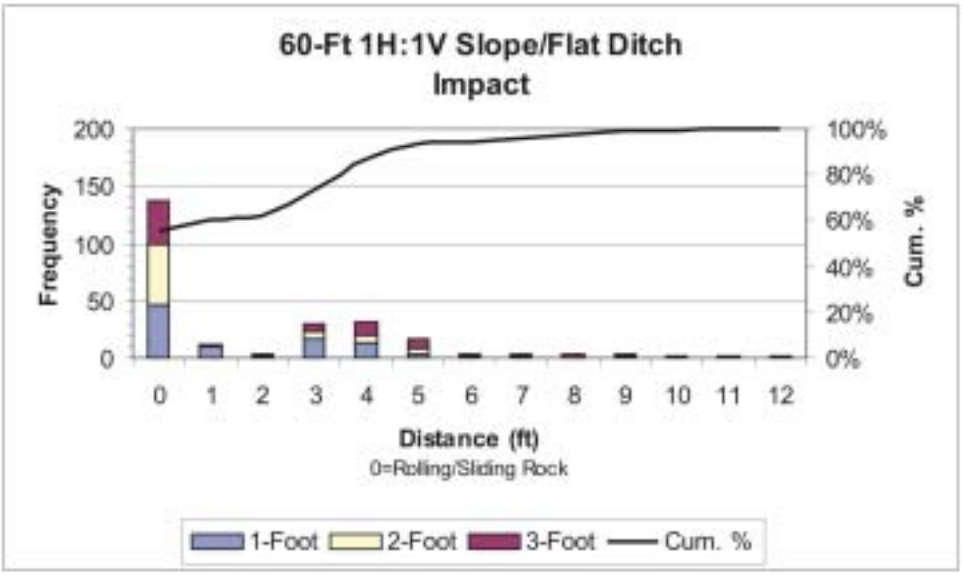

40-Ft 1H:1V Slope/4H:1V Ditch Impact
Frequency
300
250
200
150
100
50
0
100%
100%
99%
99%
98%
98%
97%
Cum. %
0
1
2
3
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

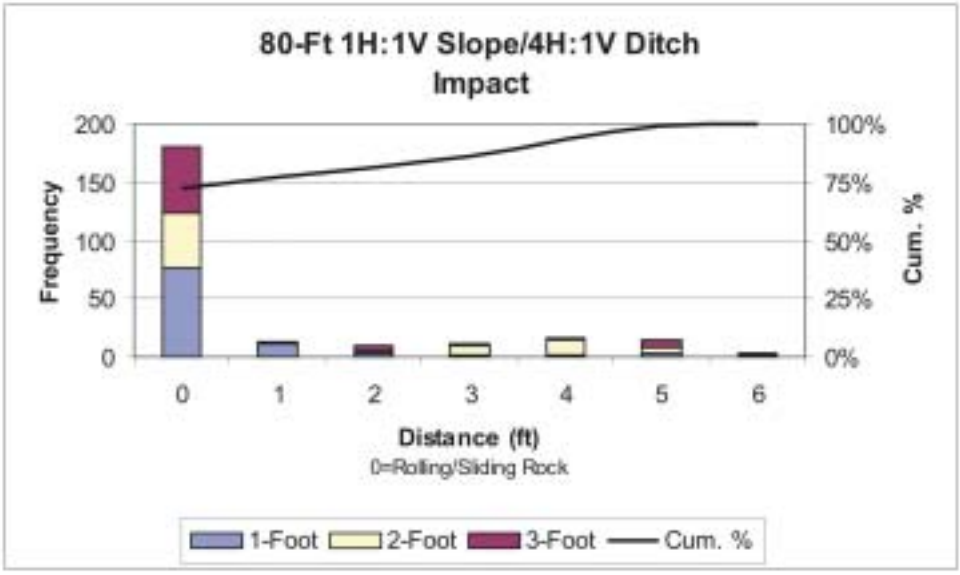

40-Ft 1H:1V Slope/6H:1V Ditch Impact
Frequency
250
200
150
100
50
0
100%
99%
Cum. %
0
1
2
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

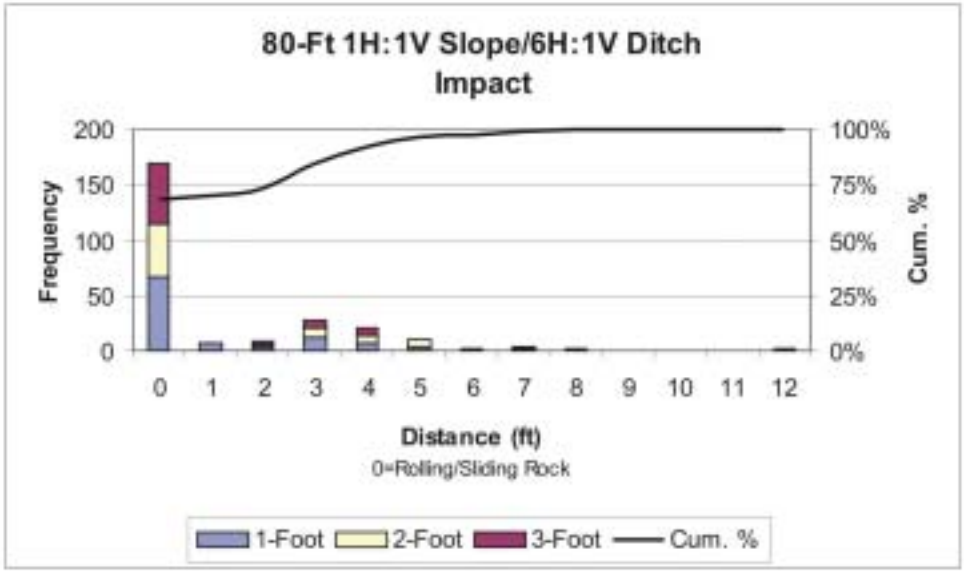

40-Ft 1H:1V Slope/Flat Ditch Impact
Frequency
250
200
150
100
50
0
100%
0%
Cum. %
0
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

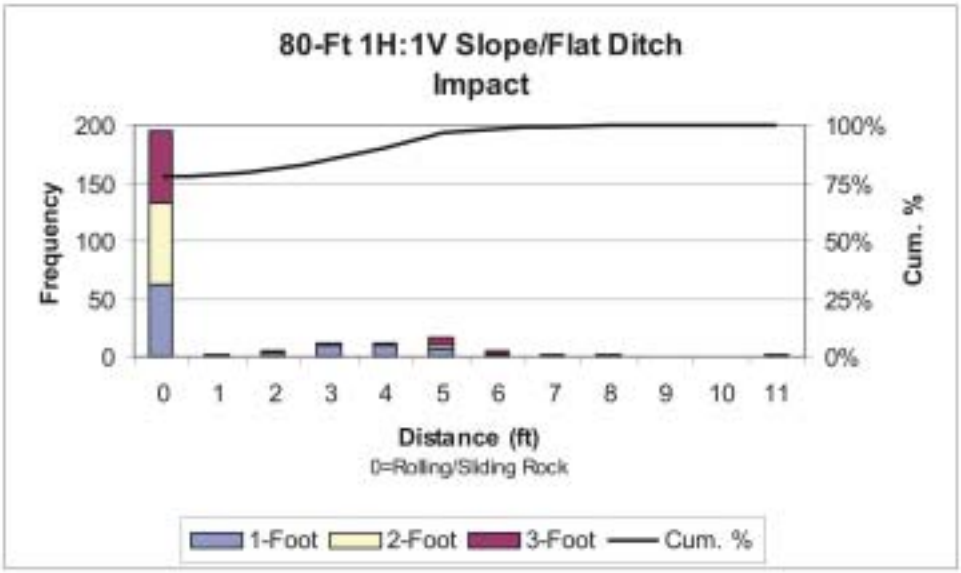

60-Ft 1H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
250
200
150
100
50
0
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %

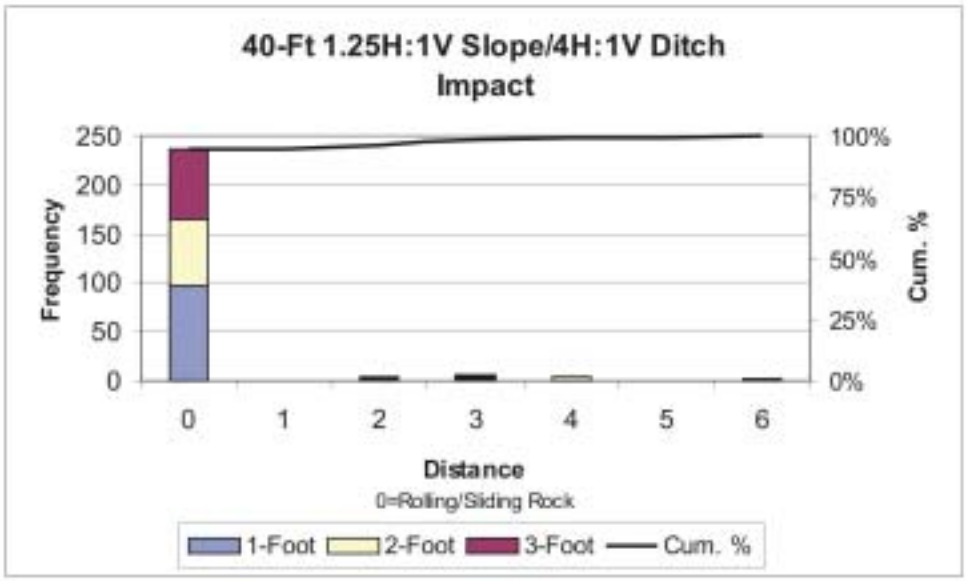

60-Ft 1H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
200
150
100
50
0
100%
75%
50%
25%
0%
0
1
2
3
4
5
6
7
8
9
10
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %


60-Ft 1H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
200
150
100
50
0
100%
80%
60%
40%
20%
0%
0
1
2
3
4
5
6
7
8
9
10
11
12
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft 1H:1V Slope/4H:1V Ditch
Impact
Frequency
Cum. %
200
150
100
50
0
100%
75%
50%
25%
0%
0
1
2
3
4
5
6
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft 1H:1V Slope/6H:1V Ditch
Impact
Frequency
Cum. %
200
150
100
50
0
100%
75%
50%
25%
0%
0
1
2
3
4
5
6
7
8
9
10
11
12
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft 1H:1V Slope/Flat Ditch
Impact
Frequency
Cum. %
200
150
100
50
0
100%
75%
50%
25%
0%
0
1
2
3
4
5
6
7
8
9
10
11
Distance (ft)
0=Rolling/Sliding Rock
1-Foot
2-Foot
3-Foot
Cum. %



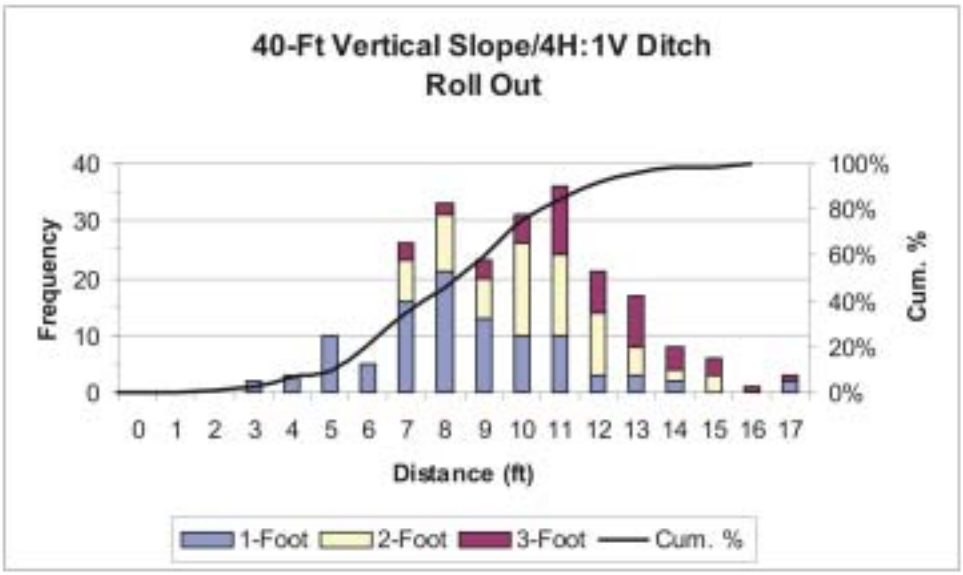
Note: This was the only 1.25H:1V slope tested. Insufficient funds were available to test additional slopes.

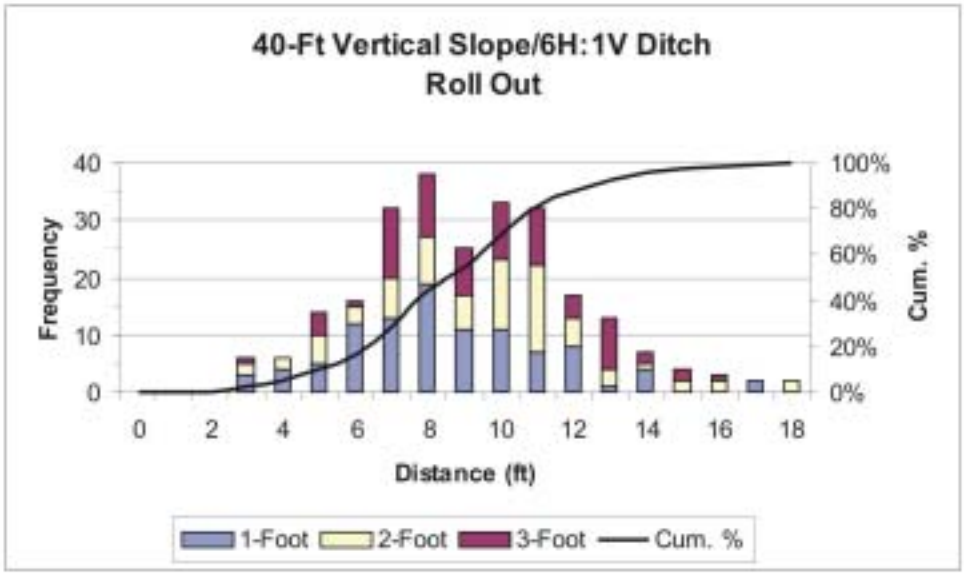
APPENDIX D: ROCKFALL ROLL OUT DISTANCE HISTOGRAMS

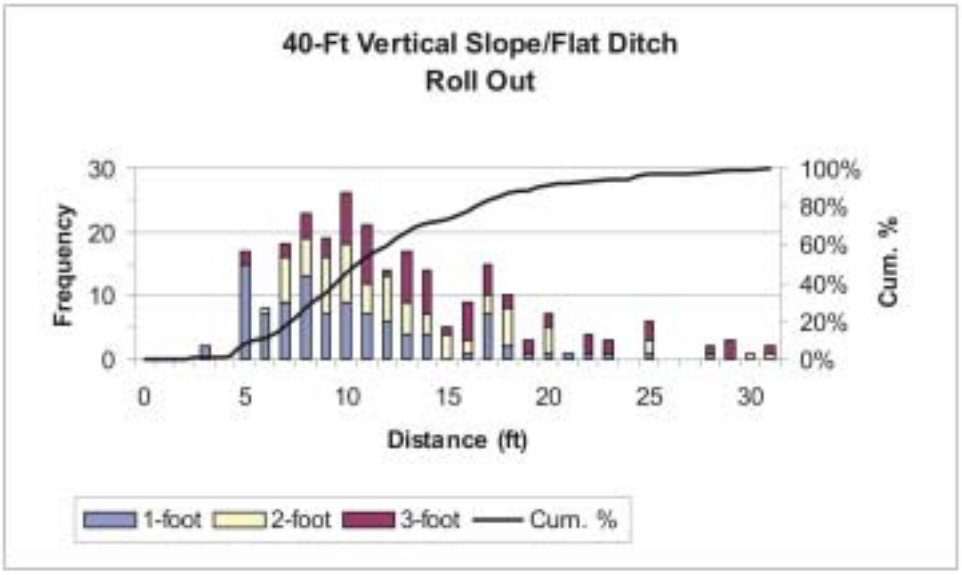
ROCKFALL ROLL OUT DISTANCE HISTOGRAMS

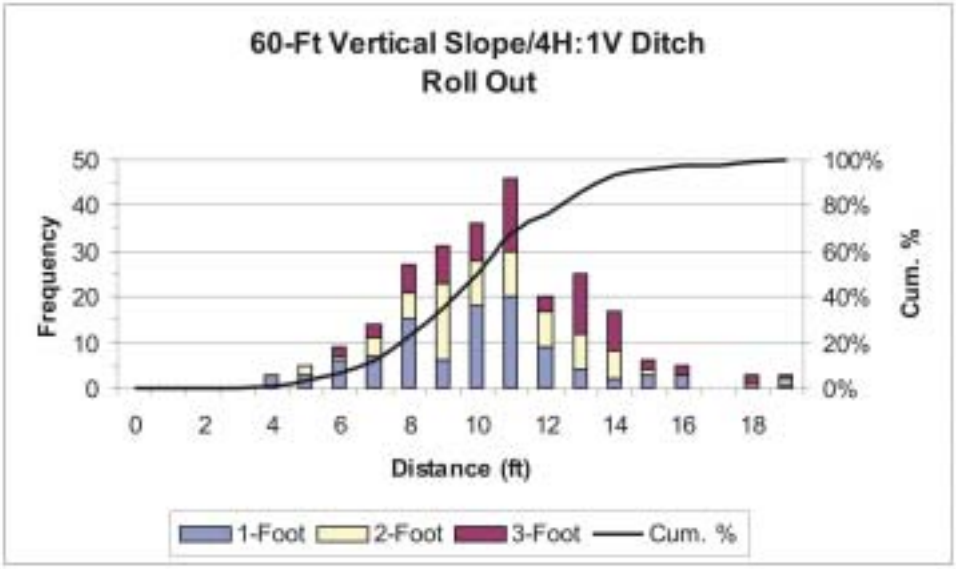
The roll out histograms have a similar appearance to the impact histograms but instead graphically represent the maximum distance each test-rock obtained from the toe of the slope as the rock rolled through the catchment area after impact. In some cases the rockfalls created a crater and did not move beyond the impact distance. This was more common with the steeper slopes. For flatter slopes, a zero distance roll out value was very rare. These general observations of rockfall roll out behavior should not be construed to mean that rockfalls from steep slopes would not result in large roll out values. The largest roll out measured was from a 0.25H:1V, 80-foot high slope. That distance was 99 feet. The roll out distances are the field measured slope distances. Field data was recorded to the nearest foot.

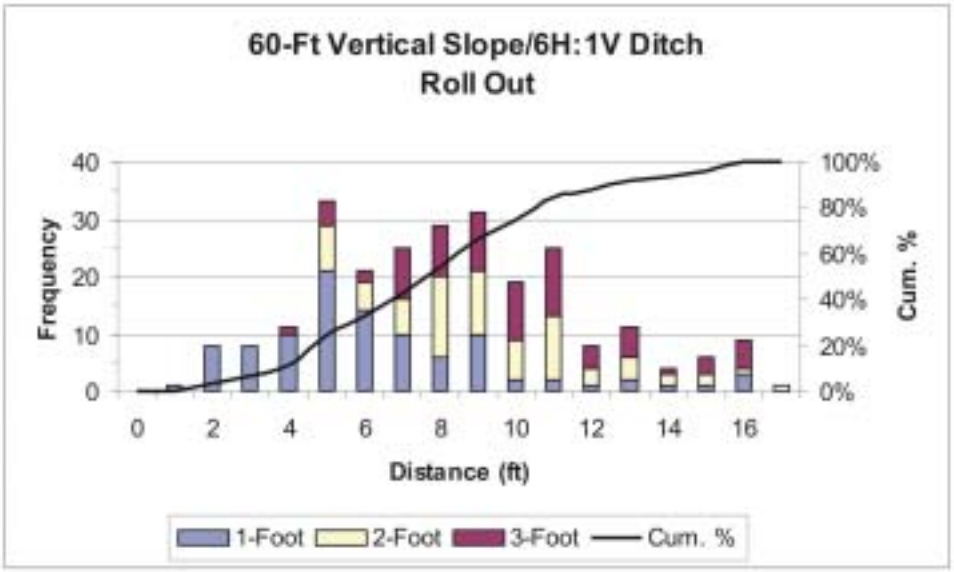
NOTE: Also included at the end of Appendix D is a limited set of data gathered from a 40-foot high, 1.25H:1V slope. The rocks rolled from this slope fell into a 4H:1V catchment area. The results were recorded but not compiled into catchment area percent retention graphs or design charts, because there were not sufficient funds to test the full suite of slope heights and catchment area inclinations for the 1.25H:1V test slope.

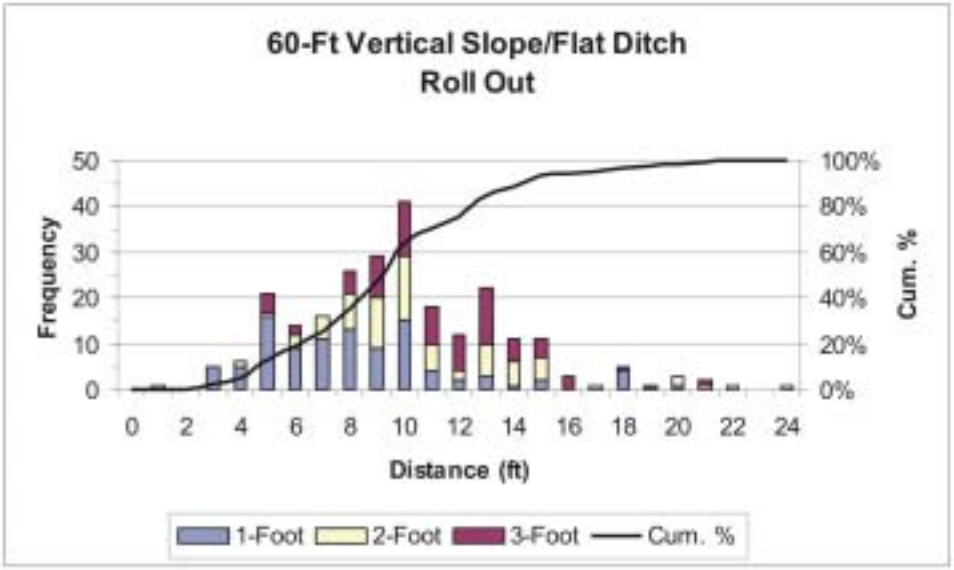

40-Ft Vertical Slope/4H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

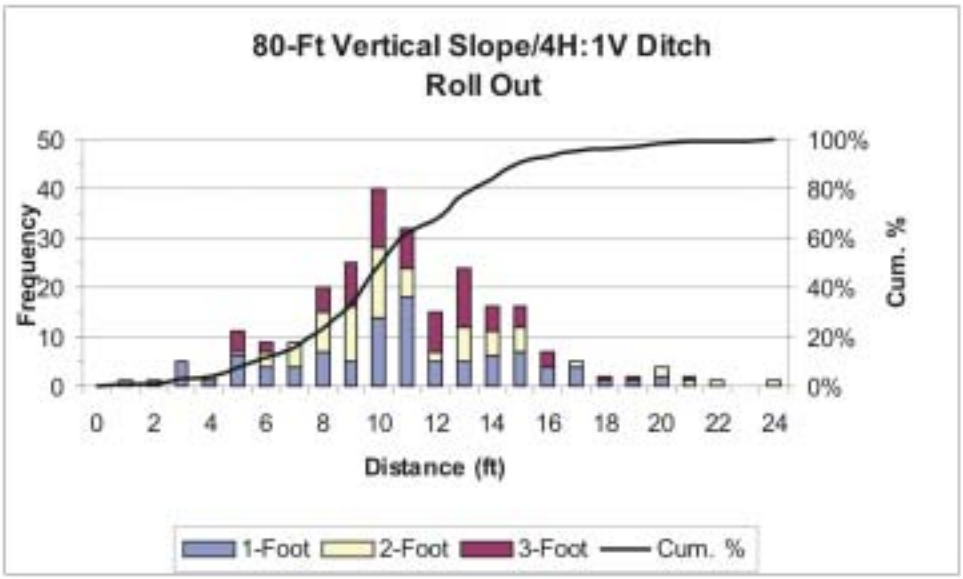

40-Ft Vertical Slope/6H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %

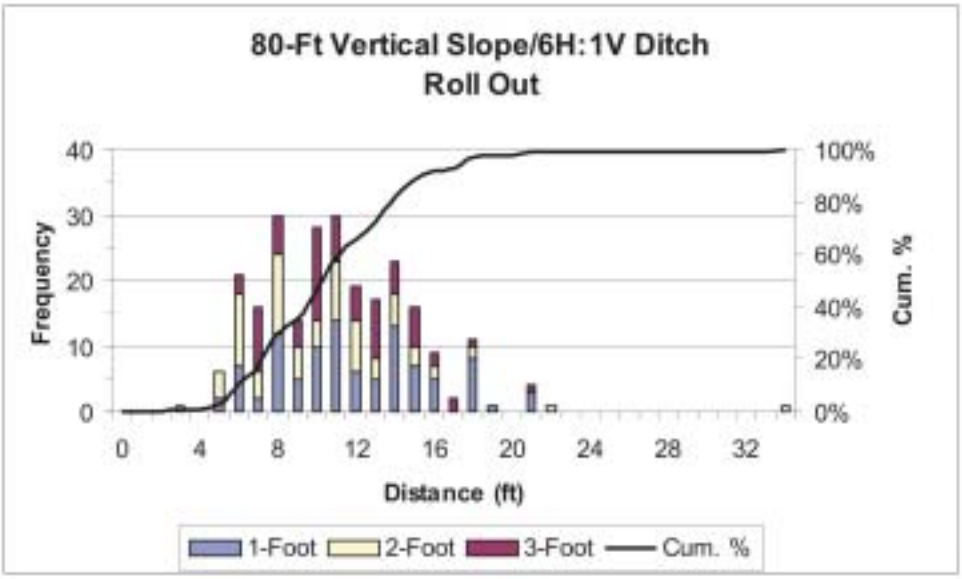

40-Ft Vertical Slope/Flat Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-foot
2-foot
3-foot
Cum. %

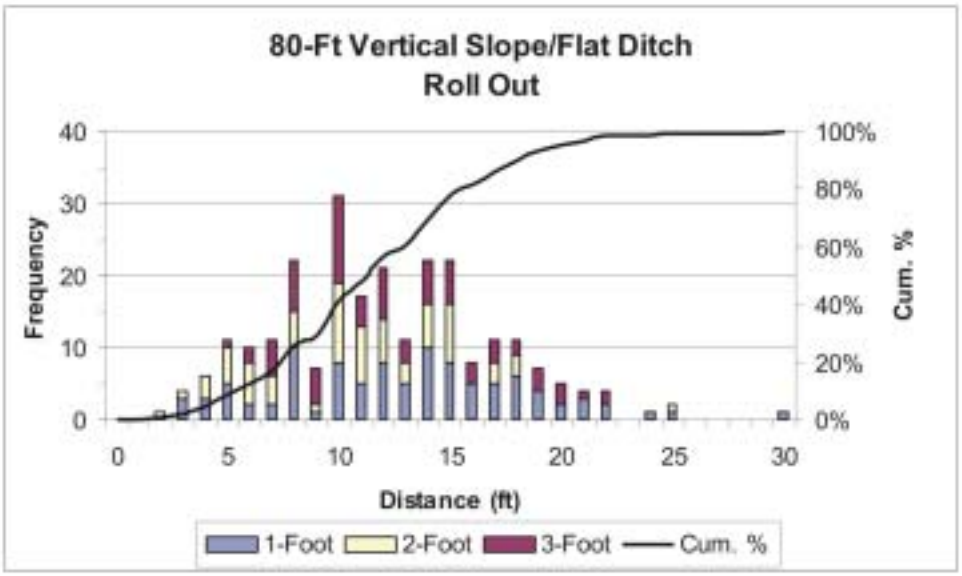

60-Ft Vertical Slope/4H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %


60-Ft Vertical Slope/6H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %


60-Ft Vertical Slope/Flat Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft Vertical Slope/4H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft Vertical Slope/6H:1V Ditch
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %


80-Ft Vertical Slope/Flat Ditch
Roll Out
Frequency
Cum. %
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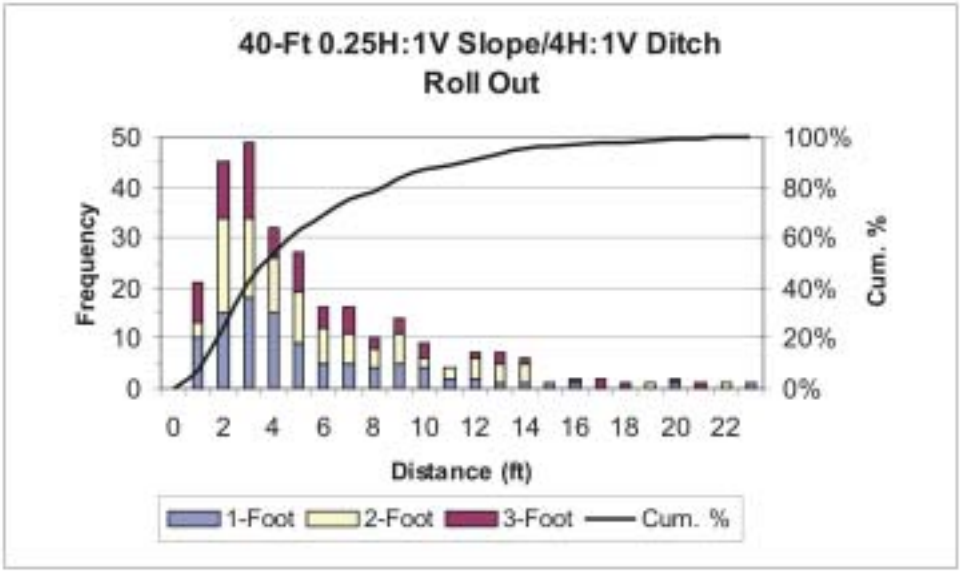
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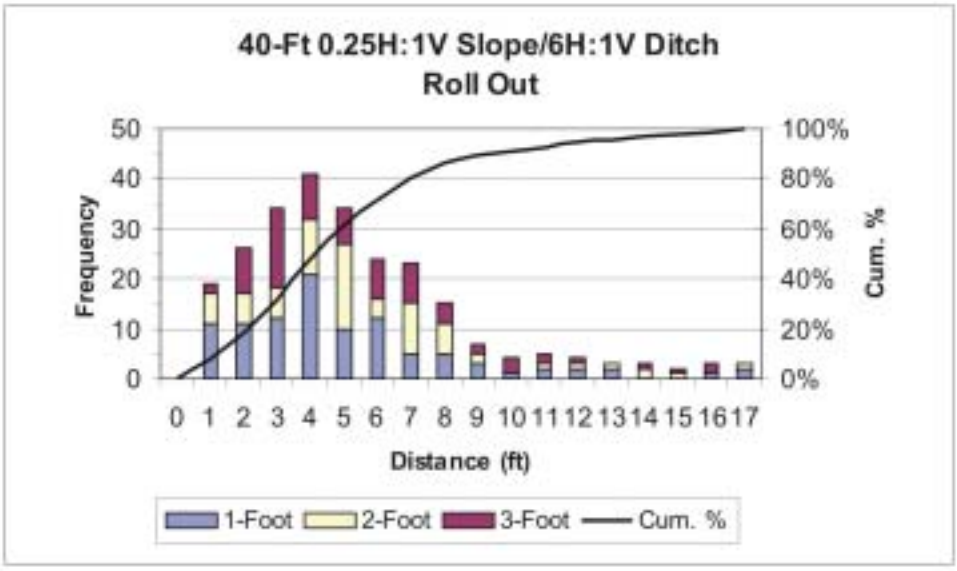
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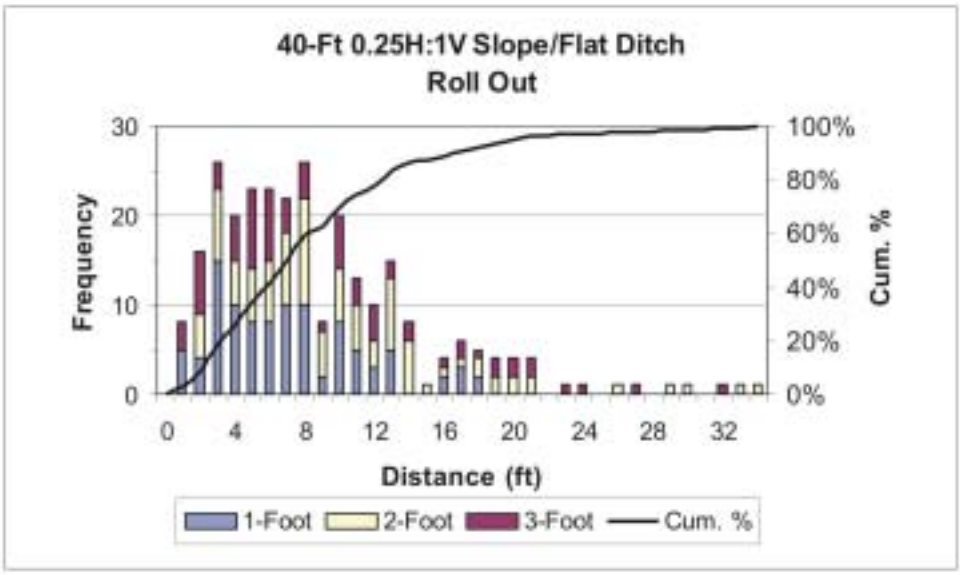
Cum. %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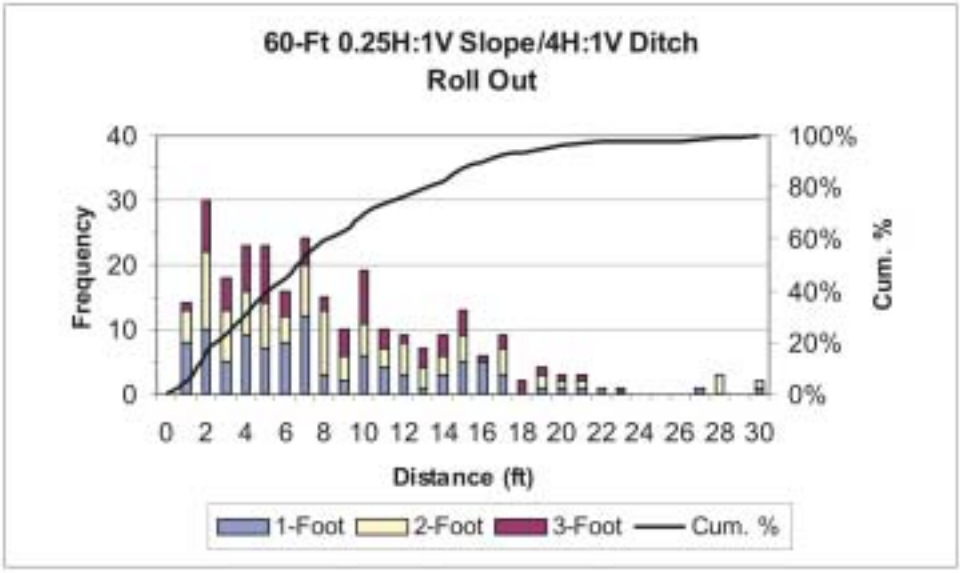
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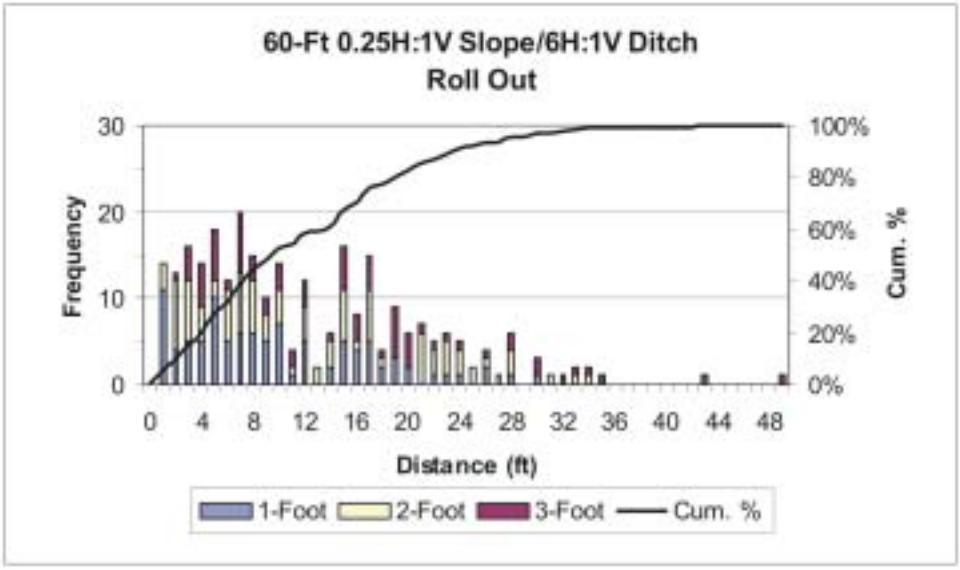
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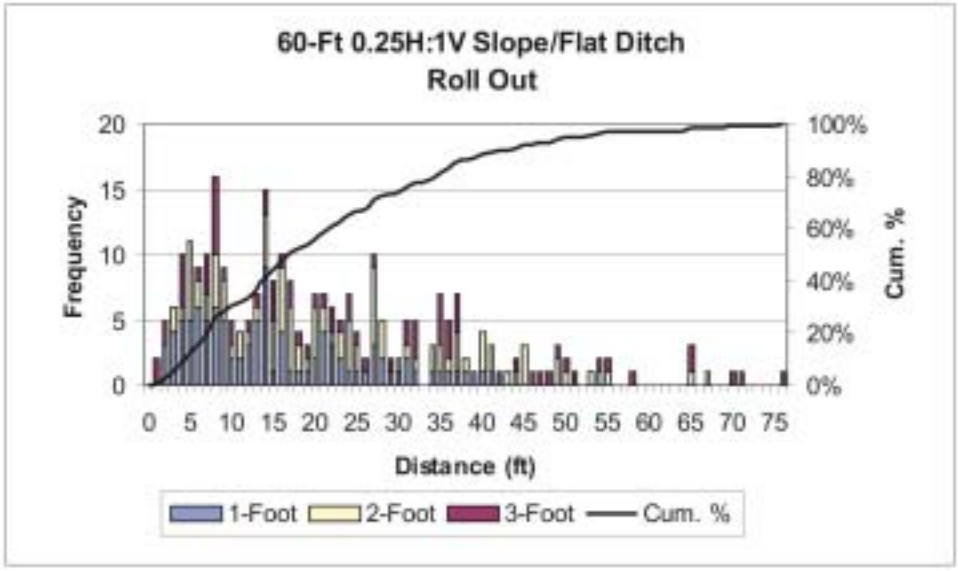
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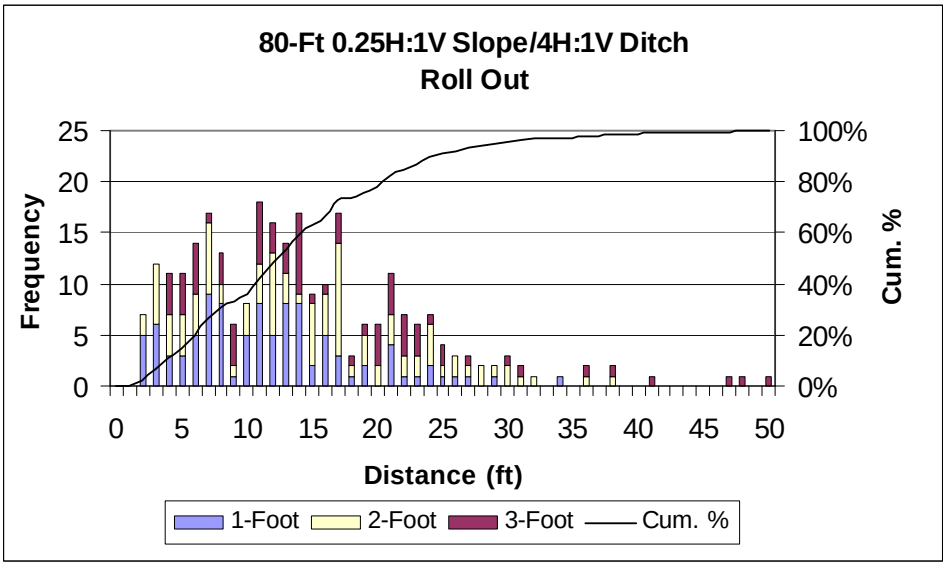
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Distance (ft)
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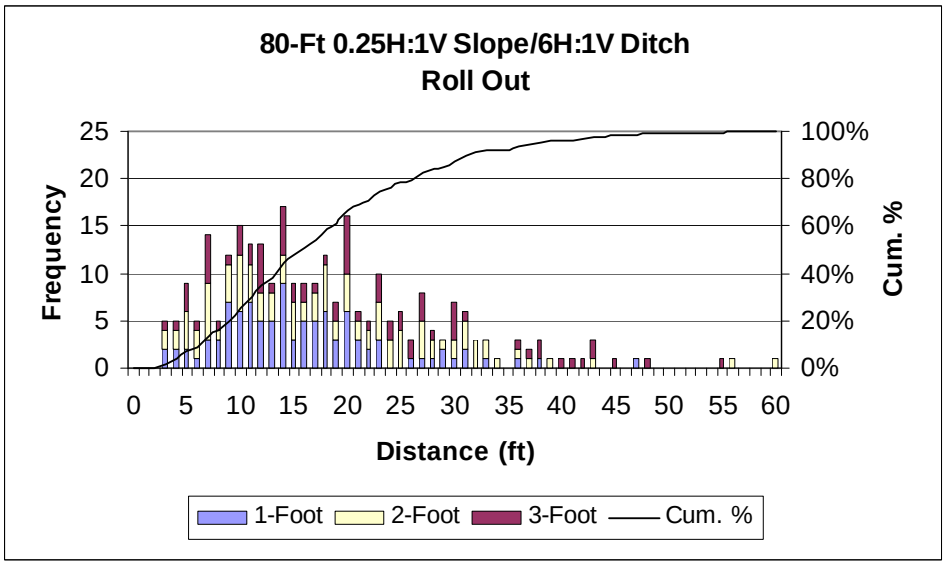
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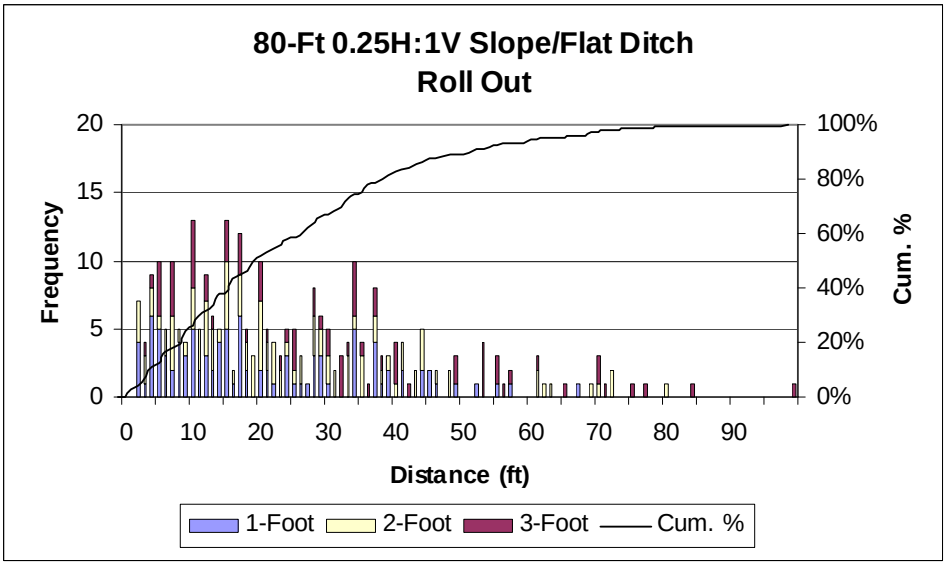
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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1-Foot
2-Foot
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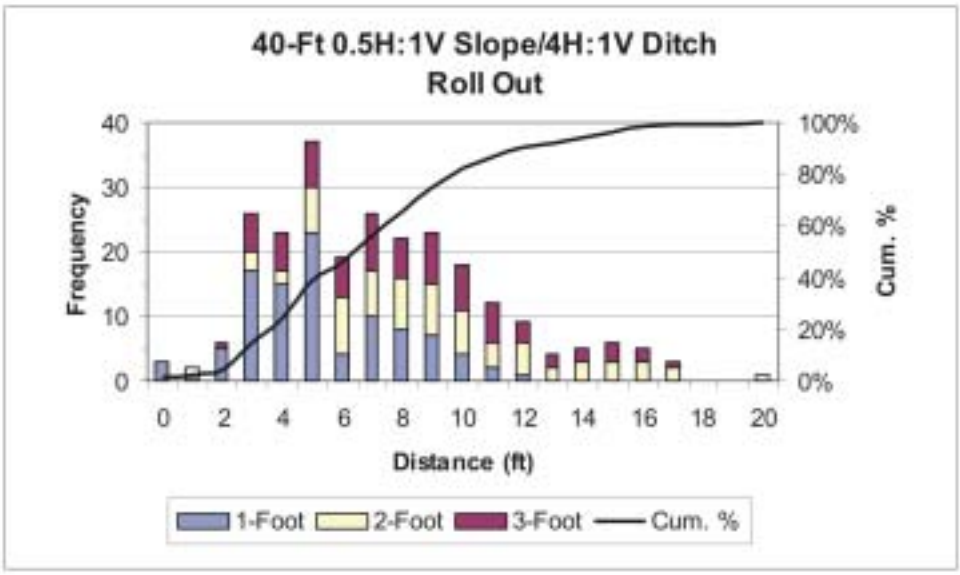
Cum. %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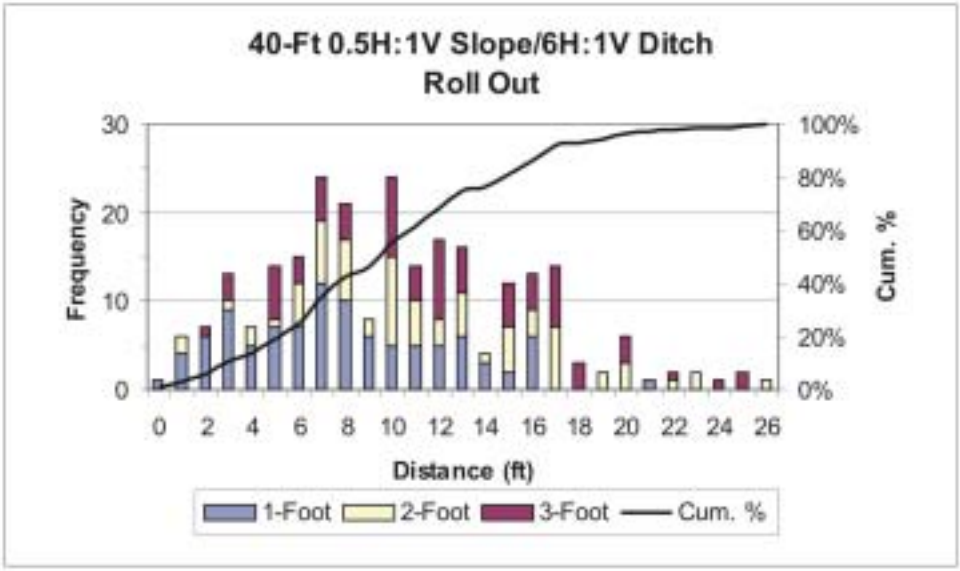
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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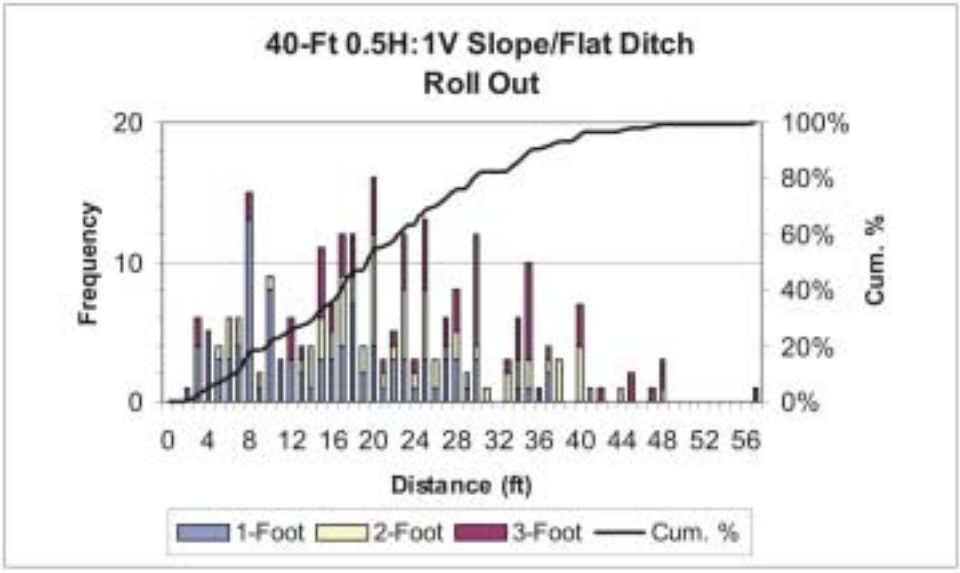
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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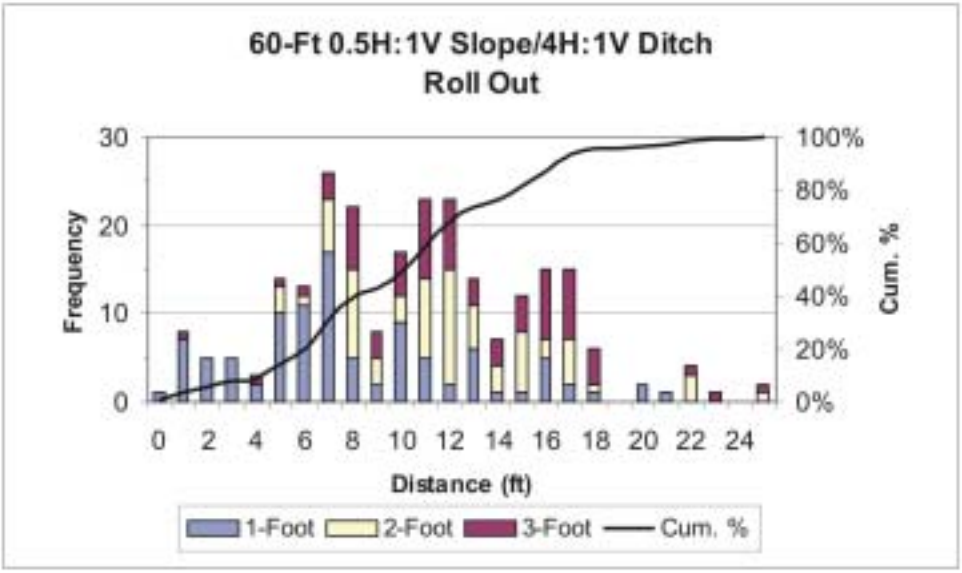
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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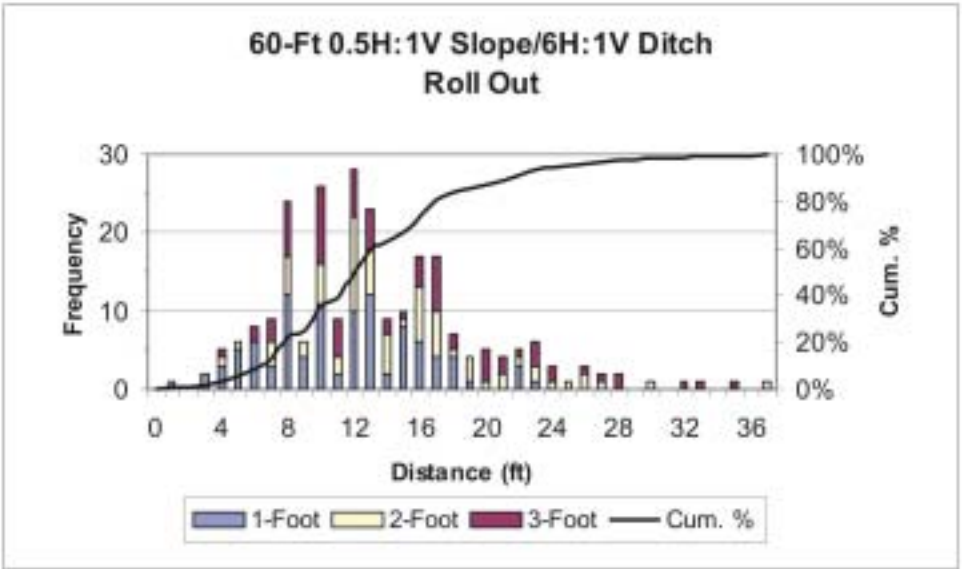
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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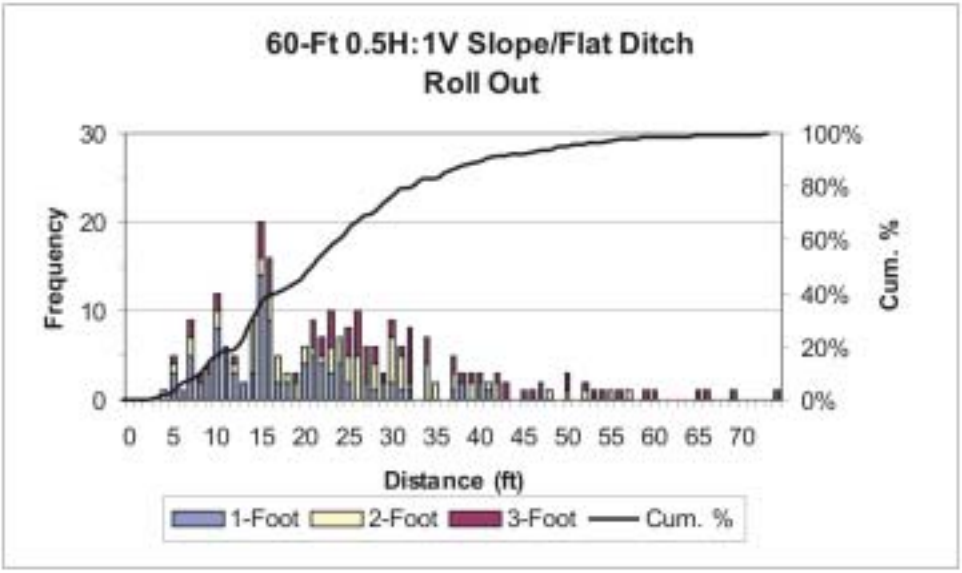
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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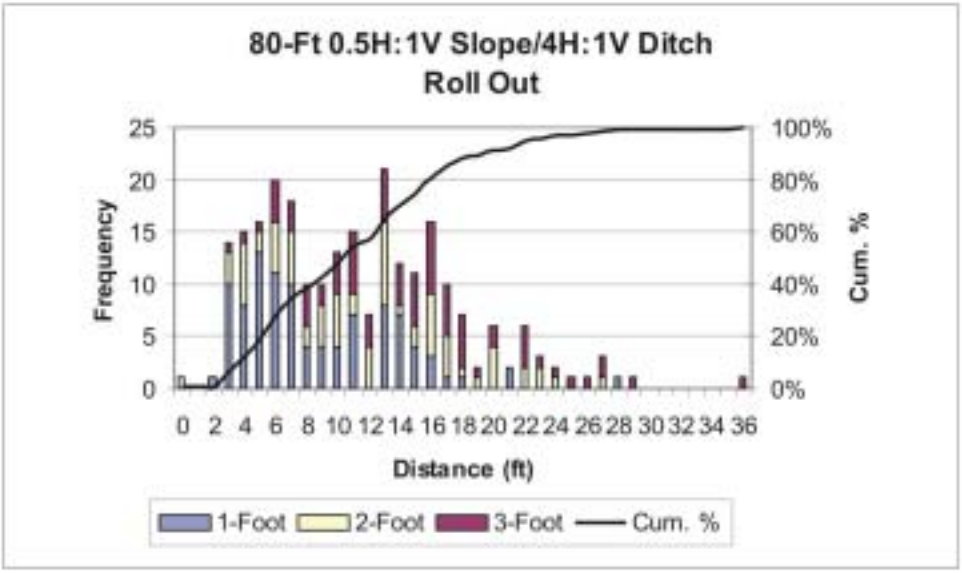
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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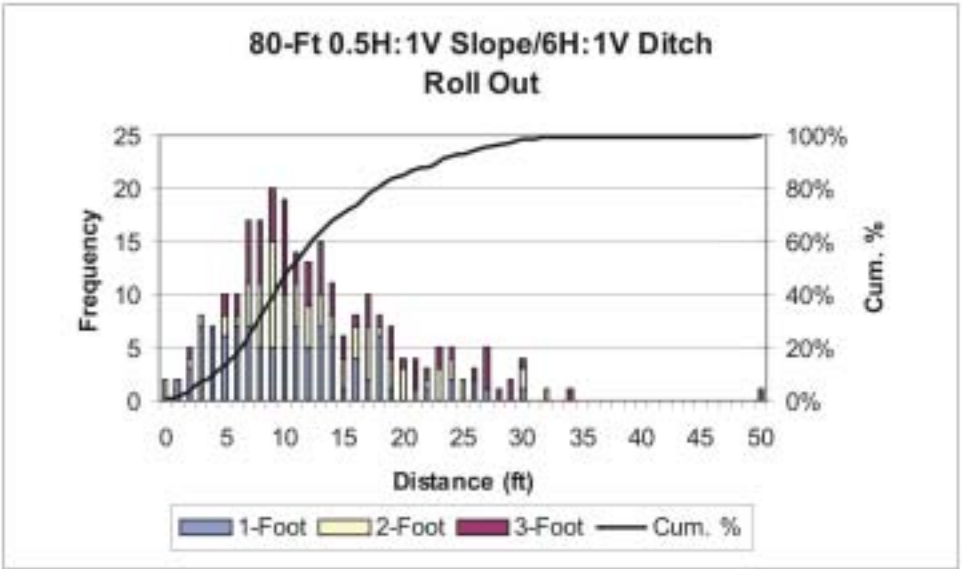
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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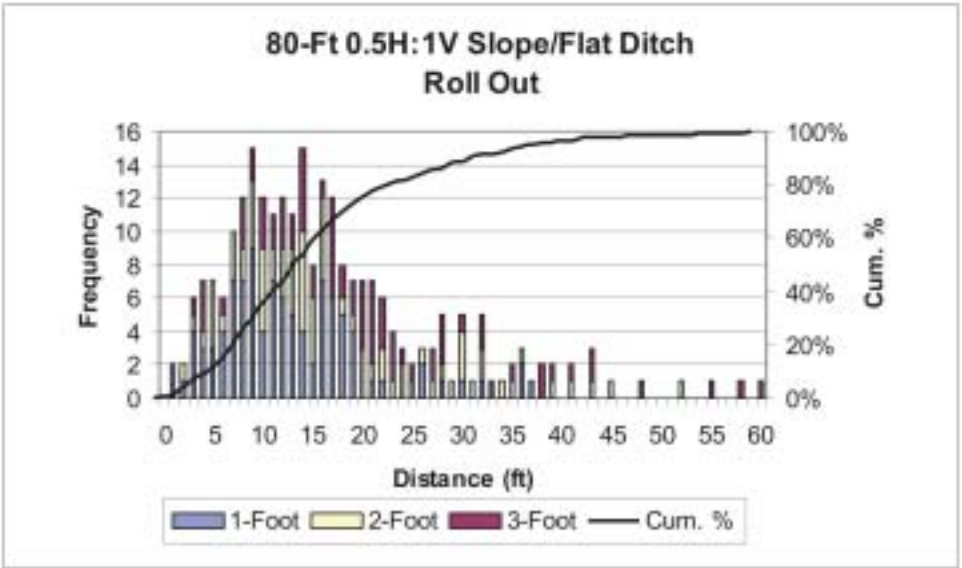
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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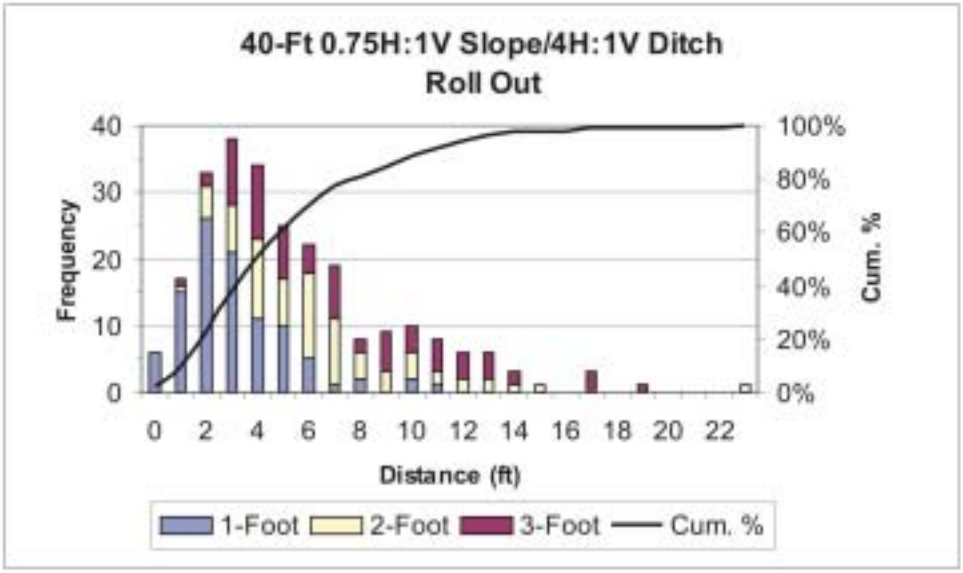
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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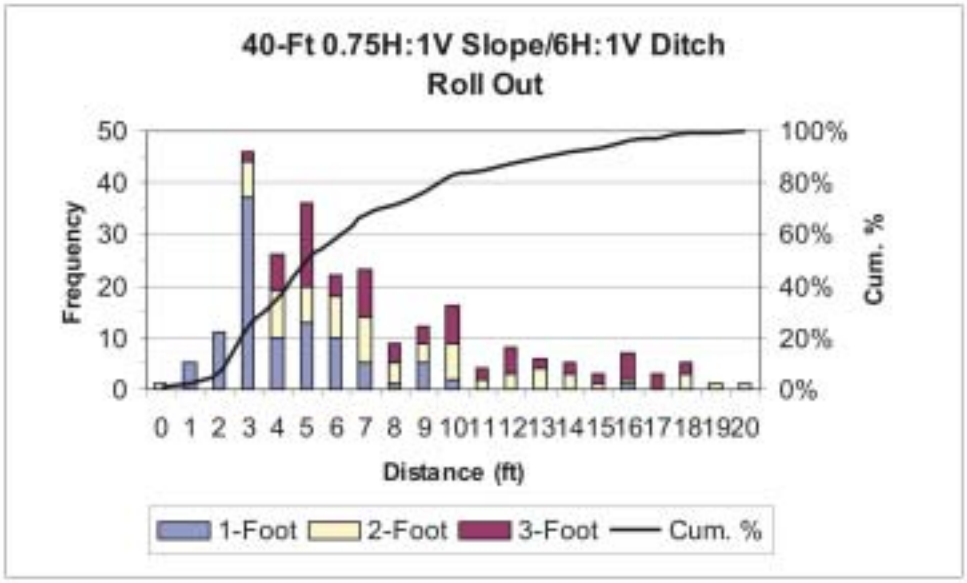
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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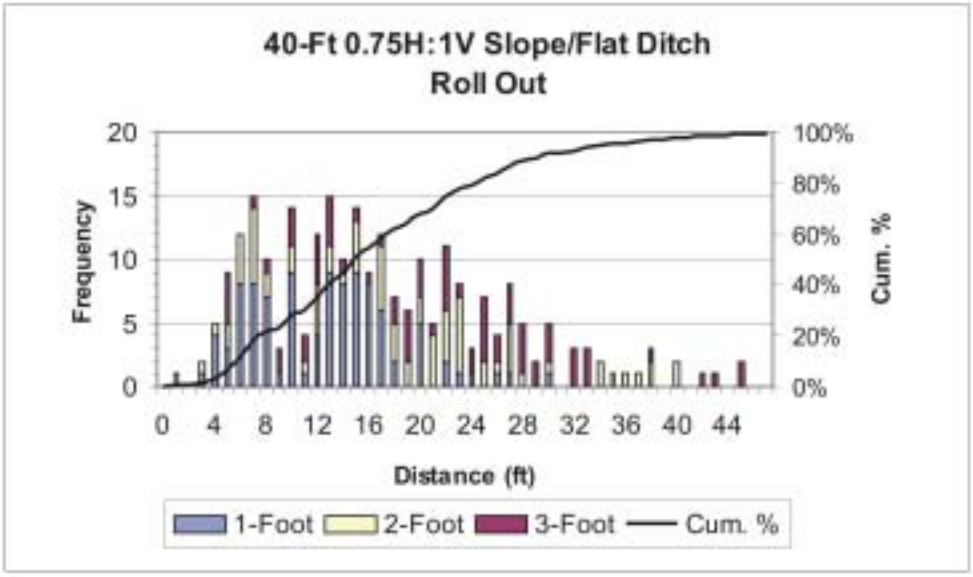
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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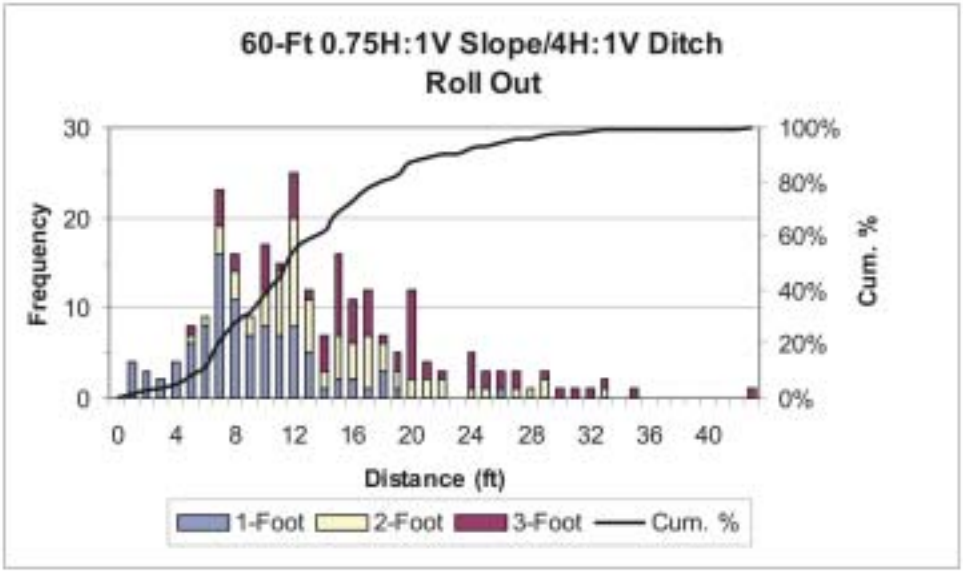
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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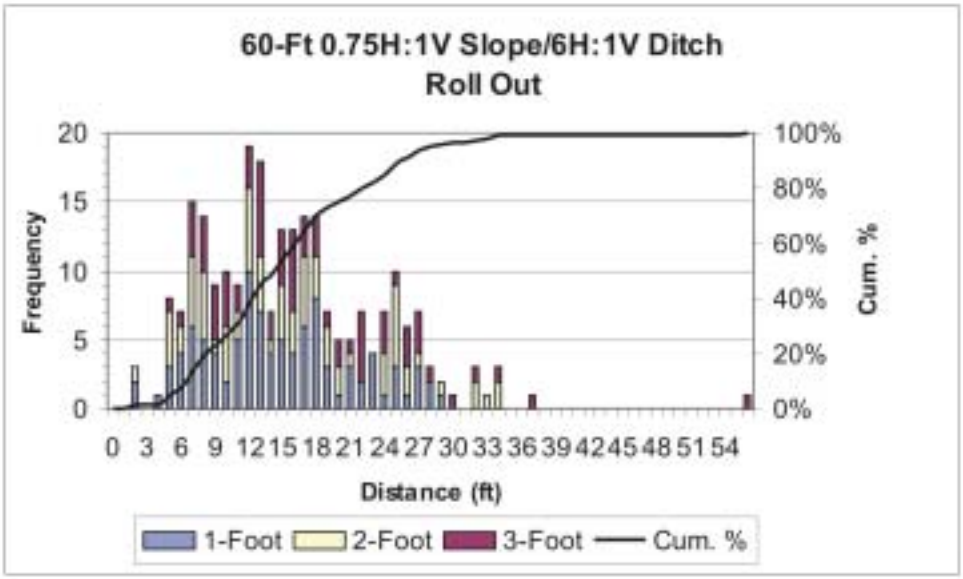
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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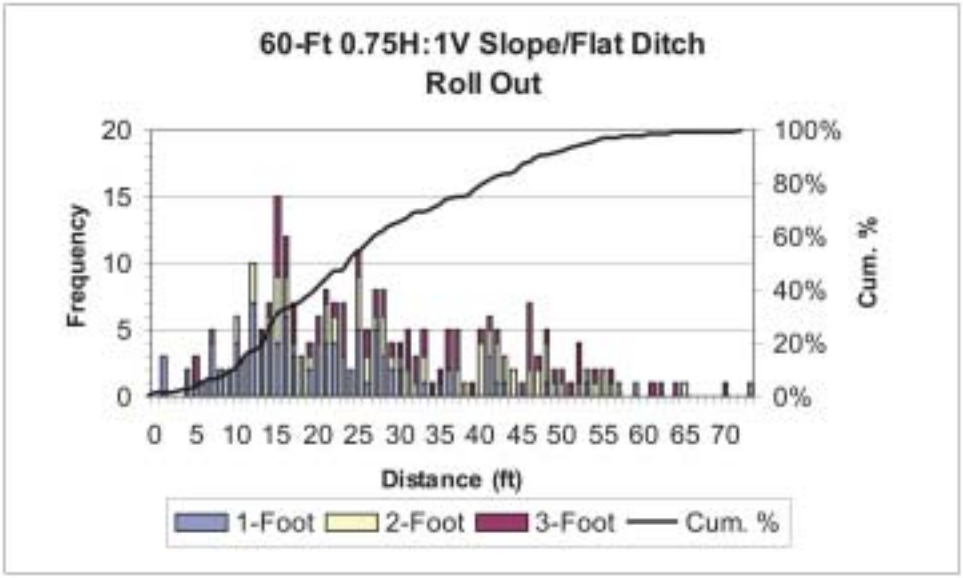
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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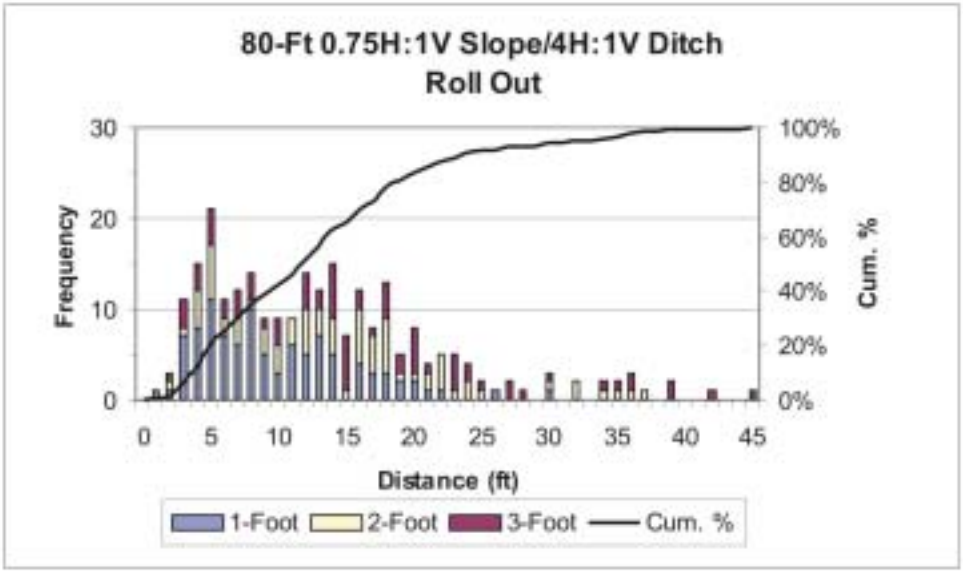
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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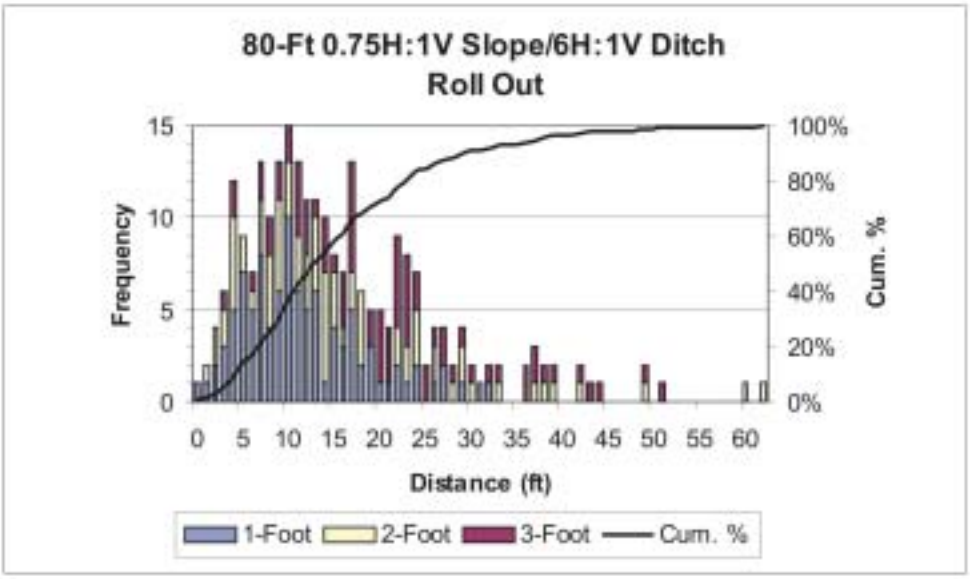
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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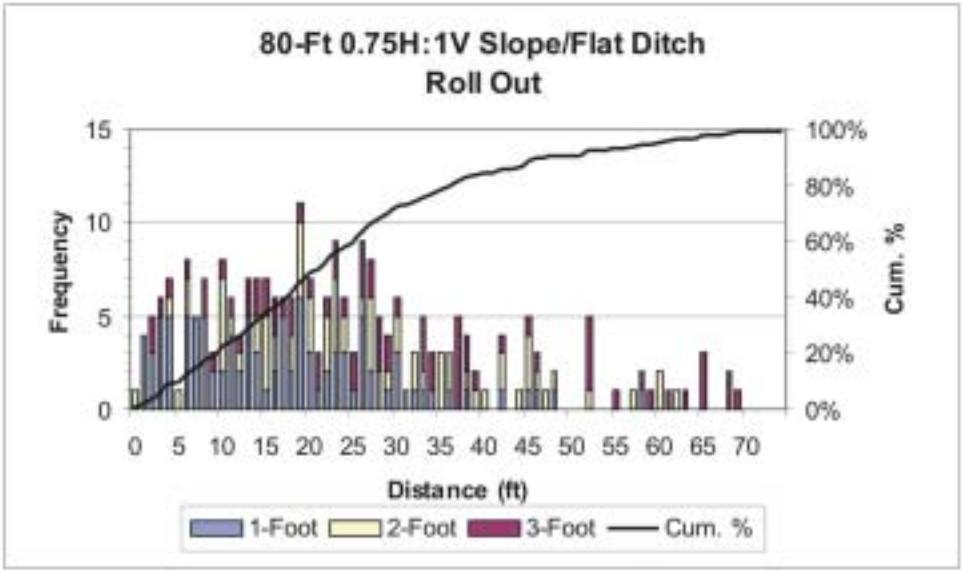
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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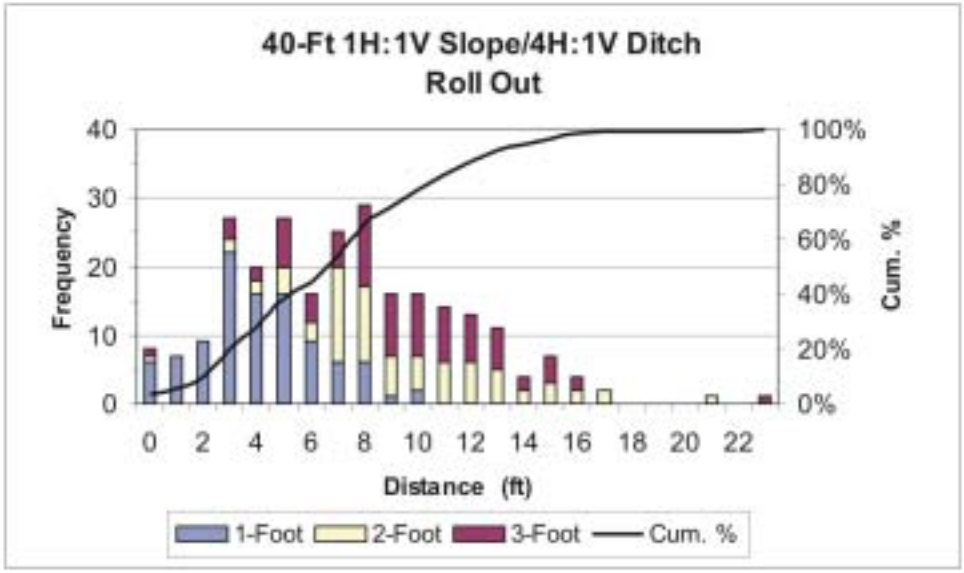
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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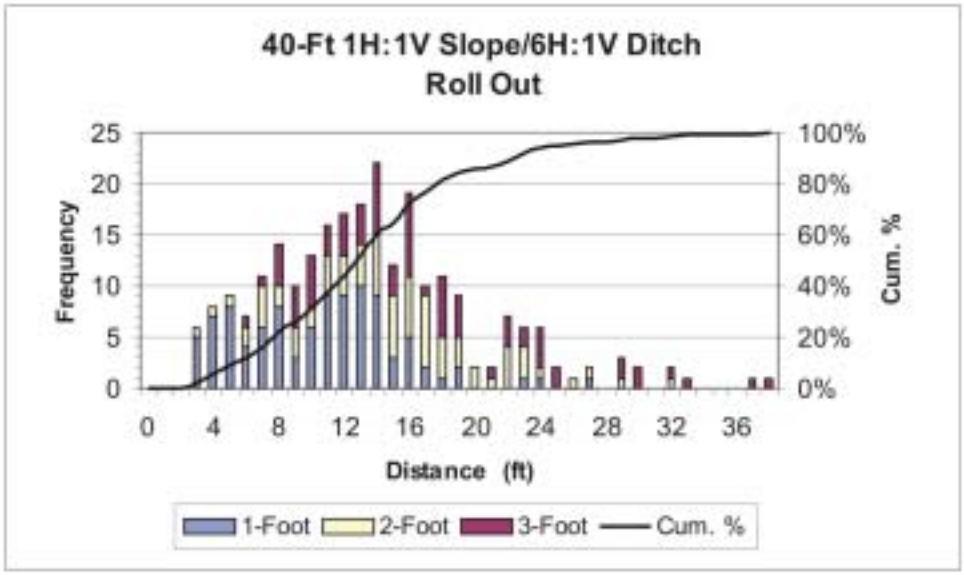
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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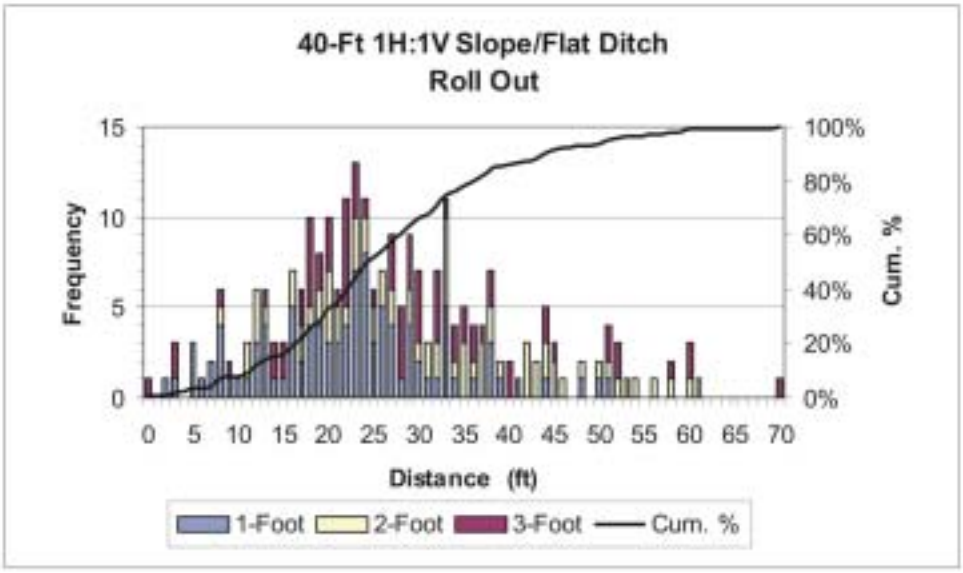
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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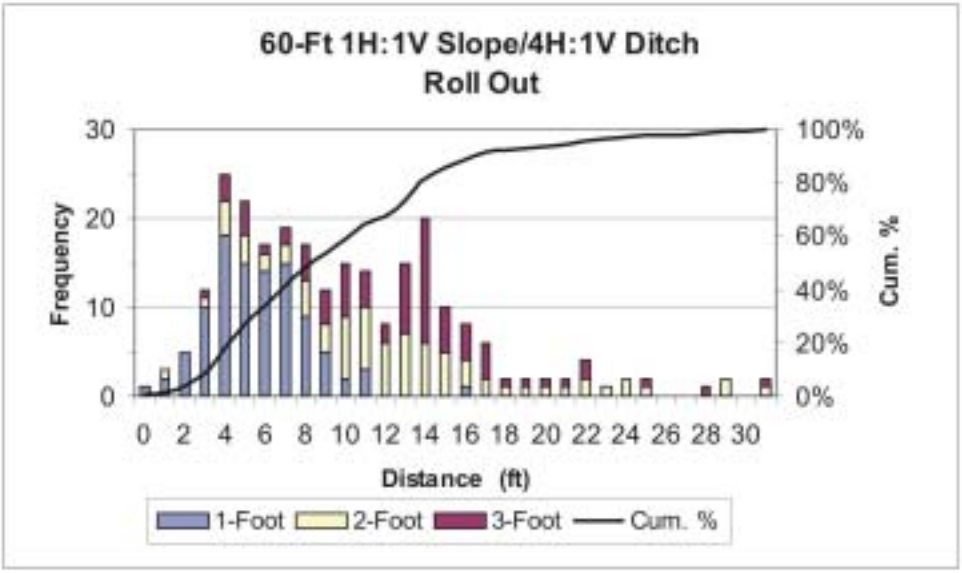
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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Roll Out
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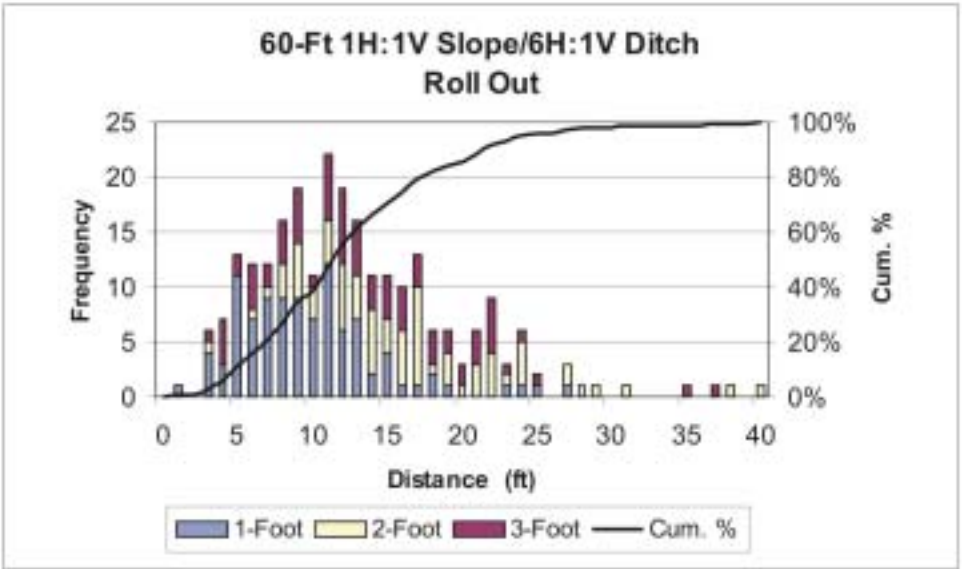
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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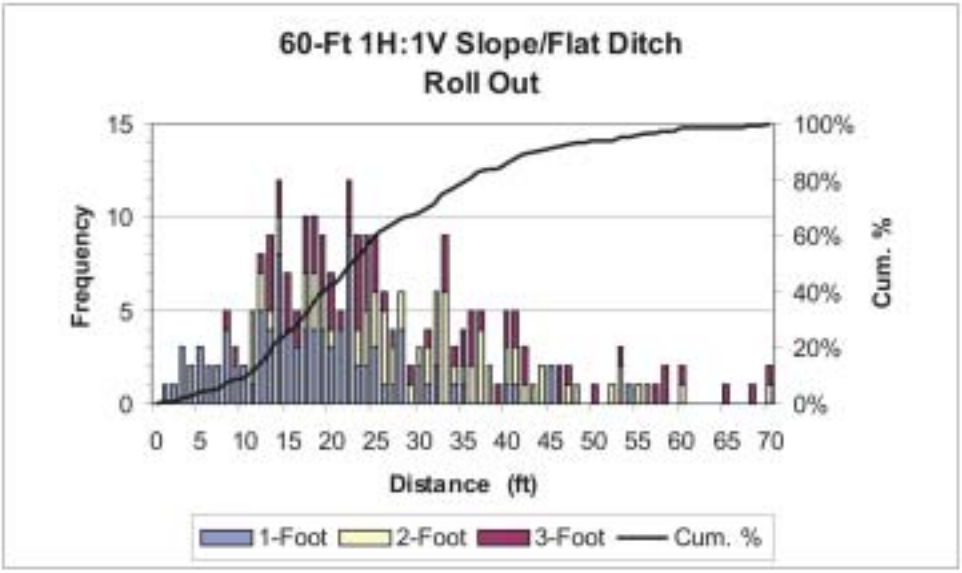
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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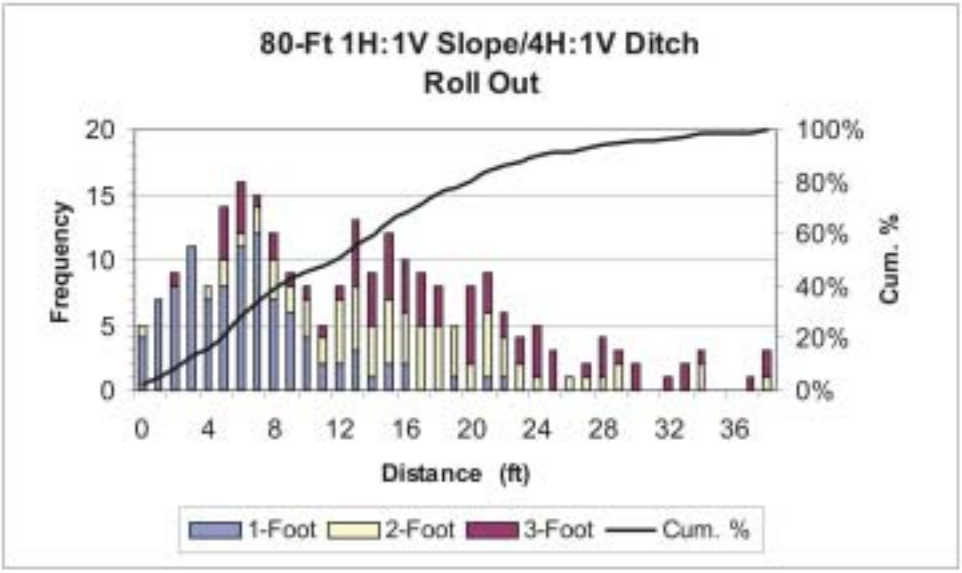
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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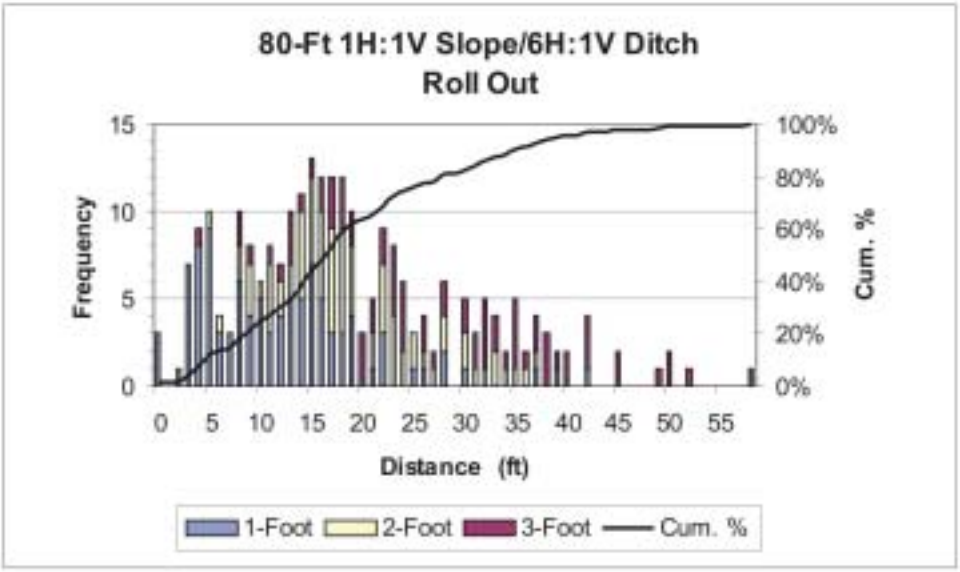
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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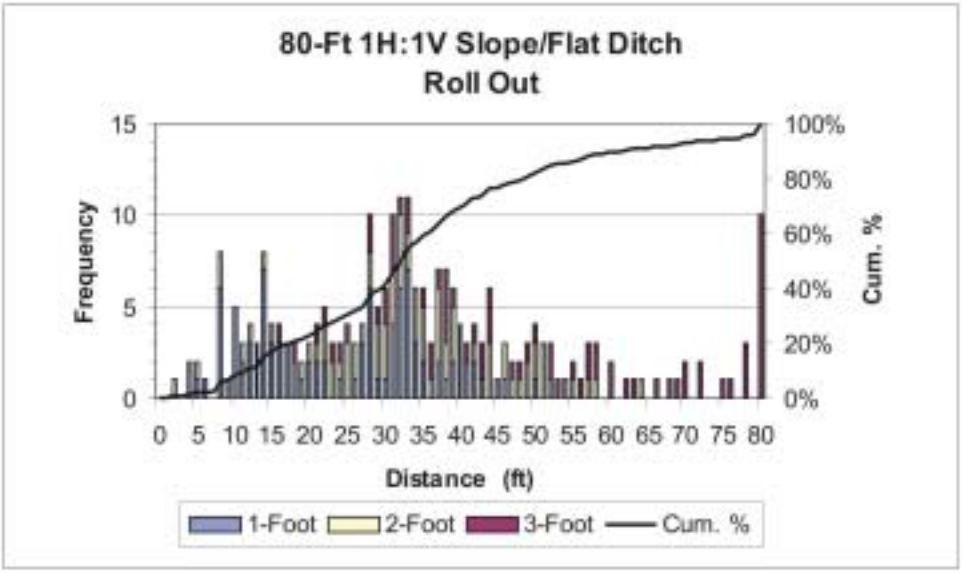
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %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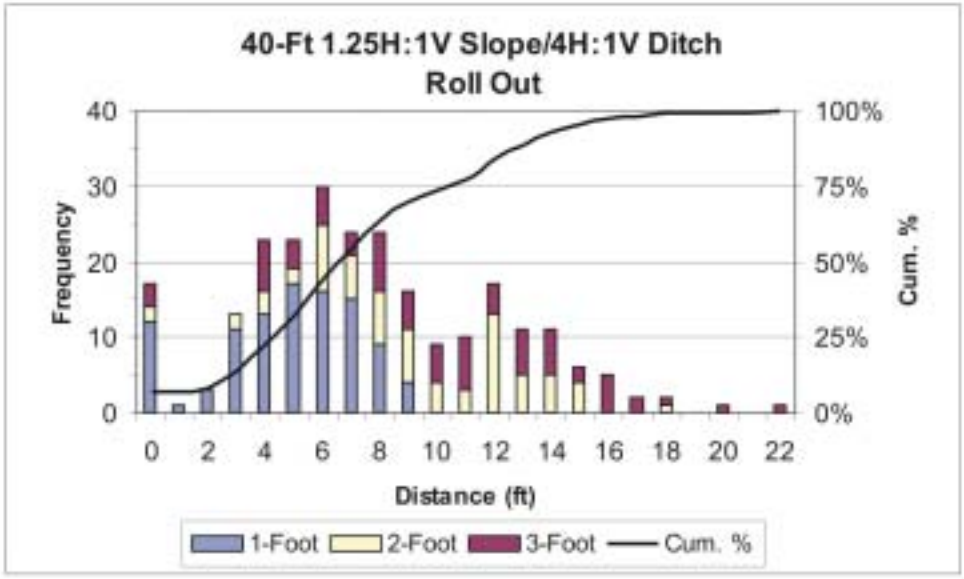
Roll Out
Frequency
Cum. %
Distance (ft)
1-Foot
2-Foot
3-Foot
Cum. %



Note: This was the only 1.25H:1V slope tested. Insufficient funds available to test additional slopes.

APPENDIX E: ROCKFALL ENERGY DATA

ROCKFALL ENERGY DATA

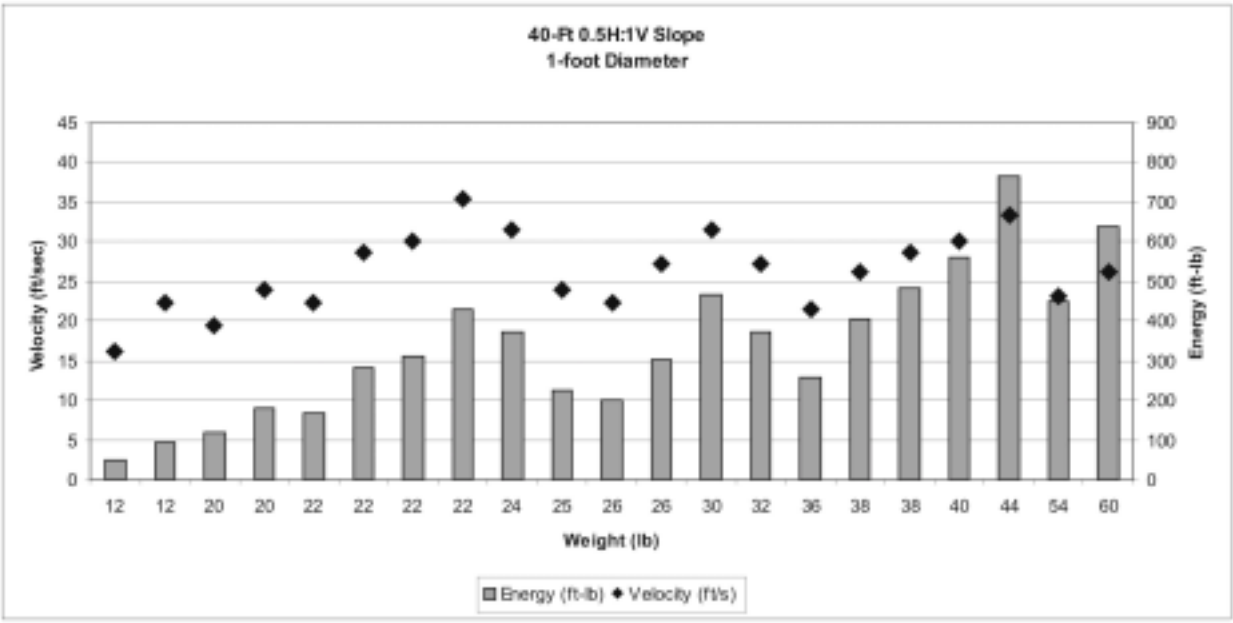
Selected rockfall energy data was recorded for the 0.5H:1V and 0.75H:1V slopes from the three heights tested. Sets of reference marks were placed on the slopes just above the toe of slope. Rocks within the one, two, and three-foot categories were weighed and video taped during rolling. By analyzing the video data, the time it took the rolling rocks to pass through the reference marks was used to determine the rockfall velocity. The weight and velocity data was used to calculate the kinetic energy of the falling rocks upon entering the catchment area.

The rockfall velocities are a function of cutslope angle and height and the amount of time the rocks are in contact with the slope. Velocities tended to be within a narrow range of values for each of the two slope angles tested with slight increases as the slope height increased. The variations are primarily attributable to the path taken by the rockfall during descent.

In general, when in contact with the slope, friction slows the rocks and lowers the resulting energies. Because the rocks are less often in contact with the slope (bouncing not rolling) on the 0.5H:1V slopes, the resulting velocities and energies are higher than for the 0.75H:1V slopes. This relationship explains why rolling rocks will come to a complete stop on flatter slopes and not make it to the catchment area.

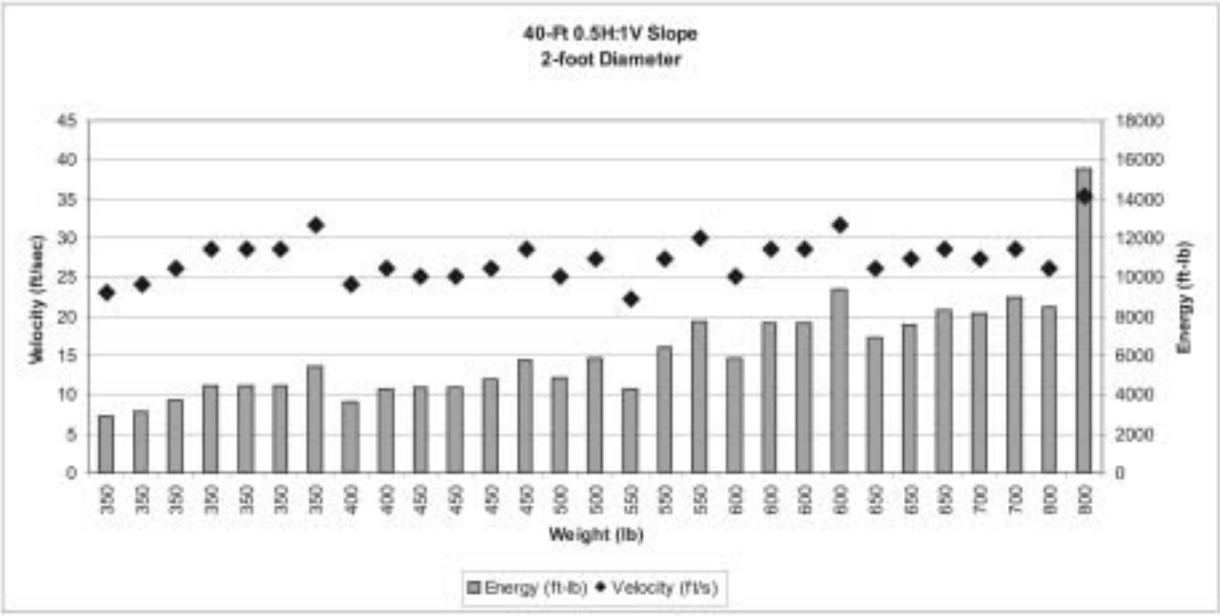
ENERGY OF 1-FOOT DIAMETER ROCKS
40-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
12	20	37	1.23	16.22	49
12	20	27	0.90	22.22	93
20	20	31	1.03	19.35	117
20	20	25	0.83	24.00	180
22	20	27	0.90	22.22	170
22	20	21	0.70	28.57	281
22	20	20	0.67	30.00	309
22	20	17	0.57	35.29	428
24	20	19	0.63	31.58	374
25	20	25	0.83	24.00	225
26	20	27	0.90	22.22	201
26	20	22	0.73	27.27	302
30	20	19	0.63	31.58	467
32	20	22	0.73	27.27	372
36	20	28	0.93	21.43	258
38	20	23	0.77	26.09	404
38	20	21	0.70	28.57	485
40	20	20	0.67	30.00	563
44	20	18	0.60	33.33	764
54	20	26	0.87	23.08	449
60	20	23	0.77	26.09	638



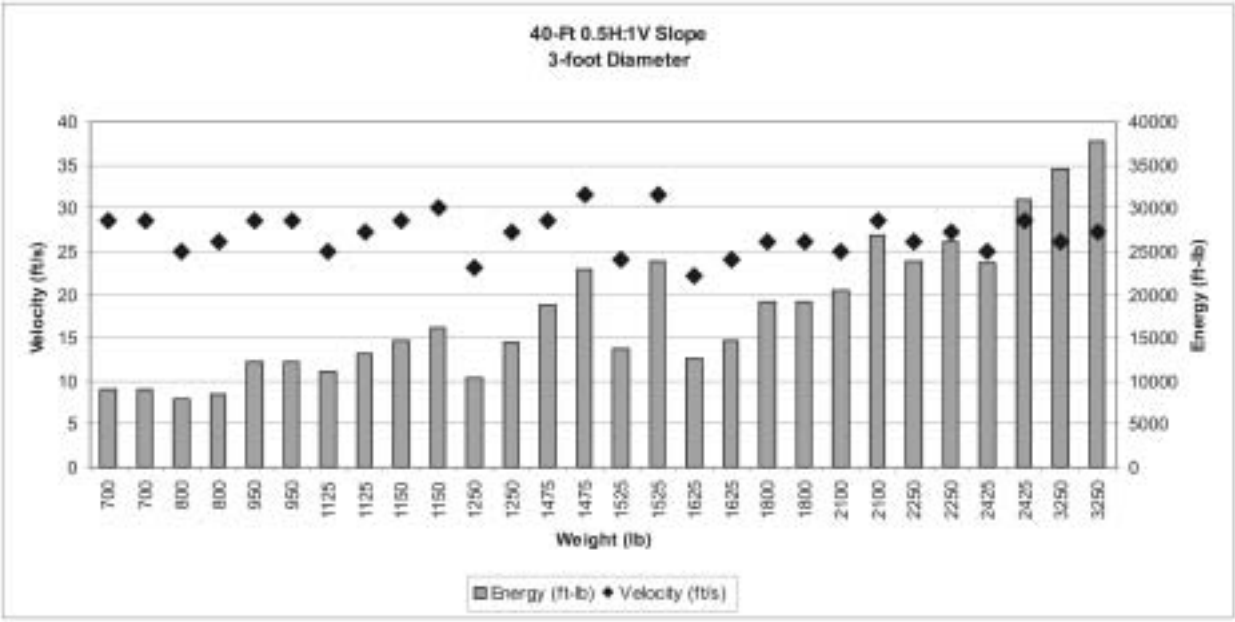
ENERGY OF 2-FOOT DIAMETER ROCKS
40-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
350	20	26	0.87	23.08	2912
350	20	25	0.83	24.00	3150
350	20	23	0.77	26.09	3722
350	20	21	0.70	28.57	4464
350	20	21	0.70	28.57	4464
350	20	21	0.70	28.57	4464
350	20	19	0.63	31.58	5454
400	20	25	0.83	24.00	3600
400	20	23	0.77	26.09	4253
450	20	24	0.80	25.00	4395
450	20	24	0.80	25.00	4395
450	20	23	0.77	26.09	4785
450	20	21	0.70	28.57	5740
500	20	24	0.80	25.00	4883
500	20	22	0.73	27.27	5811
550	20	27	0.90	22.22	4244
550	20	22	0.73	27.27	6392
550	20	20	0.67	30.00	7734
600	20	24	0.80	25.00	5859
600	20	21	0.70	28.57	7653
600	20	21	0.70	28.57	7653
600	20	19	0.63	31.58	9349
650	20	23	0.77	26.09	6912
650	20	22	0.73	27.27	7554
650	20	21	0.70	28.57	8291
700	20	22	0.73	27.27	8135
700	20	21	0.70	28.57	8929
800	20	23	0.77	26.09	8507
800	20	17	0.57	35.29	15571



ENERGY OF 3-FOOT DIAMETER ROCKS
40-FOOT, 0.5H:1V SLOPE

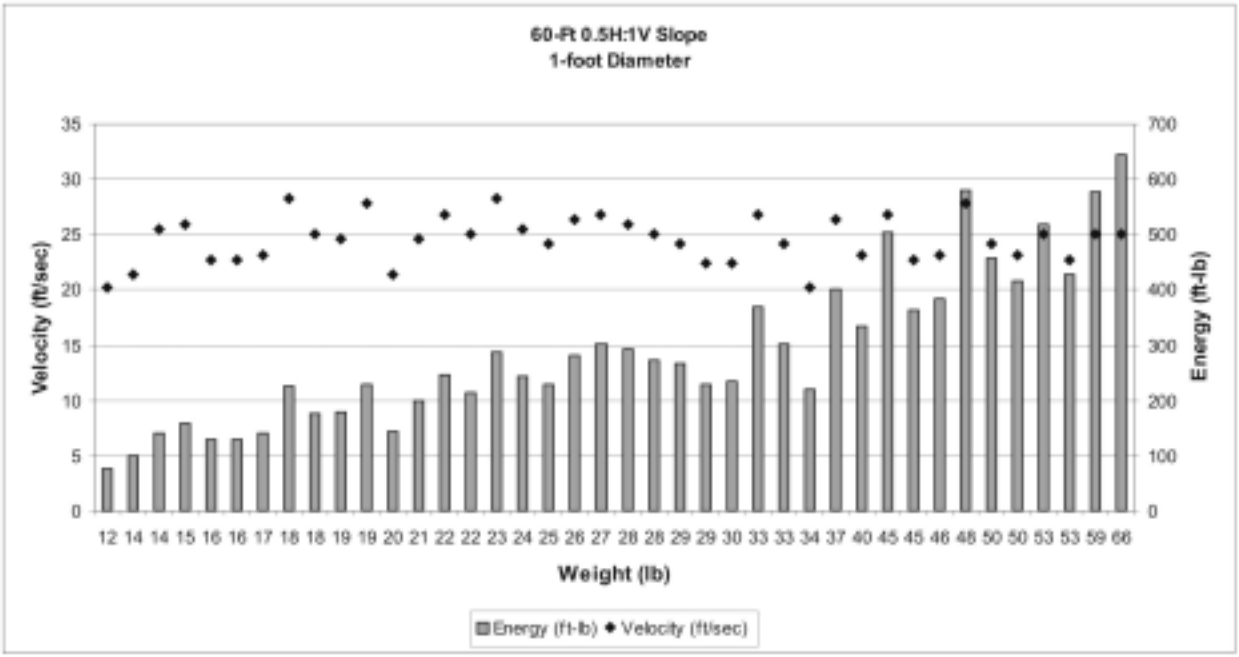
Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
700	20	21	0.70	28.57	8929
700	20	21	0.70	28.57	8929
800	20	24	0.80	25.00	7813
800	20	23	0.77	26.09	8507
950	20	21	0.70	28.57	12117
950	20	21	0.70	28.57	12117
1125	20	24	0.80	25.00	10986
1125	20	22	0.73	27.27	13075
1150	20	21	0.70	28.57	14668
1150	20	20	0.67	30.00	16172
1250	20	26	0.87	23.08	10401
1250	20	22	0.73	27.27	14527
1475	20	21	0.70	28.57	18814
1475	20	19	0.63	31.58	22983
1525	20	25	0.83	24.00	13725
1525	20	19	0.63	31.58	23762
1625	20	27	0.90	22.22	12539
1625	20	25	0.83	24.00	14625
1800	20	23	0.77	26.09	19140
1800	20	23	0.77	26.09	19140
2100	20	24	0.80	25.00	20508
2100	20	21	0.70	28.57	26786
2250	20	23	0.77	26.09	23925
2250	20	22	0.73	27.27	26149
2425	20	24	0.80	25.00	23682
2425	20	21	0.70	28.57	30931
3250	20	23	0.77	26.09	34558
3250	20	22	0.73	27.27	37771



ENERGY OF 1-FOOT DIAMETER ROCKS
60-FOOT, 0.5H:1V SLOPE

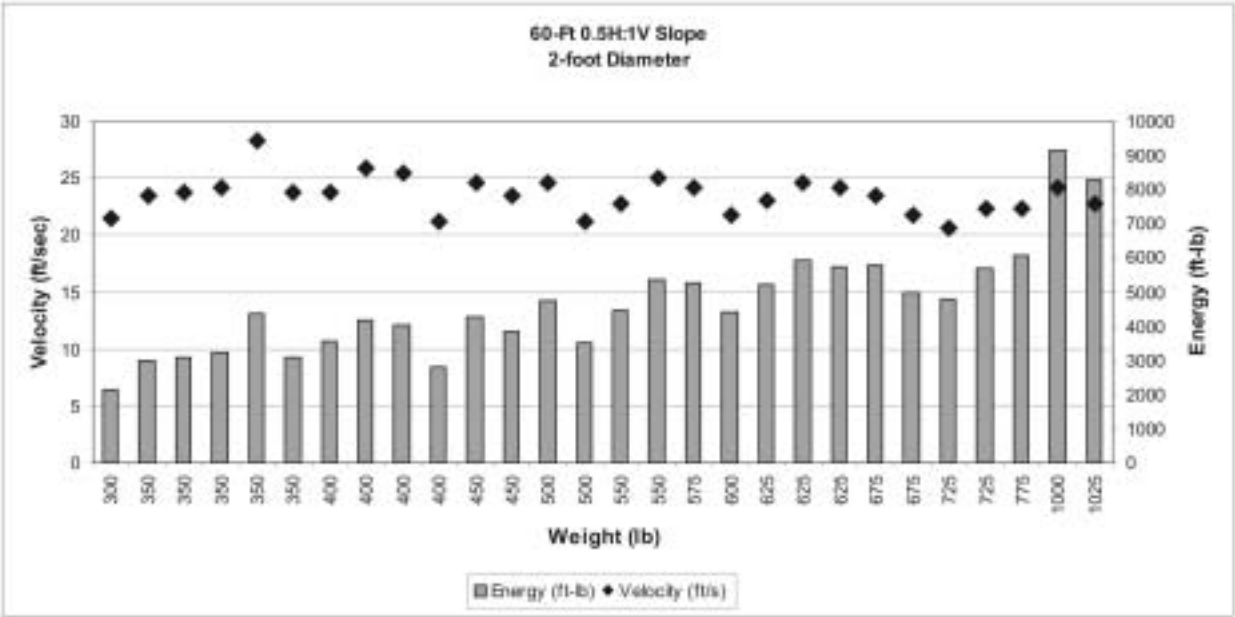
Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
12	50	74	2.47	20.27	77
14	50	70	2.33	21.43	100
14	50	59	1.97	25.42	141
15	50	58	1.93	25.86	157
16	50	66	2.20	22.73	129
16	50	66	2.20	22.73	129
17	50	65	2.17	23.08	141
18	50	53	1.77	28.30	225
18	50	60	2.00	25.00	176
19	50	61	2.03	24.59	180
19	50	54	1.80	27.78	229
20	50	70	2.33	21.43	143
21	50	61	2.03	24.59	198
22	50	56	1.87	26.79	247
22	50	60	2.00	25.00	215
23	50	53	1.77	28.30	288
24	50	59	1.97	25.42	242
25	50	62	2.07	24.19	229
26	50	57	1.90	26.32	281
27	50	56	1.87	26.79	303
28	50	58	1.93	25.86	293
28	50	60	2.00	25.00	273
29	50	62	2.07	24.19	265
29	50	67	2.23	22.39	227
30	50	67	2.23	22.39	235
33	50	56	1.87	26.79	370
33	50	62	2.07	24.19	302
34	50	74	2.47	20.27	218
37	50	57	1.90	26.32	400
40	50	65	2.17	23.08	333
45	50	56	1.87	26.79	504
45	50	66	2.20	22.73	363
46	50	65	2.17	23.08	383
48	50	54	1.80	27.78	579
50	50	62	2.07	24.19	457
50	50	65	2.17	23.08	416
53	50	60	2.00	25.00	518
53	50	66	2.20	22.73	428
59	50	60	2.00	25.00	576
66	50	60	2.00	25.00	645

ENERGY OF 1-FOOT DIAMETER ROCKS
60-FOOT, 0.5H:1V SLOPE



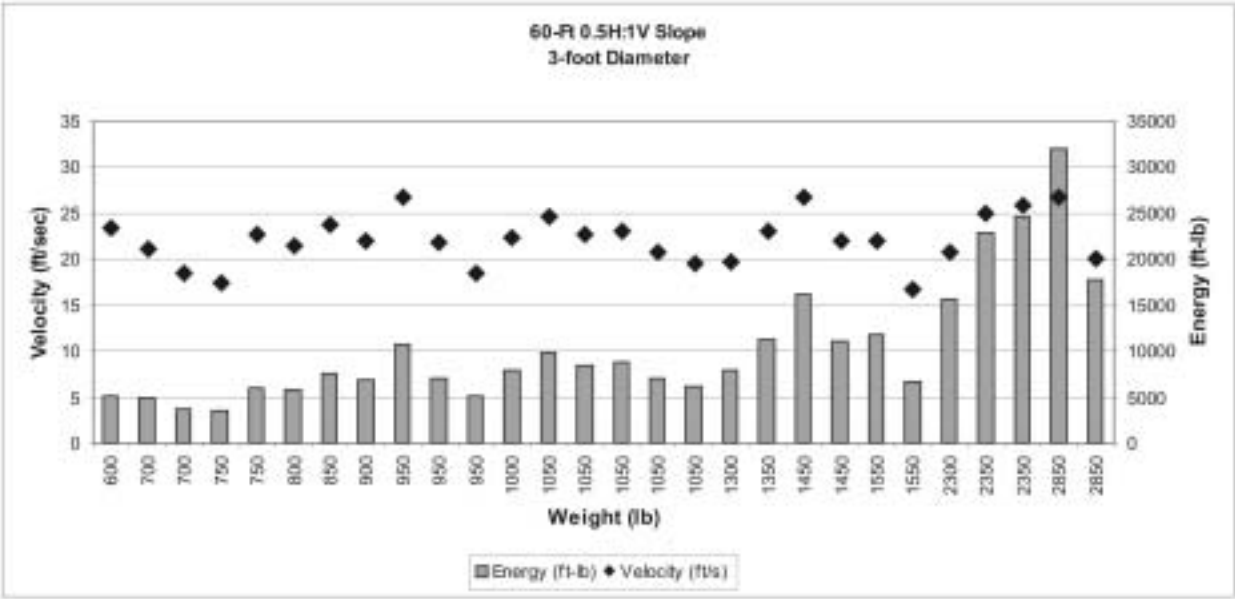
ENERGY OF 2-FOOT DIAMETER ROCKS
60-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
300	50	70	2.33	21.43	2152
350	50	64	2.13	23.44	3004
350	50	63	2.10	23.81	3100
350	50	62	2.07	24.19	3201
350	50	53	1.77	28.30	4380
350	50	63	2.10	23.81	3100
400	50	63	2.10	23.81	3543
400	50	58	1.93	25.86	4180
400	50	59	1.97	25.42	4040
400	50	71	2.37	21.13	2790
450	50	61	2.03	24.59	4252
450	50	64	2.13	23.44	3862
500	50	61	2.03	24.59	4724
500	50	71	2.37	21.13	3487
550	50	66	2.20	22.73	4439
550	50	60	2.00	25.00	5371
575	50	62	2.07	24.19	5259
600	50	69	2.30	21.74	4431
625	50	65	2.17	23.08	5201
625	50	61	2.03	24.59	5905
625	50	62	2.07	24.19	5716
675	50	64	2.13	23.44	5794
675	50	69	2.30	21.74	4984
725	50	73	2.43	20.55	4783
725	50	67	2.23	22.39	5678
775	50	67	2.23	22.39	6070
1000	50	62	2.07	24.19	9146
1025	50	66	2.20	22.73	8273



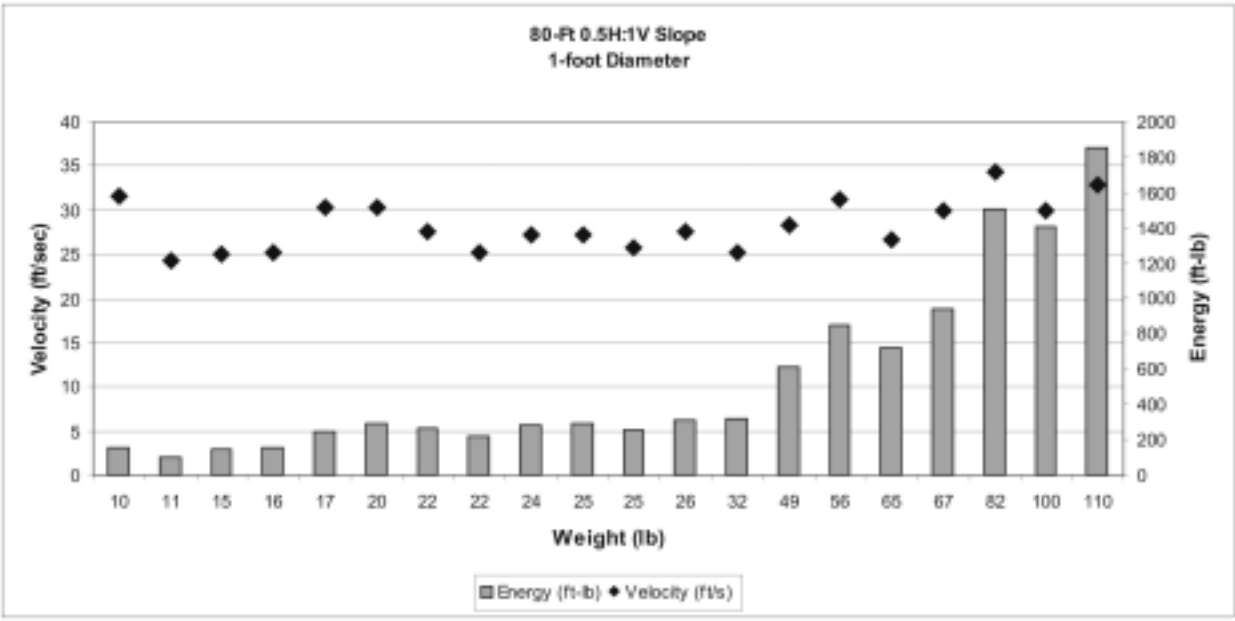
ENERGY OF 3-FOOT DIAMETER ROCKS
60-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
600	50	64	2.13	23.44	5150
700	50	71	2.37	21.13	4882
700	50	81	2.70	18.52	3751
750	50	86	2.87	17.44	3565
750	50	66	2.20	22.73	6053
800	50	70	2.33	21.43	5740
850	50	63	2.10	23.81	7529
900	50	68	2.27	22.06	6843
950	50	56	1.87	26.79	10650
950	50	69	2.30	21.74	7015
950	50	81	2.70	18.52	5090
1000	50	67	2.23	22.39	7832
1050	50	61	2.03	24.59	9920
1050	50	66	2.20	22.73	8474
1050	50	65	2.17	23.08	8737
1050	50	72	2.40	20.83	7121
1050	50	77	2.57	19.48	6226
1300	50	76	2.53	19.74	7913
1350	50	65	2.17	23.08	11233
1450	50	56	1.87	26.79	16255
1450	50	68	2.27	22.06	11024
1550	50	68	2.27	22.06	11785
1550	50	90	3.00	16.67	6727
2300	50	72	2.40	20.83	15598
2350	50	60	2.00	25.00	22949
2350	50	58	1.93	25.86	24559
2850	50	56	1.87	26.79	31950
2850	50	75	2.50	20.00	17813



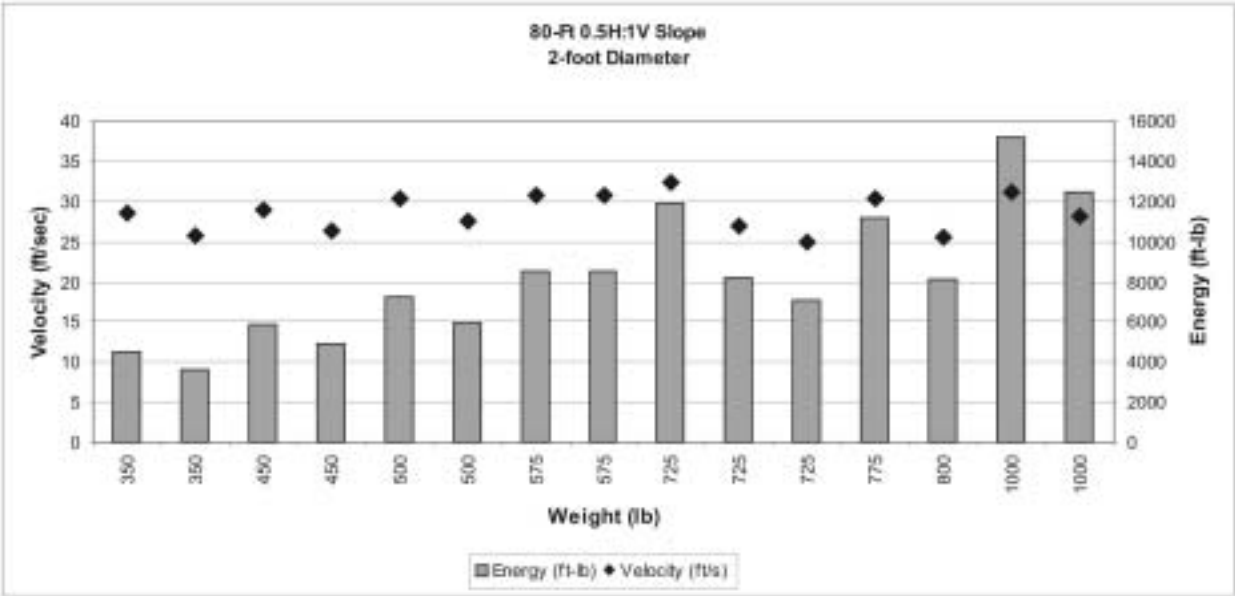
ENERGY OF 1-FOOT DIAMETER ROCKS
80-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
10	80	76	2.53	31.58	156
11	80	99	3.30	24.24	101
15	80	96	3.20	25.00	146
16	80	95	3.17	25.26	160
17	80	79	2.63	30.38	245
20	80	79	2.63	30.38	288
22	80	87	2.90	27.59	262
22	80	95	3.17	25.26	219
24	80	88	2.93	27.27	279
25	80	88	2.93	27.27	291
25	80	93	3.10	25.81	260
26	80	87	2.90	27.59	309
32	80	95	3.17	25.26	319
49	80	85	2.83	28.24	610
56	80	77	2.57	31.17	850
65	80	90	3.00	26.67	722
67	80	80	2.67	30.00	942
82	80	70	2.33	34.29	1506
100	80	80	2.67	30.00	1406
110	80	73	2.43	32.88	1858



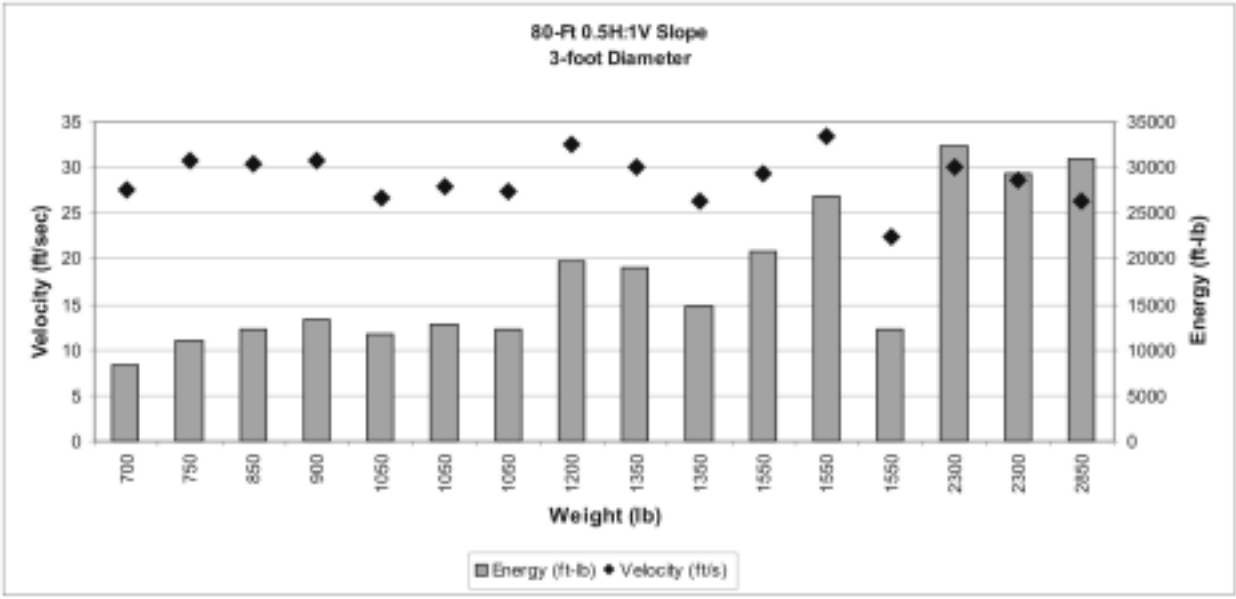
ENERGY OF 2-FOOT DIAMETER ROCKS
80-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
350	80	84	2.80	28.57	4464
350	80	93	3.10	25.81	3642
450	80	83	2.77	28.92	5879
450	80	91	3.03	26.37	4891
500	80	79	2.63	30.38	7210
500	80	87	2.90	27.59	5945
575	80	78	2.60	30.77	8506
575	80	78	2.60	30.77	8506
725	80	74	2.47	32.43	11916
725	80	89	2.97	26.97	8238
725	80	96	3.20	25.00	7080
775	80	79	2.63	30.38	11176
800	80	94	3.13	25.53	8148
1000	80	77	2.57	31.17	15180
1000	80	85	2.83	28.24	12457



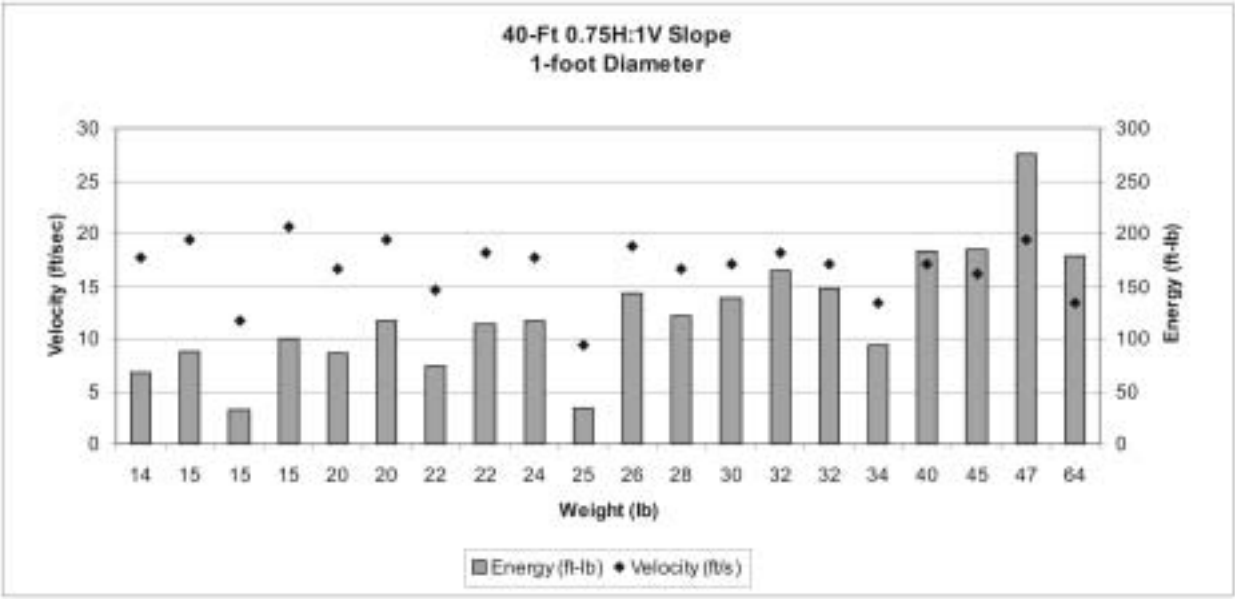
ENERGY OF 3-FOOT DIAMETER ROCKS
80-FOOT, 0.5H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
700	80	87	2.90	27.59	8323
750	80	78	2.60	30.77	11095
850	80	79	2.63	30.38	12258
900	80	78	2.60	30.77	13314
1050	80	90	3.00	26.67	11667
1050	80	86	2.87	27.91	12777
1050	80	88	2.93	27.27	12203
1200	80	74	2.47	32.43	19722
1350	80	80	2.67	30.00	18984
1350	80	91	3.03	26.37	14672
1550	80	82	2.73	29.27	20747
1550	80	72	2.40	33.33	26910
1550	80	107	3.57	22.43	12184
2300	80	80	2.67	30.00	32344
2300	80	84	2.80	28.57	29337
2850	80	91	3.03	26.37	30975



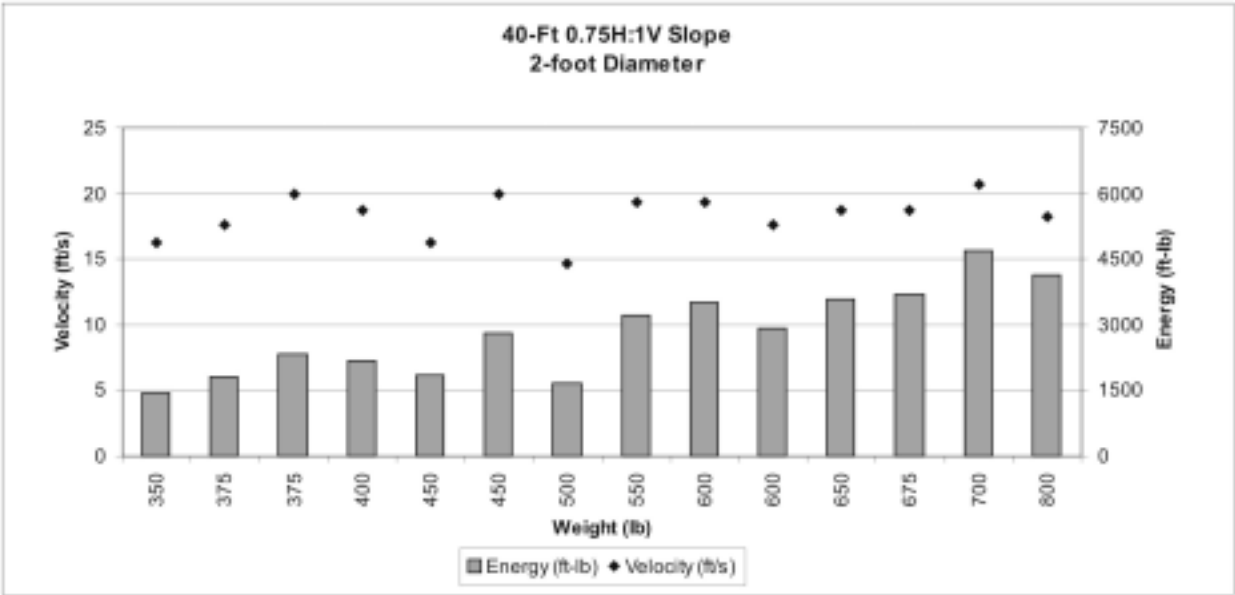
ENERGY OF 1-FOOT DIAMETER ROCKS
40-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
14	20	34	1.13	17.65	68
15	20	31	1.03	19.35	88
15	20	51	1.70	11.76	32
15	20	29	0.97	20.69	100
20	20	36	1.20	16.67	87
20	20	31	1.03	19.35	117
22	20	41	1.37	14.63	74
22	20	33	1.10	18.18	114
24	20	34	1.13	17.65	117
25	20	64	2.13	9.38	34
26	20	32	1.07	18.75	143
28	20	36	1.20	16.67	122
30	20	35	1.17	17.14	138
32	20	33	1.10	18.18	165
32	20	35	1.17	17.14	147
34	20	45	1.50	13.33	94
40	20	35	1.17	17.14	184
45	20	37	1.23	16.22	185
47	20	31	1.03	19.35	275
64	20	45	1.50	13.33	178



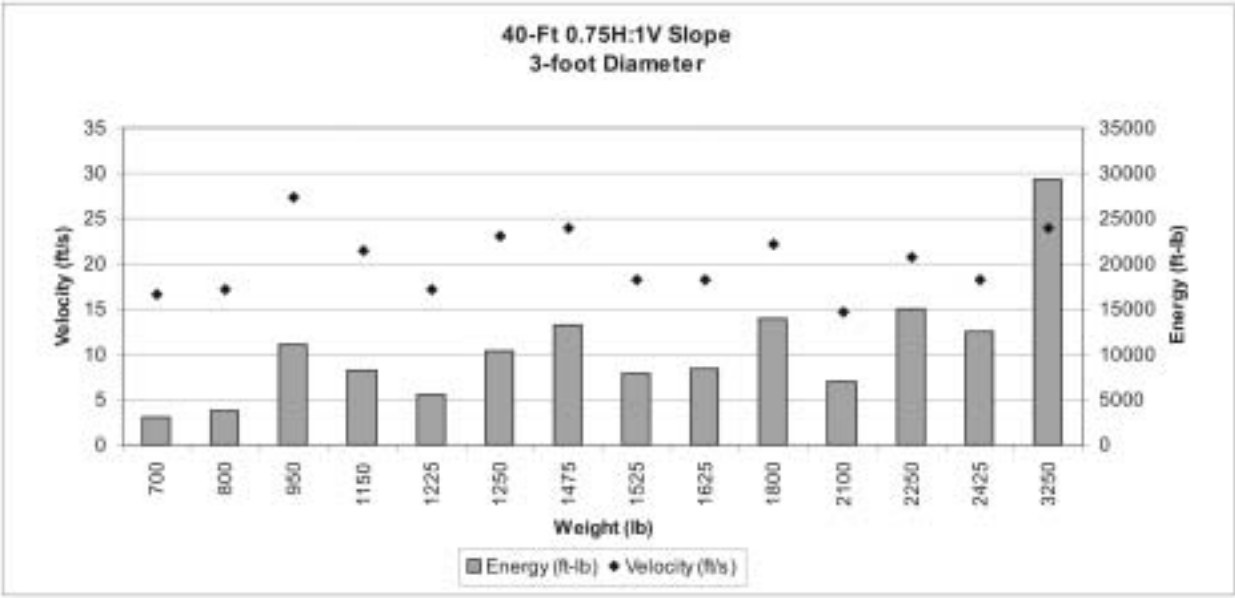
ENERGY OF 2-FOOT DIAMETER ROCKS
40-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
350	20	37	1.23	16.22	1438
375	20	34	1.13	17.65	1825
375	20	30	1.00	20.00	2344
400	20	32	1.07	18.75	2197
450	20	37	1.23	16.22	1849
450	20	30	1.00	20.00	2813
500	20	41	1.37	14.63	1673
550	20	31	1.03	19.35	3219
600	20	31	1.03	19.35	3512
600	20	34	1.13	17.65	2920
650	20	32	1.07	18.75	3571
675	20	32	1.07	18.75	3708
700	20	29	0.97	20.69	4682
800	20	33	1.10	18.18	4132



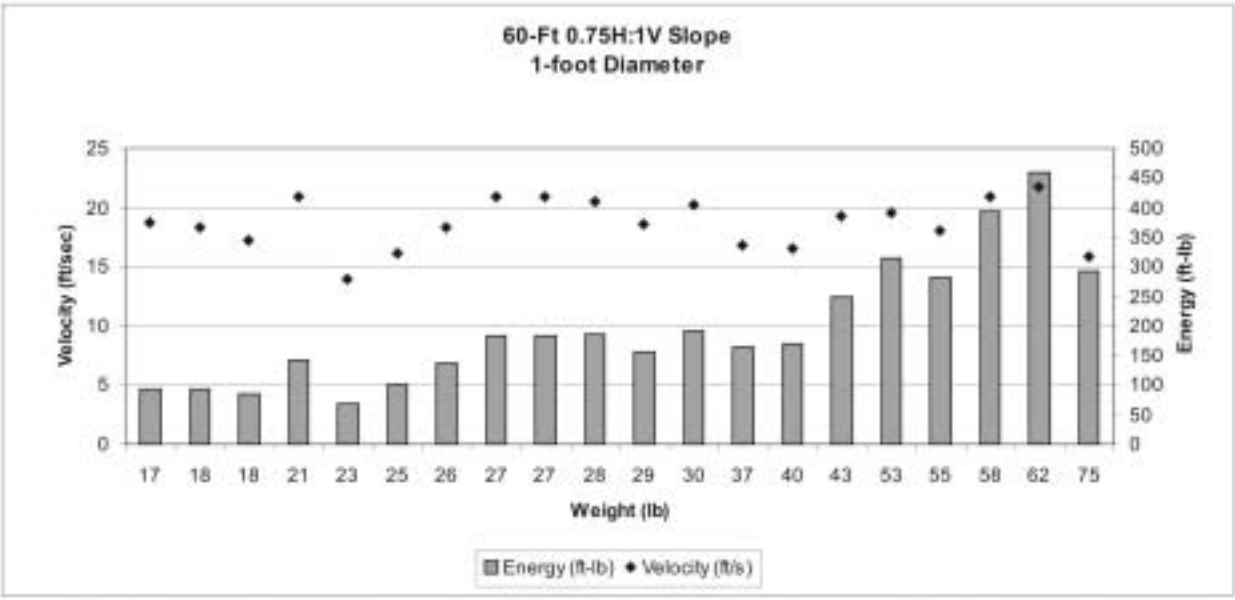
ENERGY OF 3-FOOT DIAMETER ROCKS
40-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
700	20	36	1.20	16.67	3038
800	20	35	1.17	17.14	3673
950	20	22	0.73	27.27	11041
1150	20	28	0.93	21.43	8251
1225	20	35	1.17	17.14	5625
1250	20	26	0.87	23.08	10401
1475	20	25	0.83	24.00	13275
1525	20	33	1.10	18.18	7877
1625	20	33	1.10	18.18	8394
1800	20	27	0.90	22.22	13889
2100	20	41	1.37	14.63	7027
2250	20	29	0.97	20.69	15049
2425	20	33	1.10	18.18	12526
3250	20	25	0.83	24.00	29250



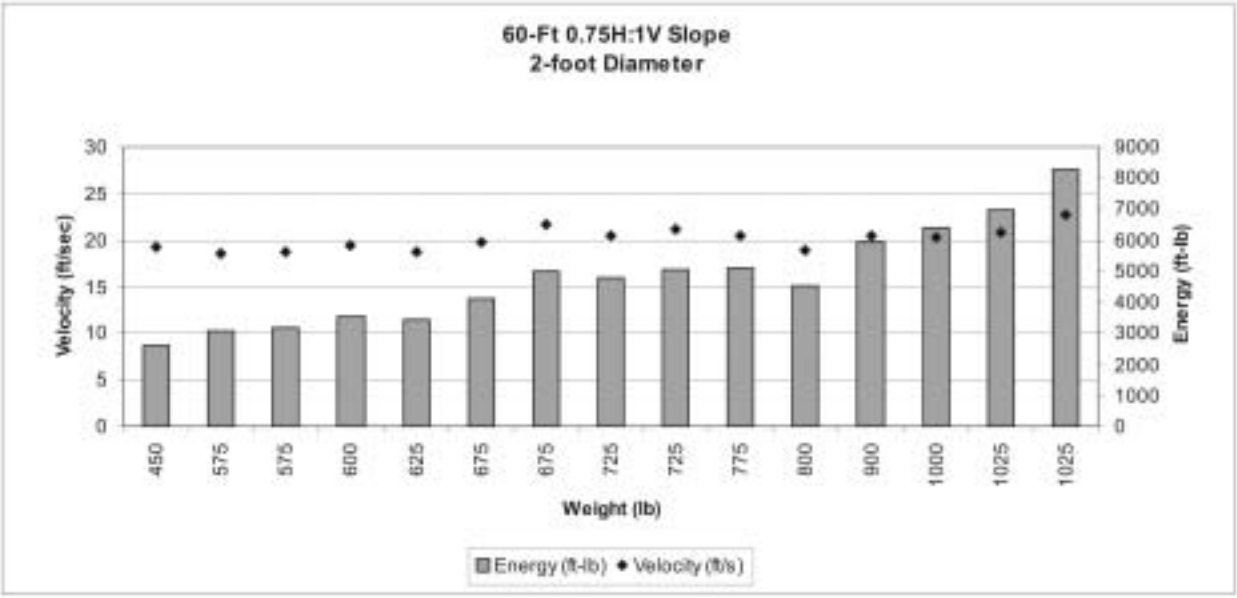
ENERGY OF 1-FOOT DIAMETER ROCKS
60-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
17	50	80	2.67	18.75	93
18	50	82	2.73	18.29	94
18	50	87	2.90	17.24	84
21	50	72	2.40	20.83	142
23	50	108	3.60	13.89	69
25	50	93	3.10	16.13	102
26	50	82	2.73	18.29	136
27	50	72	2.40	20.83	183
27	50	72	2.40	20.83	183
28	50	73	2.43	20.55	185
29	50	81	2.70	18.52	155
30	50	74	2.47	20.27	193
37	50	89	2.97	16.85	164
40	50	91	3.03	16.48	170
43	50	78	2.60	19.23	248
53	50	77	2.57	19.48	314
55	50	83	2.77	18.07	281
58	50	72	2.40	20.83	393
62	50	69	2.30	21.74	458
75	50	95	3.17	15.79	292



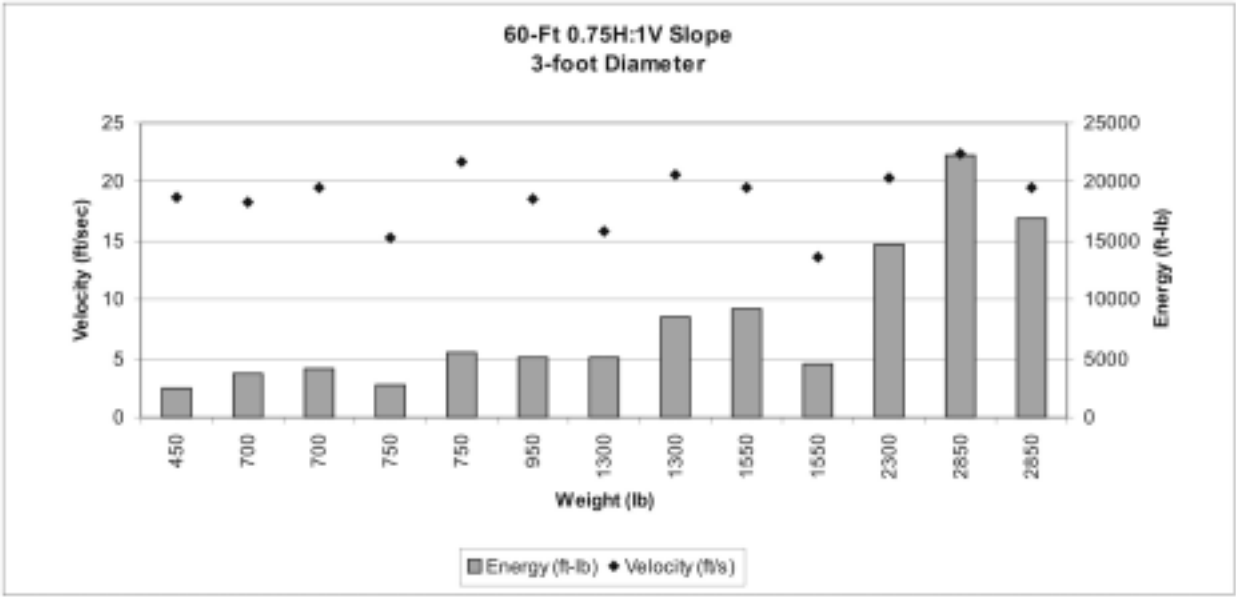
ENERGY OF 2-FOOT DIAMETER ROCKS
60-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
450	50	78	2.60	19.23	2600
575	50	81	2.70	18.52	3081
575	50	80	2.67	18.75	3159
600	50	77	2.57	19.48	3558
625	50	80	2.67	18.75	3433
675	50	76	2.53	19.74	4108
675	50	69	2.30	21.74	4984
725	50	73	2.43	20.55	4783
725	50	71	2.37	21.13	5056
775	50	73	2.43	20.55	5113
800	50	79	2.63	18.99	4506
900	50	73	2.43	20.55	5937
1000	50	74	2.47	20.27	6420
1025	50	72	2.40	20.83	6951
1025	50	66	2.20	22.73	8273



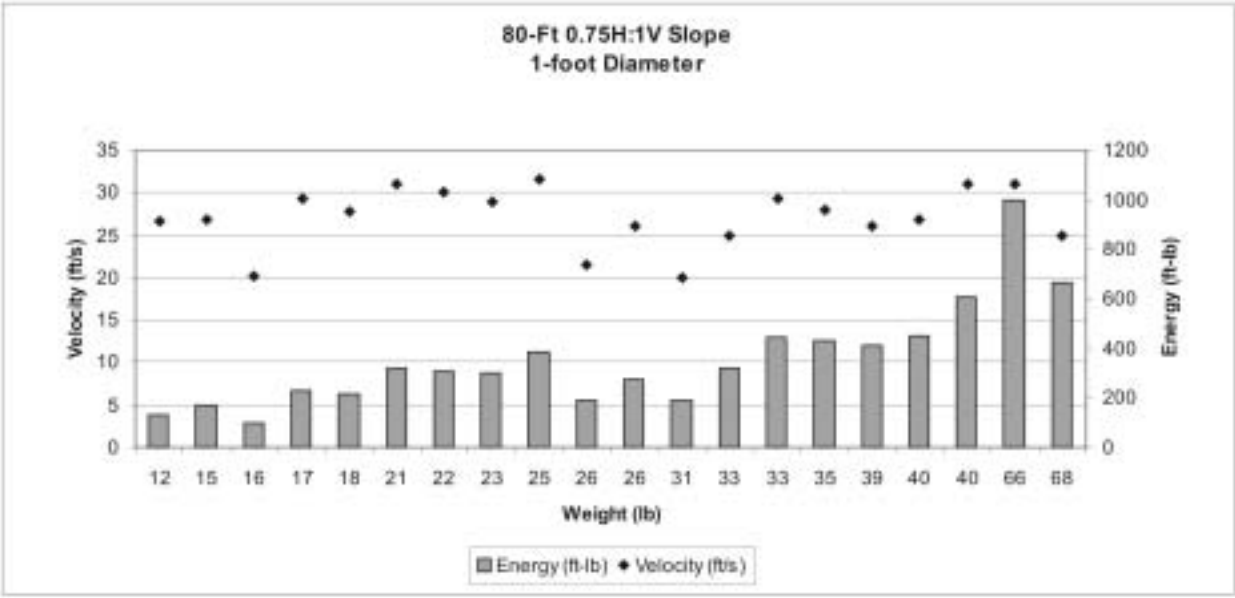
ENERGY OF 3-FOOT DIAMETER ROCKS
60-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
450	50	80	2.67	18.75	2472
700	50	82	2.73	18.29	3660
700	50	77	2.57	19.48	4151
750	50	98	3.27	15.31	2745
750	50	69	2.30	21.74	5538
950	50	81	2.70	18.52	5090
1300	50	95	3.17	15.79	5064
1300	50	73	2.43	20.55	8576
1550	50	77	2.57	19.48	9191
1550	50	110	3.67	13.64	4503
2300	50	74	2.47	20.27	14766
2850	50	67	2.23	22.39	22320
2850	50	77	2.57	19.48	16899



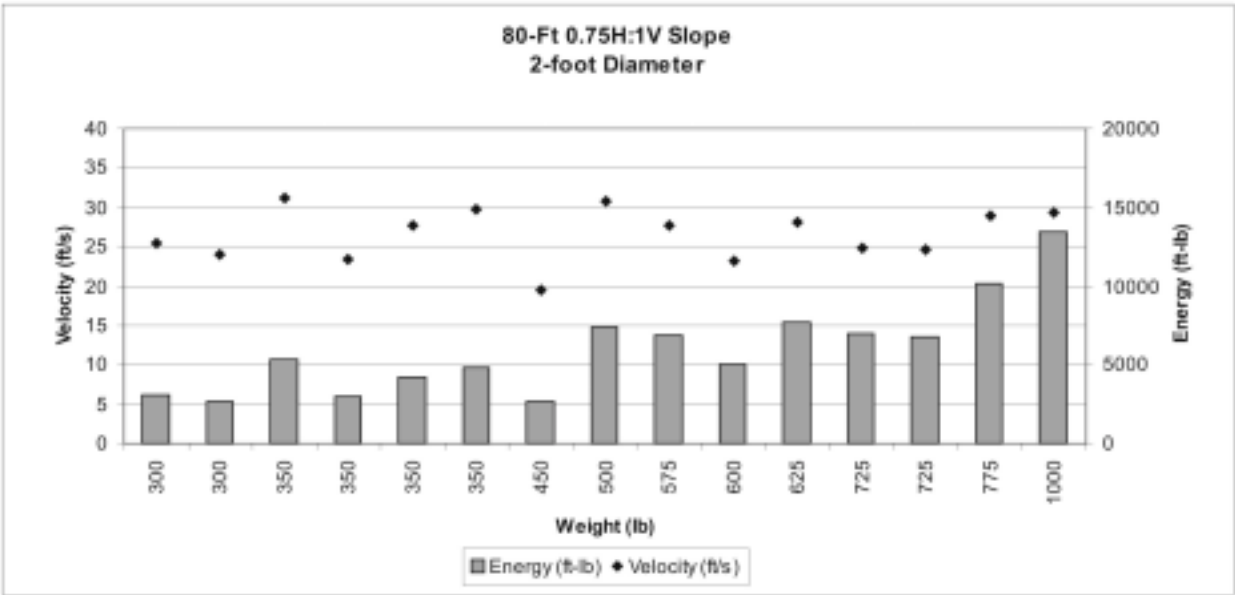
ENERGY OF 1-FOOT DIAMETER ROCKS
80-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
12	85	96	3.20	26.56	132
15	85	95	3.17	26.84	169
16	85	127	4.23	20.08	101
17	85	87	2.90	29.31	228
18	85	92	3.07	27.72	216
21	85	82	2.73	31.10	317
22	85	85	2.83	30.00	309
23	85	88	2.93	28.98	302
25	85	81	2.70	31.48	387
26	85	119	3.97	21.43	187
26	85	98	3.27	26.02	275
31	85	128	4.27	19.92	192
33	85	102	3.40	25.00	322
33	85	87	2.90	29.31	443
35	85	91	3.03	28.02	429
39	85	98	3.27	26.02	413
40	85	95	3.17	26.84	450
40	85	82	2.73	31.10	604
66	85	82	2.73	31.10	997
68	85	102	3.40	25.00	664



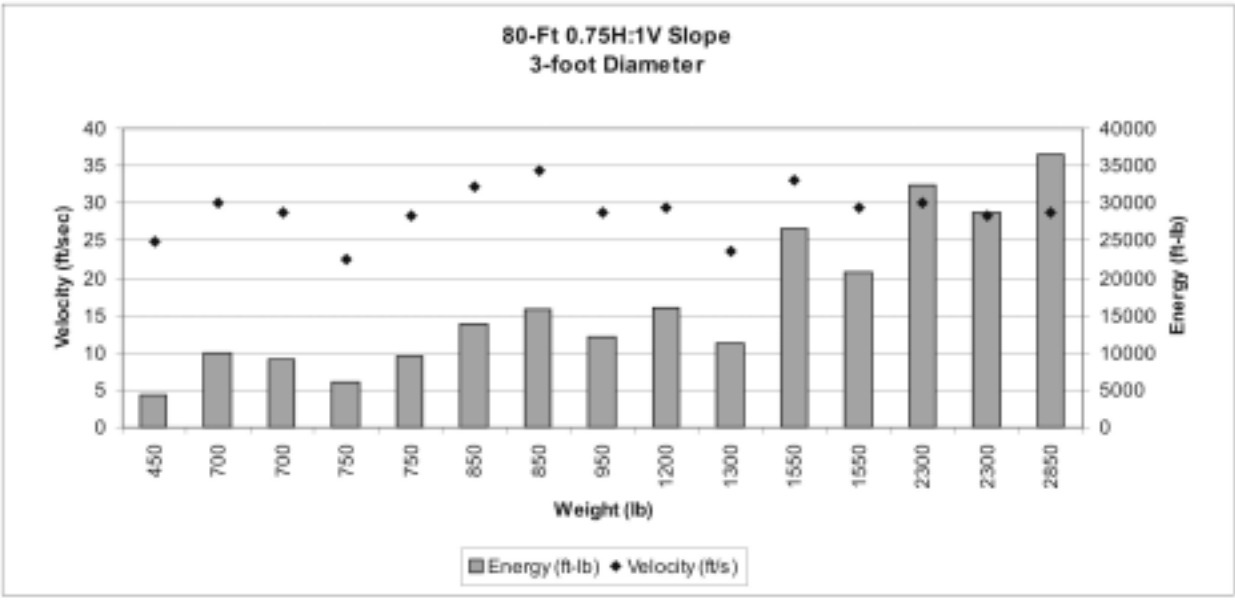
ENERGY OF 2-FOOT DIAMETER ROCKS
80-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
300	85	100	3.33	25.50	3048
300	85	106	3.53	24.06	2713
350	85	82	2.73	31.10	5289
350	85	109	3.63	23.39	2993
350	85	92	3.07	27.72	4201
350	85	86	2.87	29.65	4808
450	85	131	4.37	19.47	2664
500	85	83	2.77	30.72	7374
575	85	92	3.07	27.72	6902
600	85	110	3.67	23.18	5038
625	85	91	3.03	28.02	7668
725	85	103	3.43	24.76	6943
725	85	104	3.47	24.52	6810
775	85	88	2.93	28.98	10168
1000	85	87	2.90	29.31	13423



ENERGY OF 3-FOOT DIAMETER ROCKS
80-FOOT, 0.75H:1V SLOPE

Wt	Distance (ft)	Frames	Time (sec)	Velocity (ft/sec)	Energy (ft-lb)
450	85	103	3.43	24.76	4310
700	85	85	2.83	30.00	9844
700	85	89	2.97	28.65	8979
750	85	113	3.77	22.57	5968
750	85	90	3.00	28.33	9408
850	85	79	2.63	32.28	13838
850	85	74	2.47	34.46	15771
950	85	89	2.97	28.65	12186
1200	85	87	2.90	29.31	16108
1300	85	108	3.60	23.61	11324
1550	85	77	2.57	33.12	26561
1550	85	87	2.90	29.31	20806
2300	85	85	2.83	30.00	32344
2300	85	90	3.00	28.33	28850
2850	85	89	2.97	28.65	36557



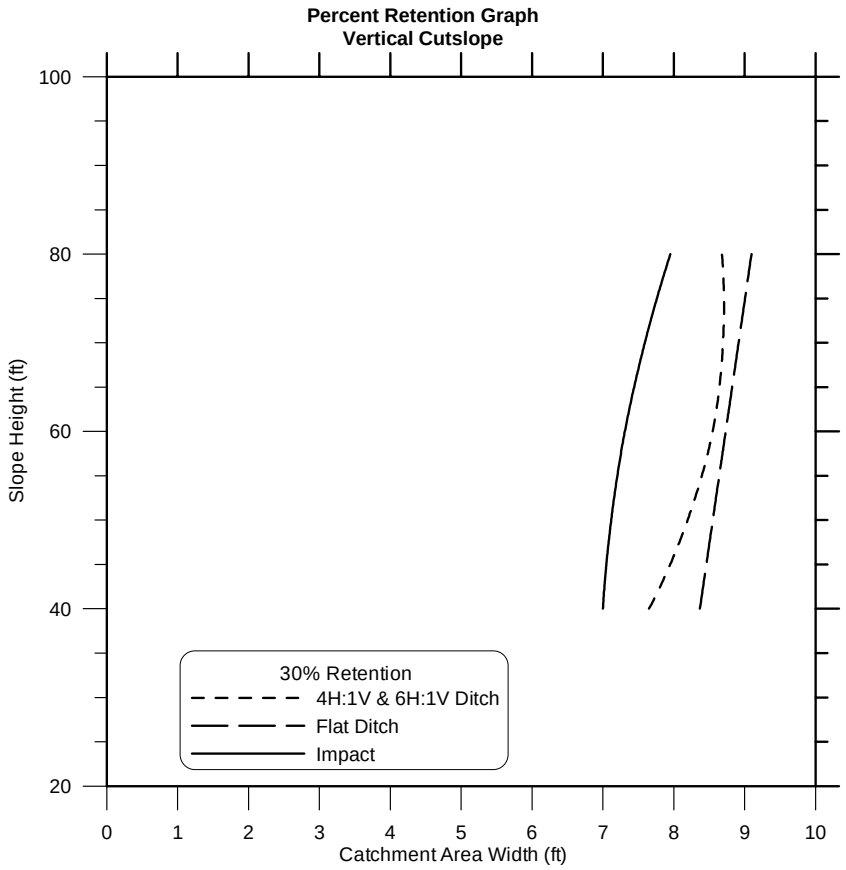
APPENDIX F: CATCHMENT AREA PERCENT RETENTION GRAPHS

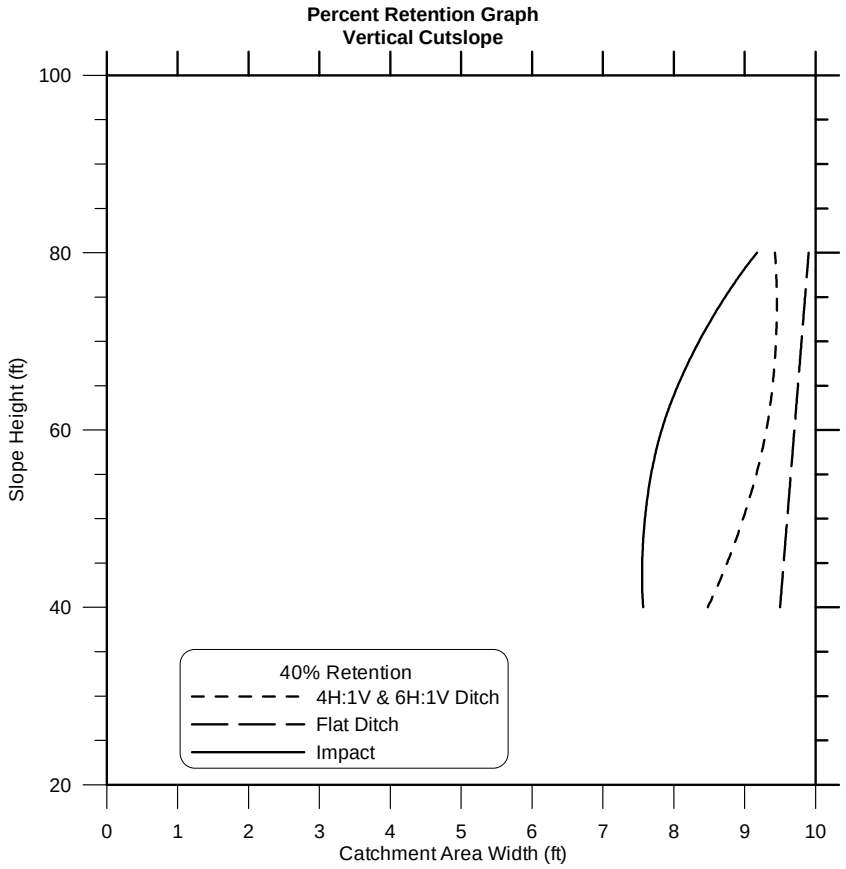
CATCHMENT AREA PERCENT RETENTION GRAPHS

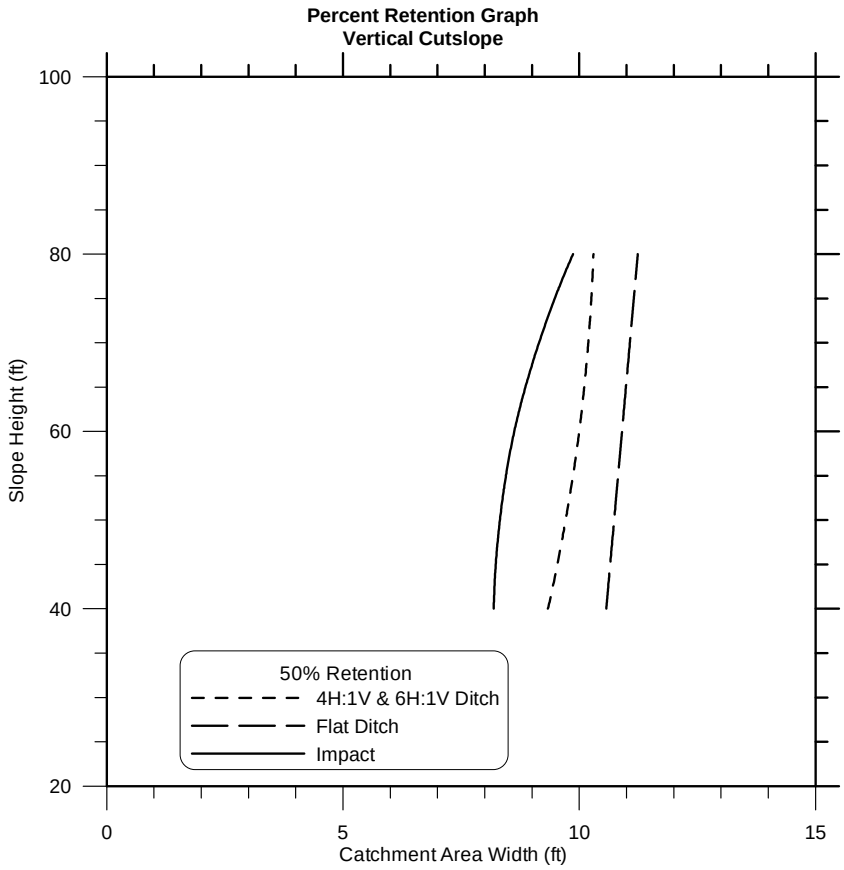
Complete sets of Catchment Area Percent Retention Graphs are included here for the vertical, 0.25H:1V, 0.5H:1V, 0.75H:1V, and 1H:1V cutslopes. These graphs are a compilation of the research results from the 40-, 60- and 80-foot high slopes for the flat-bottom, 6H:1V and 4H:1V slope catchment area configurations. The retention graphs incorporate the maximum impact and roll out measurements for each percentage indicated as described in the text in Section 4.2.

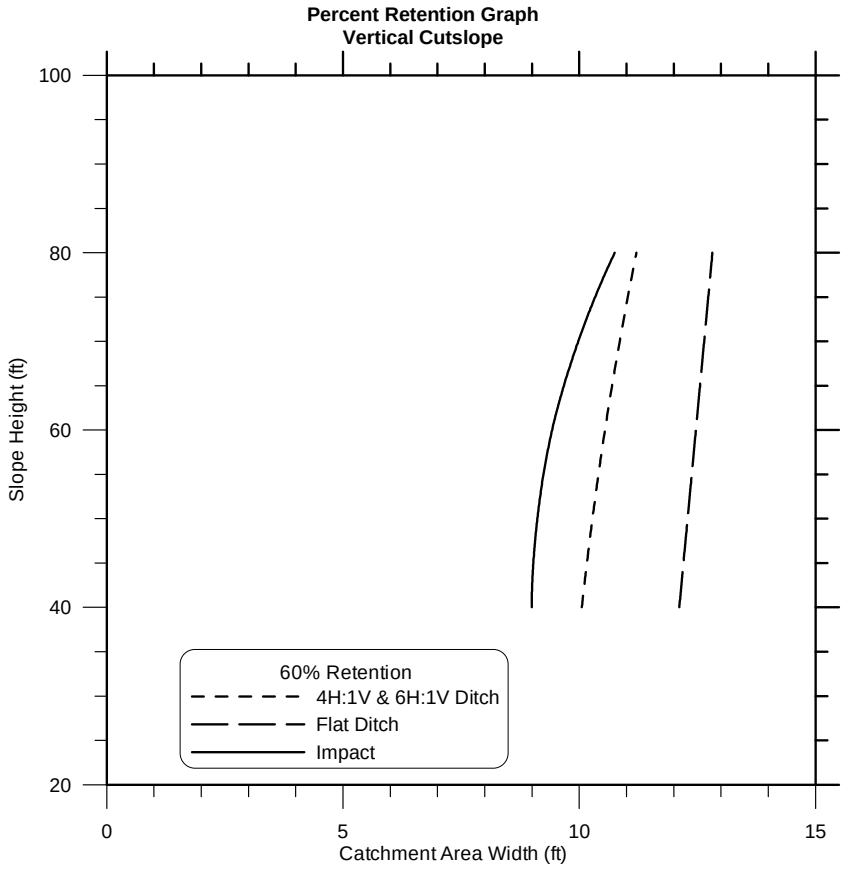
In some cases, the results were similar enough that the results plotted as a single curve. For example, this can be seen on the vertical slope, 99% retention graphs. The results from the 6H:1V and 4H:1V catchment area slopes were very similar. Only one curve was developed for these two catchment area slopes on this graph.

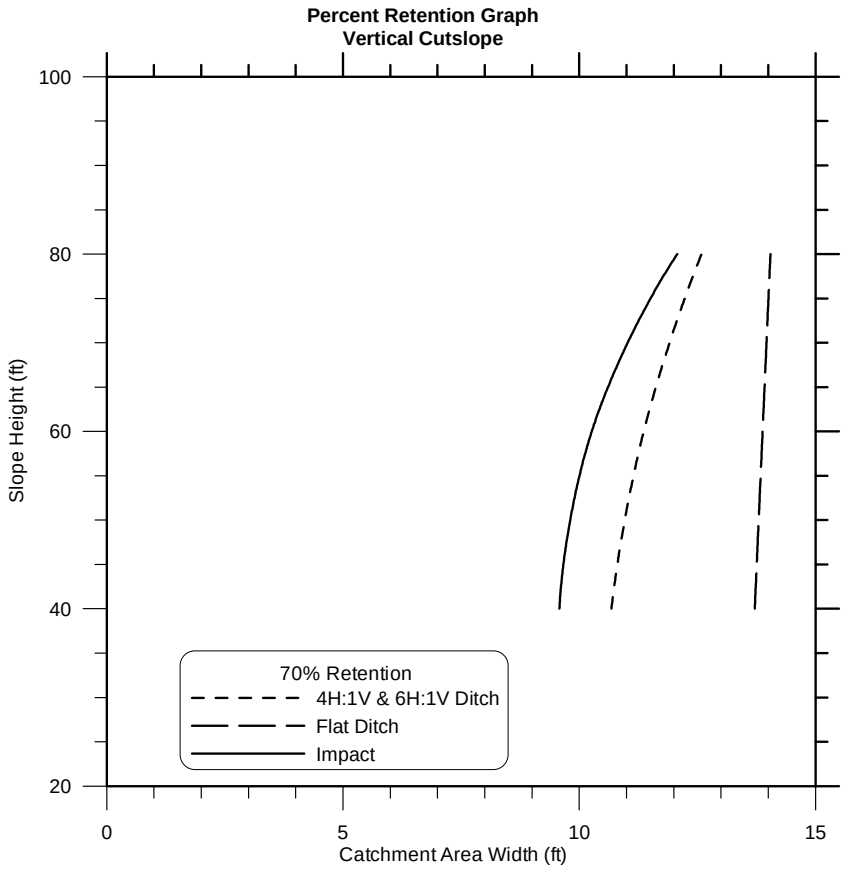
NOTE: To facilitate practical design usage, the field measured catchment area impact and roll out <u>slope</u> distances have been converted to <u>horizontal</u> catchment area width on the percent retention graphs.

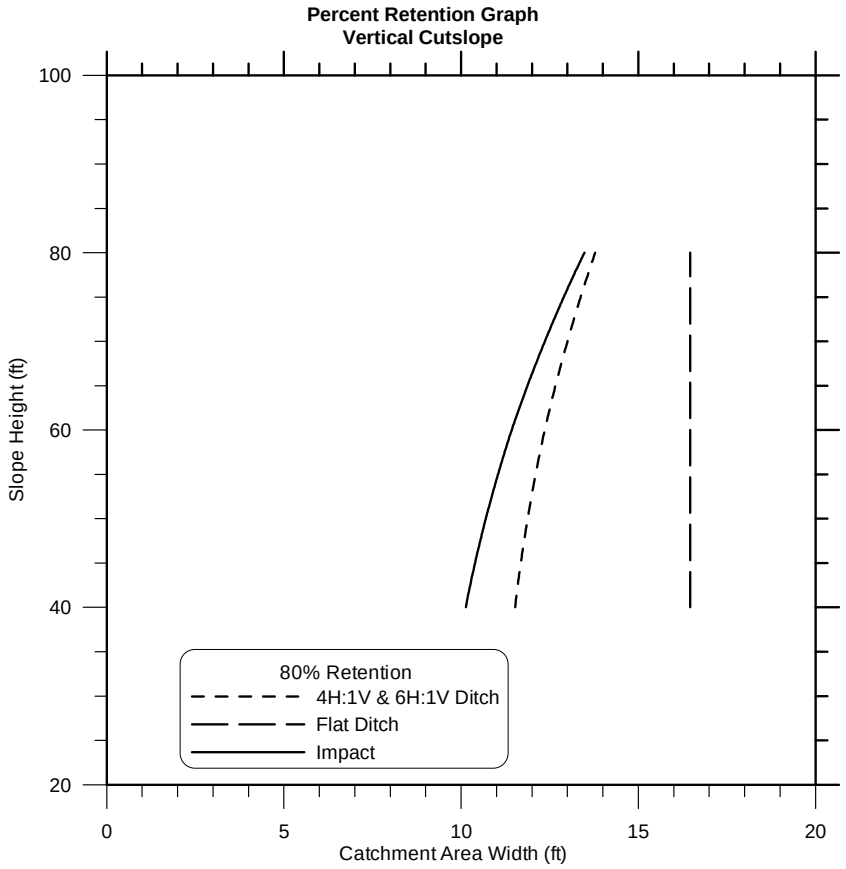

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
Catchment Area Width (ft)
30% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

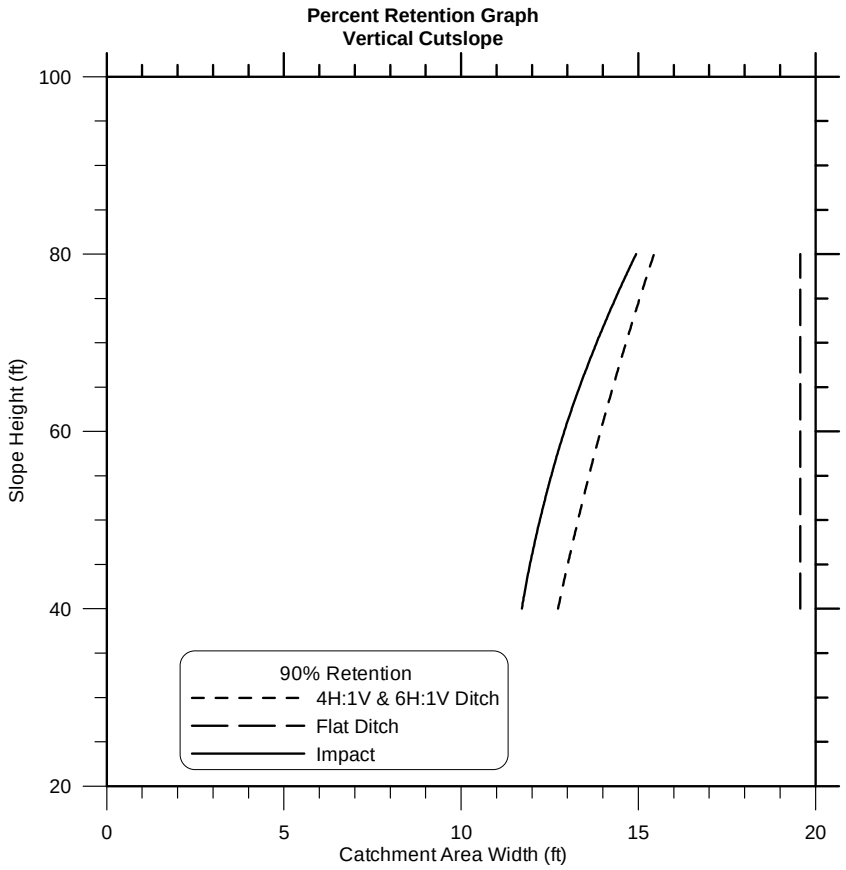

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
Catchment Area Width (ft)
40% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

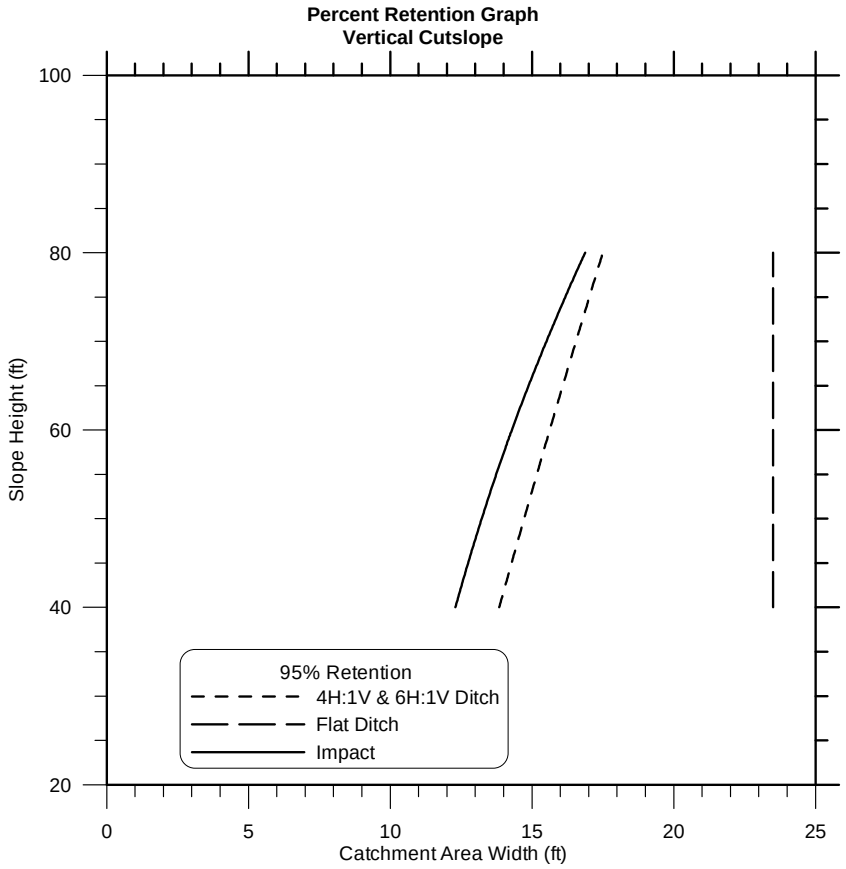

Percent Retention Graph
Vertical Cutslope
100
80
60
40
20
Slope Height (ft)
0
5
10
15
Catchment Area Width (ft)
50% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

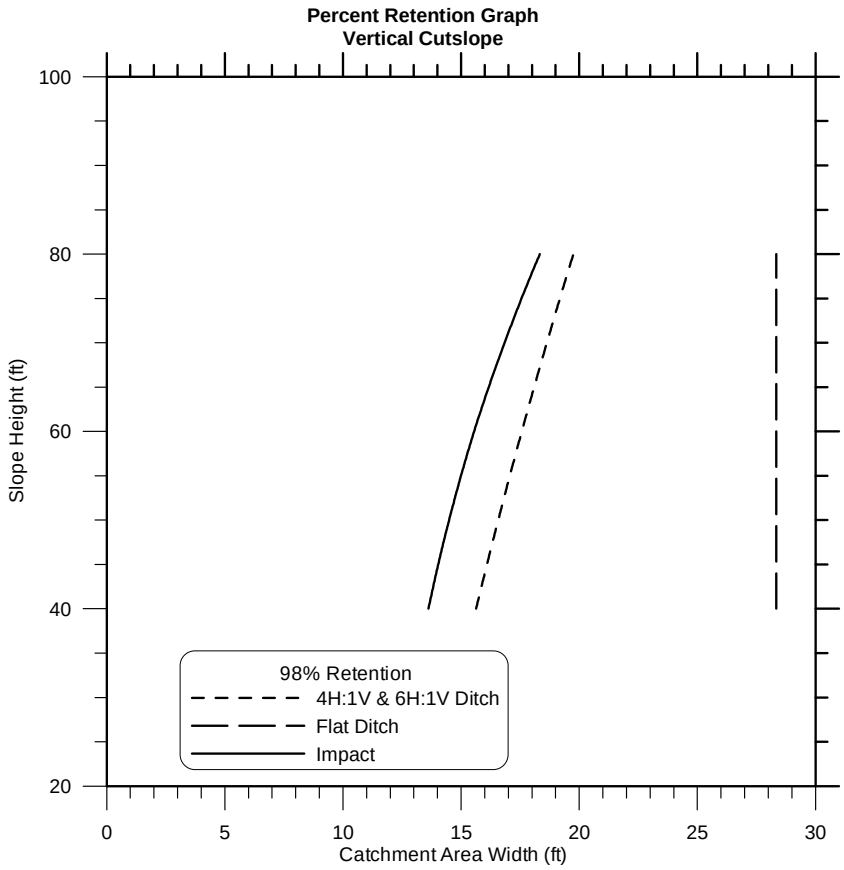

Percent Retention Graph
Vertical Cutslope
100
80
60
40
20
Slope Height (ft)
0
5
10
15
Catchment Area Width (ft)
60% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

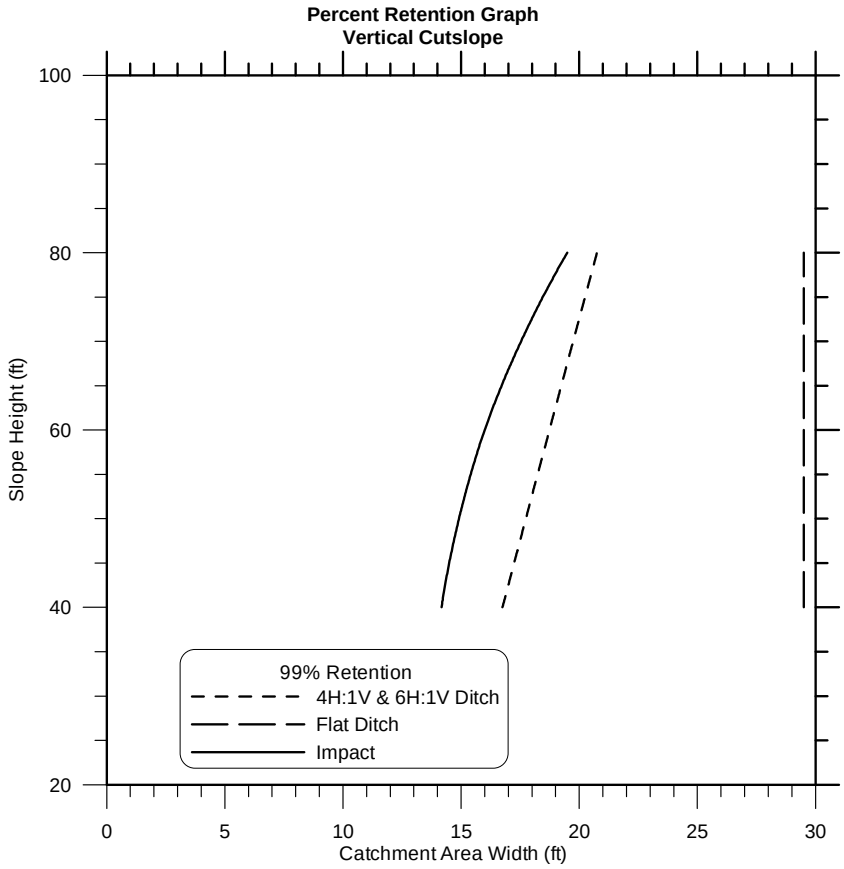

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
70% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

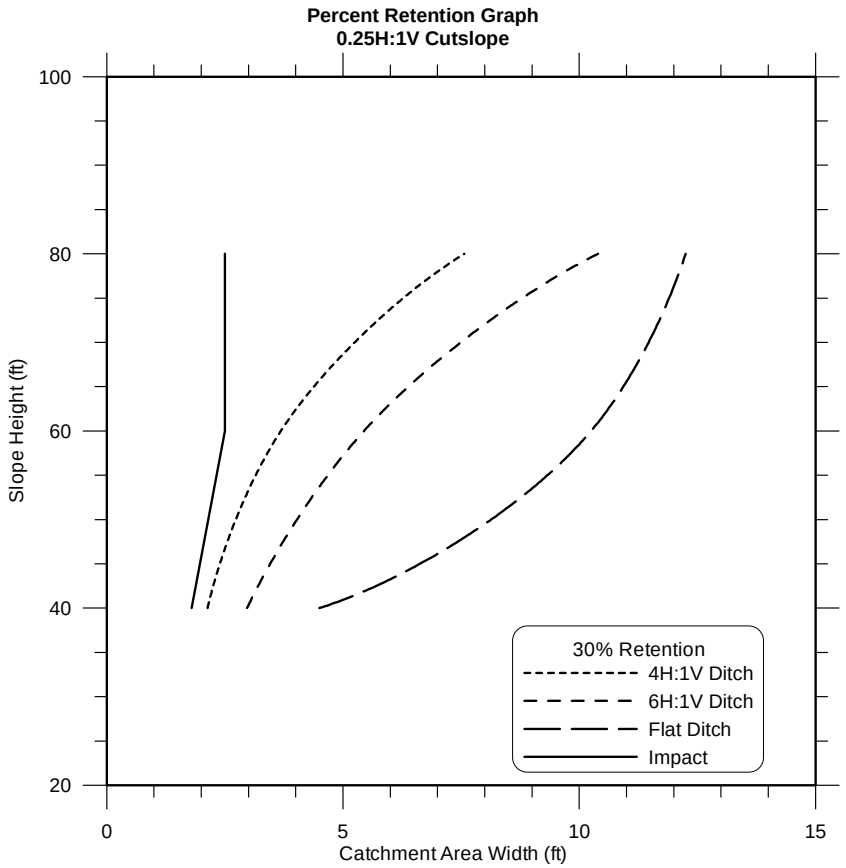

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
80% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

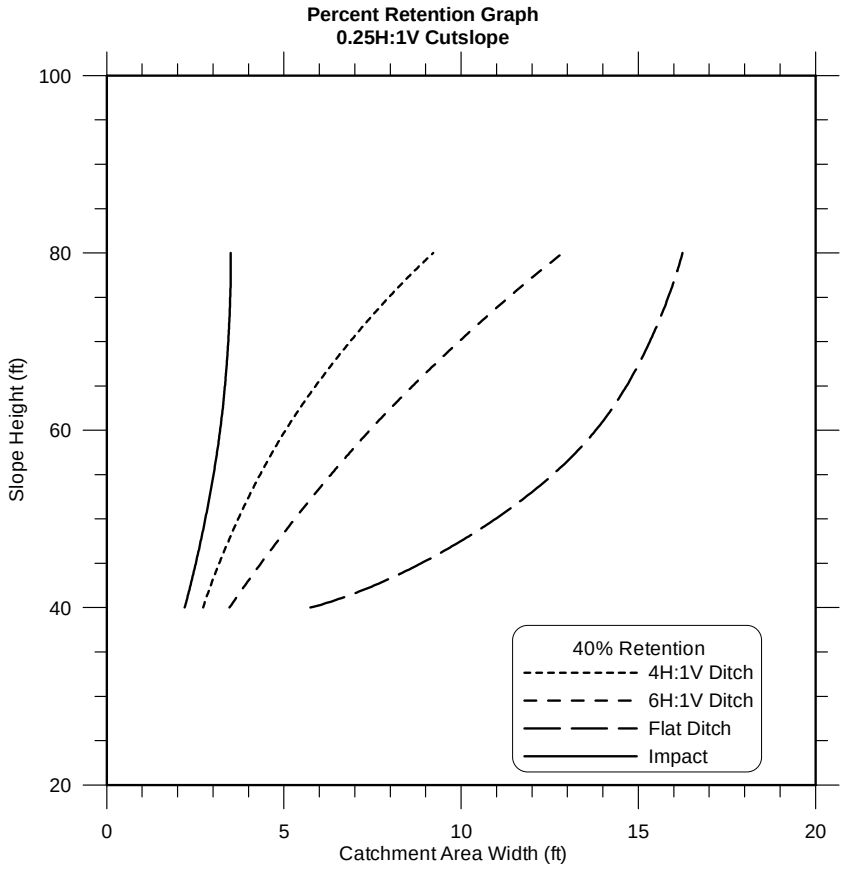

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
Catchment Area Width (ft)
90% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

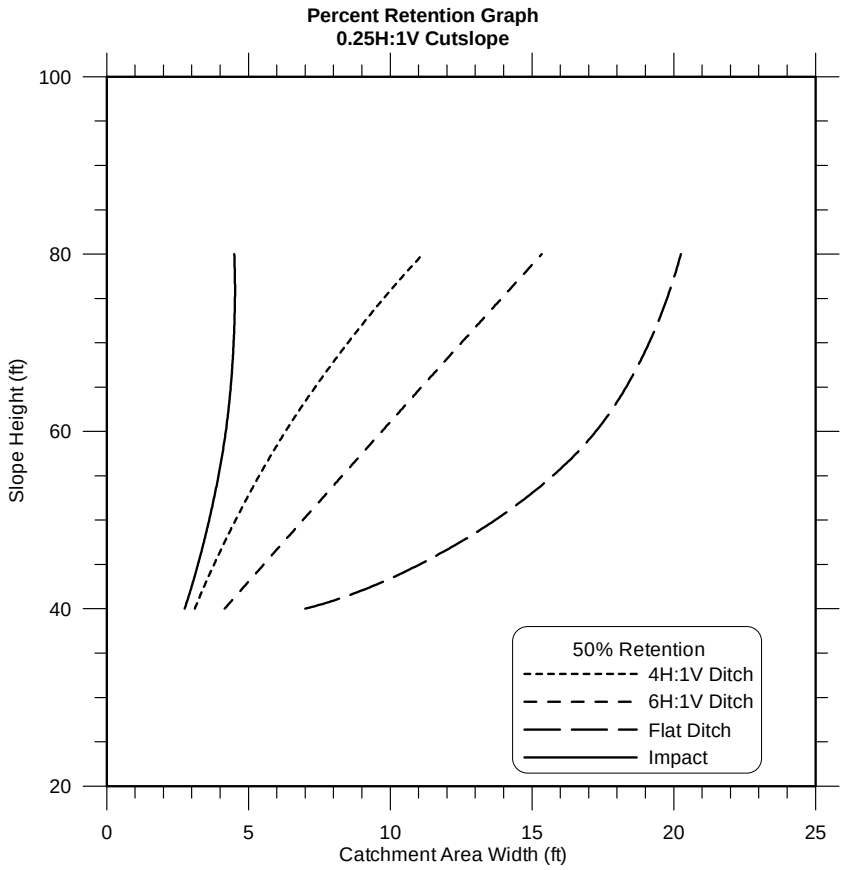

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
Catchment Area Width (ft)
95% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

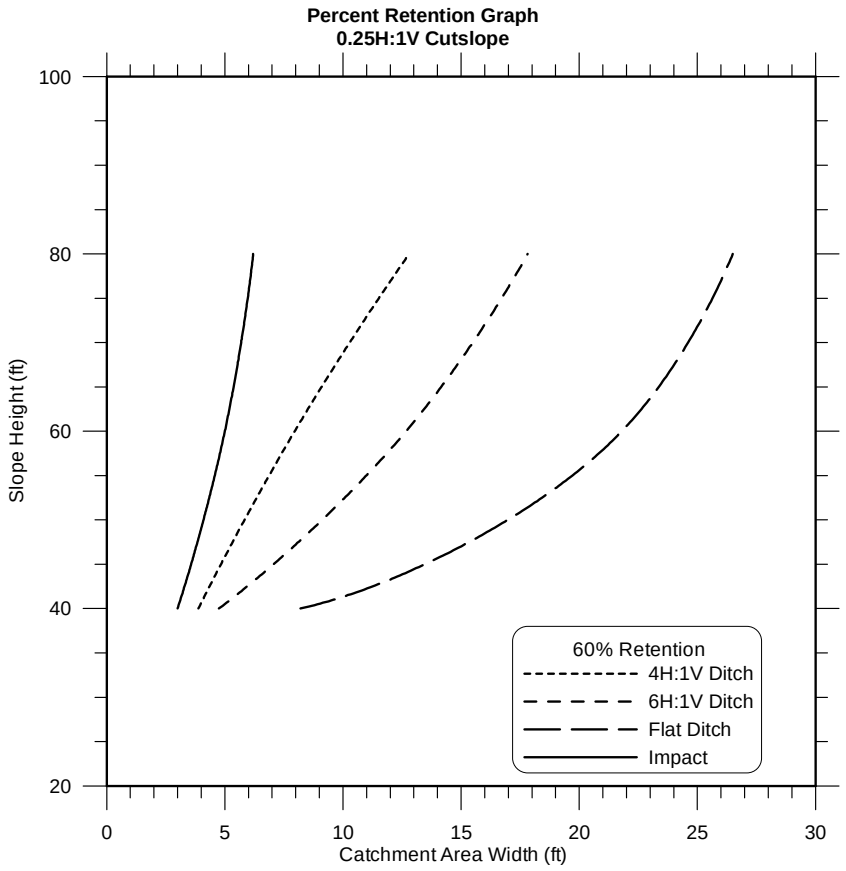

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
98% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact

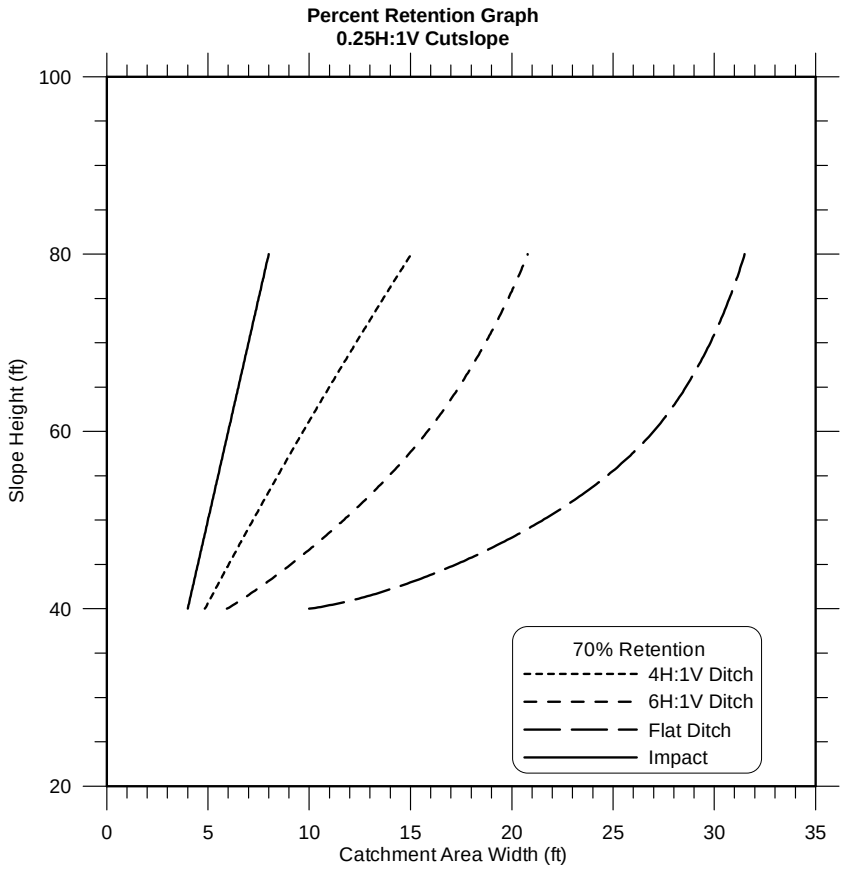

Percent Retention Graph
Vertical Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
99% Retention
4H:1V & 6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
30% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
40% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
50% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
60% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
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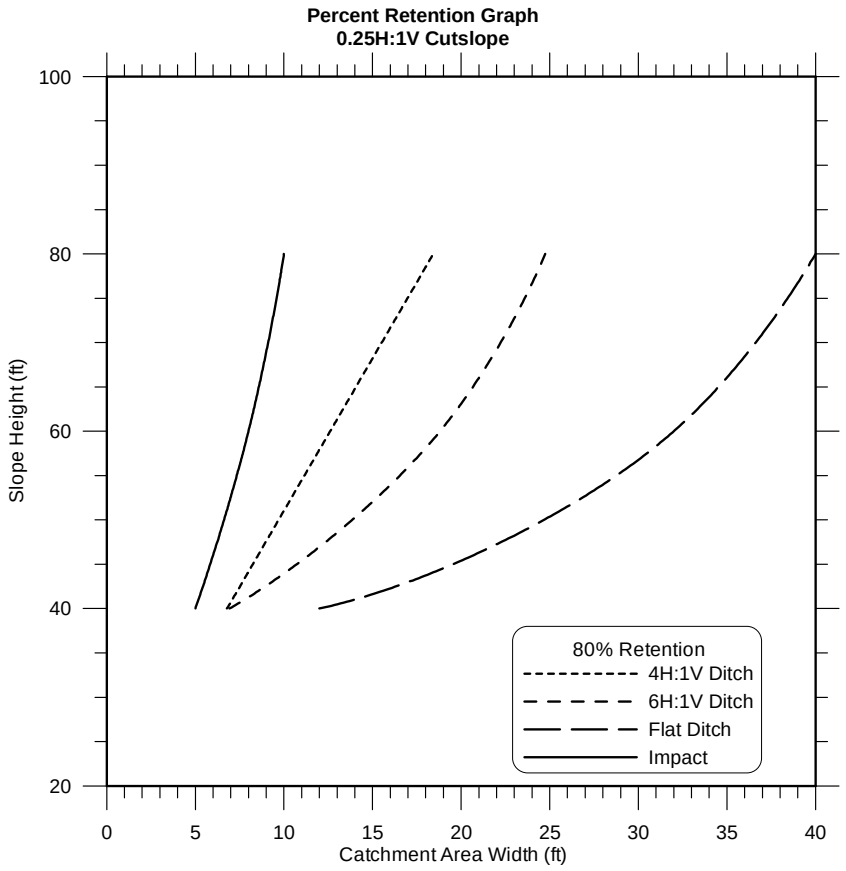
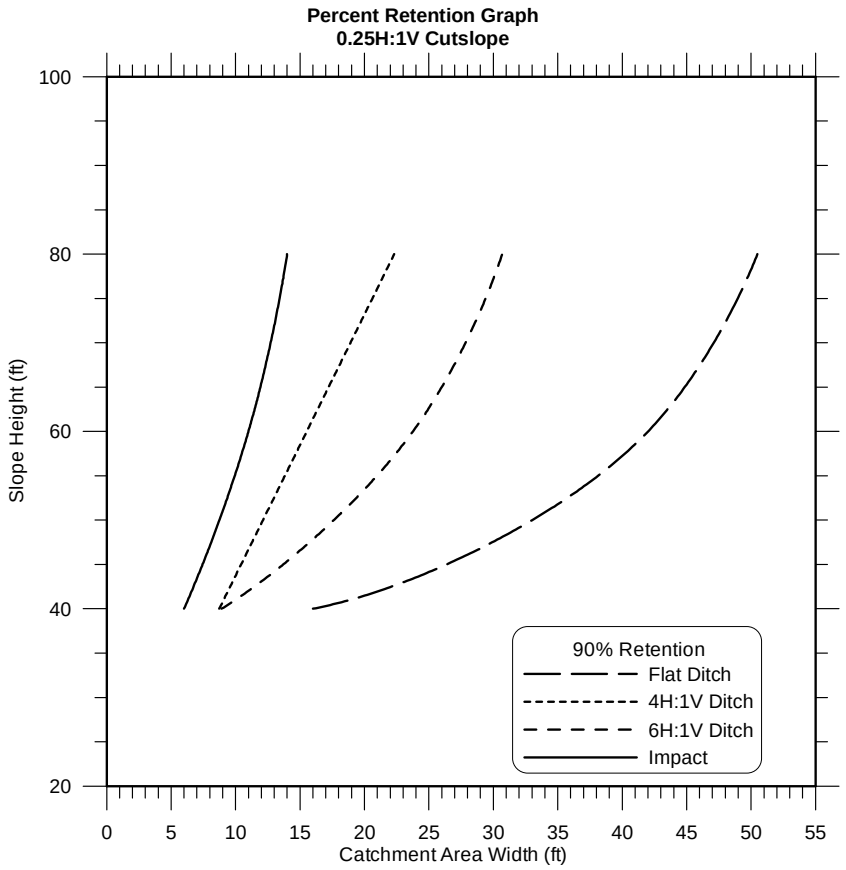
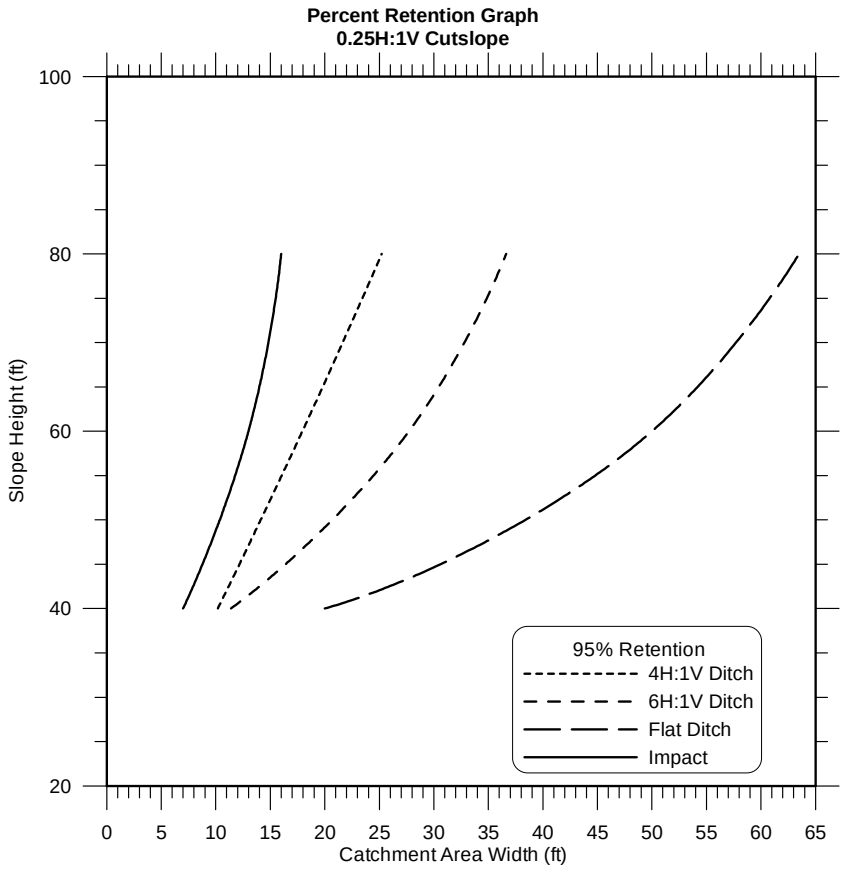
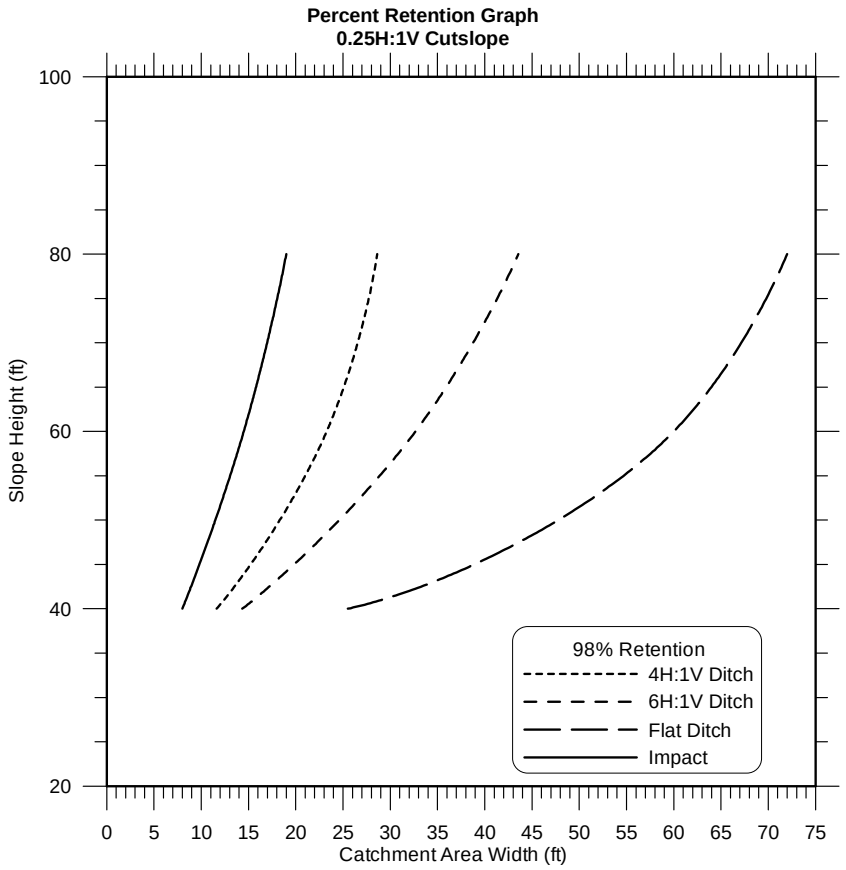
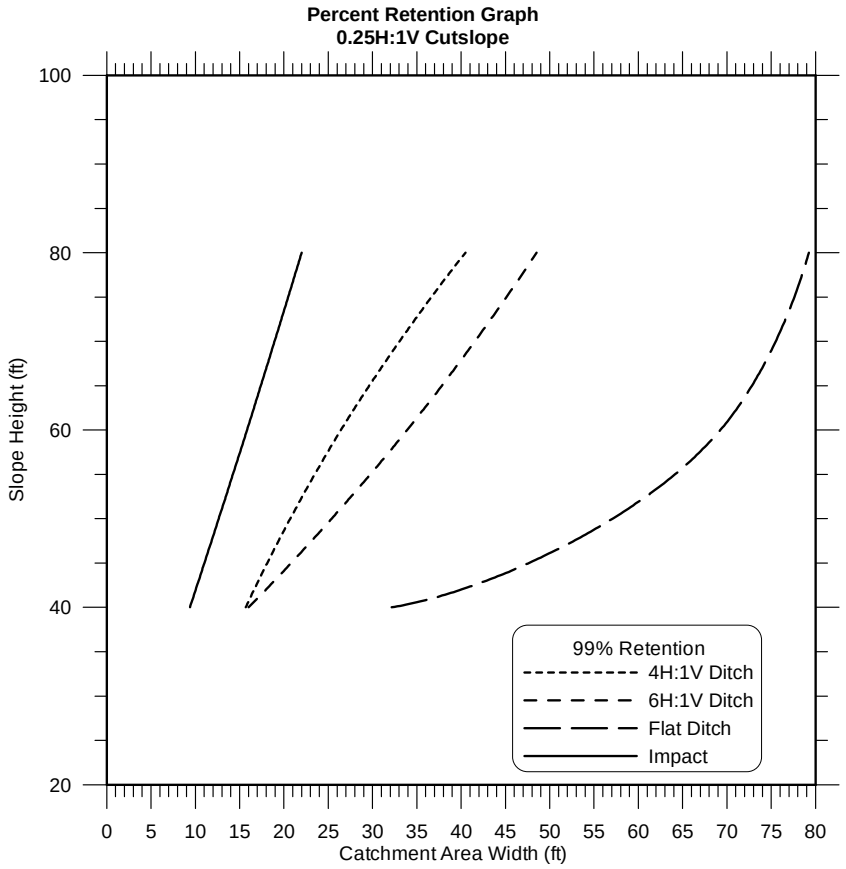
15
20
25
30
35
70% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

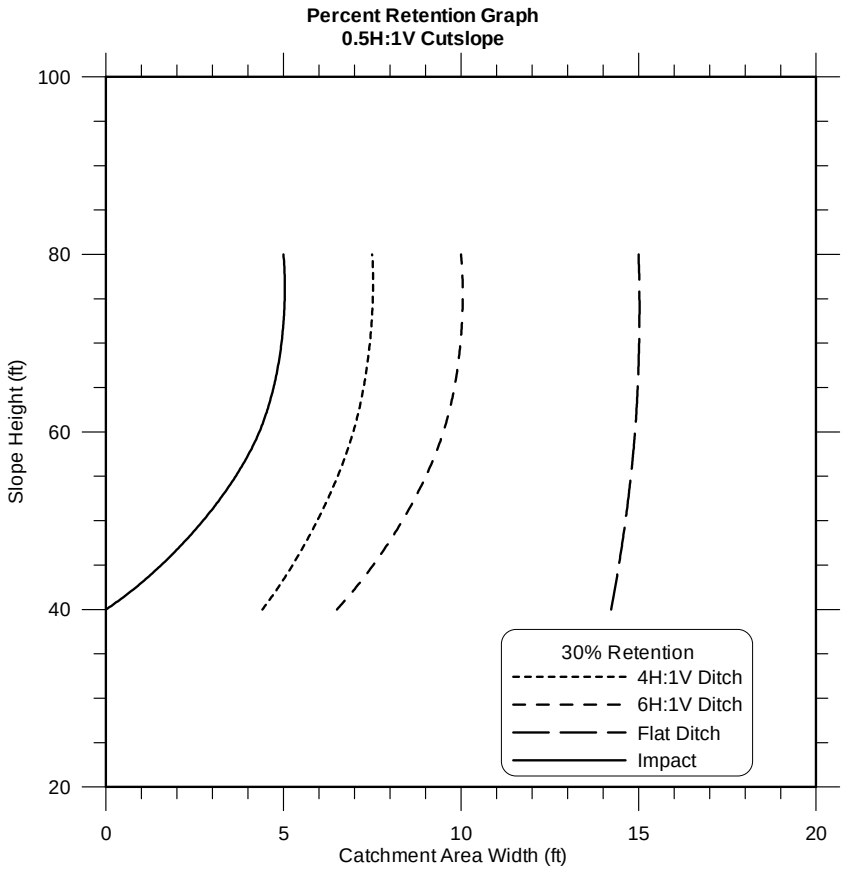

Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
80% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

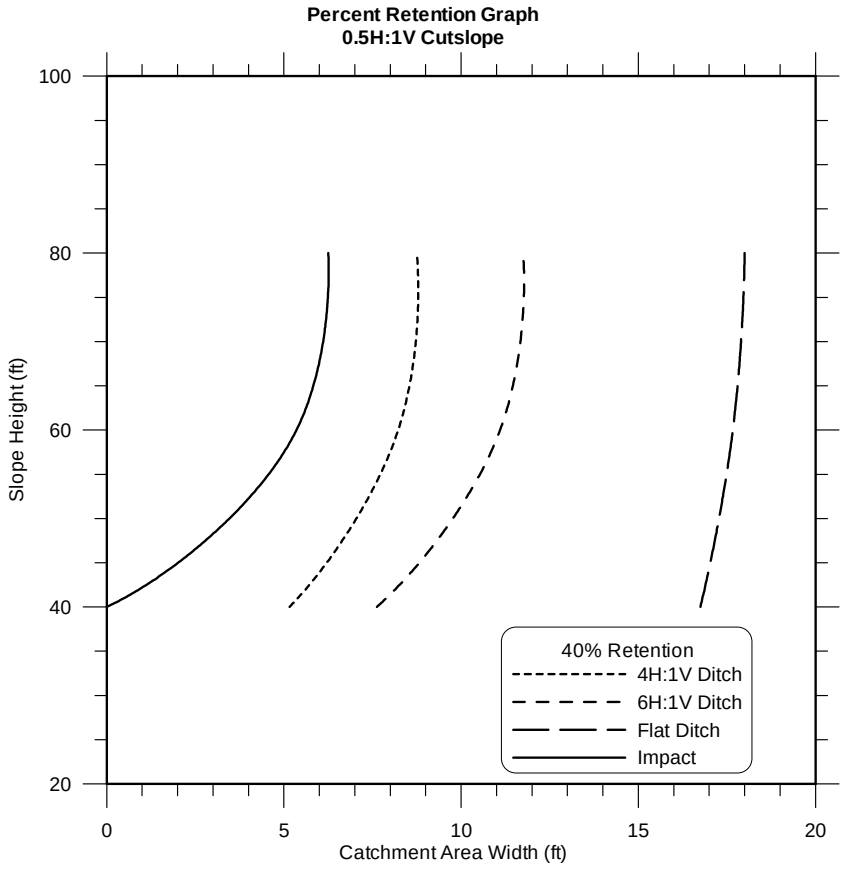

Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
90% Retention
Flat Ditch
4H:1V Ditch
6H:1V Ditch
Impact

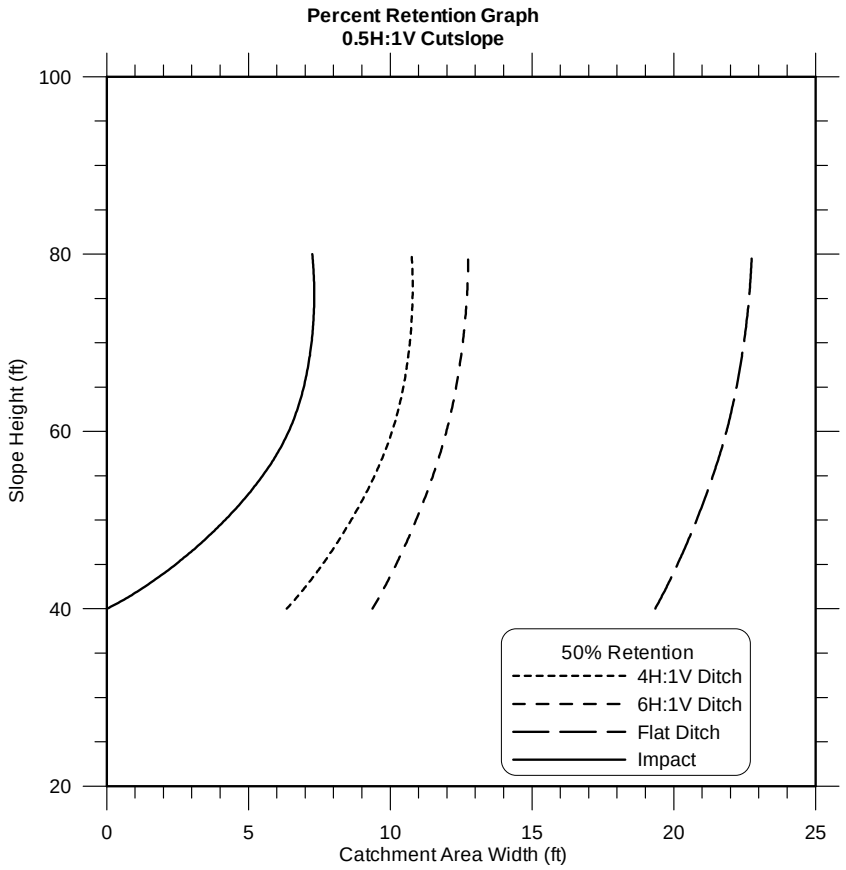

Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
60
65
95% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

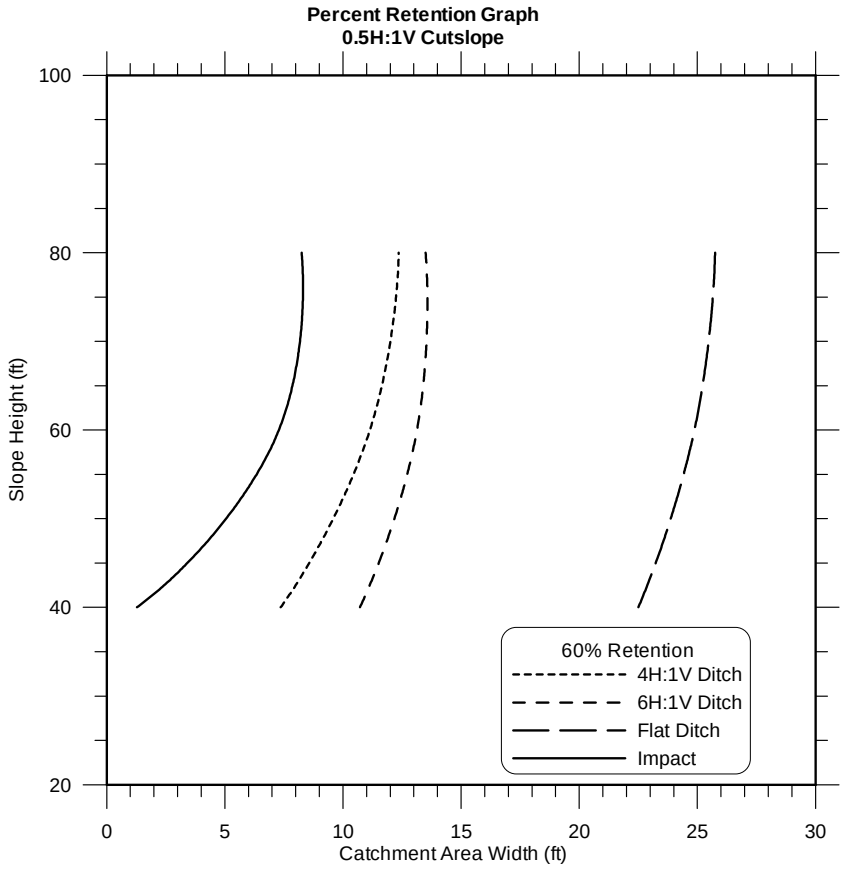

Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
Catchment Area Width (ft)
98% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

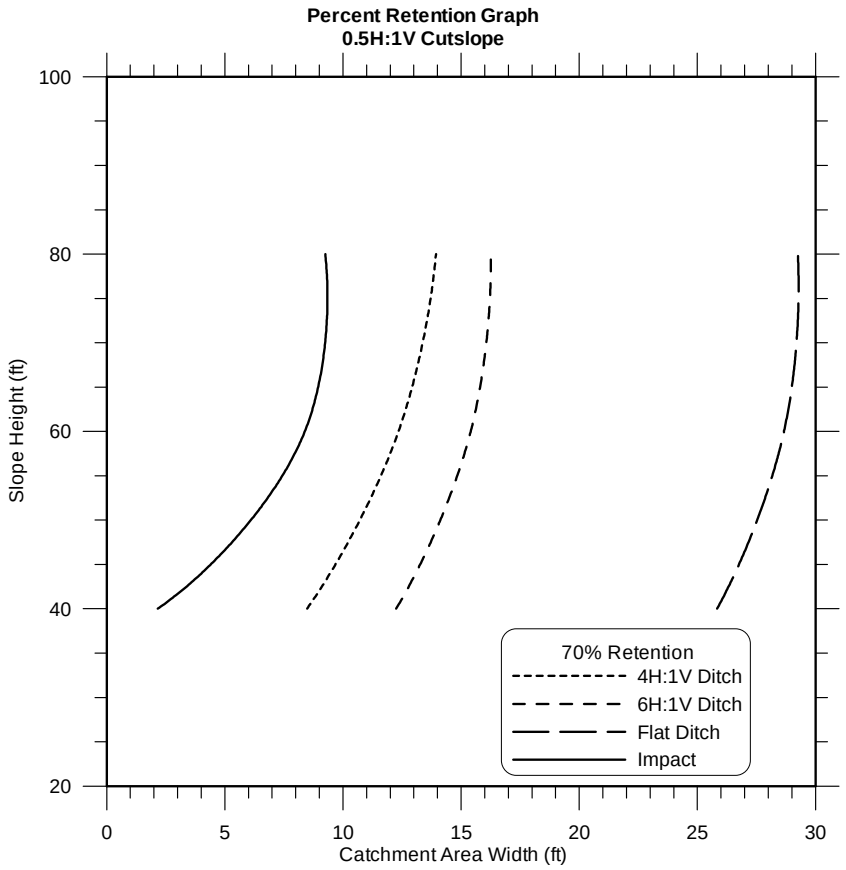

Percent Retention Graph
0.25H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Catchment Area Width (ft)
99% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

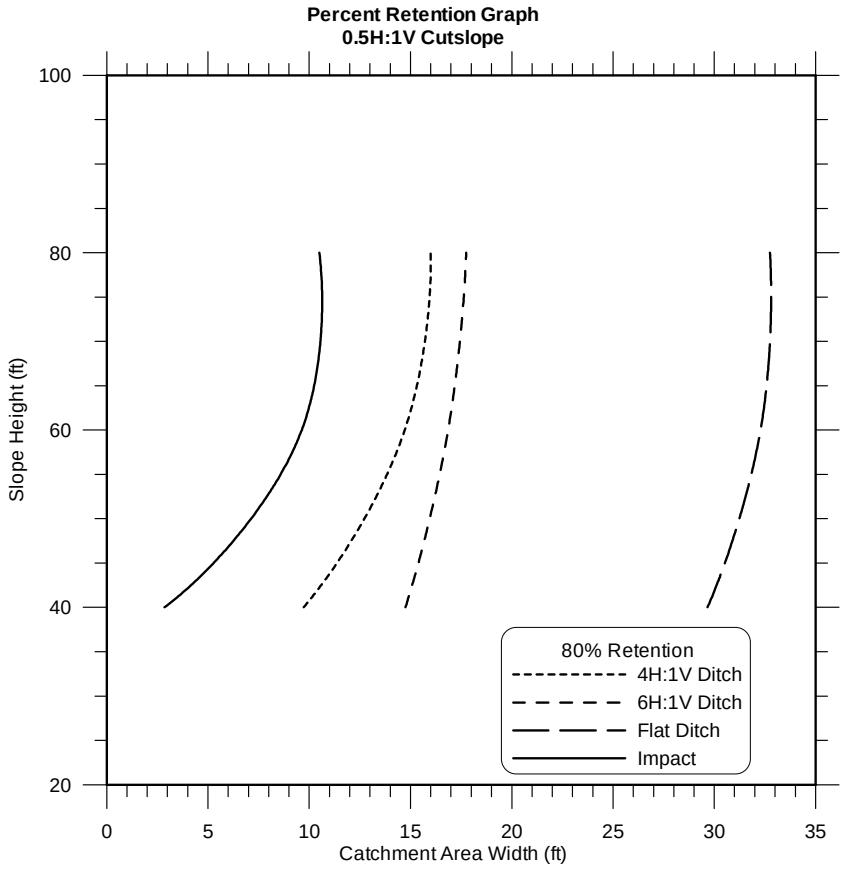

Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
30% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

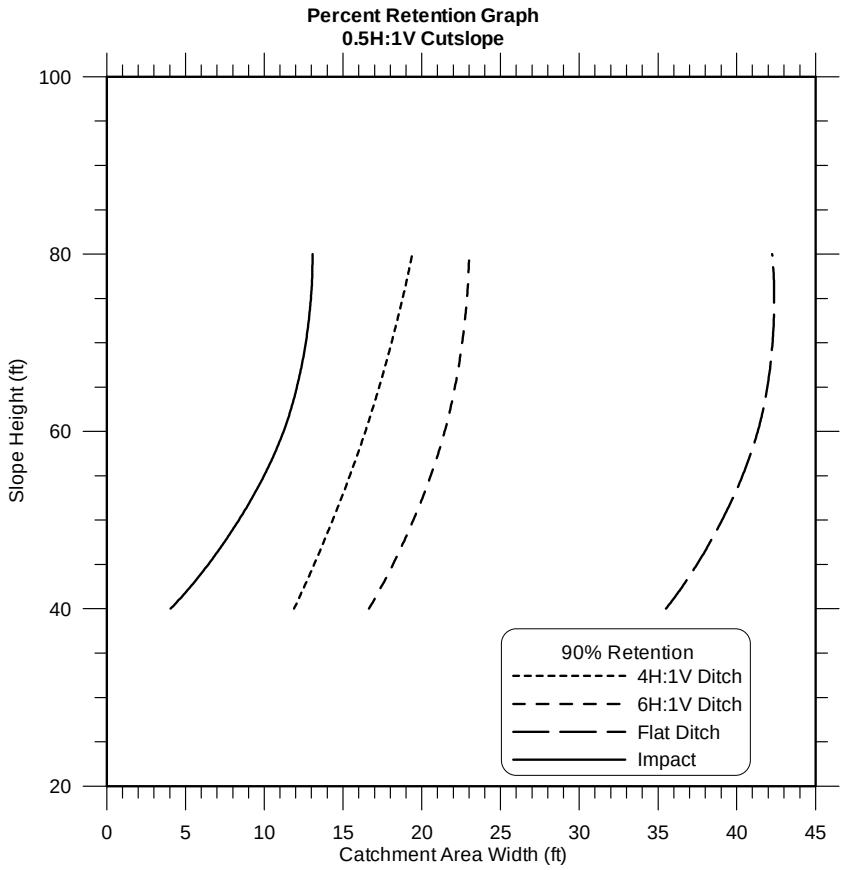

Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
40% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

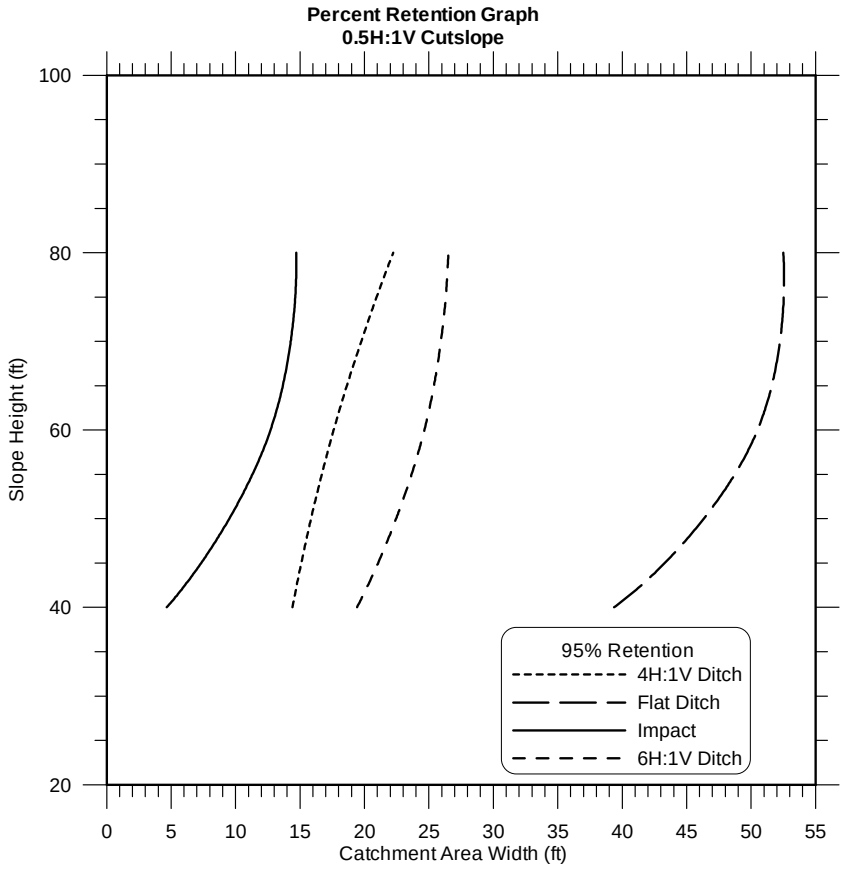

Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
50% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

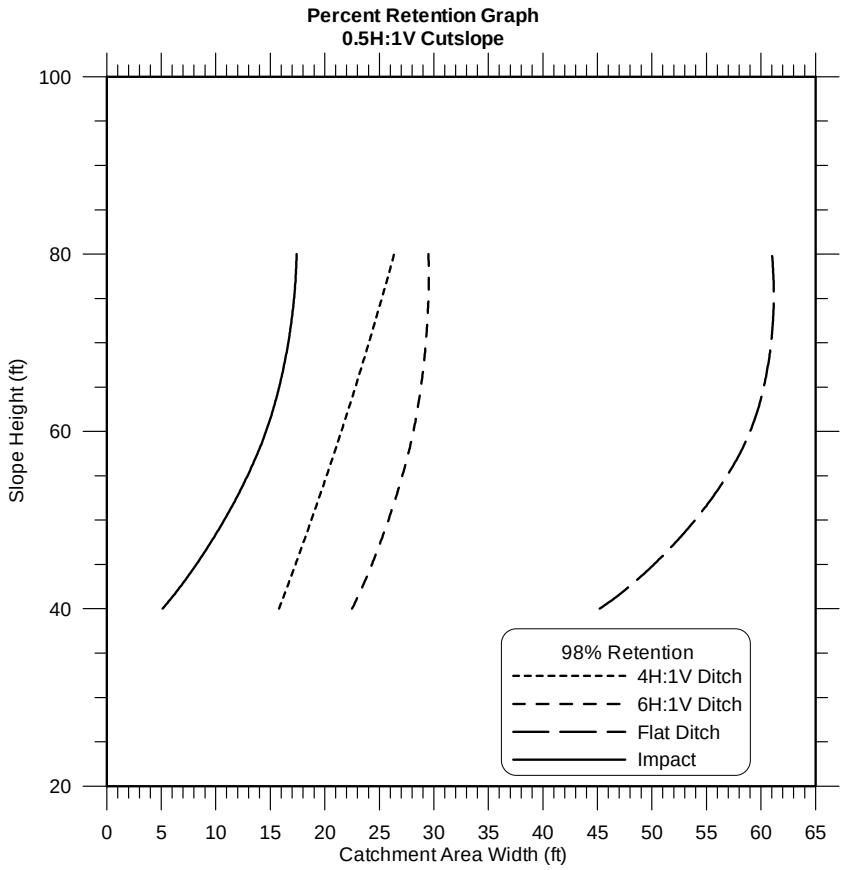

Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
60% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

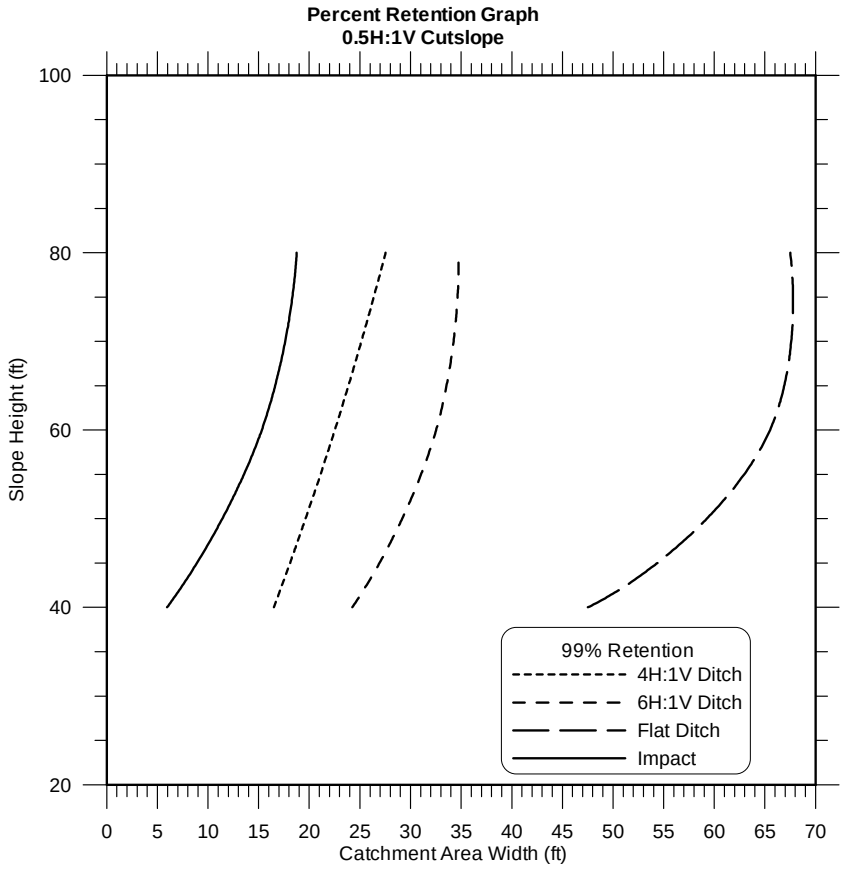

Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
70% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
80% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
90% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
95% Retention
4H:1V Ditch
Flat Ditch
Impact
6H:1V Ditch


Percent Retention Graph
0.5H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Catchment Area Width (ft)
98% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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0.5H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
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25
30
35
40
45
50
55
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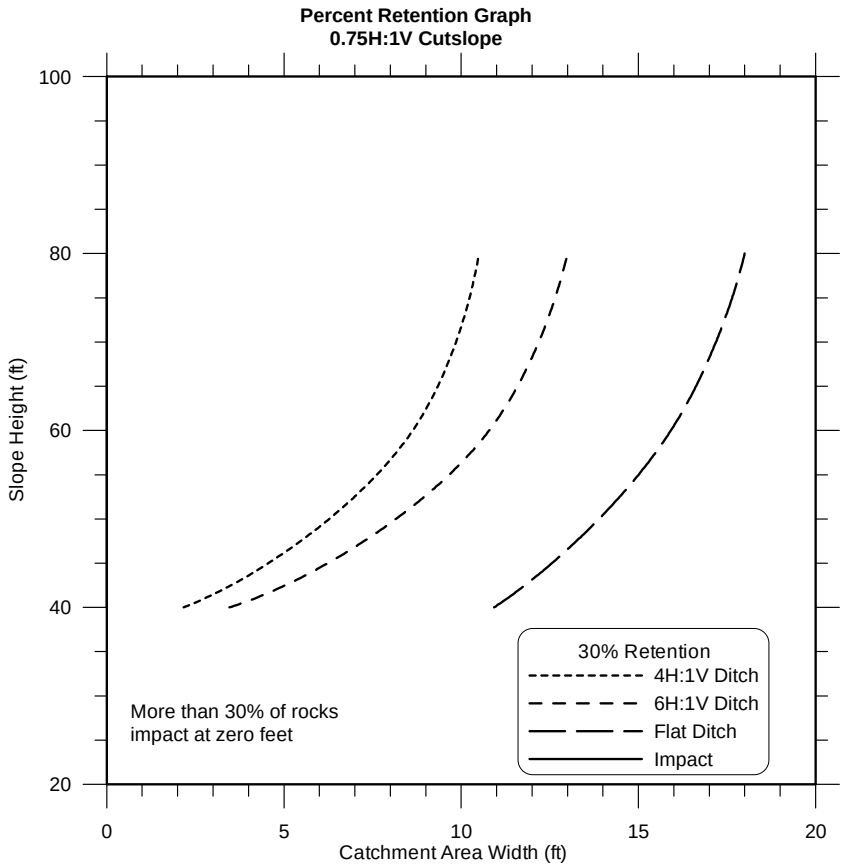
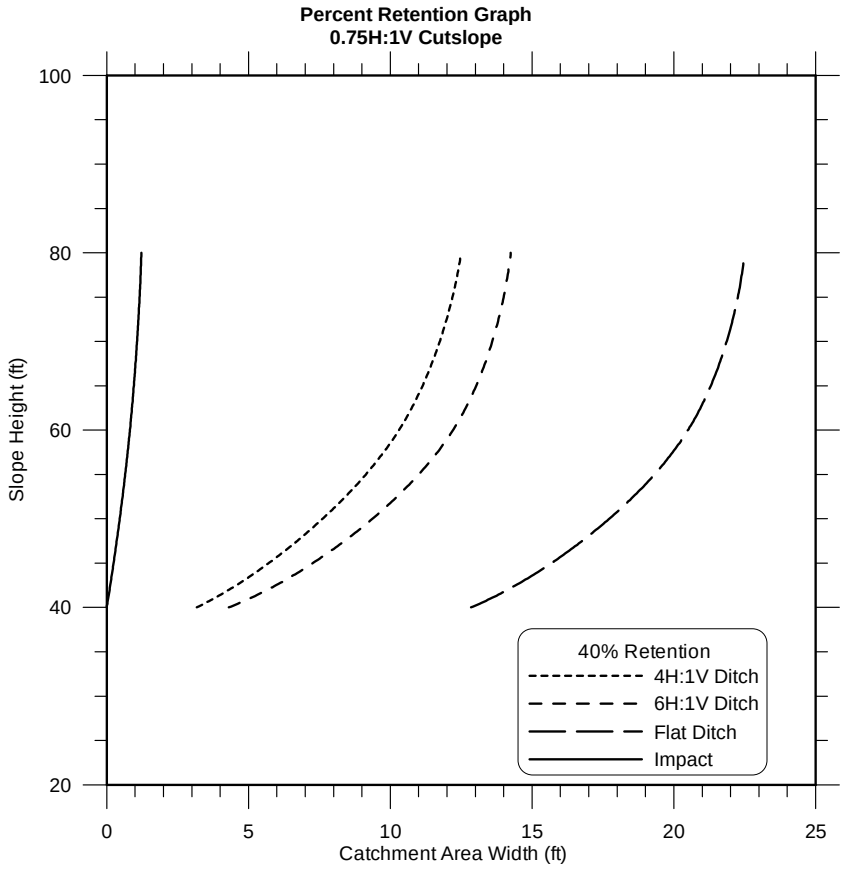
70
Catchment Area Width (ft)
99% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.75H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
More than 30% of rocks
impact at zero feet
30% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
0.75H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
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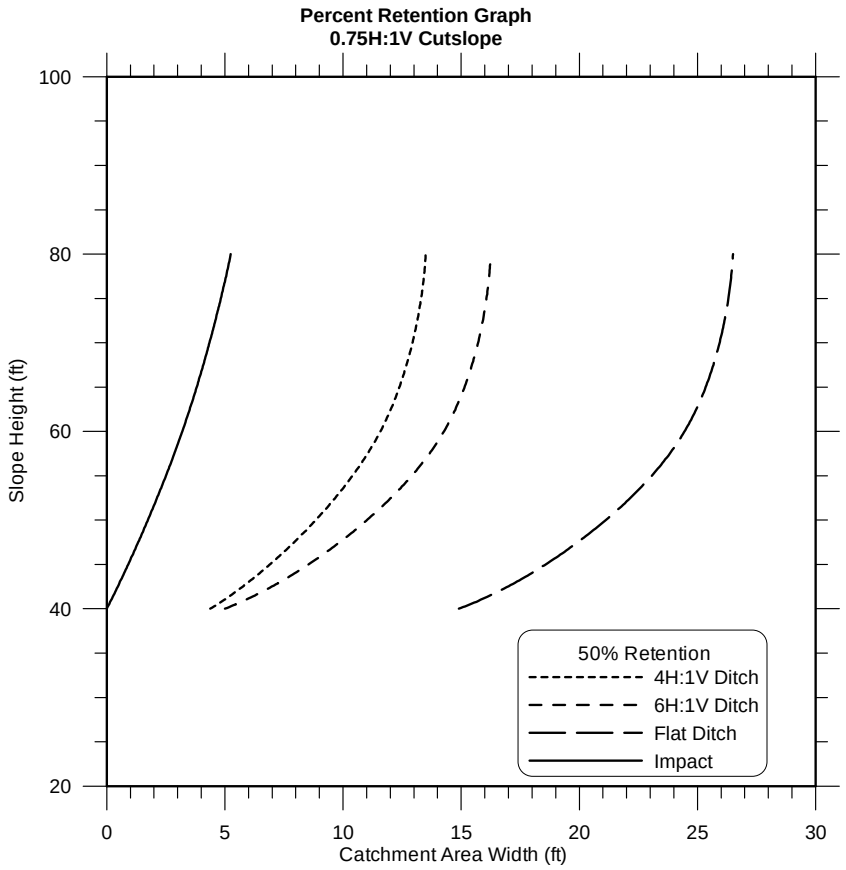
15
20
25
40% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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Slope Height (ft)
Catchment Area Width (ft)
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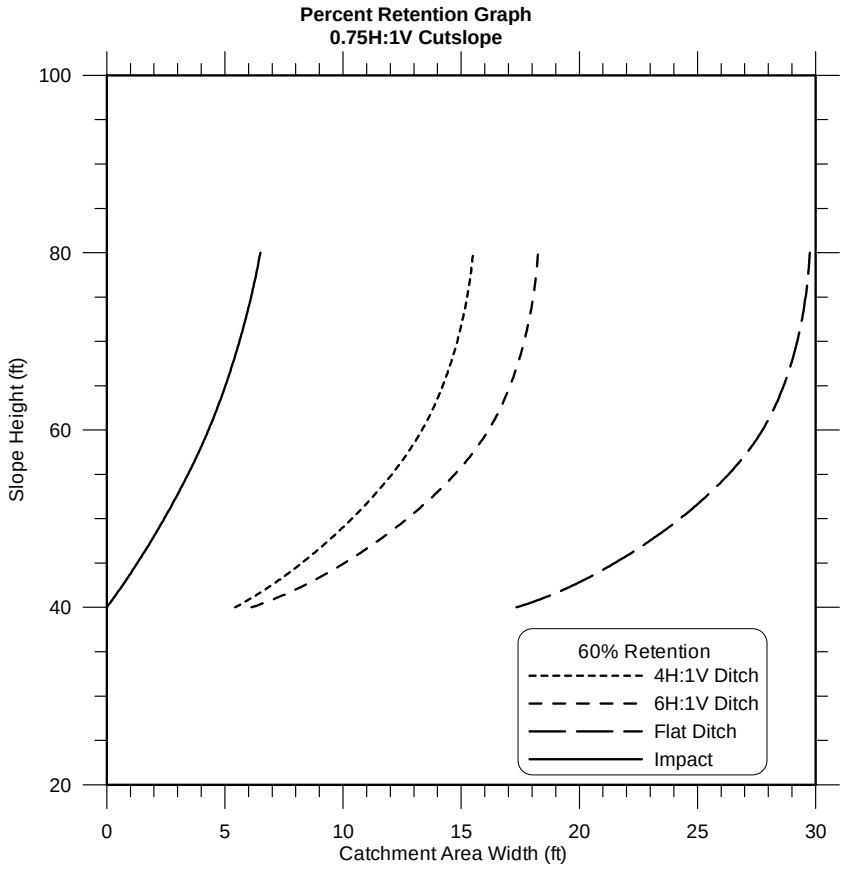
25
30
50% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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Slope Height (ft)
Catchment Area Width (ft)
100
80
60
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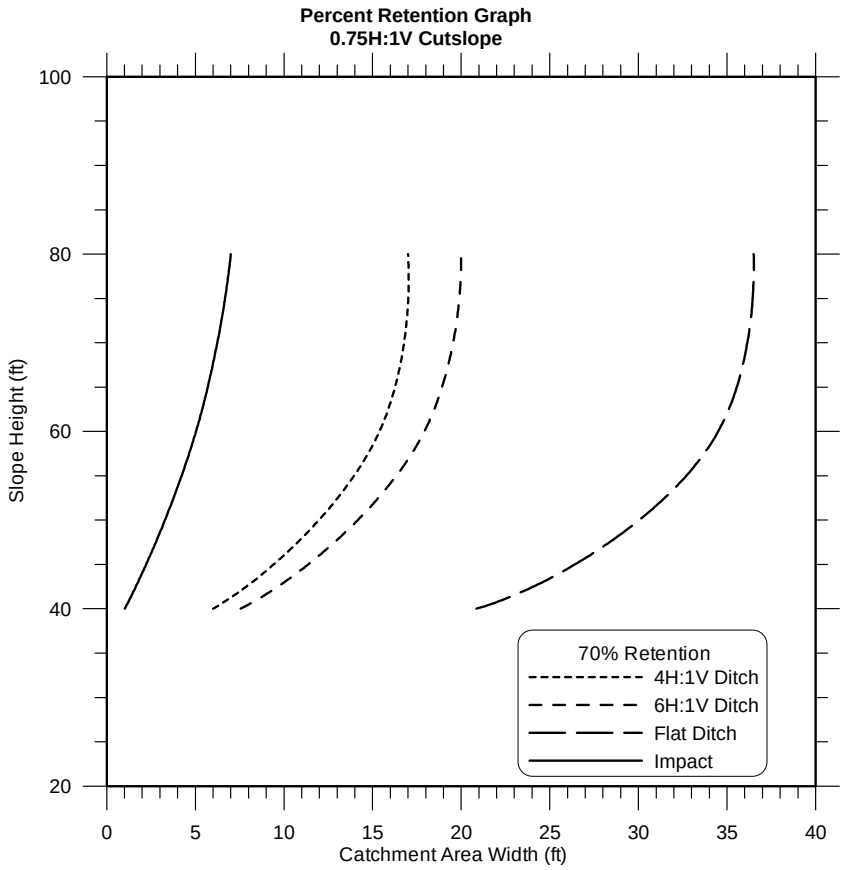
25
30
60% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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Slope Height (ft)
Catchment Area Width (ft)
100
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60
40
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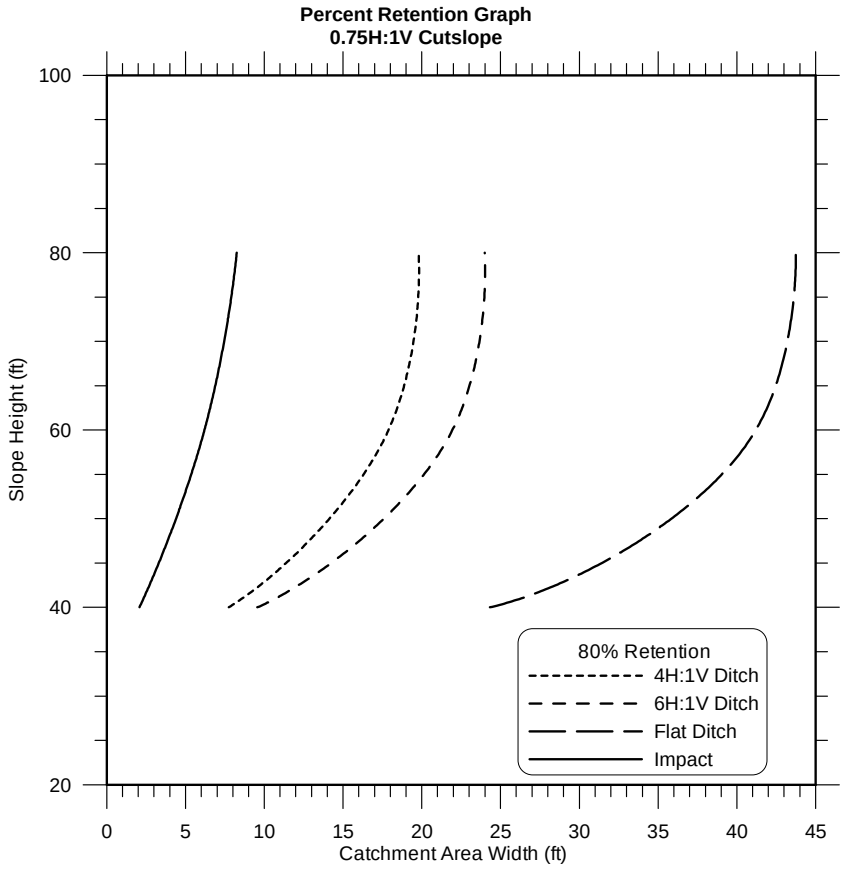
35
40
70% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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0.75H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
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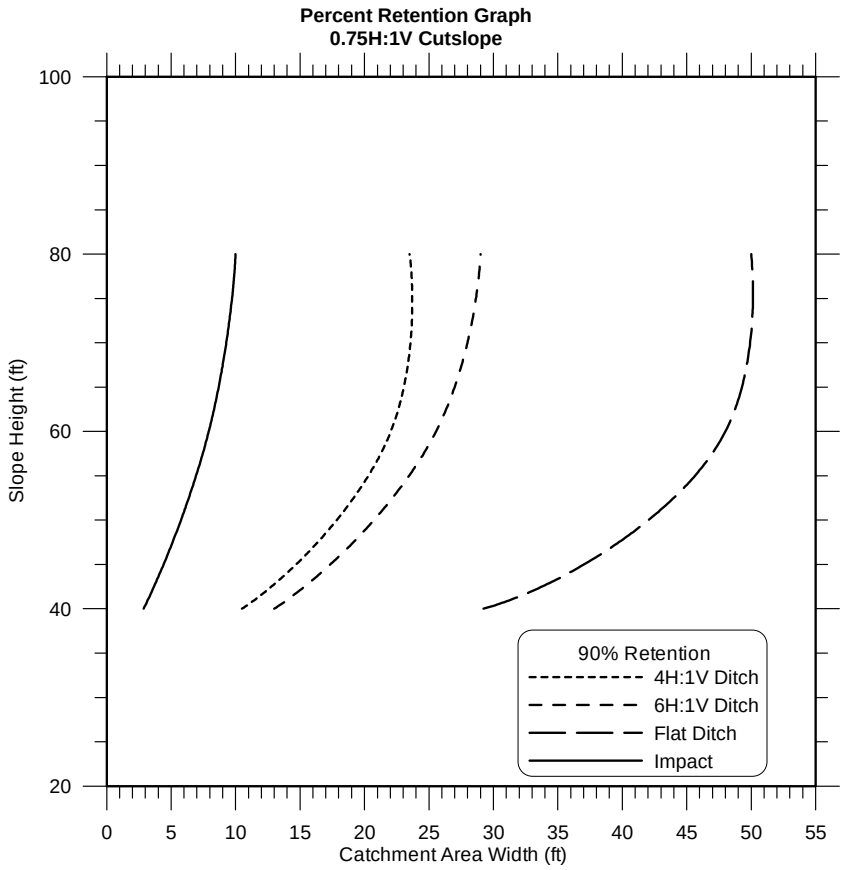
45
80% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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0.75H:1V Cutslope
Slope Height (ft)
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25
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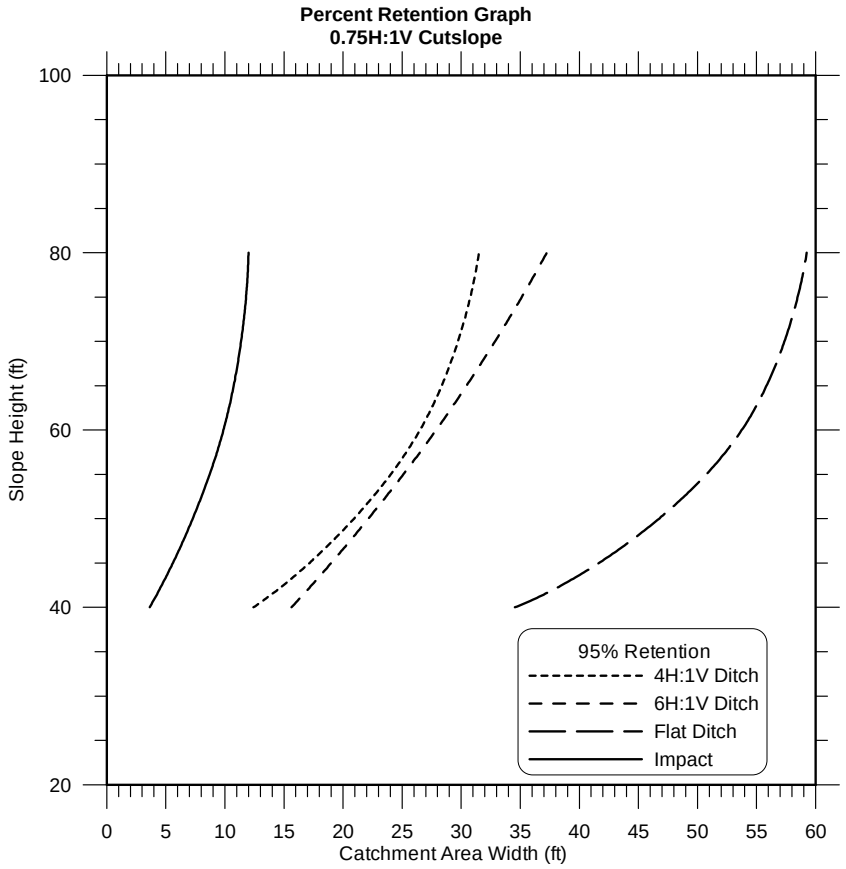
50
55
Catchment Area Width (ft)
90% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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Slope Height (ft)
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20
25
30
35
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45
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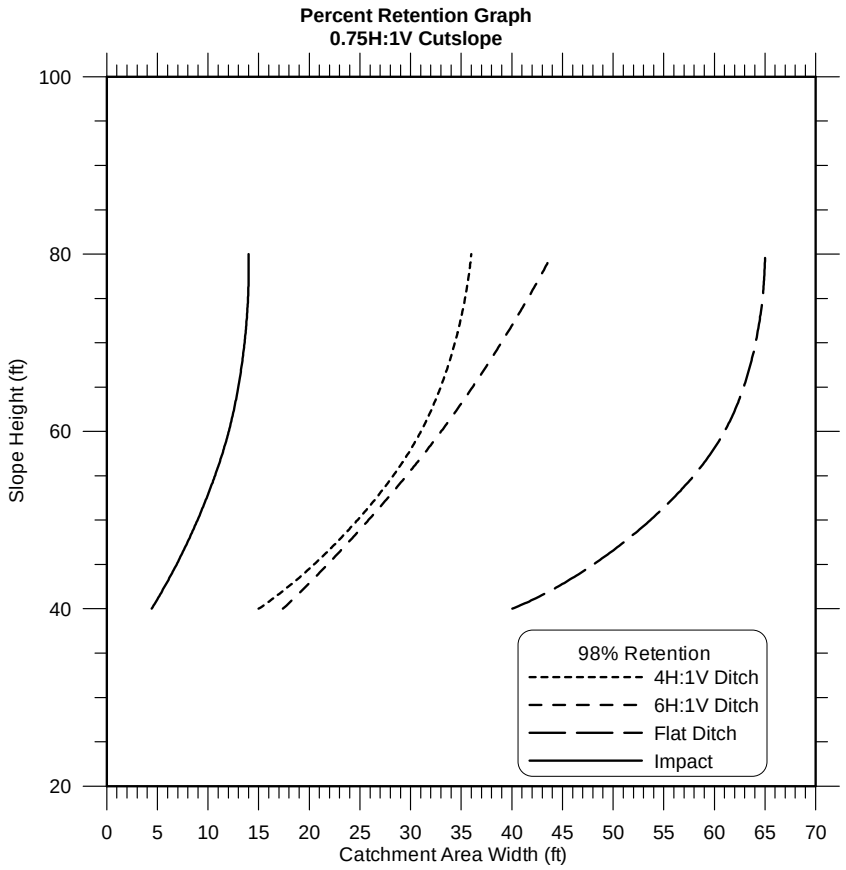
55
60
Catchment Area Width (ft)
95% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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0.75H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
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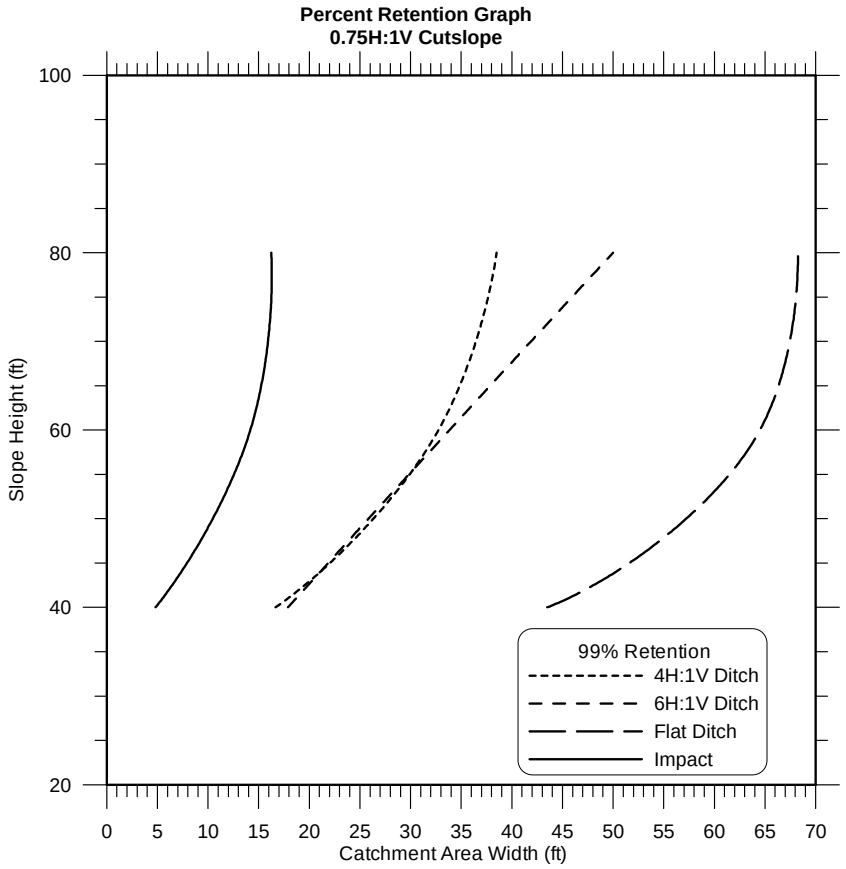
40
20
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
98% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact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0.75H:1V Cutslope
Slope Height (ft)
Catchment Area Width (ft)
100
80
60
40
20
0
5
10
15
20
25
30
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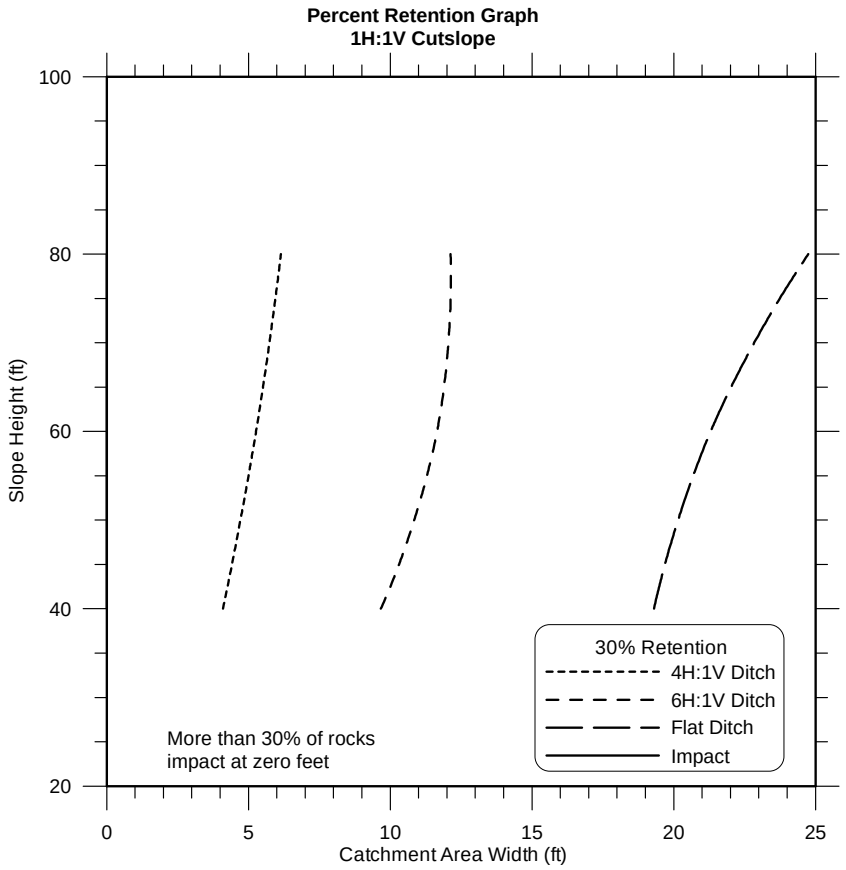
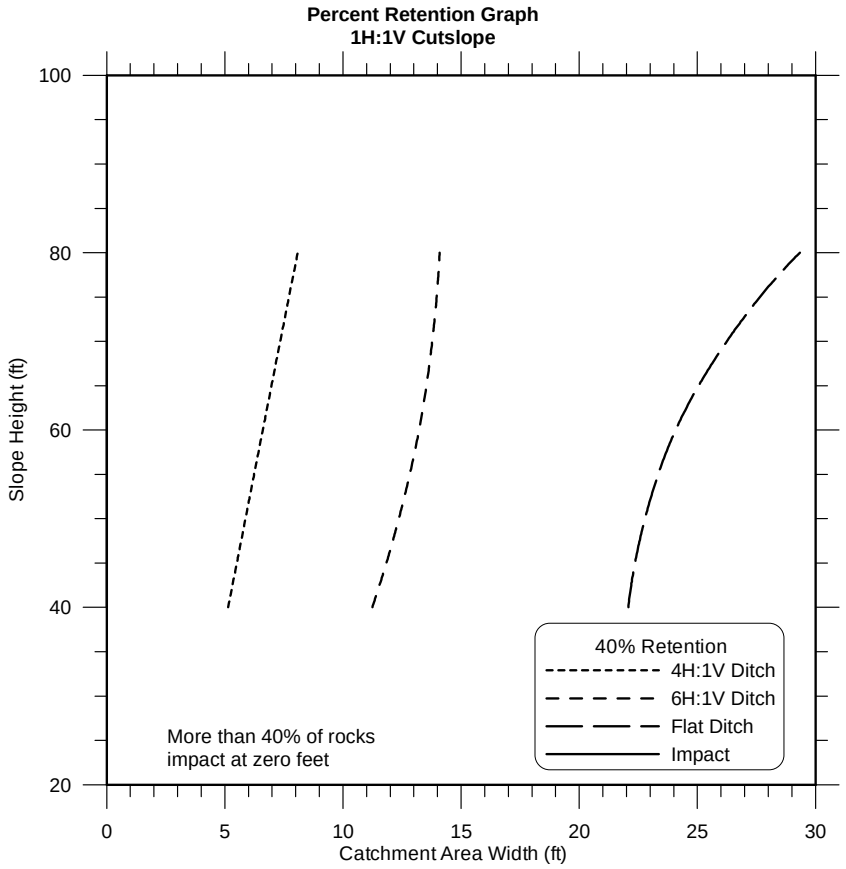
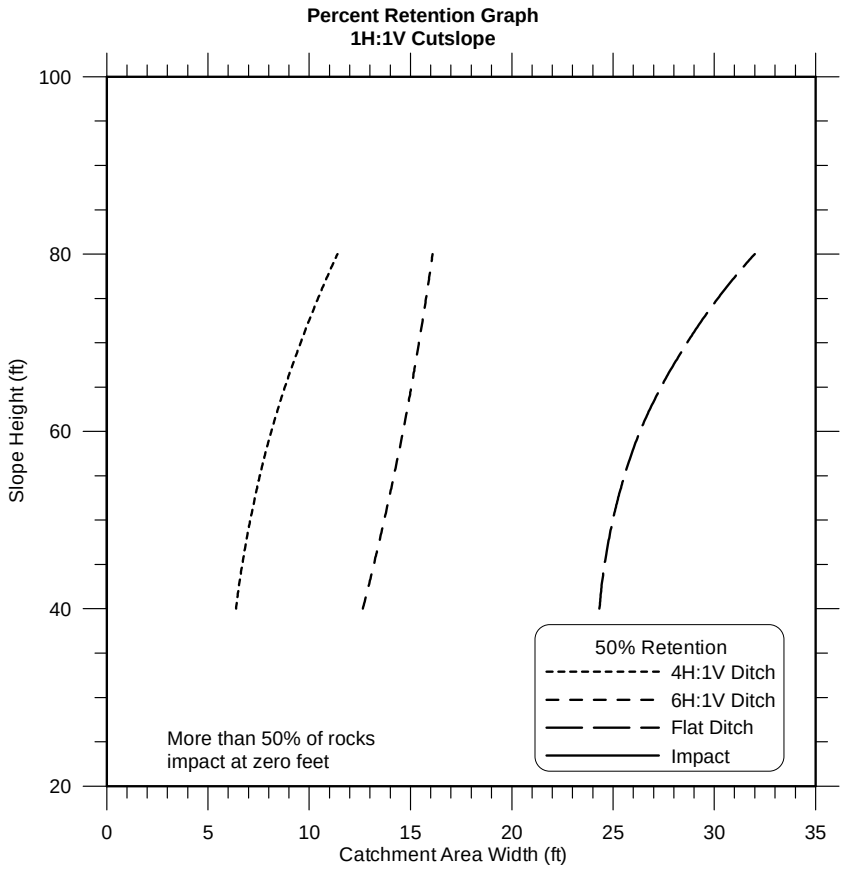
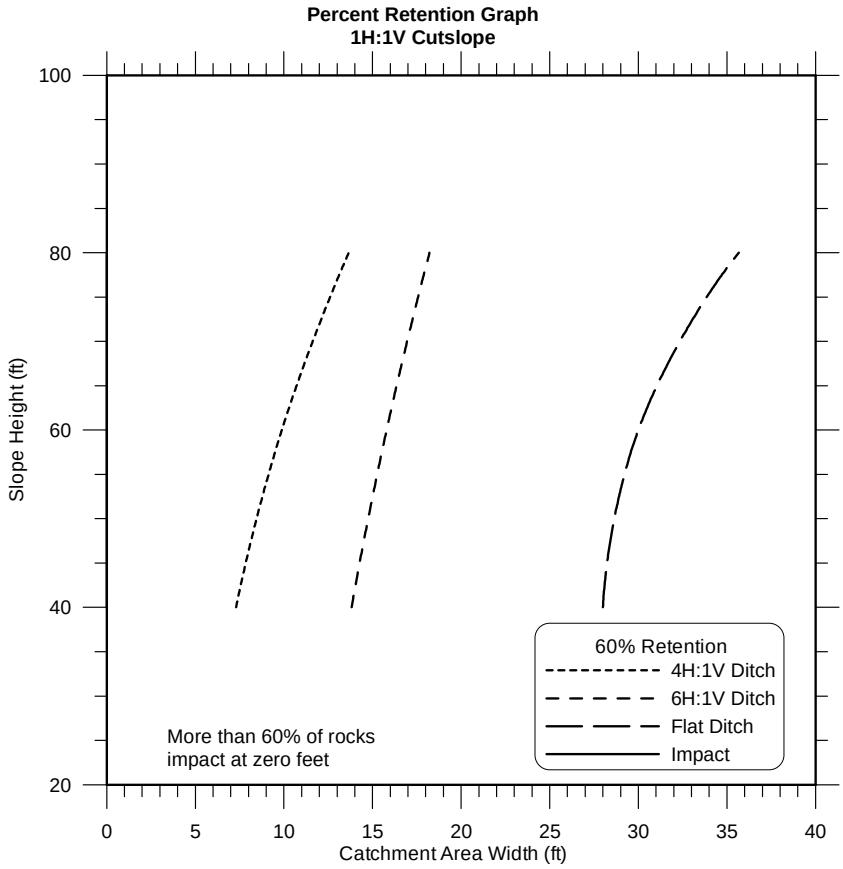
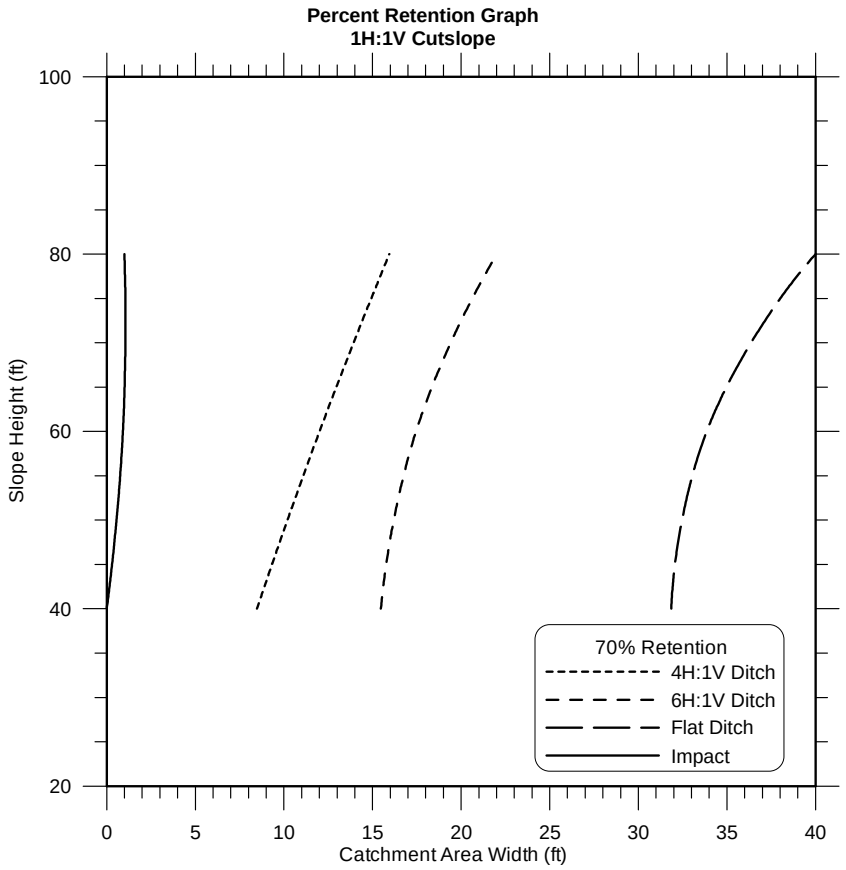
45
50
55
60
65
70
99% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

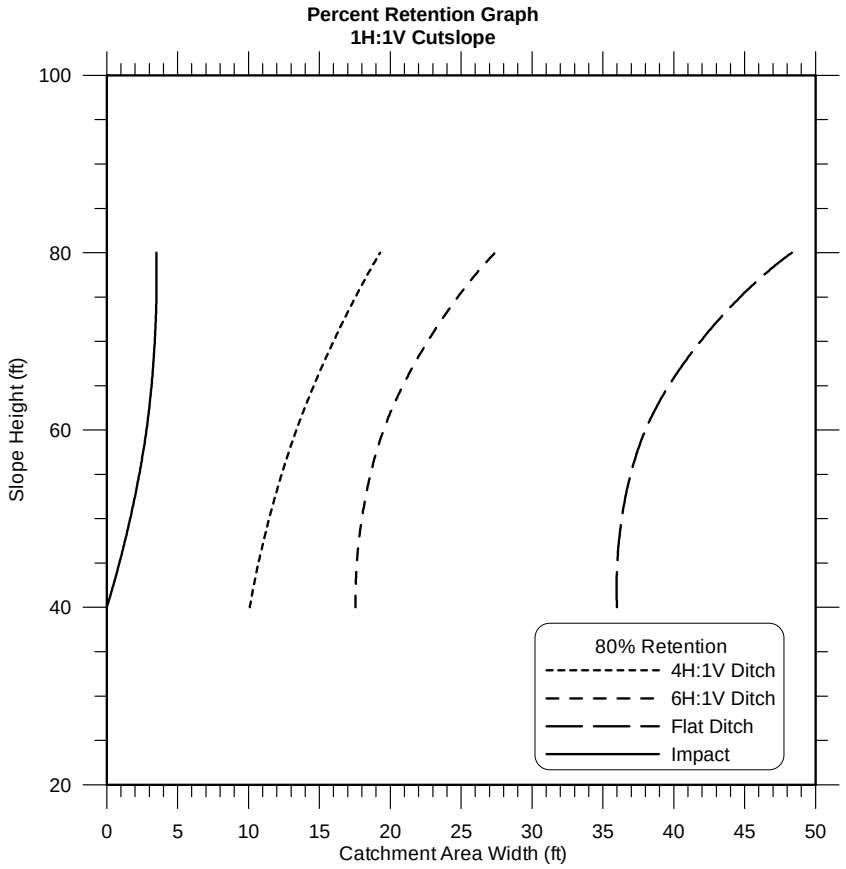

Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
Catchment Area Width (ft)
30% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact
More than 30% of rocks
impact at zero feet

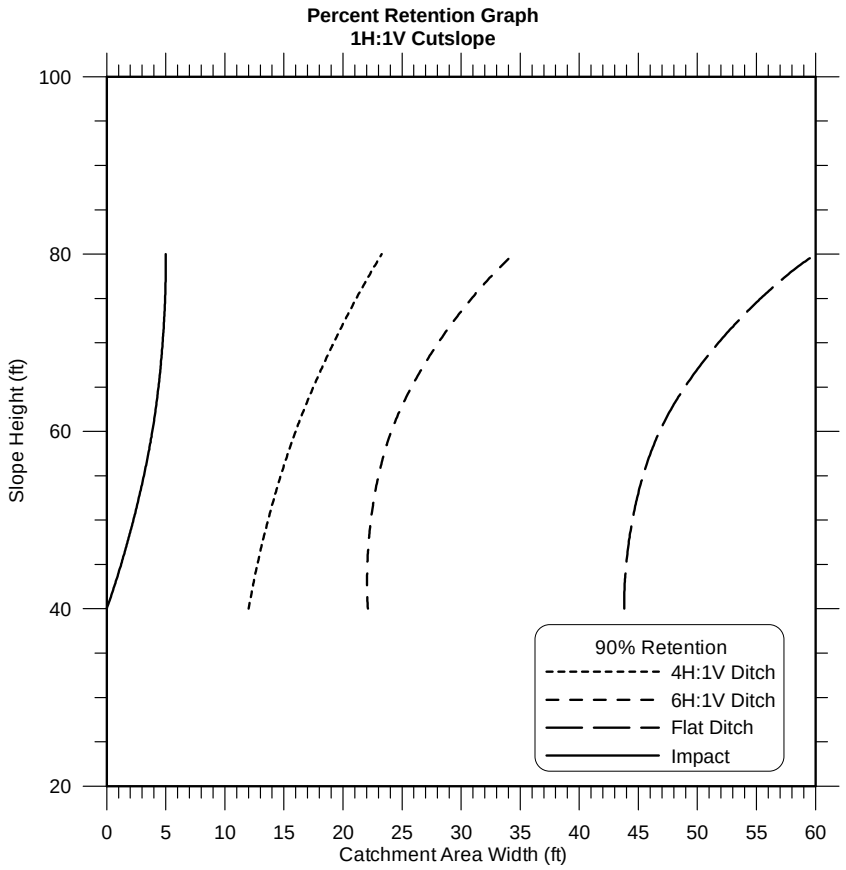

Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
Catchment Area Width (ft)
40% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact
More than 40% of rocks
impact at zero feet

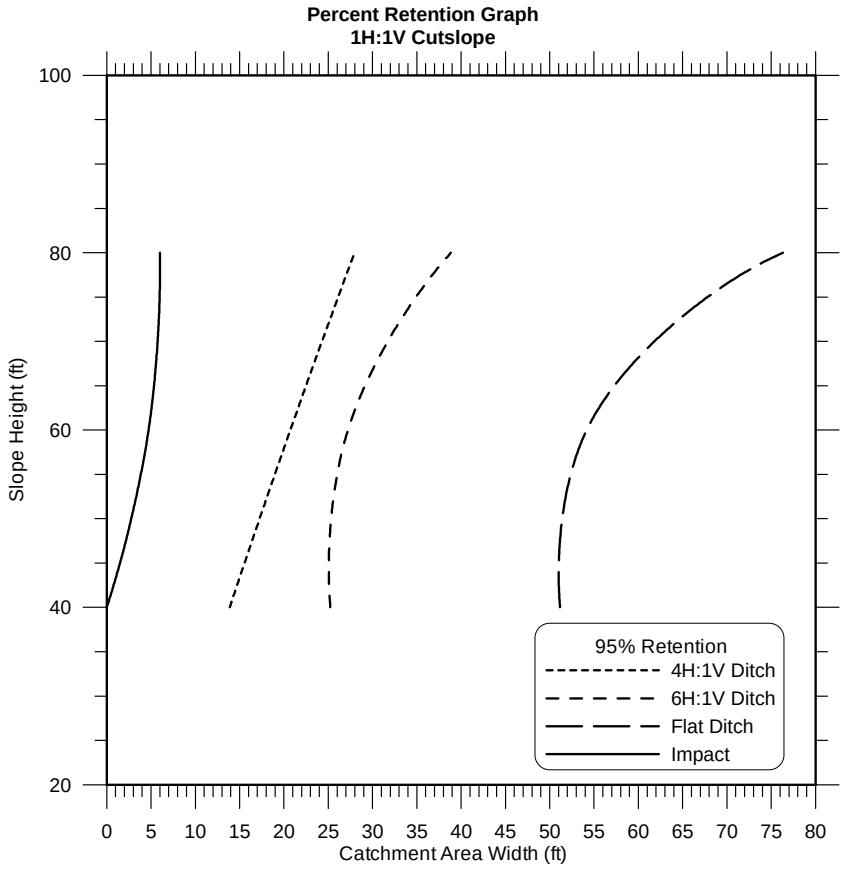

Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
Catchment Area Width (ft)
50% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact
More than 50% of rocks
impact at zero feet

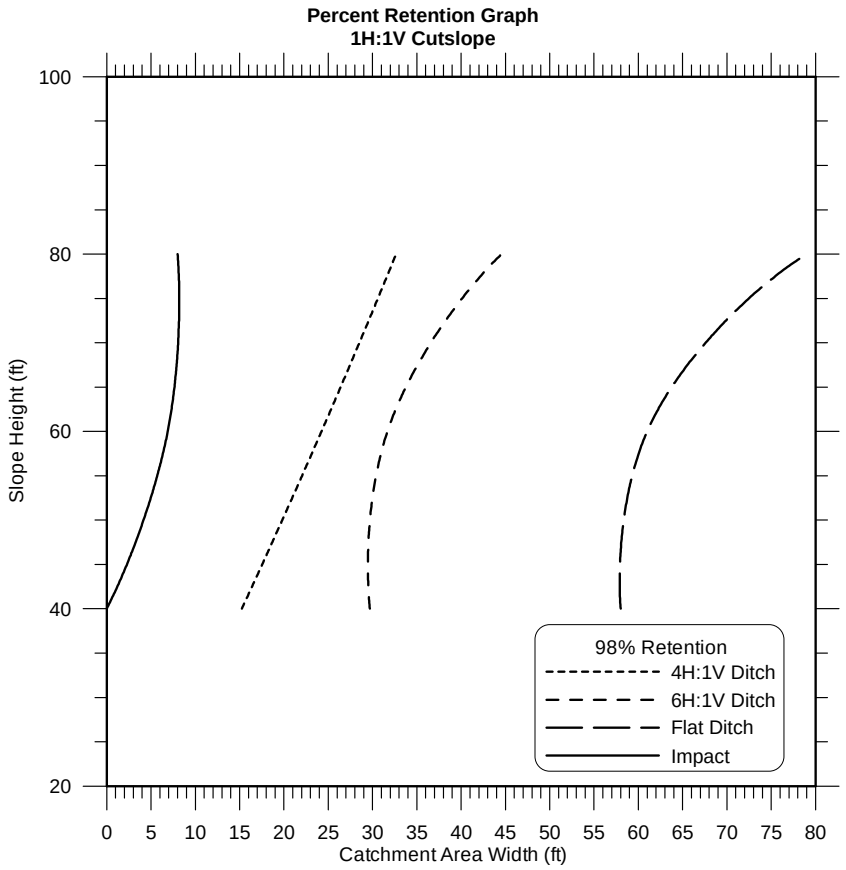

Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
Catchment Area Width (ft)
60% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact
More than 60% of rocks
impact at zero feet

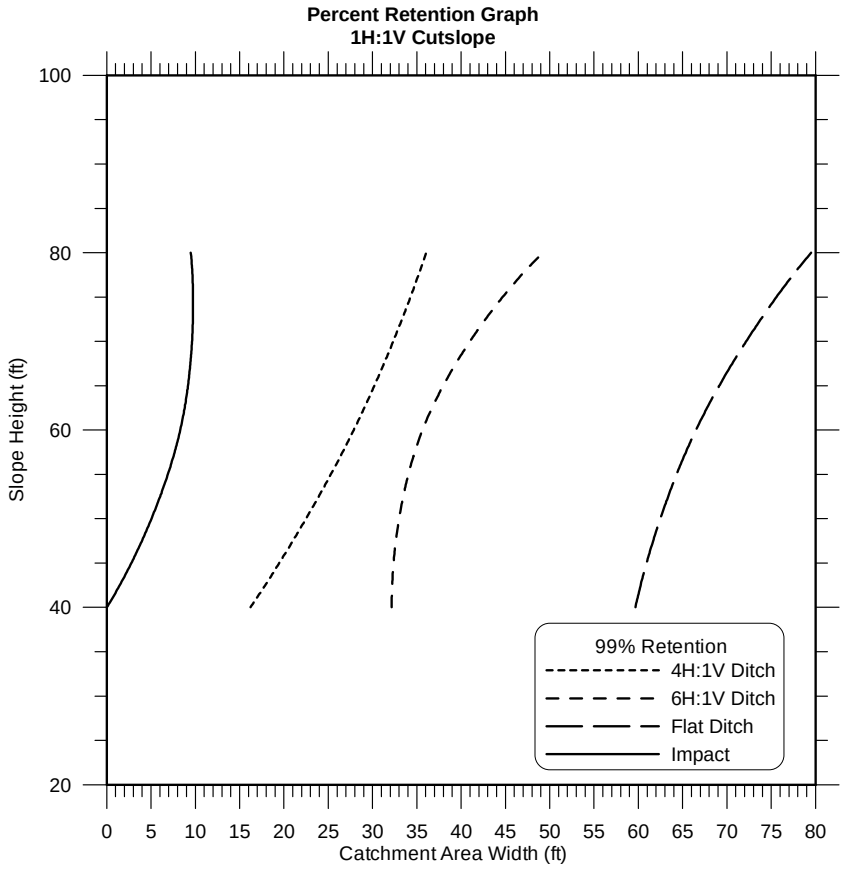

Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
Catchment Area Width (ft)
70% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
Catchment Area Width (ft)
80% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
60
Catchment Area Width (ft)
90% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
Catchment Area Width (ft)
95% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Catchment Area Width (ft)
98% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact


Percent Retention Graph
1H:1V Cutslope
Slope Height (ft)
100
80
60
40
20
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80
Catchment Area Width (ft)
99% Retention
4H:1V Ditch
6H:1V Ditch
Flat Ditch
Impact

APPENDIX G: PROJECT CASE STUDY APPLICATION EXAMPLES

PROJECT CASE STUDY APPLICATION EXAMPLES

Case study examples from Arizona, California, Federal Highway Administration - Central Federal Lands Highway Division (FHWA-CFLHD), New York, Oregon, Washington and Wyoming have been provided to further illustrate the practical application and use of the rockfall catchment area design charts to dimension rockfall catchment areas. The Technical Advisory Committee members contributed case studies from their agency's actual projects where the new design criteria and design charts have been used for new designs or as part of a comparison between past design practice and the new design guidelines. Two of the projects (Arizona and New York) included the use of site specific rock rolling, combined with computer simulation, to aid in the rockfall mitigation design. The case histories also illustrate the types of benefit/cost comparisons and judgment applied by experienced geotechnical practitioners to arrive at final catchment area design recommendations.

The **Arizona** project involves highway widening of a portion of US 191 near the town of Morenci, AZ. Existing cutslopes generate substantial rockfall onto the road during rainstorms. Interesting features of this project include the use of actual rock rolling from one of the cutslopes during construction, combined with computer simulation using CRSP, to determine the extent of draped slope mesh required. This was necessitated by a roadway design decision to reduce the rockfall catchment area width and depth below that called for by the Ritchie criteria. ADOT also provides a comparison to the new design charts.

The **California** project involves a curve correction along State Route 101 near the Monterey and San Benito county line by Caltrans District 5. The California project illustrates benefits of the new design charts to estimate percent rockfall retention and use of a flatter slope catchment versus a very deep Ritchie ditch.

The **FHWA-CFLHD** project includes a cut widening for a realignment of New Mexico Forest Highway, Route 45 near Sunspot, New Mexico.

The **Oregon** project is a cut widening being done as part of a roadway alignment improvement project on US 26 in the Mt. Hood National Forest.

The Oregon and FHWA-CFLHD examples are projects where the rockfall catchment areas had already been designed prior to the new design charts becoming available. These case studies illustrate "after the fact" catchment area width and cost comparisons of the as designed catchment area widths based on the Ritchie criteria to the widths given by the new design charts.

The **New York** (Corning Bypass) project involves highway widening on State Route 17. This project utilized site specific rock rolling, combined with computer simulation, to determine the required height of a rockfall catchment fence, when roadway design changes reduced the available catchment area width.

The **Washington** project involves highway widening on a project on SR-243 in eastern Washington. The Washington case study compares use of the new design charts to current WSDOT rockfall ditch criteria (modified after Ritchie) to dimension new rockfall catchment areas and illustrates benefits of the new design charts. The Washington case study also illustrates the importance and benefit of paying attention to constructibility considerations as part of design.

The **Wyoming** project illustrates use of the new design charts to dimension a new rockfall catchment area constructed as part of a highway-widening project on US 26-89 in the Snake River Canyon.

Regional Pooled Fund Study SPR-3 (032)

Arizona Case History

INTRODUCTION

In 1999, The Arizona Department of Transportation was in the process of designing the reconstruction of 2.5 miles of US 191, just south of the mining town of Morenci, located in the eastern portion of the state. The purpose of the reconstruction was to widen the road from two to three lanes and to allow for a larger radius in a horseshoe curve in the middle of the project. The existing cuts are 40 to 60 feet high, ¼H:1V slopes, with 2 to 3 foot wide ditches. During the rainy season, the slopes in this area shed a large quantity of rounded cobbles and boulders 6 to 18 inches in diameter. Maintenance forces patrol the road with a snowplow to keep the rocks cleared off the road surface.

GEOLOGY

The site is located in the Central Mountain Region of the state, between the Basin and Range Providence and the Colorado Plateau. The predominant geological unit encountered in this area is the Gila Conglomerate; a Pliocene age geologic unit made up of sand, gravel, cobbles, and boulders in a lithified, reddish-brown to brown matrix of silt and clay. The area is hilly and the elevation ranges from 3,320 to 4,280 feet. The principal drainages in the area are narrow, deeply incised channels, with vertical walls.

DESIGN METHODOLOGY

A consultant was retained to do the geotechnical design portion of this project. Cuts ranging from 50 to 130 feet high, were designed at ¼ (H): 1(V). The consultant used the Ritchie criteria to develop a design consisting of a 25 foot wide flat-bottomed ditch with a depth of 8 feet. The Colorado Rockfall Simulation Program (CRSP) was used to verify the adequacy of the design.

Mid-way through the design process, a managerial decision was made to eliminate the Ritchie style ditches and to narrow them to 17 foot width with a 4H:1V foreslope. The ADOT Geotechnical Design Section was directed to check the slopes during construction and to determine empirically if the rockfall would encroach on the roadway. If it did, draped mesh would be added to the slopes.

After construction had begun, a team from the ADOT Geotechnical Design Section went to the site and selected a slope that was approximately 90 feet high, on which to perform the rock rolling. Since the excavation was not complete, the impact area was

flat soil and the only compactive effort applied was through the passing of the excavation equipment. The newly cut slopes were relatively uniform and contained an abundance of loose, 12 to 18 inch size boulders, at the crest. (See Photos 1 and 2.)

Photo 1:Arizona US 191 project. This shows the cut that the rocks were rolled from. Construction is in progress. View is Southbound.

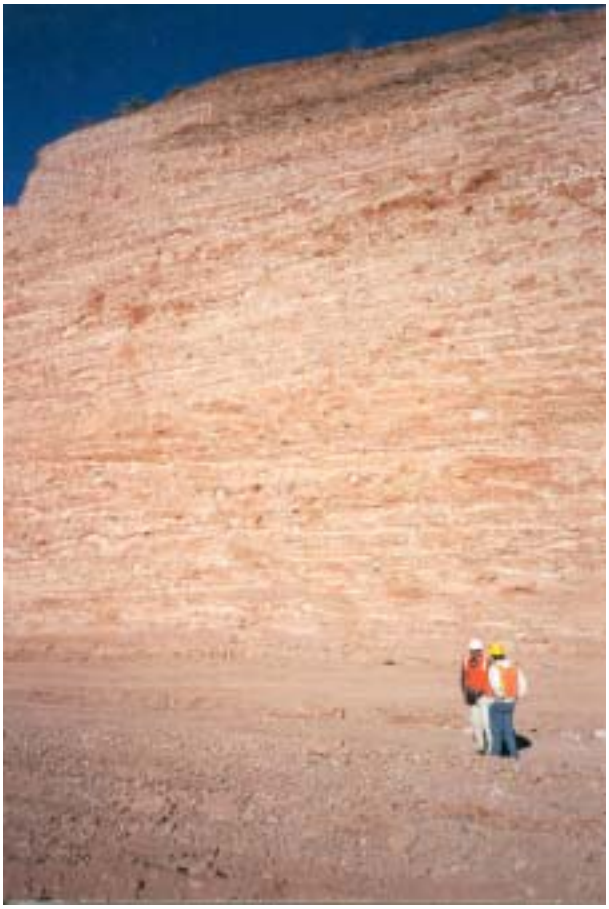


Photo 2: Arizona US 191 project. Close-up of the slope the rocks were rolled off.

The plan was to see how many of the rolled rocks would roll through the 25 foot wide catchment area (17 foot ditch plus future 8 foot paved shoulder width) and encroach onto the future traveled portion of the roadway. A total of twenty boulders were released from the top of the cut and eight of them (40%) came to rest in excess of 25 feet from the base of the slope.

This data was used to further calibrate the CRSP and the final geometry was then entered into CRSP. The simulation predicted that 24% of the rockfall from the top of a 90 foot cut would encroach onto the traveled lanes of the roadway, compared to 40% from the field rock rolling trial.

Since it was known that there is a high volume of rocks that are shed from the existing cuts in this area during a rainstorm, it was decided to design for a 99% containment of

the rockfall in the cut ditch. CRSP was once again used to simulate various heights of rockfall origination and the results indicated that mesh installed from the top of the slope to a distance of 40 feet above the toe of the slope would provide the containment desired.

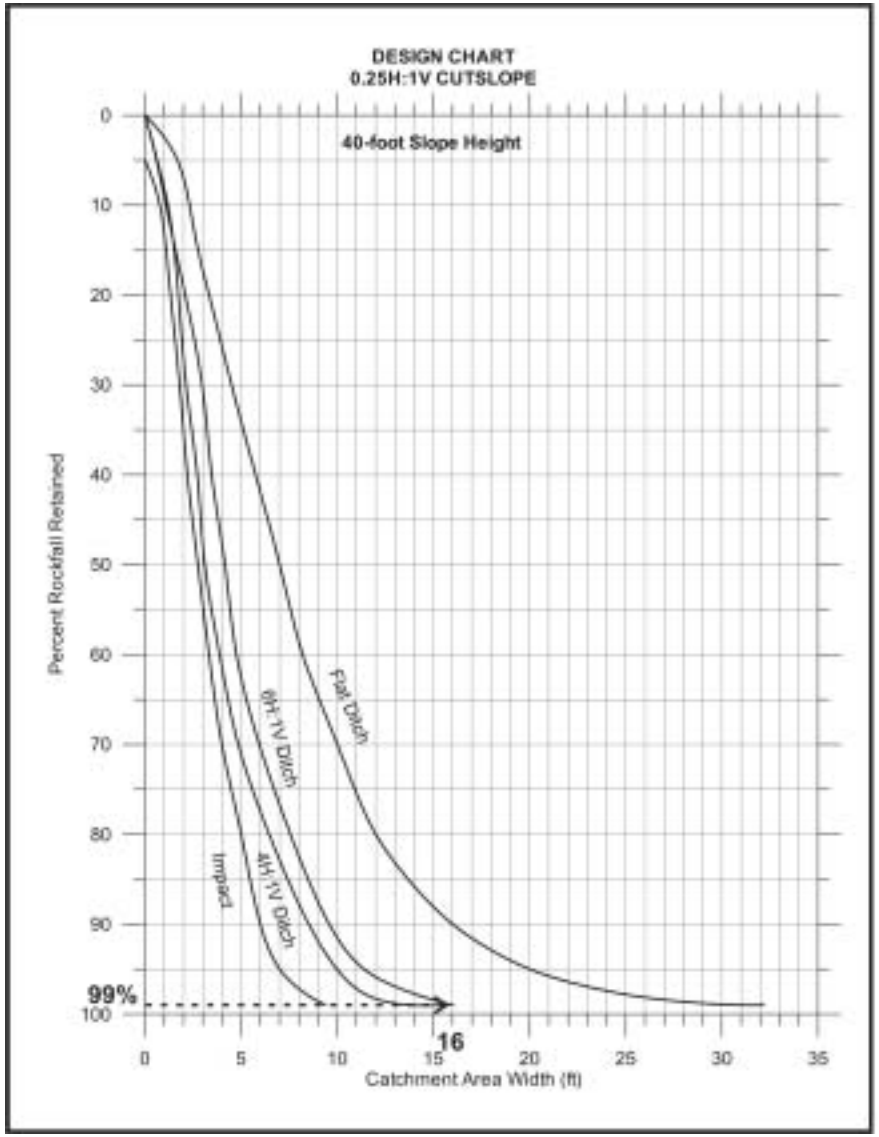
This section of roadway has been opened to traffic prior to the mesh being installed (See Photo 3). It does experience a high volume of rocks on the road during a rainstorm but not as many as prior to the construction of the wider ditches.

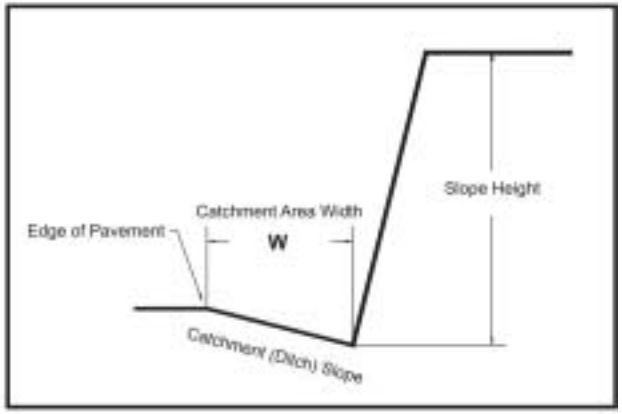
A construction contract has been awarded to install the mesh and mesh installation will start in October of 2001.

Photo 3: Arizona US 191 project. Shows the completed cut slopes and rockfall catchment ditches just prior to opening for traffic. Draped mesh not yet installed. View is Northbound.

COMPARISON TO DESIGN CHARTS

If the design charts included in this new Design Guide had been available and used for design for this project instead of CRSP, an almost identical design height for the mesh would have been chosen. If an assumption is made that when a rockfall falls from the bottom of the wire mesh drape, it has a very low velocity or angular momentum, then the chart for the forty foot high ¼H:1V cut slope could be used to verify that a sixteen foot wide ditch would contain 99% of the rockfall (see Figure 1). This provides the ADOT Geotechnical Design Section confidence in the validity of the new Design Charts. The complete suite of Design Charts adds significantly to our ability to prepare improved rockfall mitigation designs.





Quick Reference - 40-Ft Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (ft)	**W** (ft)	**W** (ft)	**W** (ft)
50%	3	3	4	7
75%	4	6	7	11
80%	5	6	8	12
85%	5	7	8	14
90%	6	9	10	16
95%	7	10	11	20
99%	9	16	16	32

Figure 1: Arizona Case Study Design Chart

Case Study of a Fallout Area Using New Design Charts
Regional Pooled Fund Study SPR-3 (032)
California Case History

Introduction

In 1998 California Department of Transportation (Caltrans) District 5 proposed a curve correction along State Route 101 near the Monterey and San Benito county line. Route 101 is a major north south corridor. Part of the upgrade was to realign the southbound corridor through the existing undeveloped median via a through cut. This area is comprised of rolling hills, steep drainage, and oak groves. A cut slope investigation was performed which included geologic field mapping, a subsurface boring investigation, a discontinuity analysis and a seismic refraction study.

Photo 1: Cut Slope with Catchment

Geology

The cut area is within the Pinecate Formation, which is comprised of medium to coarse-grained quartzose sandstone with lenses of pebble conglomerate. The sandstone is massive and exposed as large blocks on the surface. Studies indicated that the major controlling structural discontinuities have a favorable orientation for global stability. Minor fracturing could create small blocks of rock up to 2 feet in dimension. Slope raveling could generate rockfalls within the cut slope face. Typical seismic velocities for this material ranges between 4200 to 5700 feet per second to between 6500 and 10,000 feet per second.

Design and Risk Considerations

Realigning through undeveloped natural land poses many challenges one of which is to minimize the corridor footprint and balance the earthwork. Environmental personnel needed to reduce impacts to terrestrial resources, cultural resources, visual resources, and associated costs of mitigation. Reduction of the impact on cultural resources was of particular importance.

Cut slope design approach was to steepen the cut slopes to the maximum allowable slope inclination and maintain global stability. The associated risk is accepting local instabilities such as rockfalls. It was observed that similar road cuts within this formation were globally stable but local stability was marginal creating occasional rockfall. Rockfall control on the new cuts is provided by a catchment ditch. In cross section steeper cuts with catchment indicated reduced quantities and minimized land impacts (Figure 1). Ditch dimensioning was done using the Ritchie criteria.

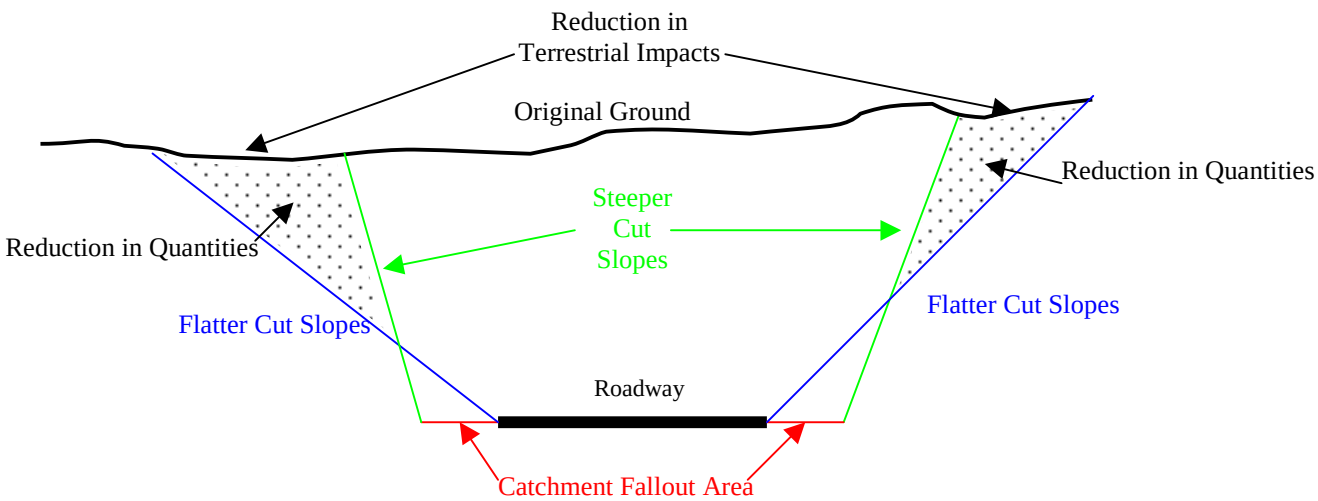


Figure 1: Cross Section

Recommendations

Maximum slope height is 45 feet. Average slope height was 40 feet or less. The recommended design for this location was to excavate the cut slope at a 1/4: 1 slope ratio and provide 16 feet of catchment area at grade with a 10:1 backslope. Including the 5-foot shoulder total available catchment between the base of the slope and the edge of traveled way increased to 21 feet. Catchment area is defined as the distance from the base of the cut slope to the edge of traveled way. The proposed catchment is designed to contain rock from free falling onto the traveled way.

The Ritchie Criteria was used to determine rockfall fallout width. A Ritchie depth was not recommended due to the hazard a roadside ditch presents. Instead a backslope was incorporated into the rockfall fallout area design. The final backslope is 10:1 due to increasing rock hardness and

associated excavation difficulties. Comparison of the designed ditch to the new design chart (Figure 2) indicates that the recommended ditch will contain 100 percent of the free falling rocks and 90-95 percent of the rocks rolling away from the slope. Increasing the ditch to 100 % for roll out would have required removal of cultural and environmental resources. The design slopes preserve these resources. Obtaining 100 % containment catchment would have increased excavation costs and impacts on local landfills. Mitigation costs for resource loss would have been significant both in dollars and time to complete the project. Resource dollar amounts are not available.

Results

During the course of the excavation rocks were dislodged from the slope face. Most of these rocks were less than or equal to 1 foot in dimension. Of those all were contained within the proposed catchment width. The cut was completed in June 2001.

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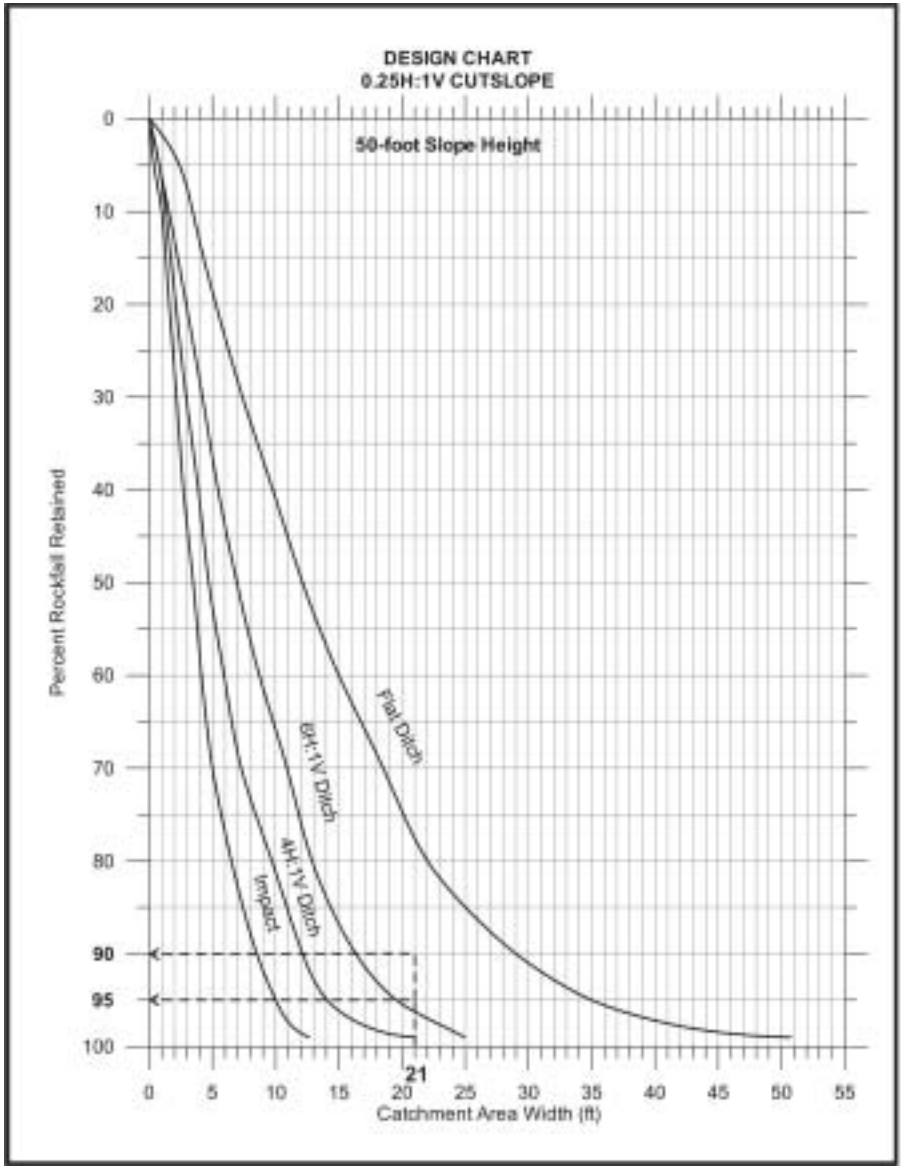
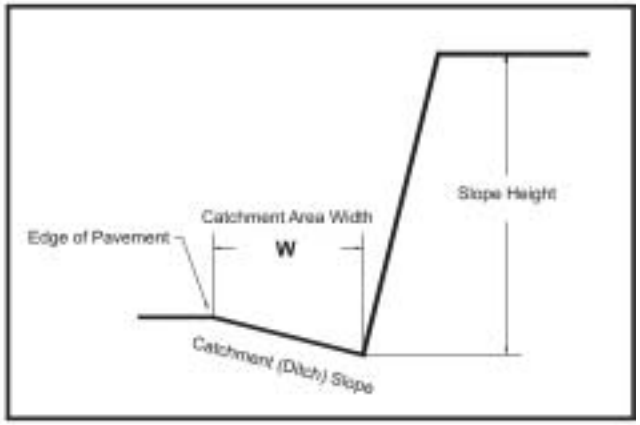




Quick Reference - 50-Ft Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (ft)	**W** (ft)	**W** (ft)	**W** (ft)
50%	3	5	7	12
75%	6	8	12	20
80%	7	10	13	22
85%	7	11	14	25
90%	8	12	16	29
95%	10	14	19	35
99%	13	21	25	51

Figure 2: California Case Study Design Chart

REGIONAL POOLED FUND STUDY SPR-3 (032)

FHWA-CFLHD CASE HISTORY

PROJECT DESCRIPTION

The Sacramento River Road project, also referred to as the Sunspot Road project, includes a proposed realignment of New Mexico Forest Highway Route 45 beginning near Timberon and continuing northwesterly 21.5 km to the intersection with State Highway 6563 near Sunspot, New Mexico. The Sacramento River Road is being designed as two construction projects. The first project, PFH 45-1(4), begins as project Station 12+480 and continues 9.2 km northwest to the intersection with State Highway 6563 at Station 21+700. The second project, PFH 45-1(5), begins near Timberon and continues about 12.3 km to the beginning of Project PFH 45-1(4). This case study deals with the rock cuts associated with the first project, PFH 45-1(4).

This project, located east of Alamogordo, New Mexico contains approximately 2.2 km of rock cut of up to 20 m in height. The Average Daily Traffic in the year 2000 is 860.

GEOLOGY

Bedrock along the alignment consists of thinly bedded to massive limestone with a gentle bedding dip and appears to be variable in magnitude and direction. The thinly bedded limestone is visible in existing road cuts and as colluvium on the slopes. Where exposed in road cuts, the limestone appears clayey and in some locations interbedded with thin beds of mudstone. The massive limestone outcrops naturally on both sides of the valley at various locations along the alignment. The road cuts down through the stratigraphy and, consequently, the character of the

limestone is expected to vary along the alignment. Cuts may expose cavities and caves up to several meters in size, and open discontinuities created from solution weathering.

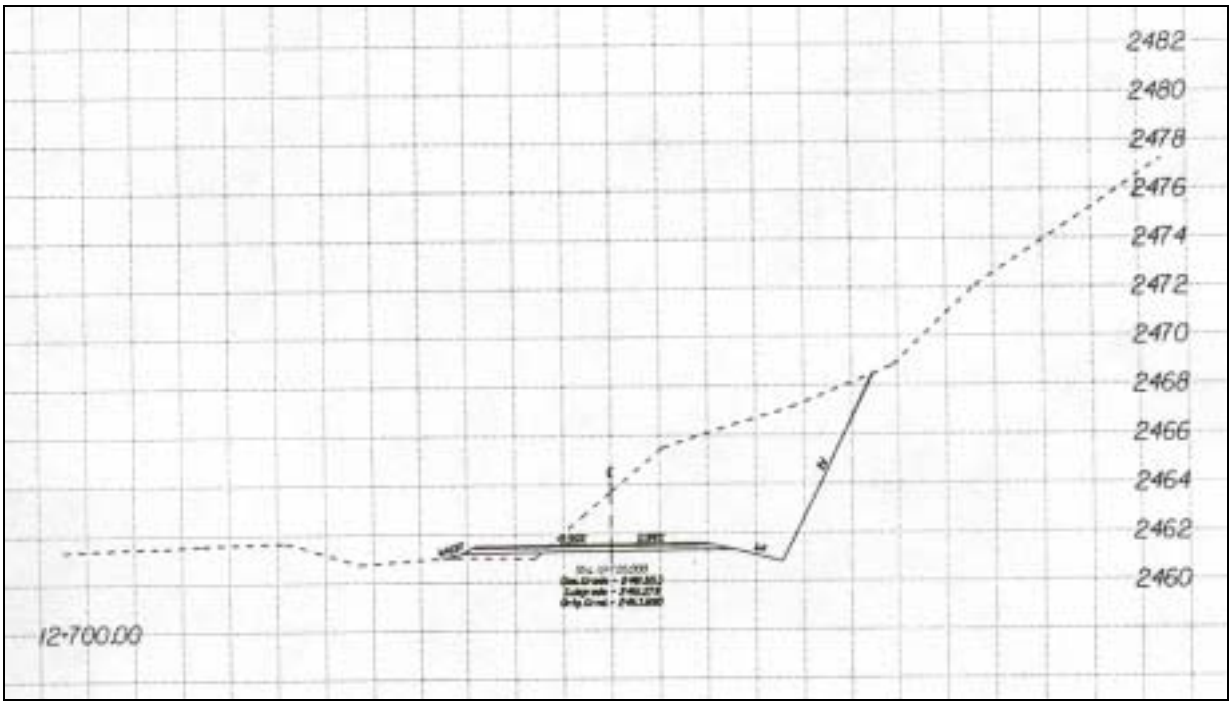
Rock cuts through the massive limestone beds with discontinuity spacing of more than 0.5 m, should perform satisfactorily with cut ratios near vertical, and a slope ratio of 8V:1H is appropriate for design. It is possible that portions of the proposed rock cuts (up to 20 m in height) will be comprised of both massive and thinly bedded strata. The thinly bedded strata of limestone may not have the necessary rock mass strength to stand as steeply as the massive strata. Furthermore, rockfall frequency will be undesirably high. A slope ratio of 2V:1H is appropriate for the thinly bedded strata.

ROCK SLOPE DESIGN

For overall slope stability and practicality of construction, a uniform 2V:1H slope ratio was selected for design.

ROCKFALL PROTECTION MEASURES

Other than ditch design, no rockfall protection such as rock bolting, strapping, mid-slope fences, draped wire mesh nor rockfall collection fences were designed for this project.



DITCH WIDTH DESIGN

Many design criteria are modifications of the Ritchie criteria developed in 1963 (Ritchie, A. M., 1963, "Evaluation of Rockfall and its Control," Highway Research Board, No. 17, pp.13-28). Using the Ritchie criteria, the collection ditch's width and depth is evaluated based on the slope ratio and height of the rock cut.

The Oregon Department of Transportation (ODOT) published a report (FHWA-OR-GT-95-05, "The Nature of Rockfall as the Basis for a New Fallout Area Design Criteria for 0.25:1 Slopes", 1994) presenting findings form a study analyzing the performance of several rockfall collection ditches.

An evaluation of the ditch design for a 2V:1H cut slope ratio and two slope heights (12.5 m and 18.5 m) was conducted by comparing three alternate design criteria: 1) the Modified Ritchie criteria; 2) a 1:4 ditch with a width of 3 m; and 3) ODOT data for a 1:4 ditch and 90% rockfall retained.

For this project, the design criteria used for ditches below cut slopes was a 3 m wide ditch with a 1:4 ditch slope. The slope/ditch design typical section is attached.

12.5 m is approximately the average height of the proposed rock cuts. 18.5 m is approximately the maximum height of the proposed rock cuts. The Modified Ritchie ditch has a flat bottom and steep side slope next to the roadway. Ritchie based his design criteria on the ditch being wide enough to have the rockfall impact within the ditch width and then relying on the deep ditch depth to prevent the rock from rolling up onto the highway. The % retention given for the Ritchie ditch width in the following comparison tables is estimated using the ODOT based IMPACT distance chart for 2V:1H slopes. Refer to Figures 1 and 2.

Table 1
Comparison of Ditch Design Alternatives for 12.5 m High Rock Slope

Design Criteria	Slope Ratio (v:h)	Ditch Width m	Comments
Modified Ritchie (flat ditch bottom at design depth below road	2:1	5.1	Ditch depth = 1.8 m **Est. 99% rockfall retention**
3 m ditch width 1:4 ditch slope	2:1	3	**Est. 82% rockfall retention** From ODOT data based 2:1 slope
ODOT criteria **for 90% rockfall retention** 1:4 ditch slope	2:1	3.5	**Est. 90% rockfall retention** From ODOT data for 2:1 slope

Table 2
Comparison of Ditch Design Alternatives for 18.5 m High Rock Slope

Design Criteria	Slope Ratio (v:h)	Ditch Width m	Comments
Modified Ritchie (flat ditch bottom at design depth below road	2:1	6	Ditch depth = 2 m **Est. 99% rockfall retention**
3 m ditch width 1:4 ditch slope	2:1	3	**Est. 52% rockfall retention** From ODOT data based 2:1 slope
ODOT criteria for **90% rockfall retention** 1:4 ditch slope	2:1	5.1	**Est. 90% rockfall retention** From ODOT data based 2:1 slope

BENEFIT/COST COMPARISON

For this project, there was no separate bid item for Rock Excavation, but was included in the bid item for Roadway Excavation. There was also no bid item for Rock Blasting, however the Special Contract Documents included specifications concerning rock blasting that directed the contractor to use controlled blasting techniques. The bid quantity for Roadway Excavation was 200,000 m^3 and the bid price was $5.00/$m^3$.

The following tables show a cost comparison for the project design ditch versus the Modified Ritchie and the ODOT criteria ditches. The cost is expressed as a ratio of the cost of the project design ditch and was determined by calculating the additional excavation that would be necessary for the additional ditch width required by the Modified Ritchie and the ODOT criteria as compared to 3 m for the project design ditch.

Table 3
Cost Comparison of Alternatives for 12.5 m High Rock Slope

Design Criteria	Slope Ratio (v:h)	Ditch Width m	Cost Ratio
Modified Ritchie (flat ditch bottom at design depth below road	2:1	5.1	1.67
3 m ditch width 1:4 ditch slope	2:1	3	1.00
ODOT criteria for **90% rockfall retention** 1:4 ditch slope	2:1	3.5	1.23

Table 4
Cost Comparison of Alternatives for 18.5 m High Rock Slope

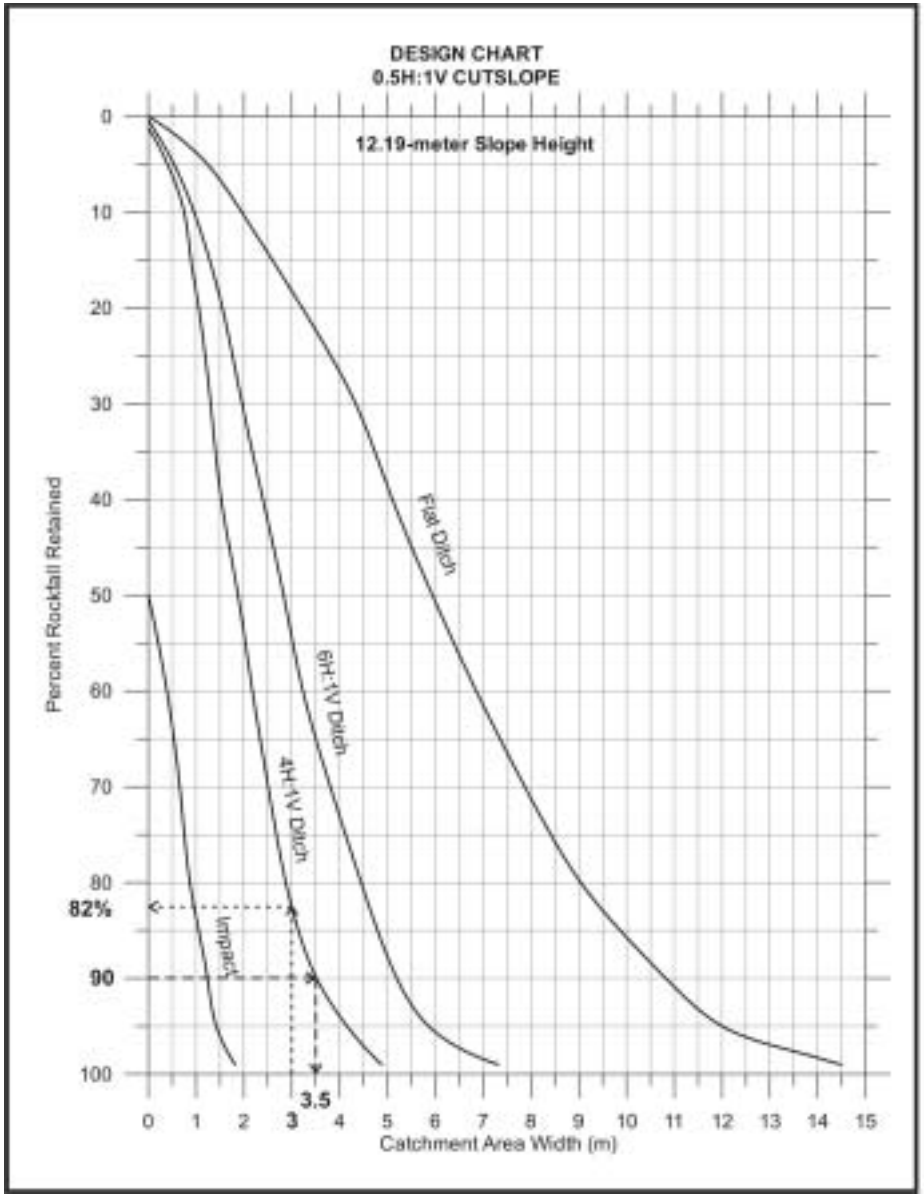
Design Criteria	Slope Ratio (v:h)	Ditch Width m	Cost Ratio
Modified Ritchie (flat ditch bottom at design depth below road	2:1	6	1.95
3 m ditch width 1:4 ditch slope	2:1	3	1.00
ODOT criteria for **90% rockfall retention** 1:4 ditch slope	2:1	5.1	1.56

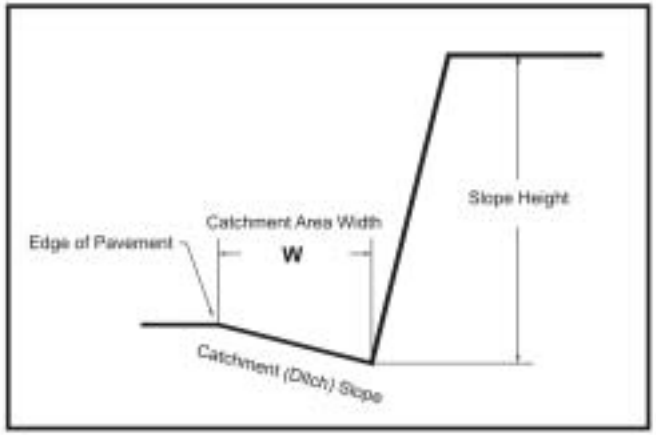
CONCLUSIONS

The Ritchie ditch design, while giving the most conservative ditch width and depth is not preferred because it is much more costly the deep ditch immediately adjacent to the roadway does not meet current roadside safety clear zone requirements. A 2 m deep ditch would require a barrier, such as concrete jersey barrier or metal guard rail along the shoulder.

The 3 m wide ditch is unconservative, providing only an estimated 52% and 82% rockfall retention for the 18.5 m and 12.5 m high slopes, respectively.

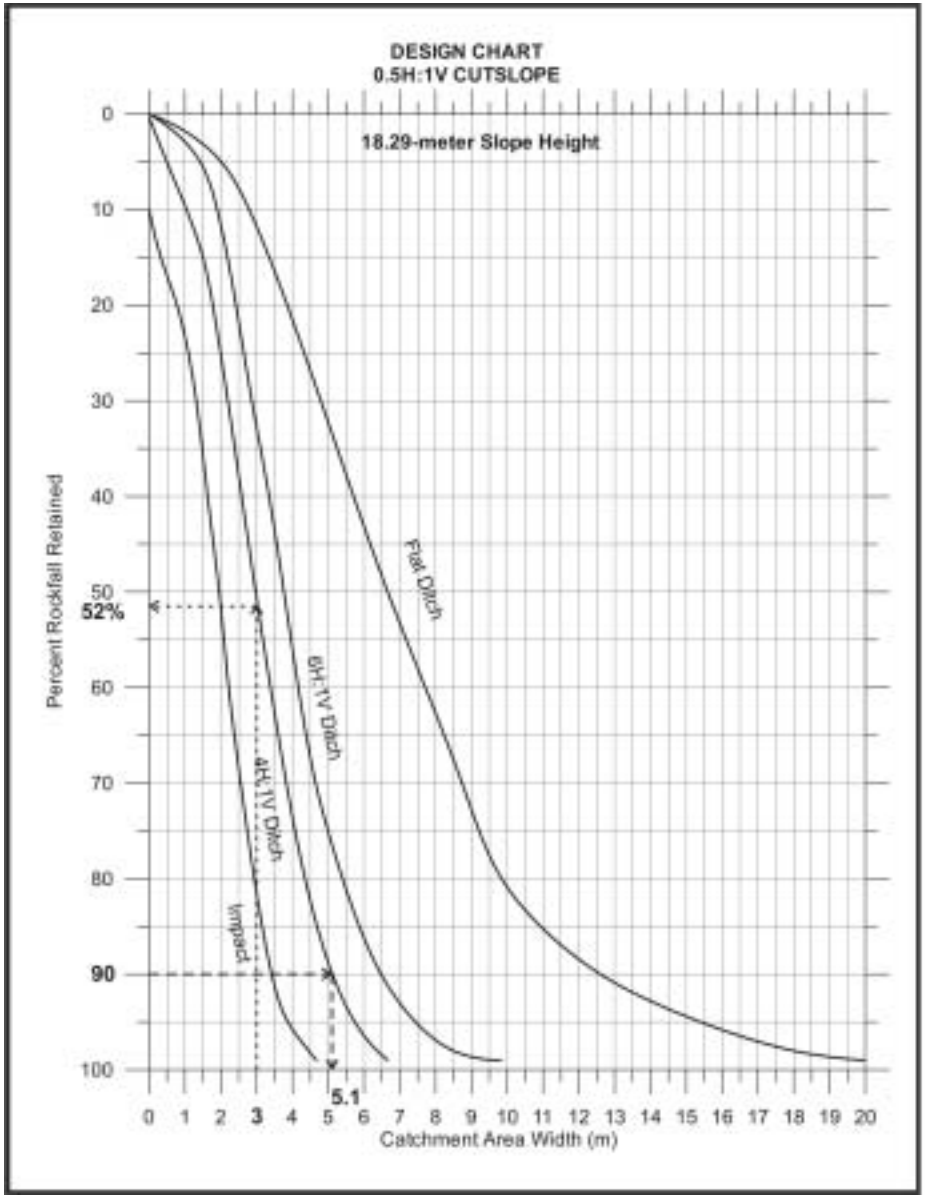
For a new design, the ODOT based 90% rockfall retention ditch design calling for 3.5 m and 5.1 m wide 1:4 sloped ditches for the 12.5 m and 18.5 m slope heights, respectively, appears to provide the best cost/benefit and would be the preferred design.

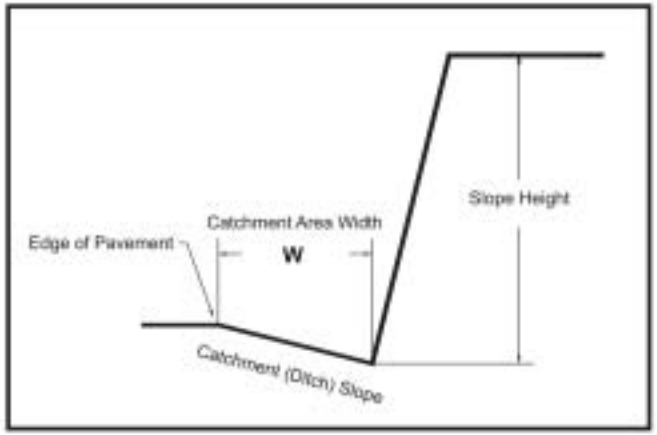




Quick Reference - 12-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	0.0	1.9	2.8	5.9
75%	0.8	2.7	4.1	8.5
80%	0.9	2.9	4.5	9.0
85%	1.0	3.3	4.8	9.8
90%	1.2	3.5	5.2	10.8
95%	1.4	4.3	5.9	12.0
99%	1.8	4.9	7.3	14.5

Figure 1: FHWA - CFHLD Case Study





Quick Reference - 18-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	2.0	3.0	3.6	6.7
75%	2.7	4.0	4.9	9.3
80%	2.9	4.4	5.4	9.8
85%	3.3	4.8	5.8	11.0
90%	3.4	4.9	6.5	12.6
95%	3.9	5.8	7.4	15.4
99%	4.7	6.7	9.8	20.0

Figure 2: FHWA - CFHLD Case Study

Oregon Department of Transportation
GEOHYDRO SECTION
Geotechnical Unit

INTEROFFICE MEMO
986-3778 986-3407 FAX

TO: Liz Hunt, P.E.
Research Coordinator

October 31, 2000

FROM: Don Turner, C.E.G.
Geotechnical Designer

SUBJECT: Case Study of a Fallout Area Using New Design Charts
Regional Pooled Fund Study SPR-3 (032)

As you requested, the following is a case study of a rock cut comparing the existing rock slope, the new design charts for rock slopes, and the Ritchie Chart criteria. The format follows the one you outlined in your request for case studies from other state DOT's. The case study is pulled from a project that was already designed in 1999 and will be constructed in 2001.

Introduction

The project is located in high elevation, mountainous terrain near Mt. Hood at milepoint 49.1. The existing 3-lane highway section was constructed in a through-cut in the 1960's.

The highway experiences high use periods during the summer and winter due to its proximity to recreational activities and as the main travel route between Portland and Central Oregon. The 1997 ADT is 8,100, and is projected to rise to 13,000 in 2017. The proposed design is a realignment of the highway by moving away from the existing rockcut on the inside of the curve and making a new cut on the outside of the curve, which will create larger fallout areas on both sides of the highway. See the attached design cross-section (Figure 1).

Geology and Geologic Structure

The cut for the case study is located on the outside of a curve. The cut is up to 25 meters high and was originally constructed with uncontrolled ("coyote") blasting methods, so the resulting slope is variable between 1V:0.5H and vertical. The rock is andesite from flows of the Laurel Hill Formation. The rock is fine-grained, has some to no vesicles, and is generally gray to light brown. The rock is slightly weathered to fresh, and medium hard to hard (R-3 to R-4). The cut exhibits two predominant joint sets: one set where the joint dip direction is generally parallel to the highway and a second set where the joints are generally perpendicular to the highway. The joints are steeply dipping between 70 and 90 degrees and are moderately closely spaced (0.3 m to 1 m) with some spacing greater than 3 meters. The joints are tight (closed) to open with up to a 5 mm width. The joint surfaces show a slight amount of surface staining. Infilling in the open joints is composed of silt and soft clay.

Rockfall History/Risk Considerations

The rockfall history of the cut is that infrequent rockfall events occur, but that the site has a high rockfall hazard potential because of the high, steep, blast damaged cut and the existing narrow, shallow ditch. The ODOT Rockfall Hazard Rating System has rated the cut as a "B" type hazard, which means that the cut does not rise to the level where an RHRS score is determined. The site is on an 8-degree curve, 6 percent grade where snow and ice are a major factor in the winter months. The snow storage is limited with the narrow ditch, causing rock to sometimes deflect off the snow and land in the travel lanes. Maintenance cleanout is difficult with the short sight distance of the curve. The maximum size of the rock observed in the ditch was about 0.6 meters in diameter, and it appeared that much of the rock in the ditch had been larger pieces that broke into smaller ones during their fall. The conclusions made for the new rock slope design were that since the overall rockfall frequency was generally low, a fallout ditch and slope design should be made that will retain over 90 percent of the 0.6-meter size rock, and that the fallout zone backslope should be flat enough for easy access by cleanout equipment.

Design Considerations

Level of Risk Evaluated

The basis for ODOT geotechnical design of rock slopes is to retain at least 90 percent of the anticipated maximum sized rock when designing new rockfall areas. That percentage can be adjusted up or down based on cost or other factors of the project. In addition, the ditch design is generally recommended to be a maximum of 1.2 meters deep so that the shoulder slope

is 1V:4H or flatter for Maintenance cleanout purposes. A further design consideration is that, in some cases, the paved shoulder area between the EP (edge of pavement) and fog line can be considered as additional fallout width since a rock stopping in the paved shoulder area is not the same degree of hazard when compared to rock in a travel lane. However, on this project, with it's curved roadway alignment, the roadway pavement will have a pretty steep superelevation slope away from the cut, and any rock that rolled onto the paved shoulder has a pretty good chance of continuing to roll into the travel lane. Therefore, for this project, the additional 1.8 meter paved shoulder width between the fog line and EP was not included as part of the design fallout area width.

The rock cut for this project had already been designed prior to the research project 1V:0.5H slope new design charts becoming available. The fallout area design was arrived at through the use of the ODOT earlier developed design chart for 1V:0.25H slope, comparison to Ritchie design chart, experience, judgement and constructibility considerations. The rock cut for this project was designed with a 1V:0.5H slope for stability and with a minimum 6-meter wide fallout area for rockfall retention and to provide sufficient width for access of drill and excavation equipment to actually construct the cut widening. The fallout area was designed with a 1:6 slope.

Cost Analysis

Approximately 40,000 cubic meters of rock excavation is estimated for the cut. Controlled blasting will be used for the construction of a stable slope face, and approximately 3,200 lineal meters of control blast holes is estimated. Traffic control and limited road closure periods will be a major factor during blasting and cleanup. The heavy use of the highway during the summer and the large amount of loaded truck traffic means that the closure times will need to be the shortest time possible. This will increase the need for a well planned blasting operation in order to prevent flyrock onto the travel lanes. Rock excavation costs are estimated to be about $15.00 per cubic meter and the controlled blast holes are estimated to cost about $10.00 per lineal meter. Actual bid prices will be known when the project bids in 2001.

Discussion of Recommended Design

The recommended design ditch width and shoulder slope angle was 6 meters with a 1V:6H slope. This was judged to be adequate rockfall mitigation for a cut that will be excavated with control blast methods and wider paved shoulder widths than those that exist presently. Rockfall produced from the new cut should be minimal for many years, until the cut begins to age and additional stress relief cracks behind the new cut face.

Comparison of the Design Ditch to the Ritchie Chart

The recommended fallout area width of 6 meters of ditch is narrower than the "Ritchie" design chart shows for a 25-meter high cut with a 1V:0.5H slope. The Ritchie chart shows that the required ditch design would be about 6.9 meters wide and 1.5 meters deep. See the attached Ritchie Chart (Figure 2). Such a deep ditch is undesirable from both a roadside safety and

maintenance standpoint and would require a roadside barrier (concrete or guard rail) along the EP.

Comparison of the Designed Ditch to the New Design Chart

Upon becoming available, the new 80-foot 0.5H:1V slope/6:1 Design charts for both Impact and Roll Out were compared to the above as designed ditch. See the attached Design Chart (Figure 3). For a design ditch width of 6 meters, the new chart for Impact shows 99% of rocks retained, and for Roll Out it shows 83% of rocks retained.

If the new Roll Out Design Chart had been used in the design of the ditch, and the goal is to retain a minimum of 90%, then a fallout area of about 7 meters wide with a 6:1 slope or about 6 meters wide with a 4:1 slope, would be used. This means that the as designed ditch is about 1 meter narrower than the new 6:1 Roll Out Design Chart shows.

Benefit/Cost Comparison

A comparison was also made to a wider ditch providing 99% retention versus 90%. Using the new 80 foot, 0.5H:1V slope/6:1 ditch Roll Out chart gives a required ditch width of 10.5 meters (see Figure 3). That is 4.5 meters wider than the as designed ditch. The added 4.5 meter width results in an increase in excavation quantity of about 25% from the current design. Extrapolating that quantity to the entire cut section, the excavation quantity increases from 40,000 cubic meters to 50,000 cubic meters, with an additional cost increase of about $250,000.

In summary, If the new charts had been used in the design, the design very likely would have been either 6 meters with a 4:1 shoulder slope, or 7 meters with 6:1 slope, providing at least an estimated 90% rockfall retention. From a construction cost comparison viewpoint, it would be less expensive to excavate a deeper ditch with a 4:1 slope, than to excavate an additional 1-meter into the rockcut and have a 6:1 shoulder slope. Therefore, the final choice would be a 6-m wide ditch with a 4:1 shoulder slope.

Attachments:

Figure 1: Design Cross Section
Figure 2: Ritchie Design Chart
Figure 3: Impact and Roll Out Design Chart (metric units)

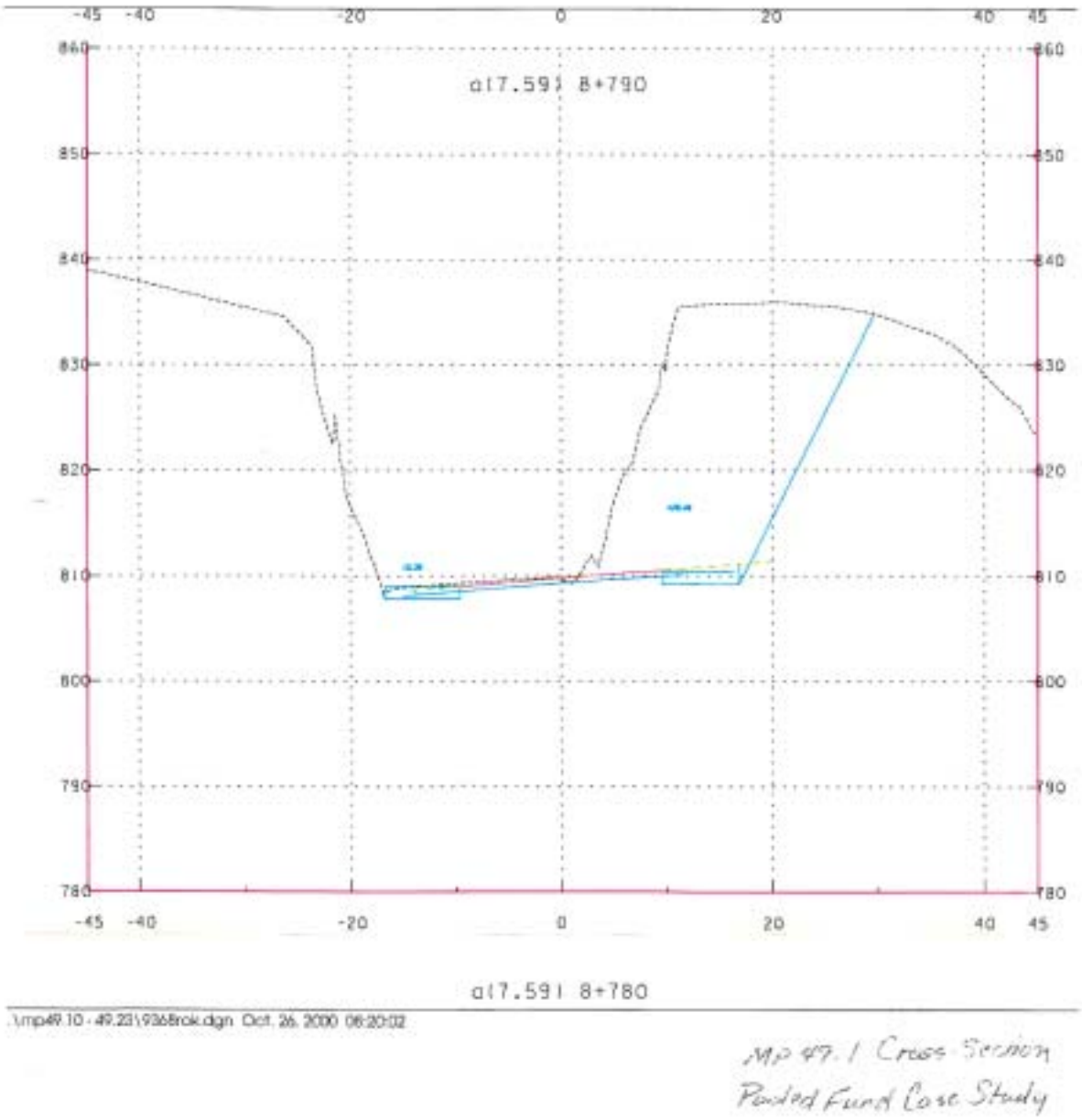


Figure 1: Design Cross Section

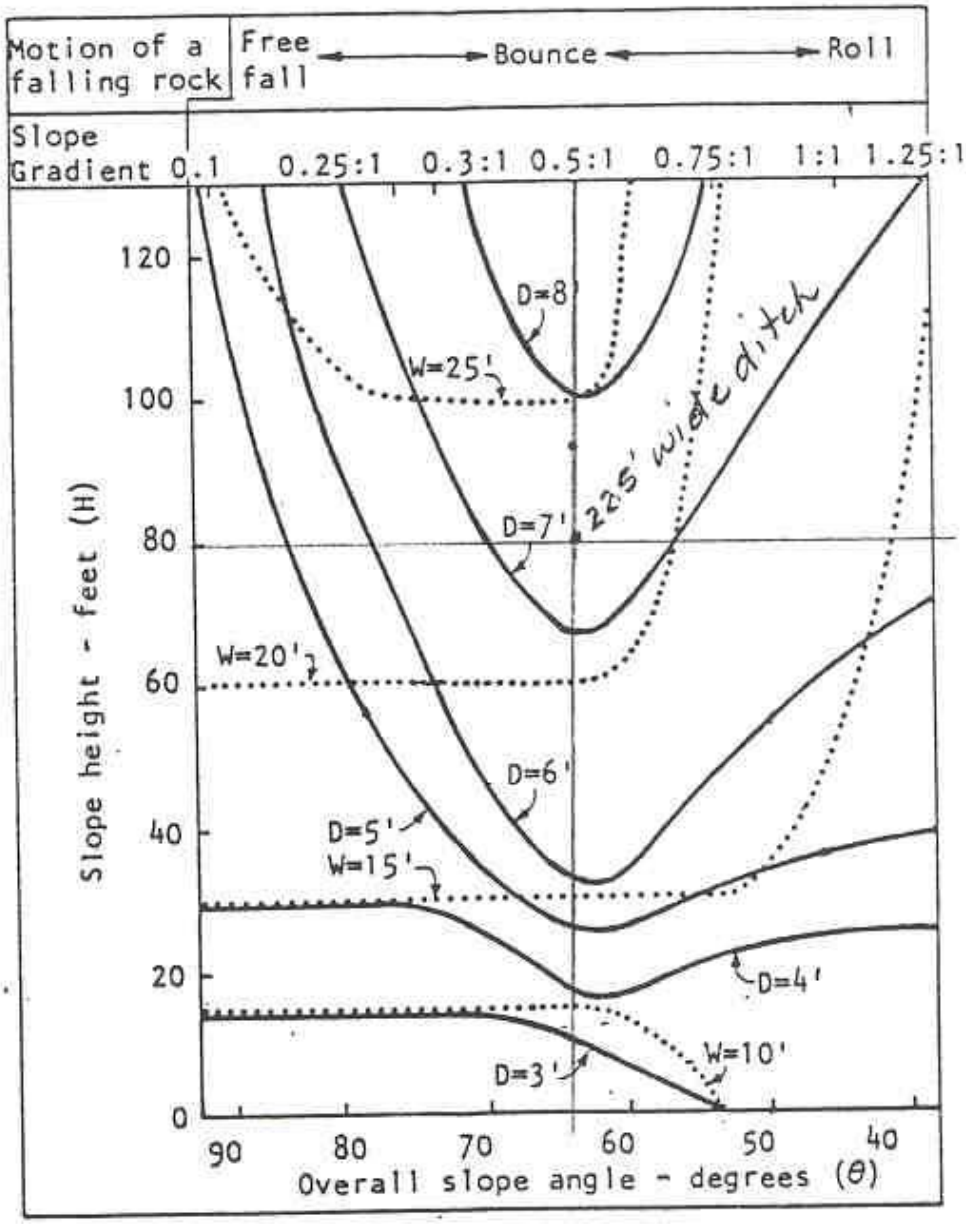
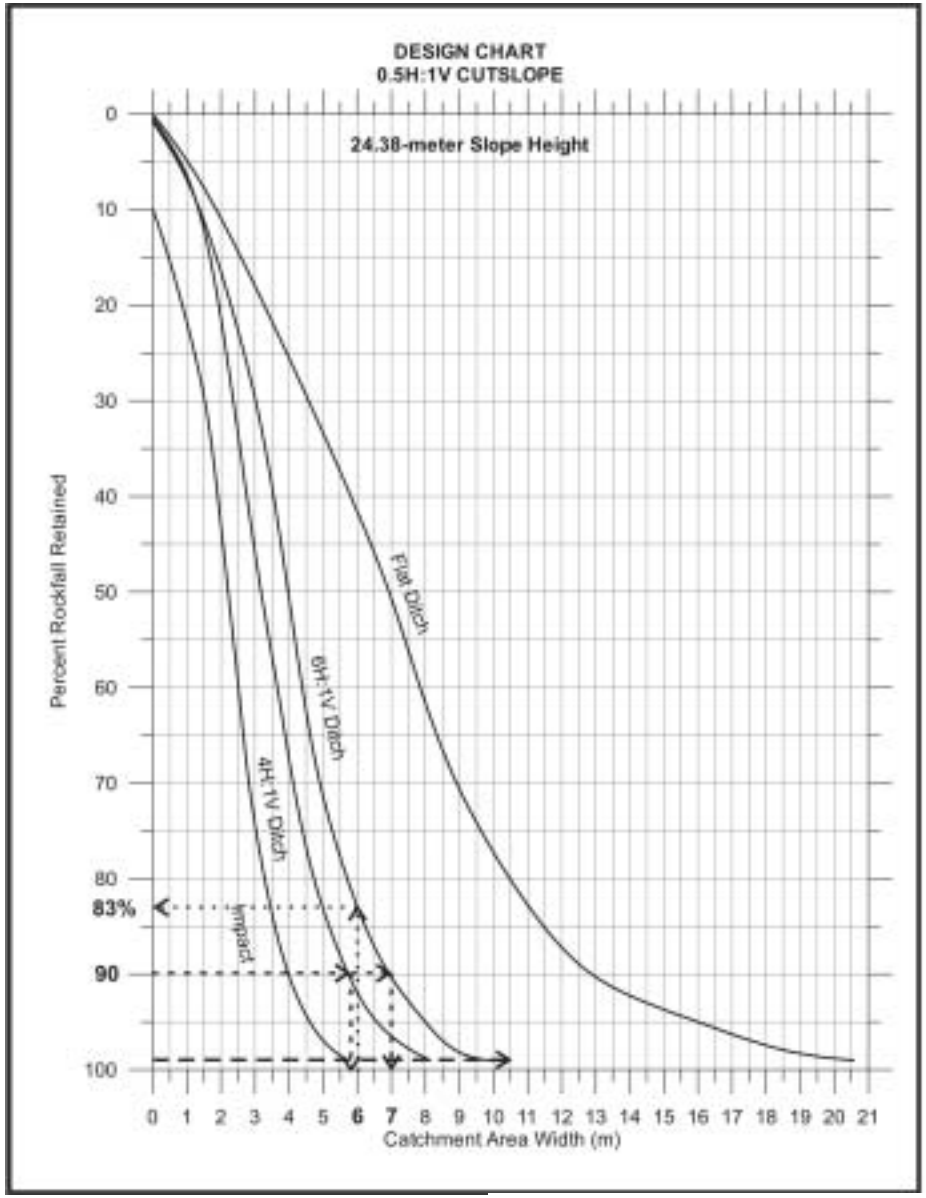
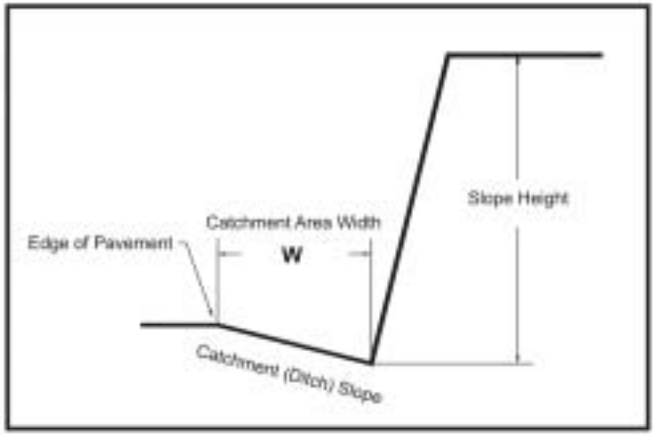


Figure 12.10(a): Ditch design chart.

Figure 2: Ritchie Design Chart





Quick Reference - 24-Meter Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (m)	**W (m)**	**W (m)**	**W (m)**
50%	2.2	3.2	4.0	6.9
75%	3.0	4.4	5.1	9.6
80%	3.2	4.7	5.7	10.5
85%	3.5	5.3	6.3	11.5
90%	4.0	5.7	6.9	12.9
95%	4.5	6.6	8.0	16.0
99%	5.7	8.1	10.5	20.6

Figure 3: Impact and Roll Out Design Chart (metric units)

NEW YORK STATE DEPARTMENT OF TRANSPORTATION CASE HISTORY

REGIONAL POOLED FUND RESEARCH STUDY SPR-3 (032)

Prepared by
Alexander Yatsevitch, Engineering Geologist 3
and
Michael P. Vierling, Engineering Geologist 2 (NYS Thruway Authority)

INTRODUCTION

The State Route 17, Corning By-Pass Project is located in Steuben County, in the Southern Tier region of central New York State along the border with Pennsylvania. The purpose of the project was to provide an interstate-level travel-way for the large volume of commercial east-west through traffic to avoid the bottleneck of downtown routing. The project involved a massive side-hill cut along the southern flank of Pine Hill north of the City of Corning. The final length of the cut is approximately 1500 feet and the height is approximately 305 feet. The maximum height of the exposed rock slope is approximately 250 feet.

Corning By-Pass Slope: Westbound

Corning By-Pass Slope: View from the top

The location is typified by broad valleys of glacial origin. The overburden is till with associated deposits, and the bedrock, typical of the region, a monotonous, thick, sequence of essentially horizontally bedded siltstones and sandstones interbedded with shales belonging to the West Falls Group of Upper Devonian age.

AADT is 25500 and expected to increase.

DESIGN

Risk considerations per se were not a basis for the original design or subsequent changes. It is NYSDOT policy to provide the most technically sound rock slope recommendations and build the safest product within the constraints in effect at the time. NYSDOT does not target an absolute risk number, nor has one considered to be acceptable.

Investigations for cut design included shallow seismic refraction and core drilling. The final design recommendation was for a slope of 1 vertical on 2 horizontal for the overburden backslope and 1 vertical on 1 horizontal for the rock slope face. At the beginning of slope excavation the contractor encountered what he claimed to be large, 6 to 8 foot boulders at the design top of rock elevation which resulted in a claim for additional payment for the excavation of the "boulders" and for redoing the earthwork at the top of slope to accommodate the lowered intercept with the revised elevation of the top of the rock slope. The claim is a side issue pertinent to the constructed maximum height of the finished rock slope as a product of redesign during construction.

All NYSDOT rock slope design is done by the Engineering Geology Section of the Geotechnical Engineering Bureau, Technical Services Division. Engineering geologists conduct pertinent investigations and research and make recommendations to project designers in the Regions who resolve constraints and generate the final plans. The Engineering Geology Section has in-house capability to determine rock depths by resistivity and seismic refraction methods. Core drilling is usually done by Regional forces. The initial "best" design recommendations for this project were changed primarily for economic considerations. New York State Department of Transportation Standard Specifications require presplit drilling and blasting for construction of rock slopes designed at 1 vertical on 1 horizontal or steeper. A maximum lift height of 60 feet is allowed, with lifts of approximately equal height. The original rock slope design included benches at regular intervals for drilling and blasting of the lifts. In an attempt to reduce the cost of excavation, the Region responsible for the project proposed that the rock could be ripped and excavated by mechanical means and requested dispensing with the requirement for presplit blasting. Accommodation was made by redesigning the rock slope excavation to a 1 vertical on 1.1 horizontal, thus also eliminating the previously included benches. Toe of slope setback from the edge of pavement remained as originally recommended at approximately 25 feet with a non-Ritchie drainage ditch profile.

Soon after beginning excavation of the redesigned rock slope the contractor was unable to rip the rock even with the largest excavators available. The operation changed to non-presplit production blasting to the projected rock slope plane followed by ripping of the loosened material to the final slope. After final cleaning, the resulting rock slope was a stair-step series of more durable sandstone/siltstone beds sandwiched between thinner shale beds. Before completion of the rock slope construction, it was also decided to add a climbing lane against the slope by eliminating the shoulder and reducing the set-back to a maximum of 10 feet, including the ditch. Also before the completion of the slope construction, a block of sandstone approximately the size of a wastebasket bounced down the slope, across the ditch area and across almost 3 lanes of the future roadway before stopping. That prompted a request for an evaluation of the slope and recommendations for rockfall mitigation.

Due to the unusually great height and flatter than normal angle of the constructed rock slope, there was no pertinent experience to rely on as a basis for mitigation recommendations. Stabilization by rock bolting or shotcreting was excluded due to the type of rock, cost and aesthetics. Reconfiguration of the catchment area profile and setback was not an option due to lane and drainage requirements. Slope mesh and drapes were eliminated on the basis of cost, constructibility and aesthetics. Barriers were the remaining option, with a catchment fence left as the only serious consideration.

The recommendations for an effective catchment fence configuration were based on actual slope field test results. Engineering geologists from NYSDOT devised a program to obtain pertinent rock rolling data utilizing available state resources. A corridor down the slope was delineated. Surveyed marker stakes color coded to chosen elevations and slope irregularities were located and measured in plan and section. Various sized and shaped rocks representative of those likely to separate from the slope were marked with high visibility paint, rolled from the top of the slope, and videotaped and measured to determine points of contact with the slope, bounce heights, impact points and resting points in relation to the toe of slope and edge of pavement. As a light aside, two bowling balls were included in the mix of rolled rocks. Contrary to everyone's intuition, but in accordance with applicable physics, neither made it half way down the slope.

The analysis of the results was used in combination with the CRSP modeling of the slope to arrive at a recommendation for the most effective location and height combination for a catchment fence, which was added to the project and installed. Due to the special restrictions on available space and edge of pavement drainage requirements in the fence location, Brugg Cable Products, Inc., technical personnel provided valuable assistance in designing a unique base for the installation of the post anchors for their product. The installed fence consisted of ninety-two 12'-8" X 15' nets mounted on embedded concrete cast-in-place foundation blocks producing a total height of fifteen feet. The final paid length was 1380 feet at an all inclusive cost of $308.89 per linear foot.

The rock slope work was started in May 1992 and the fence installation was completed in September 1995. At that time there was no reference data for even ball-park figures for important rockfall mitigation design parameters such as slope height and angle rock trajectory relationships, impact distances and final resting locations. Ritchie criteria and CRSP have applications only in limited configurations. NYSDOT's approach to a responsible solution to this design problem was to essentially perform the same procedure on that specific site as was done in this SPR-3(032) study for a wide range of slope configurations. If the Rockfall Catchment Area Design Guide had been available at that time, the information certainly would have reduced the time necessary to conduct the investigation and finalize the solution.

Regional Pooled Fund Research Study SPR-3 (032)

Washington State Department of Transportation Case Study

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Introduction

The following is a case study comparing current WSDOT rock fall ditch criteria and the new design chart for rock slopes developed through the current Regional Pooled Fund Research Study.

The site selected for this case study is located in Eastern Washington along SR-243. The proposed project is five miles in length and will included realignments to improve the horizontal geometrics, and widening of the roadway prism. A three-mile section of the project will include extensive cuts in rock, with cut heights in excess of 100 feet.

SR-243 is classified as a rural principle arterial with an Average Daily Traffic (1999) of 2306, which includes 436 trucks.

Rock Slope Design

Bedrock along the existing highway alignment consists of dark gray to black basalt of the Columbia River Basalt Group. The predominate geologic structure that controls the stability of the existing rock cuts is the columnar jointing oriented from approximately 75 degrees to near vertical (See Figure 1). Column sizes vary from 0.5 to 2 feet in diameter. Block sizes vary from 1 to 2 feet average. The existing near vertical rock slopes have been extensively damaged from uncontrolled blasting techniques employed in the past to develop the cuts. Rock fall is considered to be low to moderate, although there are areas within the existing cuts that have detached and/or dilated rock blocks several columns wide.

Based on the current conditions of the existing rock slopes and the predominance of high angle columnar jointing a 0.25(h):1(v) rock slope design was selected. Slope heights averaged approximately 80 feet. In addition, controlled blasting techniques, in accordance with WSDOT Standard Specifications, will be utilized to develop the new rock slopes.

Figure 1: Typical conditions of columnar basalt rock slopes along SR-243

Rock Slope Ditch Design

Two design approaches were utilized for the rock slope ditch design. The first approach was to utilize current WSDOT rock fall ditch criteria which is based on slope ratios and heights. This

criteria is a modification of the "Ritchie Ditch" originally developed by Art Ritchie (Ritchie, 1963). The second approach was to utilize the new rock fall ditch design criteria developed by ODOT.

The rock fall ditch developed by Ritchie (1963) was a flat bottom ditch with a minimum width of 10 feet. To control run out of the rock fall a steep 1.25 (h):1(v) ditch foreslope was integrated into the design. WSDOT has modified the original Ritchie ditch design to allow for staged development of the rockfall ditch (See Figure 2). The staged development concept for the rock fall ditch is to provide alternates that are based on local site conditions and an estimate of the severity of future rock fall (Lowell, 1987). Based on WSDOT rock slope ditch design criteria (Stage 1) the following information was obtained from the WSDOT design charts:

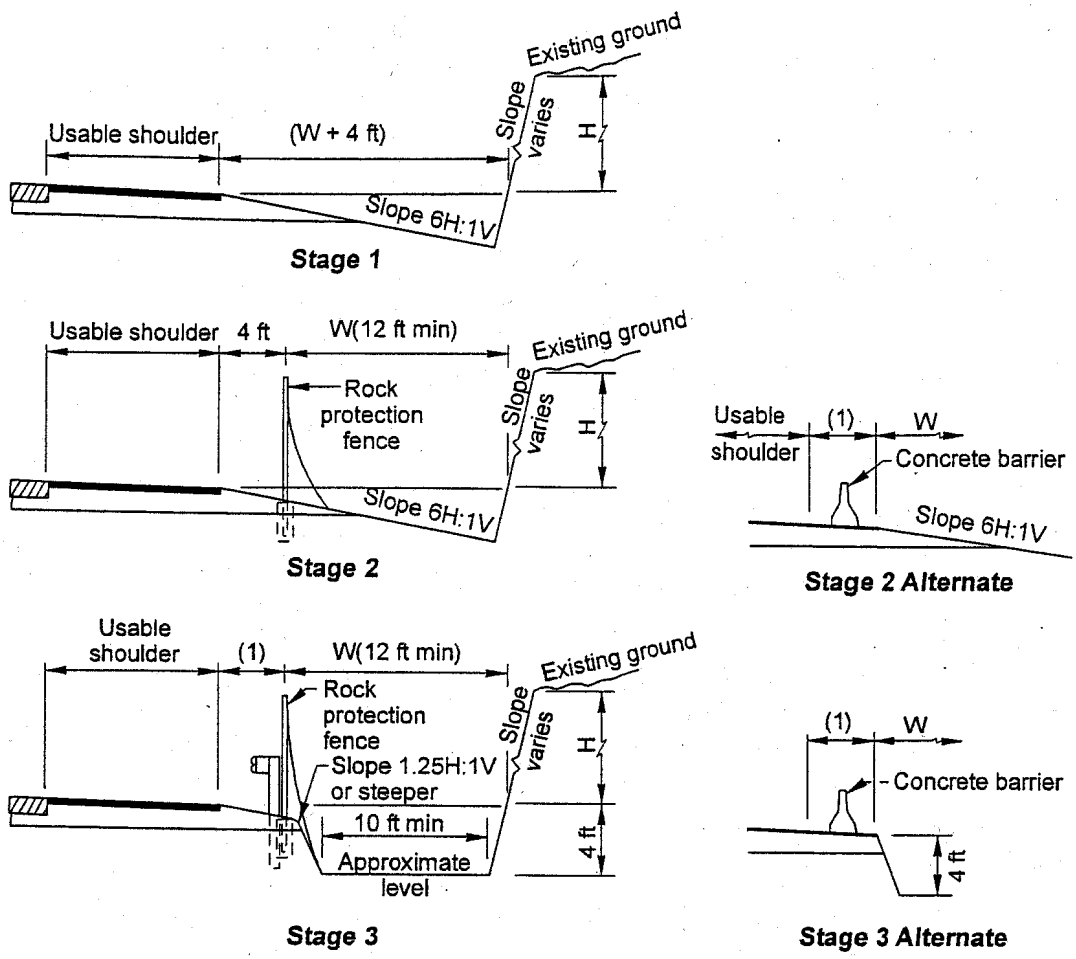
Slope Height	Slope Design	W	W+4	Ditch Slope
80 Feet	0.25(h):1(v)	20 Feet	24 Feet	6(h):1(v)

For this slope configuration a 24 foot wide rock slope ditch with a 6(h):1(v) ditch slope (Alternate A) would be recommended.

The new ODOT based design charts were utilized to provide an alternate design for the proposed rock cuts. It was decided that an appropriate design goal was to retain approximately 90 percent of the rock fall in the proposed rock slope ditch. Both the impact and roll out chart were evaluated. Based on this evaluation it was determined that roll out controlled the rock slope ditch design. The following rock slope ditch criteria was obtained from the ODOT based roll out design chart (see Figure 3):

Slope Height	Slope Design	Percent Retained	Ditch Width	Ditch Slope
80 Feet	0.25(h):1(v)	90	31 Feet	6(h):1(v)
80 Feet	0.25(h):1(v)	90	22 Feet	4(h):1(v)

For this slope configuration two rock slope ditch designs would be recommended. First, a 31 foot wide rock slope ditch with a 6(h):1(v) ditch slope (Alternate B), and second, a 22 foot wide rock slope ditch with a 4(h):1(v) ditch slope (Alternate C).



Rock Slope	H(ft)	W(ft)
Near Vertical	20-30 30-60 >60	12 15 20
0.25H:1V or 0.30H:1V	20-30 30-60 60-100 >100	12 15 20 25

Notes:

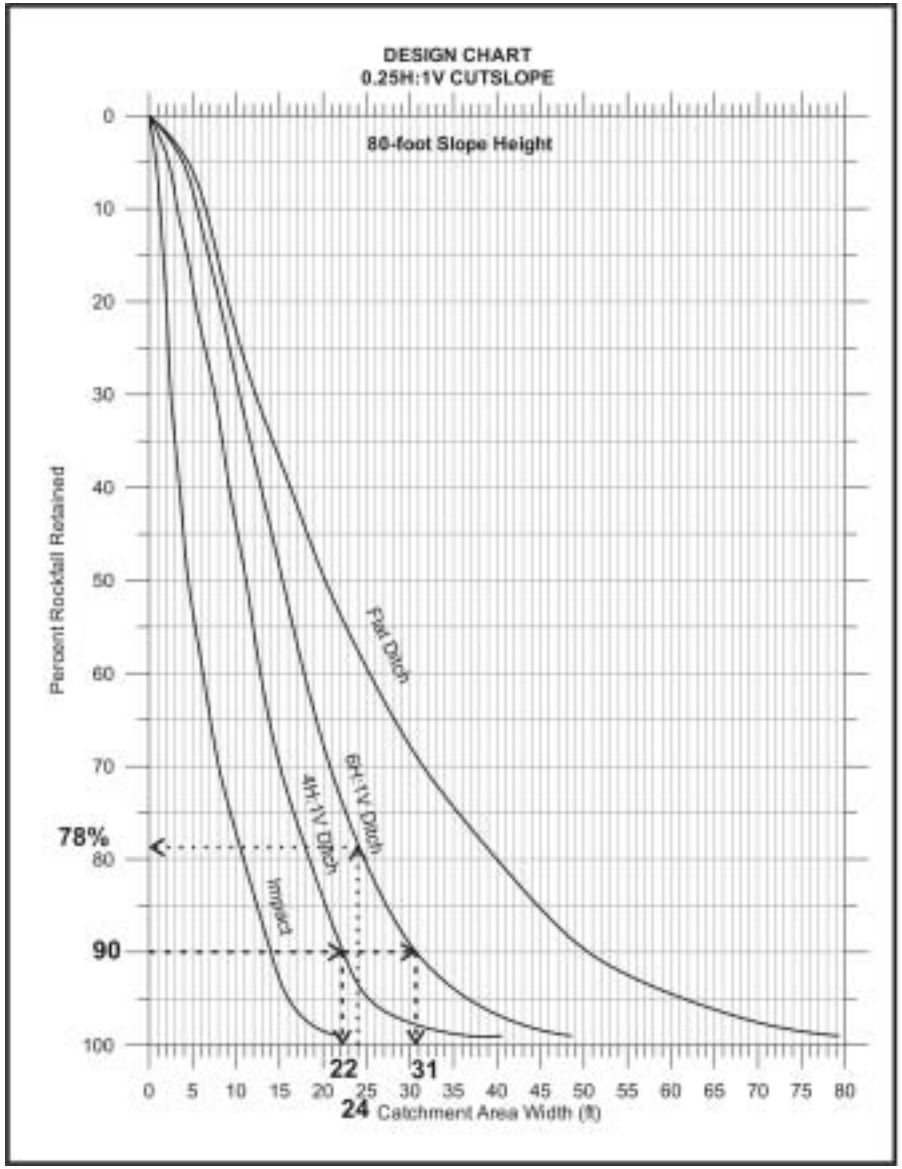
Cut heights less than 20 ft shall be treated as a normal roadway unless otherwise determined by the Region Materials Engineer.

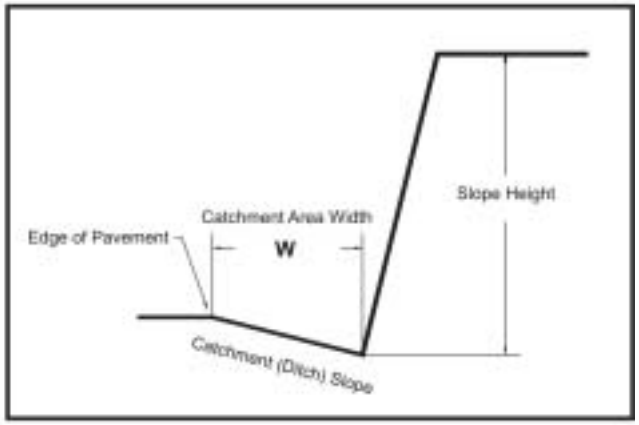
Stage 2 and 3 Alternates may be used when site conditions dictate.

Fence may be used in conjunction with the Stage 3 Alternate. See Chapter 700 for clear zone requirements.

(1) See Chapter 710 for required widening for guardrail and concrete barrier.

Figure 2: Roadway Sections in Rock Cuts, Design A





Quick Reference - 80-Ft Slope Catchment Area Width - **W**				
Percent Rockfall Retained	Impact	Catchment Area Slope		
		4H:1V	6H:1V	Flat
	W (ft)	**W** (ft)	**W** (ft)	**W** (ft)
50%	4	11	14	20
75%	9	17	23	36
80%	11	18	25	40
85%	12	20	27	45
90%	14	22	31	51
95%	16	25	37	62
99%	22	41	49	79

Figure 3: Design Chart

Comparison of the WSDOT Rock Slope Ditch Design to the New Design Charts

As detailed in the previous section of this case study, three alternate rock slope ditch designs were developed. Those alternates are summarized in the following table:

Rock Slope Ditch Alternative	Ditch Width	Rockfall Retention	Ditch Slope	Ditch Depth
A	24 Feet	78%	6(h):1(v)	4 Feet
B	31 Feet	90%	6(h):1(v)	5 Feet
C	22 Feet	90%	4(h):1(v)	6 Feet

Alternate A: Alternate A utilized current WSDOT rock slope ditch criteria. When evaluating this ditch design configuration as it applies to this case study a number of design and construction issues were raised. Those issues are detailed as follows:

1) Utilizing the new ODOT based rock slope ditch design charts it was determined that the proposed ditch configuration only retained approximately 78 percent of the rock fall (See Figure 3). This would not meet the design goal to retain approximately 90 percent of the rock fall. To mitigate the roll out problem (using WSDOT design criteria) a Stage 2 Alternate rock slope ditch design, utilizing a concrete jersey barrier on the outside edge of the roadway shoulder, would be employed (See Figure 2). Installation of concrete jersey barrier on the outside edge of the roadway shoulder, to mitigate rock fall roll out, would be undesirable if other alternates were available.

2) When the roadway template design (including the rock slope ditch geometry) was overlaid onto the original ground cross section, it was discovered that the effective bench width for the proposed rock cuts were on the order of approximately 10 feet (See Figure 4). This could present a constructibility issue for two reasons. First, the narrow working bench would present a problem in terms of the size and types of excavation equipment that could work safely on a narrow bench. Secondly, the dilated nature of the rockmass in some of the exterior portions of the existing rock cut makes it unlikely that a 10 foot working bench width could be maintained as the rock cut was brought down to grade. If the exterior portion of the benches failed it would require the slope to be "pushed back" into the slope during construction.

3) The narrow bench width would be difficult to drill and shoot. The narrow burden of the cut would only allow for one row of production blast holes, and the line holes forming the back slope of the cut would be shot as a cushion shot. Due to the dilated nature of the bedrock in portions of the cut it would be anticipated that fragmentation of the bedrock would be poor, and the condition of the final back slope less than desirable.

Alternate B: Alternate B utilizes the new ODOT based rock slope ditch criteria. This alternate provides the desired rock fall retention of 90%. In addition, the ditch section provides a wider more workable cut section (See Figure 4) and mitigates to some extent the construction risks associated with Alternate A.

Alternate C: Alternate C utilizes the new ODOT based rock slope ditch criteria. Although this alternate provided the desired rock fall retention of 90%, the construction risks that were associated with Alternate A would also apply to this rock slope ditch design.

Design Decision

Based on the discussion in the previous section of this case study, Alternate B was selected as the preferred rock slope ditch design. Although the initial cost to construct this rock slope ditch is higher than the other two alternates, the associated construction risks are minimized and the long term performance of the final back slope is enhanced.

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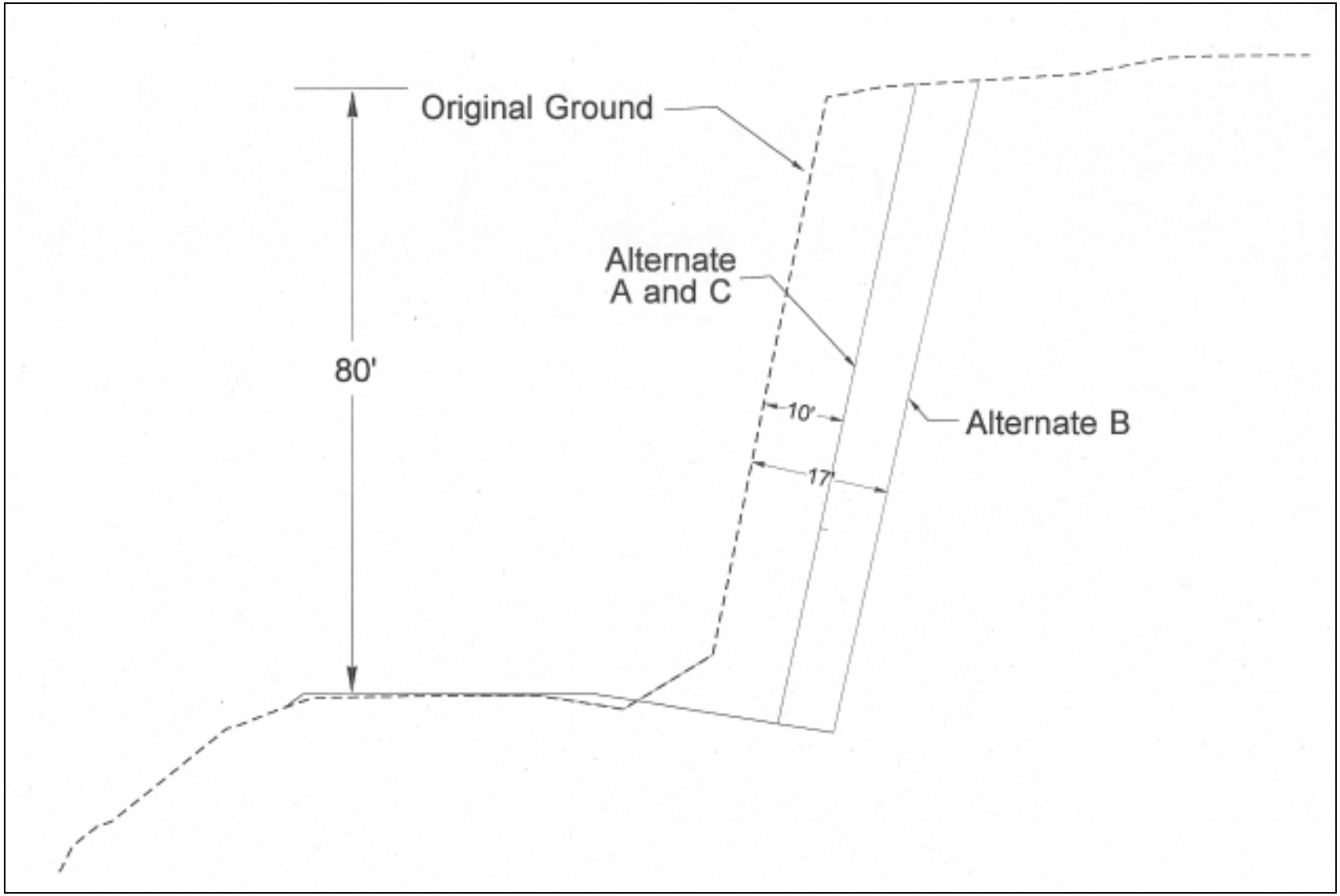

Figure 4: Alternate Rockfall Ditch Designs

Regional Pooled Fund Study SPR-3 (032)

Wyoming Case History

INTRODUCTION

One of the first slopes that WYDOT designed using preliminary information from the rockfall study was part of a highway reconstruction project on US 26-89 through Snake River Canyon approximately 25 miles southwest of the city of Jackson in northwest Wyoming. Due to increased traffic and high accident rate, this road was being upgraded from two 11' wide lanes with no shoulders to two 12' lanes with 8' wide shoulders. This additional increased template width was a design challenge due to the narrow corridor between the Snake River and the steep walls of the canyon. The overall yearly ADT on this road section at the time of construction was 2670, with summer volumes approaching 6000 VPD, making this one of highest volume two-lane primary highways in the state. The accident rate on this road section was approximately 2.5 times the state average for primary highways.

This slope was located at milepost 127.1, which is near the middle of the 24 mile long canyon. The existing backslope had a maximum height of approximately 120' and was near vertical to overhanging in some portions of the cut. The lower 80' of the cut consisted of hard, competent siltstone which dips to the west approximately parallel to the roadway at 20°. Overlying the siltstone is approximately 40' of colluvium consisting of a poorly sorted mixture of clayey sand and gravel with some cobbles and boulders.

The original ditch through the steepest portion of this cut was 3'-4' wide and approximately 1' deep (see Photo 1). This ditch configuration provided very little rock catchment. It was estimated that ditch catchment was on the order of 5-10%. In the five years prior to the reconstruction, there were four rockfall accidents reported at this site. It was observed that about equal amounts of rockfall were being generated from the colluvium and siltstone bedrock. The block size of this rockfall averaged about 12", with the maximum size being 24".

DESIGN CONSIDERATIONS

There are many different factors which affected the design of this slope. Immediately to the east of the slope, a landslide repair had been completed utilizing a combination reticulated mini pile wall and MSE wall. This landslide repair and the roadway geometrics required to meet minimum design standards dictated how far the centerline through this cut had to be moved into the slope. Once the centerline had been determined, the challenge was to design the optimum slope angle to provide the greatest stability of the rock mass while minimizing the amount of material removed from the cut.

Photo 1: The cut slope looking west before construction

Since this roadway is through a very environmentally sensitive area within the national forest, the U.S. Forest Service had a great deal of input into the design of the slope. The two main goals of the Forest Service were to reduce overall impacts or "foot print" of the roadway template and create a natural looking "aesthetically pleasing" slope. The main goal of WYDOT was to create a safe, stable slope that would require less maintenance. The other main concern of WYDOT was the large amount of material that would be generated if the slope was to be laid back. This project already had excess material as designed, and there were no available waste sites within the canyon.

FINAL DESIGN AND BENEFIT/COST COMPARISON

As a compromise to all interested parties, the final slope design configuration at this site was a "broken slope" with the bottom 80' ± of competent siltstone being cut at 0.44H:1V. The overlying 40' thickness of poorly consolidated colluvium was cut at a 1:1. The siltstone in the steep portion of the cut was presplit to avoid back break behind the cut line. The optimum slope angle (22° from vertical) in this material was to match a major joint set which was approximately parallel to the road.

The ditch section was widened from the existing 3'-4' width to a width of 23'. The shoulder ditch was designed at 6:1 slope, which resulted in a ditch approximately 4' deep. According to the rockfall design charts, this ditch should contain 99% of the rocks at impact and approximately 85% of rocks from the roll out. (Since the design slope ratio is 0.44H:1V, the 99% impact and 85% roll out retention values were estimated using interpolation between the 0.25H:1V and 0.5H:1V design charts.) This is a significant improvement from the 5-10% of rock catchment which was present before reconstruction. To go from the 85% catchment at a width of 23' to a catchment of 98% would have required a ditch width of 32'. For this particular slope, an additional 25,000 cubic yards of rock excavation would have been required for a 32' ditch. At the

unit cost for rock excavation it would have been an additional $165,000 just for the excavation. In addition, this material would have to have been truck-hauled at least 20 miles to a waste site outside of the canyon. Due to the much higher cost, lack of available waste site close-by and more adverse environmental impact, the 98% catchment design was not selected. The 85% catchment design was judged to provide the better overall risk/cost-benefit.

Additionally, it was determined that although the new ditch section increased the rockfall catchment, rock from the colluvium which was cut at 1:1 could be a hazard. To prevent the rocks from the colluvium starting to roll down the 1:1 slope and being launched at the break in slope, PVC-coated double-twist rockfall mesh was placed over the 1:1 slope. The mesh was attached along the top of the slope with anchors spaced 3' apart. The bottom of the mesh extended about 4' over the break in the slope so that the rock which worked its way out under the mesh would fall nearly straight down and be contained in the ditch.

RESULTS

This slope was completed in the fall of 1998. Since then, no rockfall accidents have been reported at this site. As seen in photos 2-4, the ditch appears to be effective in catching the rocks.

Photo 2: Looking Eastward at the cut after construction note rockfall mesh

Photo 3: Looking eastward after construction note rock catchment

Photo 4: Looking west at the whole cut after construction