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THE NATURE OF ROCKFALL AS THE BASIS FOR A NEW FALLOUT AREA DESIGN CRITERIA FOR 0.25:1 SLOPES

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16. Abstract

The data gathered from rolling nearly 2800 rocks off several 0.25H:1V slopes into three differently shaped ditches (flat, 6H:1V and 4H:1V) was used to develop 12 design charts for rock fallout areas. The data was analized using simple statistical and graphical methods. The charts can be used to size fallout areas that satisfy specific rock catching requirements. Based on slope height and the shape of the ditch, the charts identify the required fallout area widths that will restrict set percentages of rockfall ranging from 10% to 100% in 10% increments along with 95% and 98%.

This report documents the test method, the means of analysis, the research results, and sample applications of the results. The data results in both tabular and graphical form are included in the appendices.

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DISCLAIMER

THE NATURE OF ROCKFALL AS THE BASIS FOR A NEW FALLOUT AREA DESIGN CRITERIA FOR 0.25:1 SLOPES

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THE NATURE OF ROCKFALL AS THE BASIS FOR A NEW FALLOUT AREA DESIGN CRITERIA FOR 0.25:1 SLOPES
Final Report

1.0 INTRODUCTION

1.1 PURPOSE

No consistent standard for the design of rock fallout areas currently exists. In some cases, designs are loosely based on the 30-year old Ritchie ditch width and depth criteria. In others, a combination of cost, constructability, maintenance or other safety related issues guides the design process. Without a consistent standard based on extensive field testing, the result may be a design that is more expensive than necessary and/or not particularly effective at restricting rockfall from the roadway. These fallout area design practices are perpetuated by a lack of supportive research. We sought to gain a more in-depth understanding of the nature of rockfall from steep slopes and the ditch characteristics that are important in rockfall retention.

The research goals were:

1. Determine the current national practice for rock fallout area design.

2. Investigate the nature of rockfall and identify slope, ditch and rockfall characteristics that have an impact on the effectiveness of rock fallout areas for 0.25:1 slopes constructed using controlled blasting methods.

3. Develop a new mechanism for evaluating existing fallout areas and to assist with designing new or improved, cost effective, fallout areas adjacent to 0.25:1 slopes.

The Federal Highway Administration and the Oregon Department of Transportation provided the research funding. The research involved preparing a test site, rolling nearly 2800 rocks, data analysis, and preparation of this report. The results, although specific to 0.25:1 slopes, are a significant step towards the overall development of a national design criteria for rock fallout areas. With this information, transportation departments can evaluate the effectiveness of existing fallout areas, and justify expenditures by quantifying the expected improvement in fallout area effectiveness. They will also be able to design and construct fallout areas that have a predictable rock catching capability.

2. On steeper slopes, even though a rock's initial motion is by rolling, after a short distance the rocks would start bouncing and then, depending on the slope angle, either continue bouncing or go into free fall.
3. Falling rocks 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 minimum fallout width and depth based on the slope height and slope angle. His table was later adapted into a design chart (Figure 1.2) in the FHWA publication "Rock Slopes: Design, Excavation, Stabilization" (2). This chart made it easier to interpolate appropriate dimensions for a greater range of slope heights and angles. Thirty years later, Ritchie's design approach is still used by numerous state and local agencies. Additional rockfall research work has been completed by D'Appolonia (3), McCauley (4), and Evans (5).

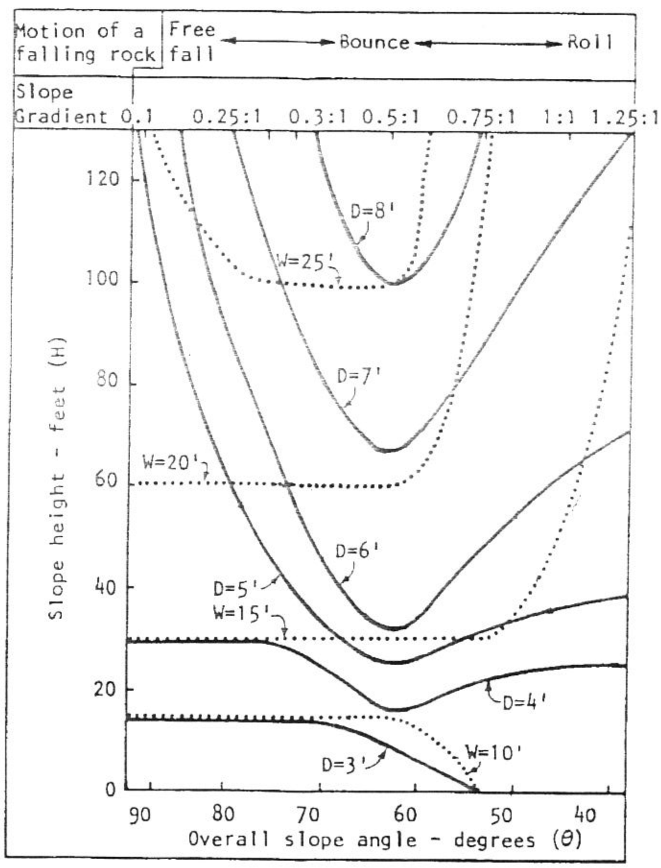


Figure 1.2: The Ritchie Fallout Design Chart

Several rockfall computer simulation programs are available that can help predict fallout area requirements. These include programs developed by Hoek (6), Wu (7), and Pfeiffer (8). Each is useful in predicting rockfall trajectories when detailed slope information is available.

Table 1: Survey results

State or Organization	Describe your design standard			How frequently do you deviate from this standard?			What is your opinion of the Ritchie Criteria?			
	Ritchie	Different Standard	None	Regularly	Occasionally	Rarely	No Opinion	Conservative	Appropriate	Inadequate
Alabama			X				X			
Alaska	X			X					X	
Arkansas			X				X			
California	X			X					X	
Colorado		X				X	X			
Connecticut		X				X	X			
Hawaii			X				X			
Indiana		X			X		X			
Iowa		X			X		X			
Maryland		X								
Missouri		X			X		X			
Montana	X					X			X	
Nebraska			X							
New Hampshire	X				X		X	X		
New Mexico	X				X			X		
New York	X								X	
North Carolina			X				X			
North Dakota			X				X			
Ohio		X				X	X			
Oklahoma		X							X	
Oregon	X			X					X	
Pennsylvania	X				X				X	
Washington	X				X			X		
West Virginia		X						X		
Wisconsin			X				X			
Wyoming			X					X		
FHWA EAST			X		X		X			
FHWA MID			X				X			
FHWA WEST	X			X				X		
FHWA 6	X							X		
FHWA 9	X								X	
TOTALS	12	9	10	4	8	4	15	7	8	0

2.0 ANALYSIS

2.1 COMPUTER SIMULATION OF ROCKFALL

Several state DOT's use computer simulation of rockfall as a tool to help in designing fallout areas. The most commonly used program is CRSP. CRSP provides an estimate of probable bounce heights and velocities for falling rock. Recently, additional statistical capabilities have been added providing probability distributions for velocity, energy and bounce height. The program is applicable to most slope configurations. However, the simulations require detailed site condition information. Without it, the accuracy of the predictions can vary appreciably.

For this research, rockfall simulation was used to aid in the planning of the research by providing a range of expected values. The results of the field tests were compared to the simulation results to evaluate whether the computer model was reasonable. Hopefully a good match would provide a means to extrapolate beyond the 40 to 80-foot slope heights. The simulation used the input values in Table 2.

Table 2: Input Values Used in Rockfall Simulation

	PRESPLIT ROCK SLOPE			FALLOUT AREA		
ROCK DIAMETER	TANGENTIAL COEFFICIENT	NORMAL COEFFICIENT	SURFACE ROUGHNESS	TANGENTIAL COEFFICIENT	NORMAL COEFFICIENT	SURFACE ROUGHNESS
1.0	0.85	0.35	0.5	0.8	0.3	0.25
2.0	0.85	0.35	0.75	0.8	0.3	0.5
3.0	0.85	0.35	1.0	0.8	0.3	0.75

The coefficients and rock size used in this analysis were selected based on typical values for the type of slope materials encountered. The tangential coefficient is proportional to energy lost during an impact in the vector direction parallel to the slope. The normal coefficient relates the velocity before and after an impact in a direction normal to the slope. Larger coefficient values represent harder materials that deform less during impact. The surface roughness is the maximum variation in the slope within a slope length equal to the radius of the rock used in the simulation. Previous studies have indicated the surface roughness is the most critical factor in determining the behavior of rockfall.

2.2 THE DESIGN OF FIELD TESTS

A test site was needed that could be modified to represent the conditions encountered adjacent to highways and accommodate the construction of an 80-foot high, 0.25:1 cut slope. A state owned quarry located a few miles west of Portland, Oregon met these requirements. The existing quarry face was cut nearly vertical and it ranged from 60 to 85 feet high (Figure 2.1). The area above the quarry face was nearly flat which made it ideal as a staging area for stockpiling the rock that was to be rolled. Access to the top required improvement for all weather use.

60-foot and 80-foot test slope heights were developed by excavating the lower shot material in stages.

Three different ditch configurations were tested for each cut height. The ditches were those that are commonly constructed adjacent to highways. Each is consistent with current clear zone requirements for recoverable slopes. As shown in Figure 2.3, a flat ditch and ditches that sloped toward the cut slope at both a 6:1 or 4:1 slope were tested. The ditch surface was comprised of shot rock with a minimal percentage of soil. Due to the method of excavation, the steepest ditch (4:1) was tested first for each slope height. The 6:1 ditch and then the flat bottomed ditch followed. This allowed the rockfall impact to occur on a material that would closely approximate conditions encountered at the base of a newly constructed cut slope. In addition, a Ritchie ditch was tested at the base of the 80-foot slope (Figure 2.4). The ditch's basic shape and dimensions are shown on Figure 2.5. The back slope as constructed ranged between 1:1 and

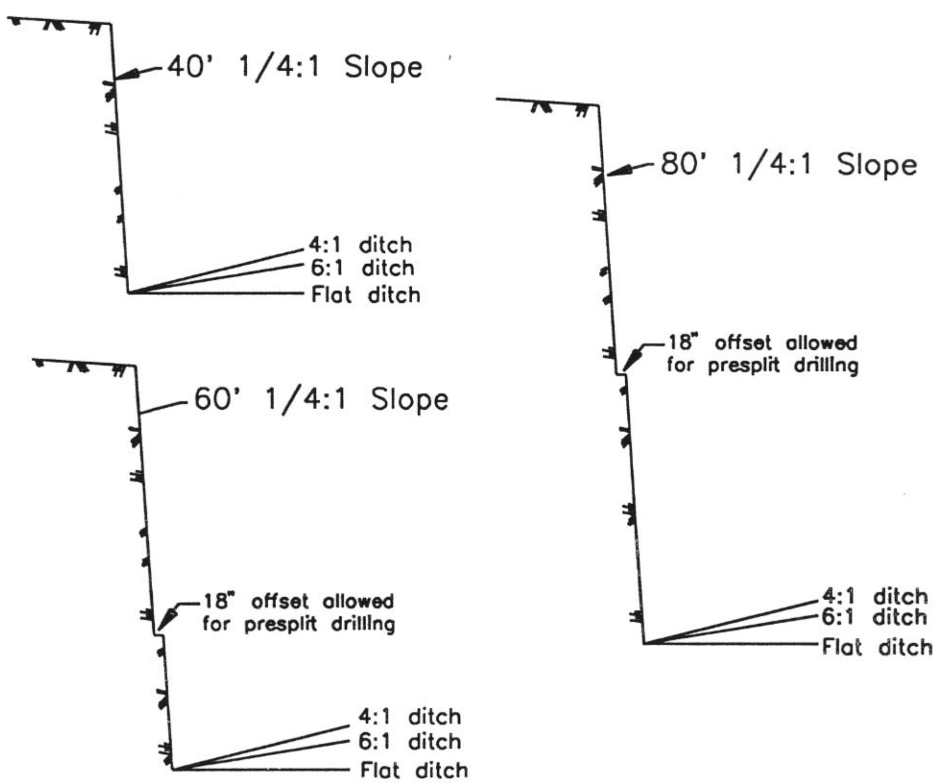


Figure 2.3: Slope and Ditch Configurations

rocks were rolled. Eight hundred twenty-five rocks were rolled from each of the three slope heights, 275 rocks for each of the three ditch shapes. Each ditch shape received 100 rocks with an average diameter of 1 foot, 100 rocks having an average diameter of 2 feet and 75 with an average diameter of 3 feet. The final set of 275 rocks was rolled into the Ritchie ditch. The test data is included in Appendix A.

In most cases, two values were recorded for each rock that was dropped, the rock's impact and roll out distance. A third value called the "furthest distance" was recorded to aid in the evaluation of roll back. Each of these terms is described in a subsequent section.

2.3 SLOPE EFFECTS AND IMPACT DISTANCE

A ditch's shape, whether flat or inclined, has no influence on where a rock will impact the ditch. Conversely, slope irregularities commonly referred to as "launch features", can greatly influence a rockfall's point of impact when the rock bounces off them during trajectory. Even though we tested a presplit slope that was relatively smooth and uniform, the effects of several "launch features" were clearly evident. These features, when combined with over and under steepened portions of the slope had a profound effect on rockfall path. As testing continued, particular prevalent rockfall paths became evident. Figure 2.6 shows a representation of rocks falling from

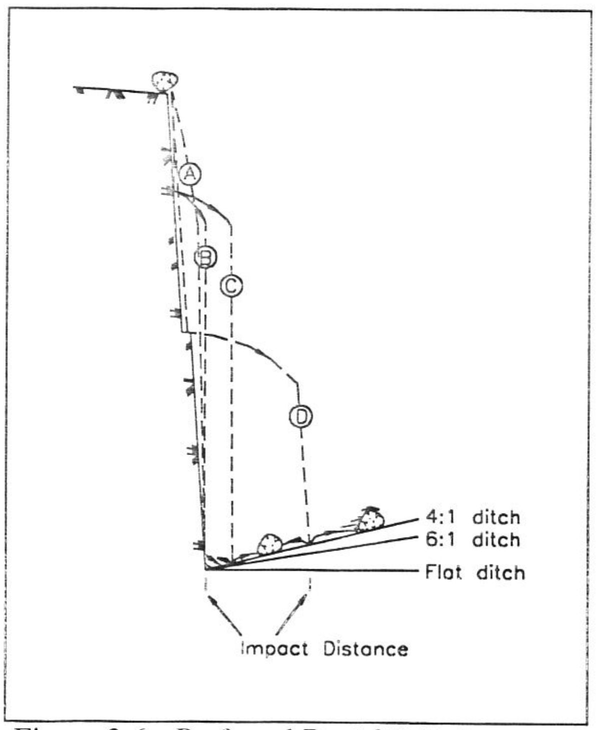


Figure 2.6 Preferred Rockfall Paths.

an 80-foot slope into a 4:1 ditch. The most common preferred paths for this slope are labeled 'A', 'B', 'C' and 'D'. Rocks which fall along path 'A' do not hit the slope until just before histogram for each slope height includes the impact data points from all ditch shapes. These histograms provide a graphical representation of frequency, or how often a certain impact value was recorded. For example, referring to the 40-foot slope graph, the impact distance with the greatest frequency was 2 feet. A comparison of these histograms and average impact values confirms that average impact distance increases with increasing slope height.

2.4 DITCH SHAPE AND ROLL OUT

Ditches with slopes ranging between flat and 4:1 are common in modern construction. Figure 2.10 shows a rock falling from an 80-foot slope, engaging a launch feature and impacting a 4:1 ditch at point 'A'. One of four outcomes are typically possible: 1) The rock remains at the point of impact, 2) The rock rolls back into the ditch and comes to rest at position 'C', 3) The rock rolls toward the road and comes to rest at position 'B', or 4) The rock rolls to position 'B', then rolls back into the ditch, and comes to rest at position 'C'.

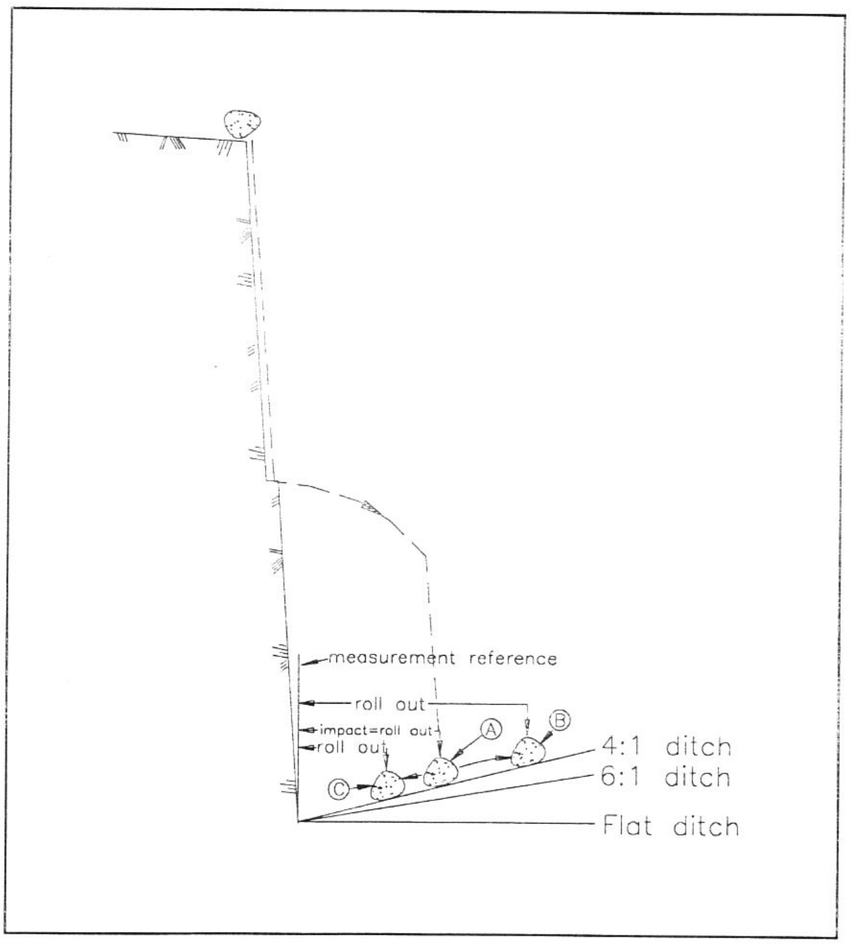


Figure 2.10: Definition of Roll Out

Outcome four represents a special case referred to as "roll back" and will be discussed separately in a later section. Roll out defined this way is simply the measured distance between the toe of the slope and the point at which the rock comes to rest.

Figure 2.11 shows roll out histograms for the 80-foot slope, separated by ditch shape. Histograms for the 40 and 60-foot slopes are included in Appendix B.

A discrepancy exists in the 80-foot slope 4:1 ditch data as it is shown. Due to limitations encountered during the excavation and reshaping of the 4:1 ditch, the actual ditch width was constrained to 35 feet. During previous tests for the 40 and 60-foot slopes, the fallout area width was large enough to accommodate all roll outs. Having only 35 feet available for the 80-foot high slope test allowed approximately 3% of the rocks to roll beyond the edge of the sloped ditch and out onto a flatter slope. This caused the distribution to have an artificially long run out. The measurements from these rocks were removed from the data set in the succeeding analysis.

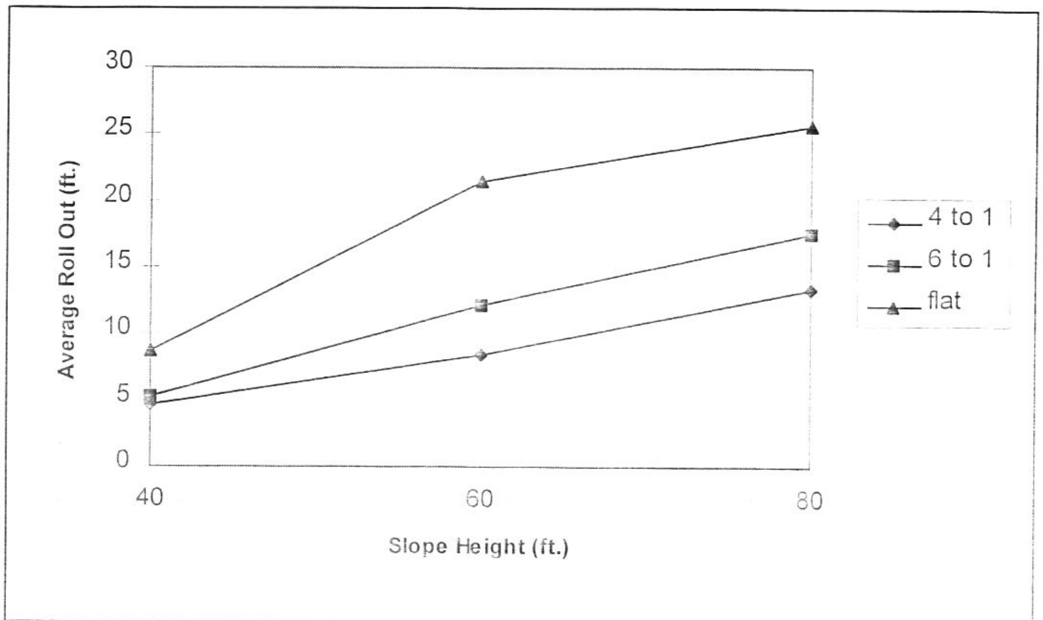


Figure 2.12: Average Roll Out vs. Slope Height

Two conclusions can be drawn from a comparison of the histograms, steeper ditches tend to retard roll out and taller slopes tend to produce larger average roll outs. Figure 2.12 was compiled from all the histogram sets and illustrates these relationships well. Using the flat shaped fallout area as a basis, the average roll out was reduced by 38% and 58% in the 6:1 and 4:1 ditches, respectively. Taller slopes tend to produce larger average roll outs because rocks falling from higher slopes obtain greater momentum. This momentum can be transferred to an enhanced launching effect upon impact with the cutslope or greater roll out in the fallout area.

2.5 IMPACT VERSUS ROLL OUT

Impact and roll out distances were recorded for each rock. Figure 2.13 is an example of an impact versus roll out graph. This particular graph represents data from the 40-foot slope and 6:1 ditch. Similar graphs for other ditch shapes and other slopes are included in Appendix C. These graphs show the frequency of rocks with the same impact and roll out values. Double digit numbers are circled. The basic relationships of preferred path can be seen in this type of

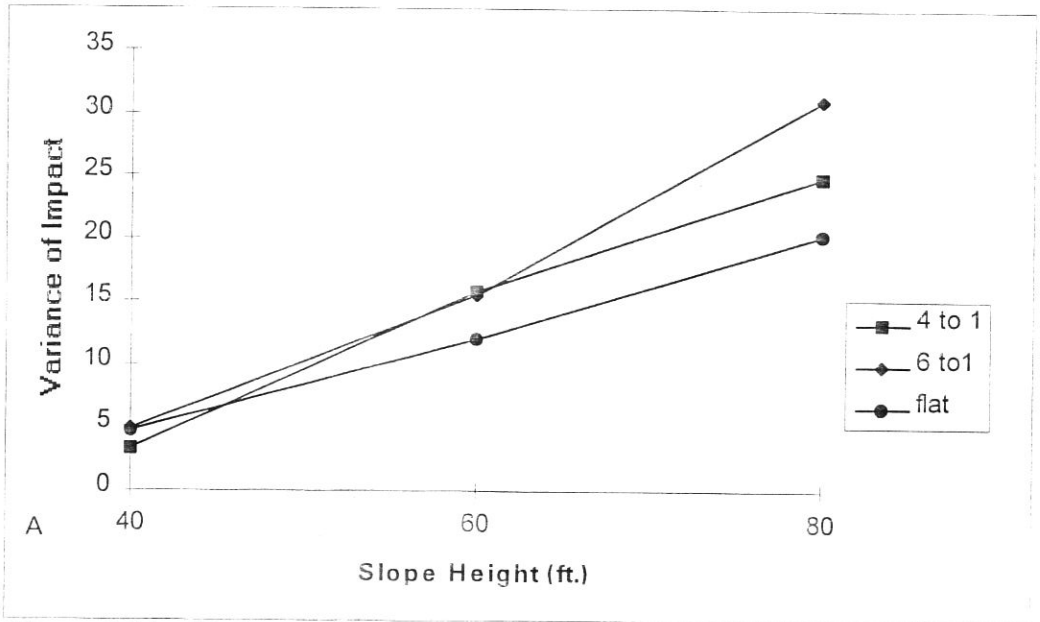


Figure 2.14: Variance of Impact by Ditch Shape

distance is independent of ditch shape the curves are seen to cross each other at various points. Figure 2.15 shows the variance of roll out plotted against slope height. In each case, roll out becomes more variable with increasing slope height and flattening of the ditch. These relationships are particularly pronounced for flat ditches at greater slope heights.

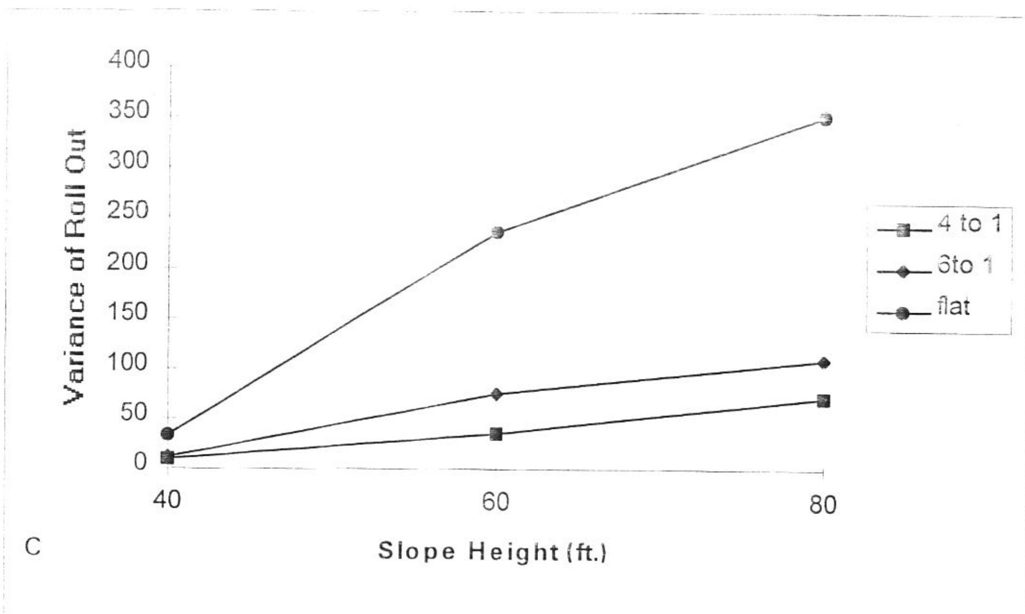


Figure 2.15: Variance of Roll Out by Ditch Shape

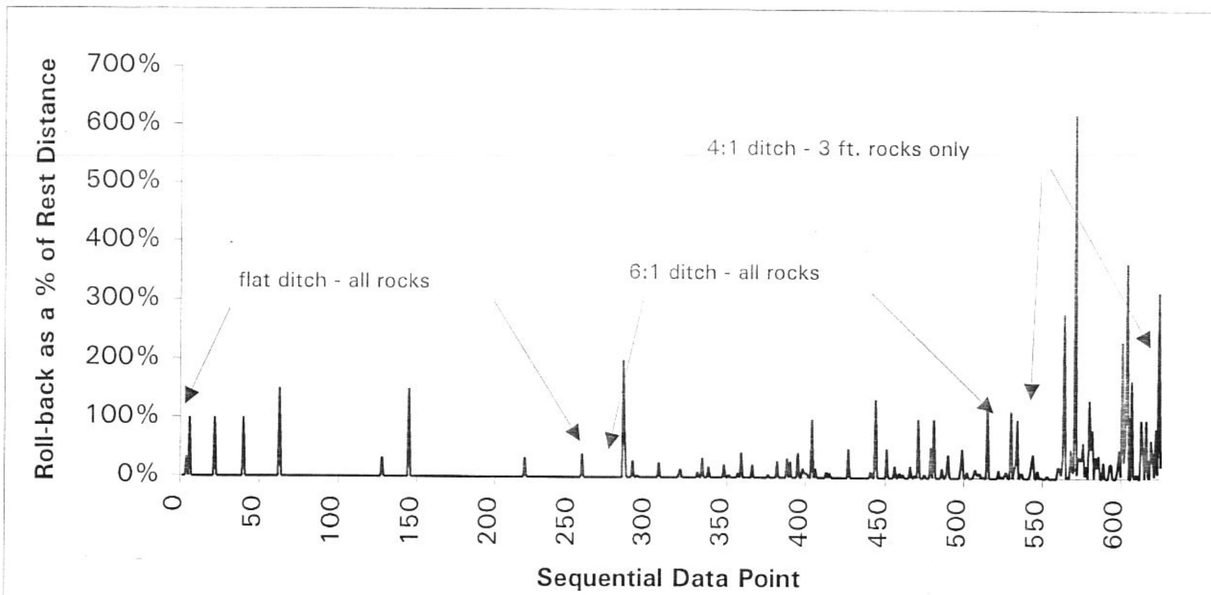
From these two graphs we can conclude that taller slopes produce impact distances that are more variable and that roll out is more variable in both taller slopes and in flatter ditches. It follows that taller slopes require wider or steeper sloped ditches in order to provide an equivalent degree

Usually, when roll back occurred, it amounted to a rock diameter or two. Intuitively, we considered roll back insignificant. However, while testing the 80-foot slope we noticed a few rocks that exhibited large roll back values. This raised questions about our earlier assessment. Obviously, if roll back was significant and we ignored it, the ditches we recommended might be undersized.

In order to better understand roll back, we began to record a third field measurement, the "furthest distance." Furthest distance is defined as the maximum distance away from the toe of the slope obtained by a rock. This value was recorded for the remainder of the rocks tested, a total of 625. We evaluated roll back by calculating it as a percentage of where a rock finally came to rest. The following example illustrates this.

Rock A impacts the ditch, rolls out to a furthest distance of 35 feet, rolls back two feet, and comes to rest 33 feet from the toe of the slope. In this case, a roll back of two feet amounts to 6% of the conventional roll out value of 33 feet.

Figure 2.17 shows roll back calculated in this way for all 625 rocks. Only 2% of rocks had roll



Roll-back as a % of Rest Distance	total rocks = 625 ave. = 10%	minimum = 0 % maximum = 620%	variance = 16% median = 0 %

Figure 2.17: Roll Back as a Percentage of Rest Distance

backs of 100% or more. One notable rock had a roll back of 620%. Even with these extreme cases included, average roll back amounted to only 10%. The mode or most common value was 0%. Given that this is a minimal value and considering that our tests were conservative by nature (all rocks rolled from the top of each slope tested), we elected to disregard roll back as significant.

2.8 THE RITCHIE COMPARISON

A. M. Ritchie published his pioneering work in 1963. For most states it remains the basis for fallout area design. For comparison purposes, the ditch we tested was shaped and sized for an 80-foot slope according to the more conservative design chart (Figure 1.2) that is based on the Ritchie criteria. Frequency histograms for the Ritchie test are shown in Appendix D.

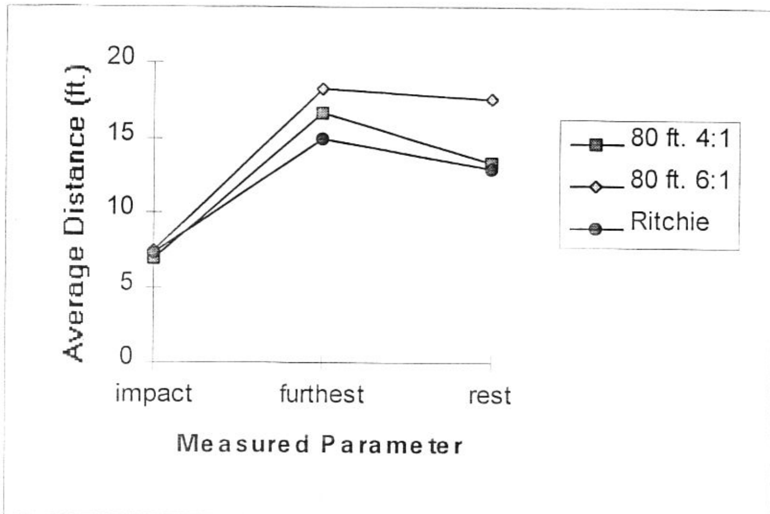


Figure 2.19: Ritchie Ditch Comparison

Figure 2.19 shows the comparison between the Ritchie test ditch data and the data obtained for the 80-foot slope for both 4:1 and 6:1 ditches. Predictably, the average impact distances for the three ditch shapes are identical. Where roll out is concerned, the Ritchie ditch out performs both the 6:1 and 4:1 ditch shapes. It shows a 2 to 4-foot advantage in furthest distance and up to a 5-foot advantage in rest distance.

Figure 2.20 shows the percent of rocks retained versus roll out distance for the tested Ritchie ditch. Both the "furthest distance" and "come to rest" curves are shown. The area between them represents roll back.

The actual width of the ditch we tested was 24 feet. Eight percent of the rocks rolled escaped this ditch. A ditch designed to the exact Ritchie criteria (20-feet wide) would have allowed 41 rocks or about 15% of the total to escape the confines of the ditch. Of these, 3 rocks would have launched beyond the ditch and the remaining 38 would have rolled through. Clearly, for this slope at least, the Ritchie criteria is not as conservative as some had previously thought.

Our Ritchie ditch obtained good furthest and rest distance numbers at the expense of allowing a relatively high number of rocks to reach the roadway. The most effective features of the Ritchie ditch are its overall depth and steep 1:1 backslope. These features, however, are rarely incorporated into modern ditches primarily because ditches this deep are hard to access by cleaning crews and the steep backslope offers no chance of recovery for the errant driver.

3.0 CONCLUSIONS

3.1 DESIGN GUIDELINES

In the early stages of dealing with potential or proven rockfall sites, designers are usually faced with evaluating the frequency and severity of the rockfall hazard. Even though rockfall related traffic accidents receive an inordinate amount of publicity they are still a relatively rare event. The probability of being involved in one is quite low. Before such an accident can occur, at least three conditions must be satisfied.

1. A rockfall event must take place.
2. The rock must enter the roadway by clearing or rolling through the fallout area.
3. The rock must strike or be struck by a vehicle.

A number of factors play a role in defining the rockfall hazard inherent to a particular site. An accepted methodology for evaluating and quantifying this hazard is the Rockfall Hazard Rating System (9). The system evaluates site conditions that are related to risk. These 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 an agency to decide how and where to spend their limited safety budget.

Because the actual risk of injury from a rockfall event is so low, the goal of rockfall retention is normally less than 100% control. The unreasonably high cost associated with 100% rockfall protection can usually not be justified by the risk to highway users. If some mitigation is decided upon and includes the construction or improvement of a fallout area, the ultimate ditch effectiveness must be considered. Through this research, we have developed design guideline charts (Figures 3.1-3.10) that can be used to evaluate this effectiveness. Agencies now have a quantitative tool with which to design fallout areas for 0.25:1 slopes based on a planned percentage of rockfall retention.

It is important to note that these design curves are conservative. In general, basalt is a durable rock which rebounds after impact and rolls well. In addition, all of the rocks started from the top of each slope height tested. In reality, rocks can and do fall from any number of heights in an actual highway cut slope. The result is that rocks which fall from heights less than the maximum or that disintegrate at impact, will not require the entire ditch to achieve the specified containment. Understanding this built in conservatism is important to the designer because changing slope heights, rock qualities and rockfall sources will often present unique problems. Examples of some applications can be found in Appendix F.

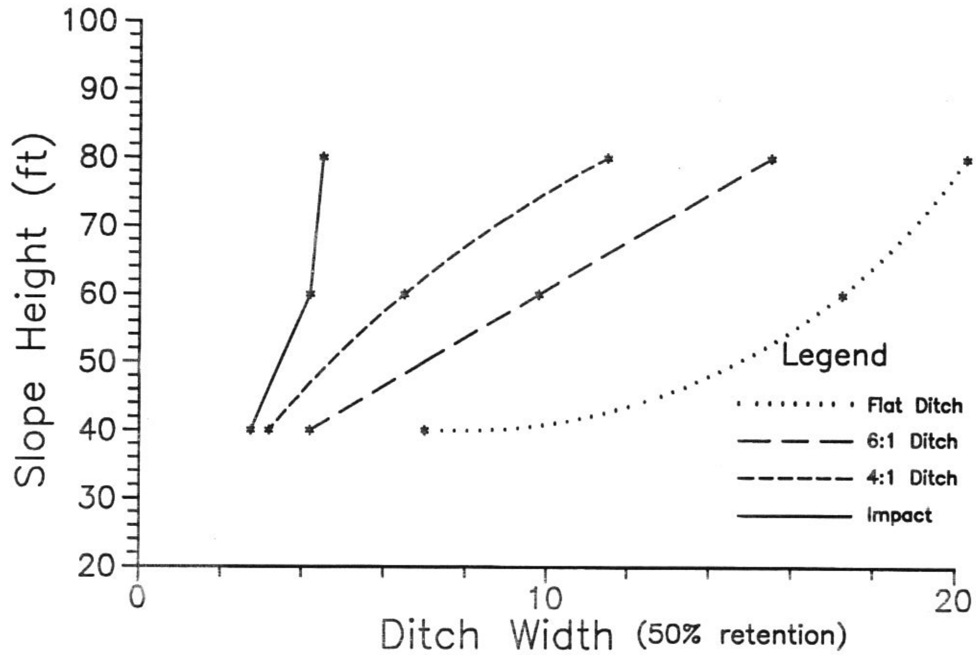


Figure 3.3: Fallout Design Curves for 50% Retention.

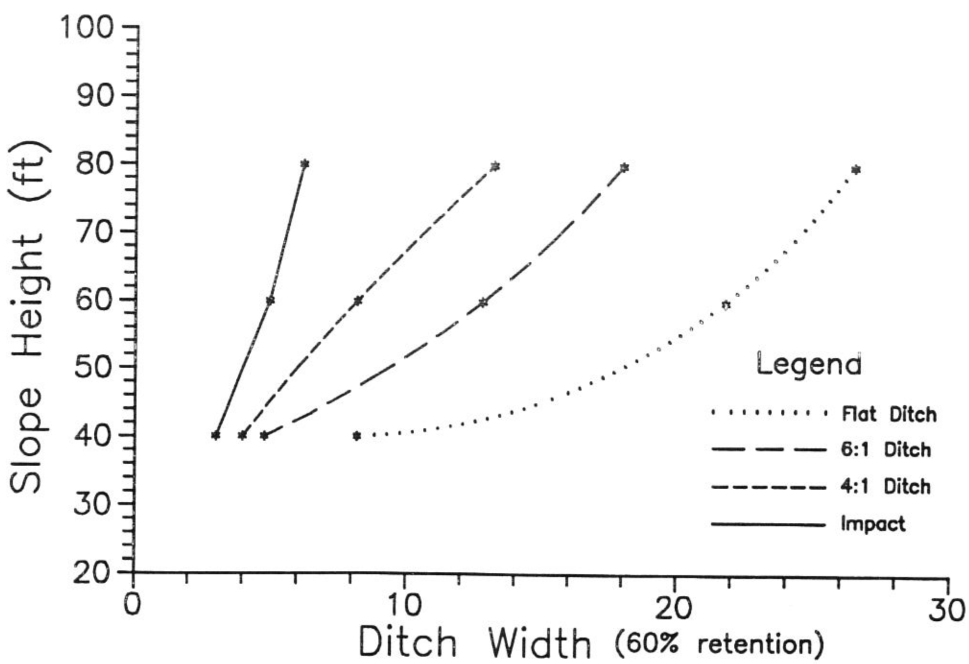


Figure 3.4: Fallout Design Curves for 60% Retention.

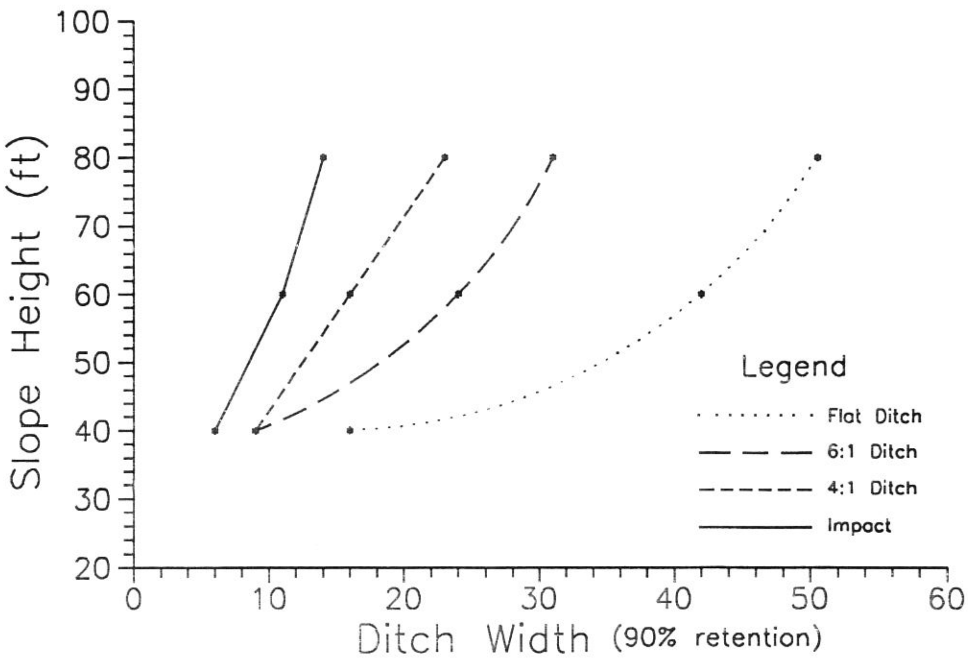


Figure 3.7: Fallout Design Curves for 90% Retention.

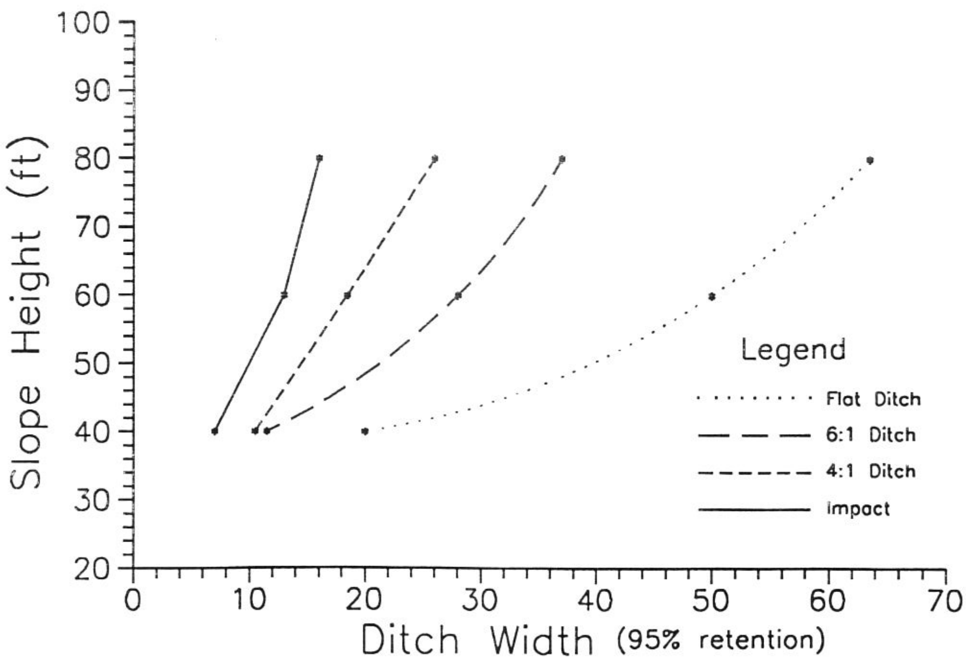


Figure 3.8: Fallout Design Curves for 95% Retention.

3.2 VALIDITY OF RESEARCH

Like all research which collects measurement data, analyzes the data and draws conclusions from them, validity depends on:

1. The thoroughness of experimental procedure,
2. The completeness of analysis, and
3. The correctness of original assumptions.

In the beginning, we used our speculation about rockfall behavior to formulate assumptions and base our experimental designs. To the best of our knowledge, prior to this, no one had ever used basic statistics to evaluate actual rockfall. We did not know what characteristic shape the distributions would take or how many rocks would have to be rolled to obtain them. So we began by rolling rocks, basing our research on the assumption that the measurements we recorded would provide us with the information required to construct a new design guideline for 0.25:1 slopes.

Based on material we have presented in the text we feel we have succeeded. Early on it became apparent that we were rolling a sufficient number of rocks to establish characteristic distributions. In fact, most relationships were evident using smaller data sets. To be certain however, we continued to roll the "standard suite" of 275 rocks into each ditch shape for each slope height we tested. Using a combination of graphical and statistical techniques provided an appropriate level of analysis and a balance between theory, experiment and conclusion that reaches the broadest possible audience.

3.3 RECOMMENDATIONS FOR IMPLEMENTATION

Because of economic concerns, difficulties with ditch clean out, constructability and the need to have a gently sloped shoulder from which an errant automobile may recover, ditches with true Ritchie shapes are seldom built. Instead, uniformly sloping 4:1 and 6:1 fallout areas are the norm. It seems ironic then that many states including Oregon, use the Ritchie criteria to size fallout areas for depth and width. We in effect, rely on a standard that has been modified to meet needs that have nothing to do with rockfall catchment.

In order to remedy this, we recommend that ODOT adopt our design charts as the new "Oregon Ditch" standard for 0.25:1 slopes in any new construction or remedial action. Since our ditches are uniformly sloped, a desirable ditch shape will be maintained. Because our system requires the selection of a percentage of rocks to be stopped, ODOT will need to evaluate legal implications and establish a policy based on acceptable risk. We can act as a resource in this endeavor.

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APPENDIX A

FIELD DATA

		40' Slope			
Flat Ditch		Flat Ditch		Flat Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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

		40' Slope			
6:1 Ditch		6:1 Ditch		6:1 Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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

		40' Slope			
4:1 Ditch		4:1 Ditch		4:1 Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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

		60' Slope			
Flat Ditch		Flat Ditch		Flat Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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	6
5	6	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' Slope			
6:1 Ditch		6:1 Ditch		6:1 Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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
14	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	4	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	8	18	2	17
13	14	9	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' Slope			
4:1 Ditch		4:1 Ditch		4:1 Ditch	
1' Rocks		2' Rocks		3' Rocks	
Impact	Roll Out	Impact	Roll Out	Impact	Roll Out
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	14
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

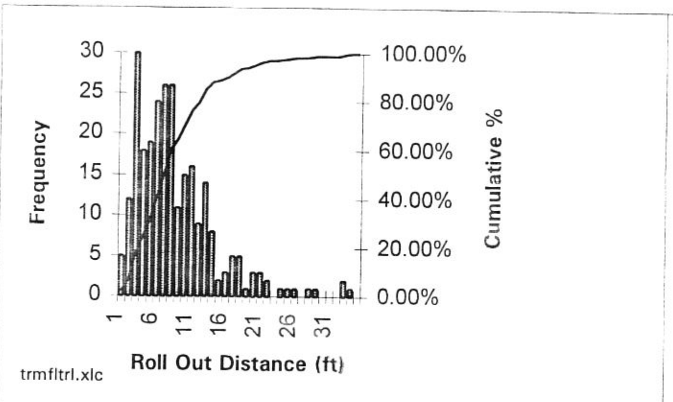
			80' Slope					
Flat Ditch			Flat Ditch			Flat Ditch		
1' Rocks			2' Rocks			3' Rocks		
Impact	Roll Out	Furthest	Impact	Roll Out	Furthest	Impact	Roll Out	Furthest
2	2	2	7	61	61	10	37	37
4	34	34	14	69	69	3	99	99
1	41	41	1	48	48	5	43	43
4	3	4	16	20	20	2	53	53
1	41	41	2	31	31	11	32	32
4	2	4	1	10	10	4	25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

6:1 Ditch			6:1 Ditch			6:1 Ditch		
1' Rocks			2' Rocks			3' Rocks		
Impact	Roll Out	Furthest	Impact	Roll Out	Furthest	Impact	Roll Out	Furthest
4	4	4	19	19	20	3	26	26
16	23	23	7	7	7	11	20	20
16	29	29	7	9	9	6	19	19
1	28	28	11	13	13	3	15	23
3	9	9	4	15	15	9	11	11
14	19	19	8	16	16	5	5	10
7	14	14	9	7	9	9	23	23
3	1	3	4	34	34	7	18	18
5	3	5	2	56	56	3	7	7
6	6	6	7	11	11	5	10	10
1	17	17	5	10	10	1	37	43
4	18	18	5	11	11	10	15	15
1	21	21	4	3	4	20	20	20
9	7	9	12	32	32	5	25	27
5	7	7	4	7	9	5	5	7
1	11	11	18	27	27	1	8	8
25	37	38	2	24	24	2	43	43
3	4	4	8	10	10	10	23	23
6	20	20	2	23	23	4	7	7
10	11	11	10	7	10	10	20	20
17	18	18	12	18	18	4	42	42
20	22	22	14	18	18	9	24	24
3	3	3	4	6	7	11	9	11
1	15	15	11	28	30	5	4	6
23	47	47	10	25	27	18	37	37
13	16	16	2	20	21	7	14	14
10	12	12	4	5	5	2	27	30
16	21	21	4	5	5	2	27	27
17	18	18	14	7	14	12	12	12
7	13	13	9	15	15	5	5	5
10	8	10	7	6	7	2	26	27
25	26	26	5	6	6	6	26	30
1	17	17	3	7	7	3	13	14
12	12	12	23	23	23	4	24	25
1	17	17	2	13	13	10	11	12
5	5	5	3	14	14	5	5	5
9	17	17	23	28	28	4	35	36
1	30	30	7	10	11	12	26	26
3	16	16	4	5	5	10	12	12
2	8	8	10	25	27	7	3	7
4	10	10	8	9	9	8	28	28
14	18	18	5	7	7	2	45	45
10	12	12	9	27	27	9	16	16
17	18	19	2	31	31	5	7	7
8	7	8	2	22	22	3	55	55
10	12	12	3	18	18	6	10	10
1	17	17	2	33	33	3	35	40
8	8	8	4	14	14	7	25	25
6	18	18	3	16	16	3	29	30
4	14	14	3	11	11	4	38	38

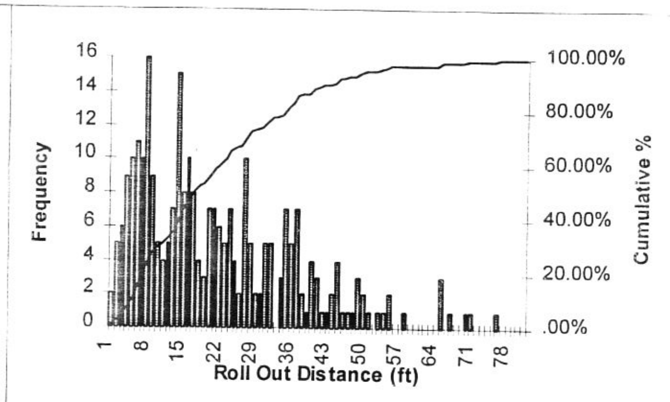
				80' Slope				
4:1 Ditch			4:1 Ditch			4:1 Ditch		
1' Rocks			2' Rocks			3' Rocks		
Impact	Roll Out	Furthest	Impact	Roll Out	Furthest	Impact	Roll Out	Furthest
1	14		3	6		5	22	22
12	14		3	6		3	16	16
8	8		19	17		4	21	22
1	16		3	28		6	41	41
12	15		2	24		9	27	27
7	24		14	13		9	9	9
5	8		4	12		6	14	14
11	12		10	7		5	13	13
7	7		4	18		4	5	5
12	14		3	3		3	10	12
8	17		2	7		10	12	14
7	7		1	21		18	17	18
14	19		1	28		12	15	20
7	3		12	16		19	5	19
16	17		1	6		3	12	12
5	3		15	21		4	46	48
3	3		5	7		7	7	7
6	11		7	17		9	6	9
1	16		6	19		3	28	31
7	7		3	7		5	15	17
8	10		3	12		3	5	36
7	7		3	13		3	44	47
2	27		4	17		10	8	11
4	7		18	12		8	6	8
2	29		2	8		10	13	17
4	4		15	17		9	13	21
15	12		2	2		5	23	24
4	6		13	11		6	18	22
4	5		6	2		3	14	14
4	5		4	15		4	9	21
2	2		2	7		6	4	6
2	25		1	22		11	6	11
3	7		17	21		5	5	5
7	5		2	3		3	8	11
5	4		2	19		9	11	13
8	12		5	17		14	10	14
7	3		2	24		3	11	11
14	16		4	16		9	11	11
22	34		2	11		9	7	9
3	7		6	12		3	23	23
9	10		3	4		2	6	6
5	3		5	15		4	4	4
10	11		4	3		2	24	30
2	2		14	22		6	12	15
14	12		3	11		5	6	6
10	12		3	7		12	22	22
14	14		5	14		5	5	5
9	8		1	3		14	12	14
10	8		2	25		2	8	12
20	9		2	32		2	22	23

APPENDIX B

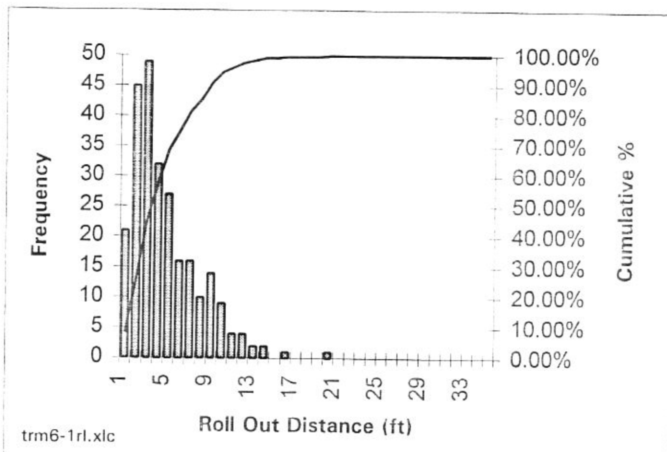
40 AND 60-FOOT ROLL OUT HISTOGRAMS



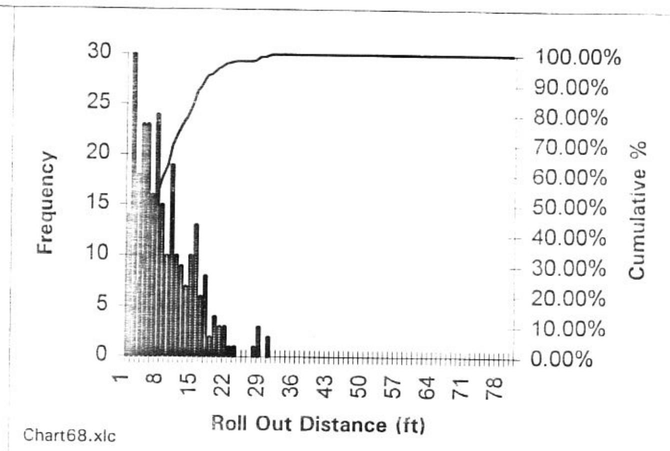
40' Slope Flat Ditch	total rocks = 264 ave. roll out = 8.7 ft.	60th percentile = 8 ft. 80th percentile = 12 ft.



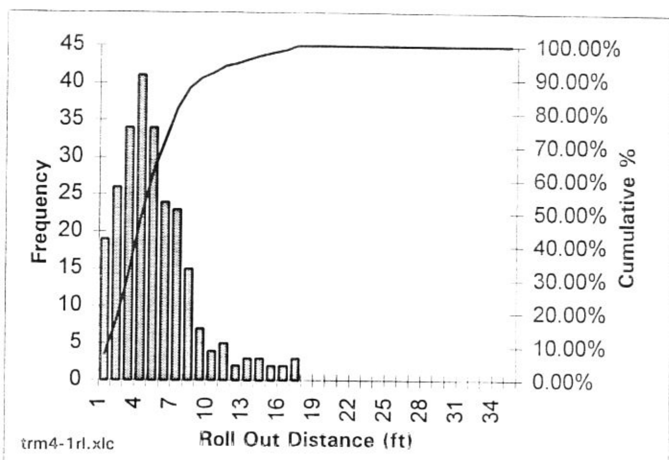
60' Slope Flat Ditch	total rocks = 275 ave. roll out = 21.4 ft.	60th percentile = 22 ft. 80th percentile = 35 ft.



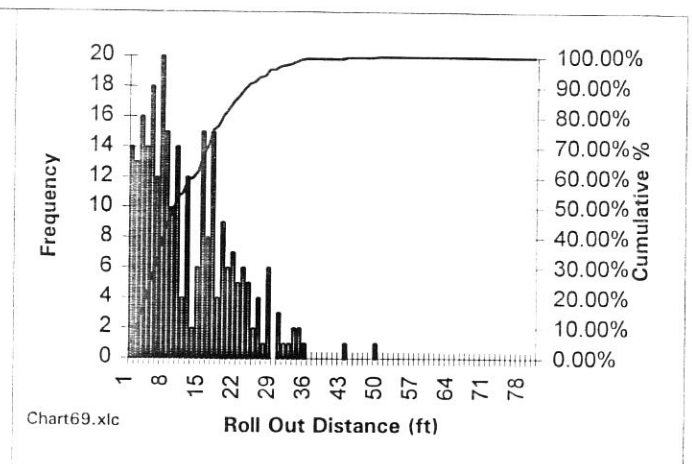
40' Slope 6:1 Ditch	total rocks = 246 ave. roll out = 5.2 ft.	60th percentile = 5 ft. 80th percentile = 7 ft.



60' Slope 6:1 Ditch	total rocks = 275 ave. roll out = 12.1 ft.	60th percentile = 14 ft. 80th percentile = 19 ft.



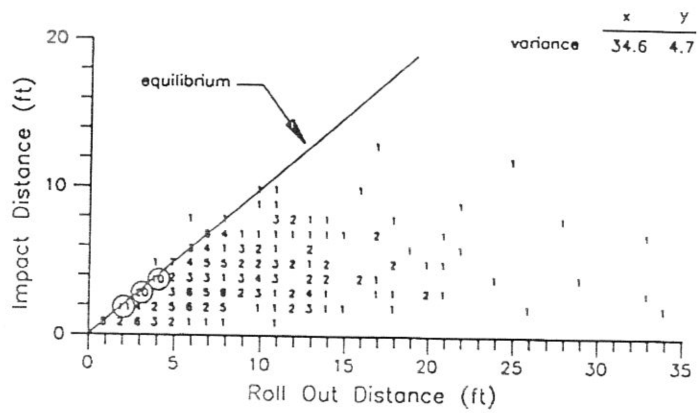
40' Slope 4:1 Ditch	total rocks = 252 ave. roll out = 4.7 ft.	60th percentile = 5 ft. 80th percentile = 7 ft.



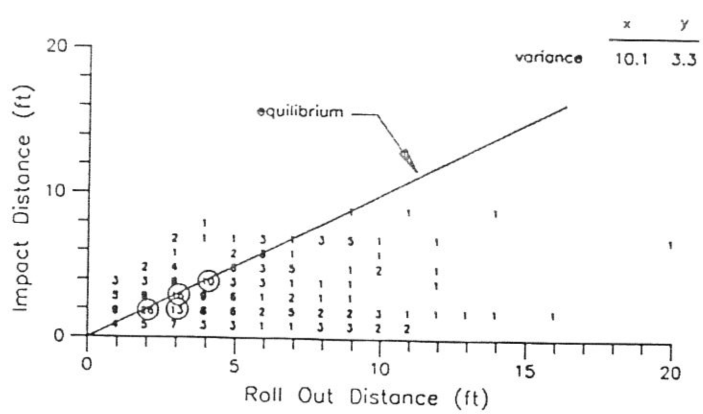
60' Slope 4:1 Ditch	total rocks = 275 ave. roll out = 8.4 ft.	60th percentile = 9 ft. 80th percentile = 14 ft.

APPENDIX C

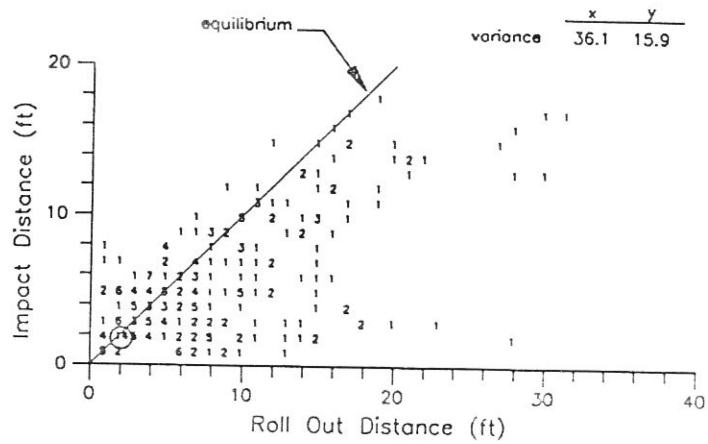
IMPACT VERSUS ROLL OUT GRAPHS



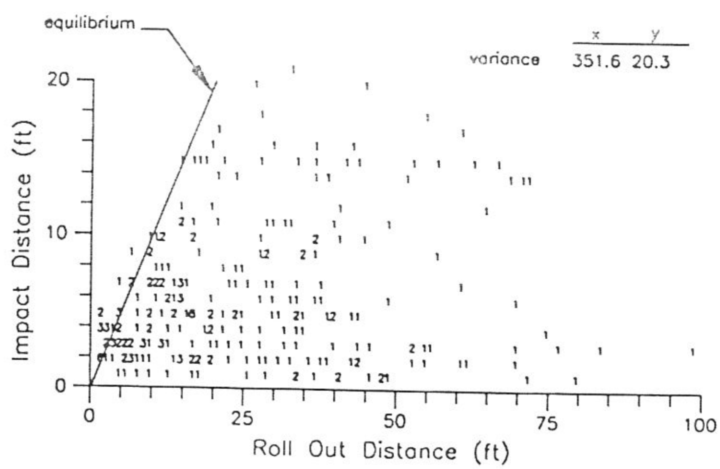
40' Slope Flat Ditch



40' Slope 4:1 Ditch



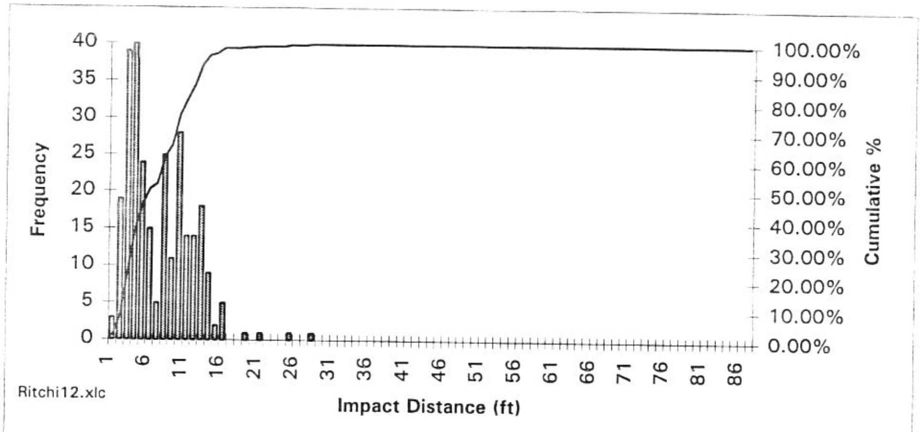
60' Slope 4:1 Ditch



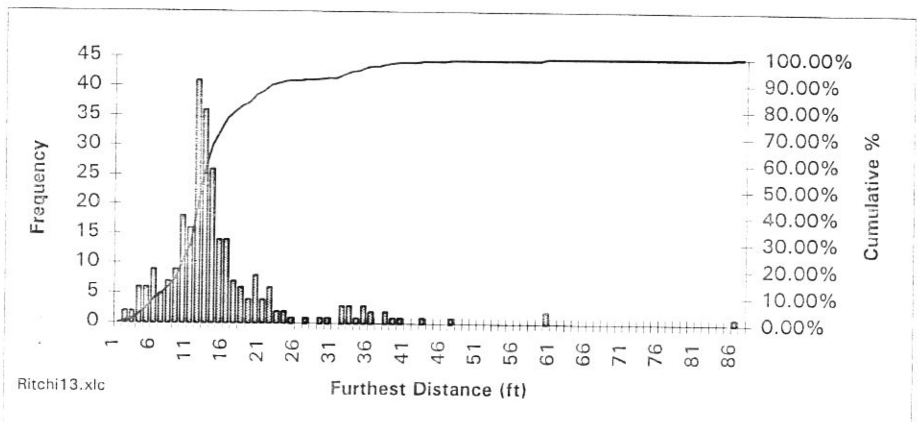
80' Slope Flat Ditch

APPENDIX D

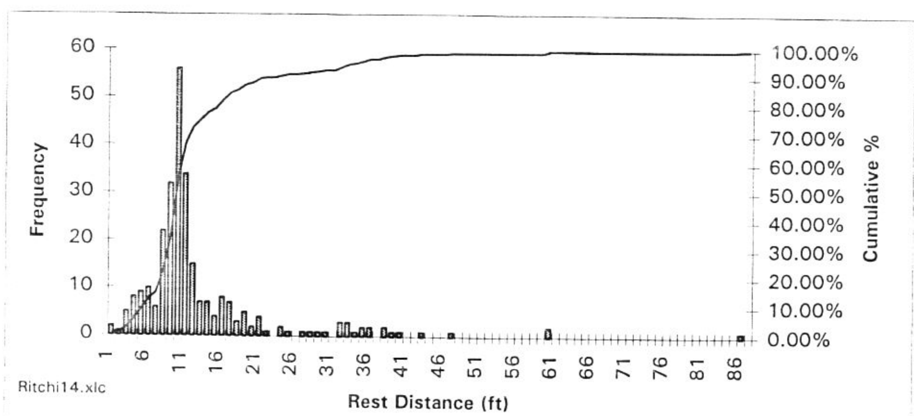
RITCHIE TEST HISTOGRAMS



Ritchie Ditch 80' Impact			
	total rocks = 275	40th percentile = 5 ft.	80th percentile = 11 ft.
	ave. impact = 7.3 ft.	60th percentile = 8 ft.	100th percentile = 28 ft.



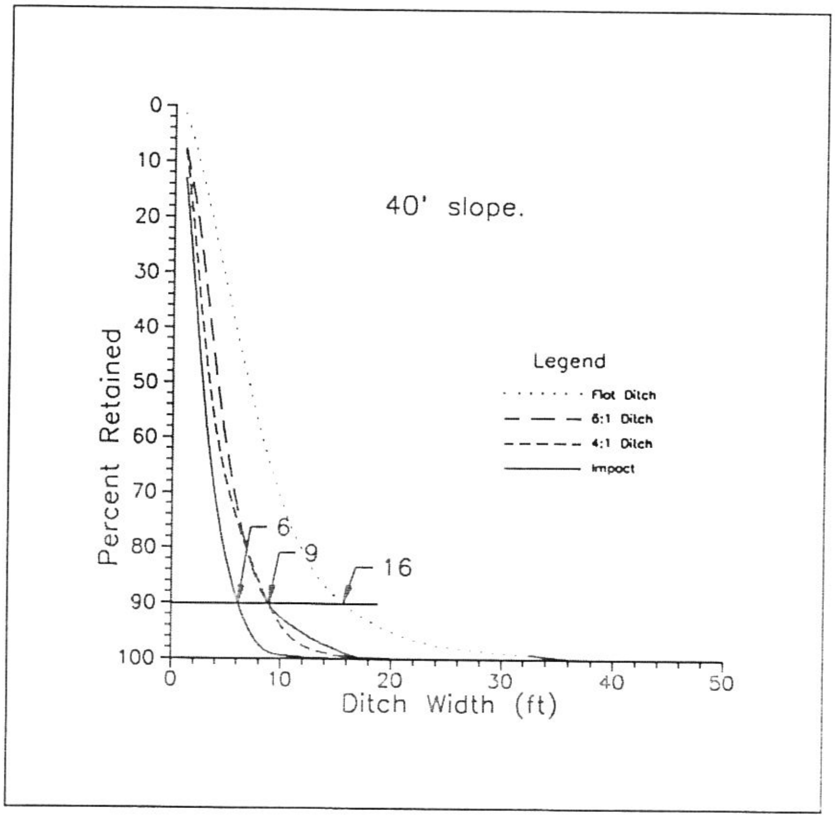
Ritchie Ditch 80' Furthest			
	total rocks = 275	40th percentile = 12 ft.	80th percentile = 18 ft.
	ave. roll out = 15 ft.	60th percentile = 14 ft.	100th percentile = 86 ft.

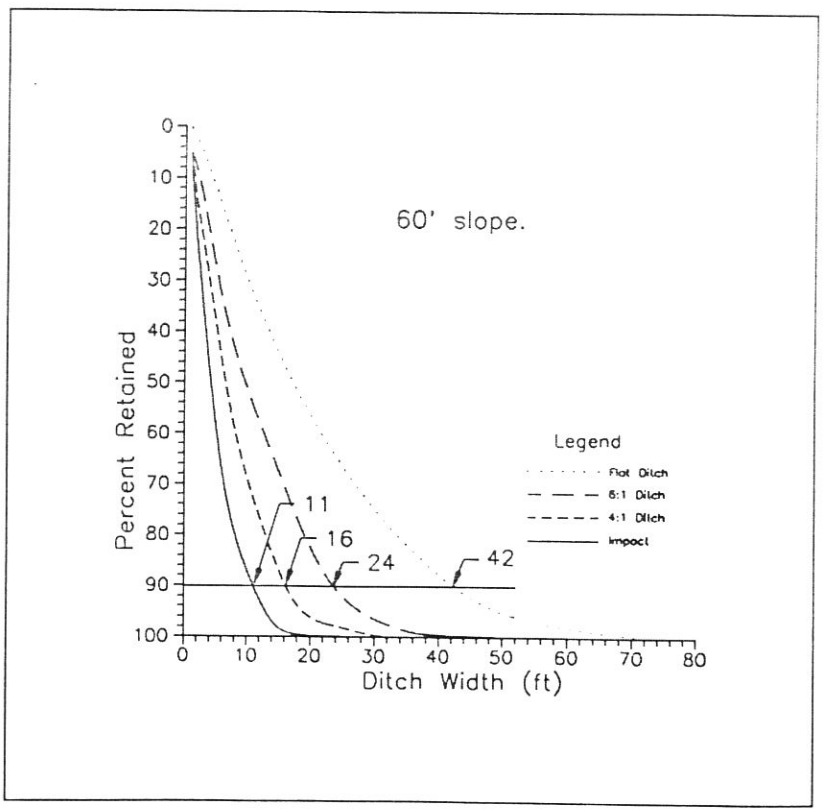


Ritchie Ditch 80' Rest			
	total rocks = 275	40th percentile = 10 ft.	80th percentile = 16 ft.
	ave. roll out = 13 ft.	60th percentile = 11ft.	100th percentile = 86 ft.

APPENDIX E

CUMULATIVE PERCENTAGE CURVES


40' slope.
Percent Retained
Ditch Width (ft)
Legend
Flat Ditch
6:1 Ditch
4:1 Ditch
Impact
6
9
16
0
10
20
30
40
50
60
70
80
90
100


60' slope.
Percent Retained
Ditch Width (ft)
Legend
Flat Ditch
6:1 Ditch
4:1 Ditch
Impact
11
16
24
42
0
10
20
30
40
50
60
70
80
90
100

APPENDIX F

APPLICATIONS

F.0 APPLICATIONS

F.1 EXISTING SLOPE EVALUATIONS

Figure F.1 shows the percentage retained curves for the 80-foot slope. In this type of graph, ditch width is plotted against a "retained cumulative percentage." For example, a line is shown that denotes the 90th percentile. This line intersects the impact curve at a ditch width of 14 feet. This means that 90% of the rocks landed (impacted) within a 14-foot wide zone adjacent to the toe of the slope. Following this 90th percentile line across, the intersection with the 4:1 ditch curve occurs at 24 feet meaning 90% of all rocks had roll outs less than or equal to this value. Using this approach, any combination of retained percentage and ditch width can be found for each of the ditches we tested. Similar graphs for 40-foot and 60-foot slopes are given in Appendix E.

Given these relationships, the effectiveness of ditches adjacent to existing 0.25:1 slopes can be evaluated. This is demonstrated in the following example:

An 80-foot high, 500-foot long highway cut has a rockfall problem. A site visit reveals that a small section possesses the greatest hazard. Rockfalls appear to be generated near the top of the cut. Ditch width is constant at 25 feet and most ditch slopes are approximately 4:1. However, the ditch grade changes to 6:1 or flatter in the problem area. Finding a ditch width of 25 feet in Figure F.1 and following it up to the 6:1 curve indicates that only 80% of the rocks falling into this section of the ditch can be expected to be retained. Approximately 20% of rocks are allowed to reach the roadway. Alternately, 92% of rockfalls are retained in a ditch of the same width with a 4:1 backslope; an increase in catchment of 12%. Recommending a simple regrading of the ditch to 4:1 would significantly increase ditch catchment and enhance public safety for a relatively low cost.

Using the data in this manner demonstrates a method for evaluating existing 0.25:1 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, ditch geometry may vary appreciably throughout a cut section. Because of this, a higher percentage of rocks may be retained than our design charts indicate. 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 ditch effectiveness is to be obtained.

A more practical approach is to reduce the potential for rock on the road along as many miles of roadway as is possible using the budget available. Hazard reduction, provides a larger benefit than if only a short section of a single 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 example illustrates such an approach:

Rockfall on the highway has been a serious problem along the high side of a 400-foot long through cut for many years. No fallout area was provided during the original construction. The agency would like to reduce the rockfall potential but is unsure what level of improvement

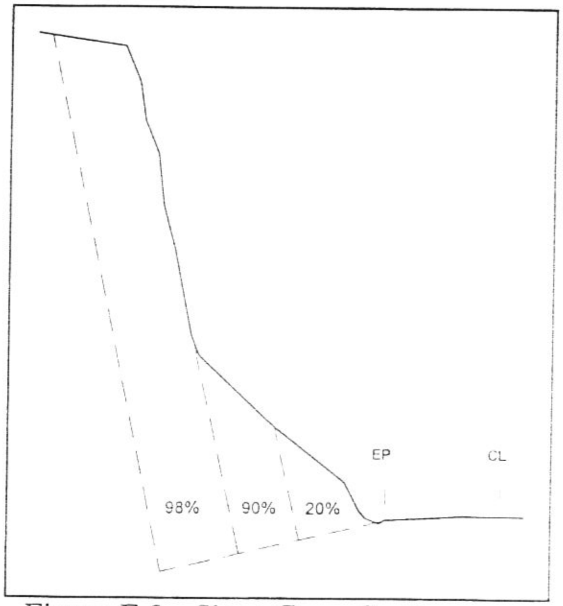


Figure F.2: Slope Cross-Section.

can be obtained for a reasonable investment. A cross section of the site is shown in Figure F.2. Rockfall is possible from anywhere on the slope. Because of the shape of the slope, excavation quantities will increase in a non-linear fashion as the ditch width is increased. Therefore, the cost of a small amount of increased width is low initially. As excavation of the entire slope is approached the cost of each increment of ditch width becomes higher. For this example, the ditch widths associated with a 20%, 90% and 98% improvement are shown.

The graph in Figure F.3 illustrates one approach to this problem. Different excavation costs based on ditch width are plotted against the percentage of rock that will be retained (for a specific slope height and ditch design). 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 discretionary