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New Risk–Consequence Rockfall Hazard Rating System for Missouri Highways Using Digital Image Analysis

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ABSTRACT

The Missouri Rockfall Hazard Rating System (MORFH RS) is a new scheme for rating rockfall hazards along the roads of the Missouri State highway system. Existing rating systems used in other jurisdictions focus on the risk of failure and ignore the consequence of failure, or they lump the ratings for risk and consequence together. Missouri highway rock cuts tend to have low heights but are typically highly weathered, with special problems from karst and paleokarst. In MORFH RS, risk and consequence factors are given equal weight but isolated from each other. MORFH RS utilizes two phases: 1) identification of the most potentially problematic rock cuts using mobile digital video logging; 2) characterization and prioritization of remediation for the potentially problematic rock cuts identified in phase 1, using MORFH RS. In phase 2 four types of parameters are evaluated: 1) parameters that can be measured on computer scaled video images; 2) parameters which are descriptive, and need field evaluation; 3) parameters which are obtained from MODOT records; 4) conditional parameters which are evaluated under specific conditions. Only those parameters were selected that were deemed meaningful and/or relatively easy to measure or estimate. Parameters were assigned to either a risk or consequence category or both. MORFH RS has been tested on sections of Missouri highways. About 300 rock cuts were evaluated and used to prepare, modify, test, and verify the system. Sensitivity analysis of the system was done by quantifying potential errors in the video measurements and by a rating comparison of 12 MODOT and University of Missouri-Rolla (UMR) personnel on 10 rock cuts along Highway 63.

INTRODUCTION

Problematic Rock Cuts and New Paradigms

Especially during the rainy and freeze–thaw seasons, rockfalls take place in both natural and man-made slopes along highway rock cuts. These rockfalls may block the roads, damage infrastructure, and cause injuries or fatalities. Many of these consequences remain unreported. Badger and Lowell (1992) summarized the experience of the Department of Highways in Washington State. They stated that "A significant number of accidents and nearly a half dozen fatalities have occurred because of highway rockfalls in the last 30 years . . . and . . . 45% of all unstable slope problems are rockfall related." Hungr and Evans (1989) mentioned that, in Canada, 13 people died because of highway rockfalls in the last 87 years, most of them on British Columbia highways.

Under the old paradigm, the response of a typical State Department of Transportation (DOT) is reactive: if a significant failure occurs, emergency funds are appropriated, and the individual rock cut is remediated. In the current litigious climate, the liability consequences of a rock failure are often very large, much larger than the cost of remediation. States are starting to recognize this, and are adapting a proactive approach based on a systematic identification, prioritization, and remediation of problem rock cuts.

Under the old paradigm, a detailed investigation and evaluation are required to evaluate the potential for rockfall at each rock cut. Factors such as unfavorable rock structure (discontinuities), adverse ground-water-related conditions, poor blasting practices during original construction or reconstruction, climatic changes, and weathering needed to be considered. Because this represents a large amount of work, it is not practical for routine analyses. Consequently, DOT's are turning to rockfall hazard rating classifications to speed up the analysis of potentially dangerous rock cuts.

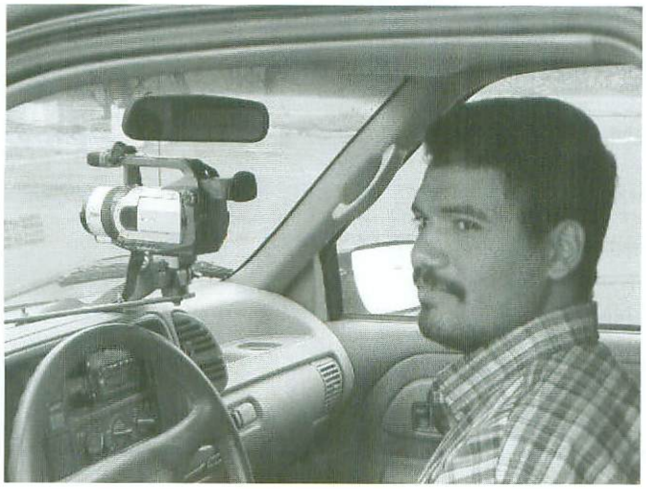


Figure 1. Digital camcorder mounted on vehicle dashboard.

There are several rockfall hazard rating systems proposed or in use today. These consider many factors, including geological factors on the slope and geometric factors, such as the size of the ditch below the slope. These are typically lumped together to produce a single number rating. In this paper, a new paradigm is introduced, whereby risk and consequence factors are considered separately.

Rock Mass Classification/Rating Systems

Classification Systems That Consider Geological Factors Only

The best methods for screening rock cuts are the classification/rating systems because they provide the ability to screen rock cuts in a short amount of time, separate the rock cuts that are fundamentally sound, and identify the rock cuts that have potential problems (Maerz et al., 2003). There are many examples for these classification systems, which include elements of design, such as Deere's rock-quality designation (RQD) system (Deere et al., 1969), Franklin's size-strength system (Franklin, 1986), Franklin's shale rating system (Franklin, 1983), Bieniawski's rock mass rating (RMR) system (Bieniawski, 1984), and Barton's Q system (Barton et al., 1974). In addition, there are several methods used for slopes. One of these methods is Romana's slope mass rating (SMR) (Romana, 1985). This system is for rock slopes and is based on Bieniawski's RMR system. These classification systems consider geological factors only and essentially classify risk only without considering the consequences of a failure.

Systems That Consider Rainfall As Well As Geological Factors

There are two systems that consider both geological factors and rainfall effect. One is the rock engineering system (RES) (Hudson, 1992), which uses the following parameters for the analysis of slope instability: lithology, folding, rainfall, previous instability, rock strength, weathering, slope orientation, slope height (SH), slope angle (SA), compaction, rock discontinuities, vicinity to faults, and hydraulic conditions. The other system is the rock mass instability index (RMIIj) developed by Ali and Hasan (2002), studying landslides in Bangladesh. They developed a new method to determine the degree of instability of slopes quantitatively, according to the cause and effect for each parameter in the RMIIj. There are some advantages of this method because it is easy to distinguish slopes based on their degree of instability. Higher values of RMIIj indicate higher degrees of slope instability. RMIIj is a quantitative representation for the degree of instability. For the RES system, it is hard to distinguish between stable and unstable slopes using field inspection. RMIIj is applied on landslides and not on rockfalls. In either of these systems, the consequences of the slope instability are not taken into account.

Rock Hazard Rating Systems

There are several rock hazard rating (RHR) systems that are designed for the highway rock cuts.

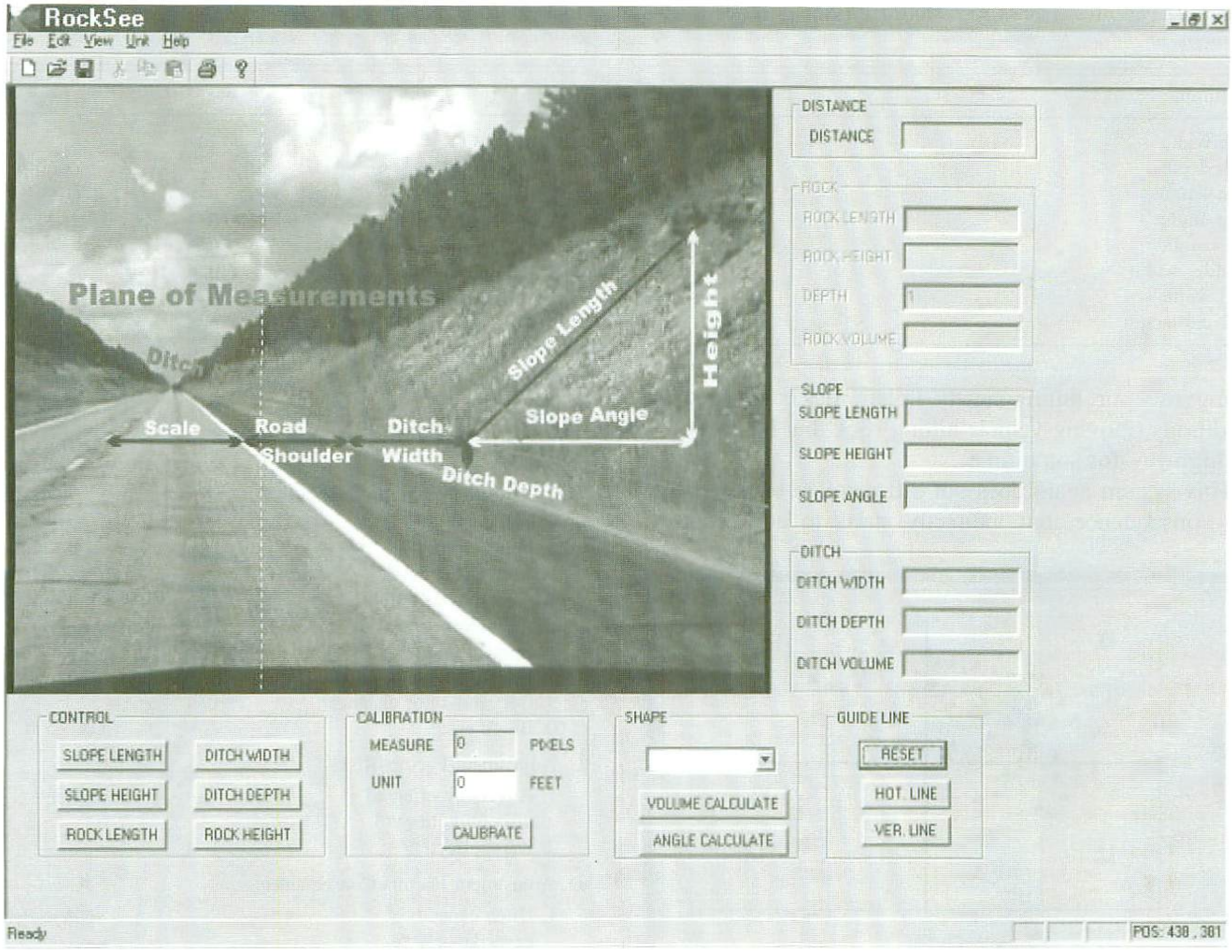
The Oregon RHR System

Oregon's RHR system (Pierson and Van Vickle, 1993) was designed for and tested on the relatively severe and high cuts in the mountainous areas of Oregon; consequently, it was built with insensitivity to small rock cuts. The detailed rating system uses 10 categories with 4 nominal rating criteria and scores, the scores being nonlinear with a cubic relationship. In addition to geological factors, the RHR system considers such consequence parameters as ditch effectiveness, average vehicle risk (AVR), design sight distance, and roadway width.

The system is not very sensitive to smaller rock cuts, and, consequently, is of limited use in a state such as Missouri. Although the Oregon RHR system considers both the risk and consequence of failures, it does not effectively separate them.

The Ontario RHR System

Ontario's RHR (RHRON) system is a modification of the Oregon system, designed for less mountainous terrains (Franklin and Senior, 1997). Ontario's glaciated topography is much more subdued than Oregon, with



DEPTH 1

MEASURE 0 PIXELS

UNIT 0 FEET

Figure 2. RockSee program to measure various parameters needed for the hazard rating system.

lower cut SHs. In this system, the authors add five new parameters to the Oregon system and several parameters are redefined. They define the RHRON value as:

$$RHRON(\%) = (F1 + F2 + F3 + F4) \times \frac{100}{36},$$

in which

$F1$ = magnitude: "How much rock is unstable?"
$F2$ = instability: "How soon or often is the rock likely to come down?"
$F3$ = reach: "What are the chances of this rock reaching the highway?"
$F4$ = consequence: "How serious are the consequences of the blockage?"

The difficulty with this system is that it is somewhat arbitrary; there is no separation between risk factors and consequence factors, and it is time-consuming to measure such a large number of factors. Some factors need laboratory analysis and this will add much time and cost to the evaluation.

New York Rock Slope Rating Procedure

The New York Department of Transportation has developed a rating system for rockfall hazard in New York State (New York Department of Transportation, 1996). This system uses three factors for computing the relative risk of a rockfall: a geological factor (*GF*), a section factor (*SF*), and a human-exposure factor (*HEF*). They use this formula as a total relative risk:

$$\text{Total Relative Risk} = GF \times SF \times HEF.$$

GF considers the properties of the rock slope. *SF* considers the risk that fallen rock would actually reach the highway lanes and is dependent on the geometry of ditch and shoulder to the rock slope offset. *HEF* considers both active conditions (moving vehicle hit by

Table 1. *The average error in percent for each type of scaled video measurement.*

Measurable Factors	Error (%)
Ditch width	6.0
Ditch depth	8.6
Slope length	4.2
Slope angle	2.7
Cliff height	3.9
Shoulder width	7.6
Road width	2.7
Rock cut length	6.8

falling rock or hitting newly fallen rock) and passive conditions (moving vehicle hitting rock that has been on the highway for some time).

This system again does not differentiate between risk and consequence, but indirectly starts to address consequences. The connection between the rated *GF* and the more analytical *SF* and *HEF* is ambiguous and may be tenuous.

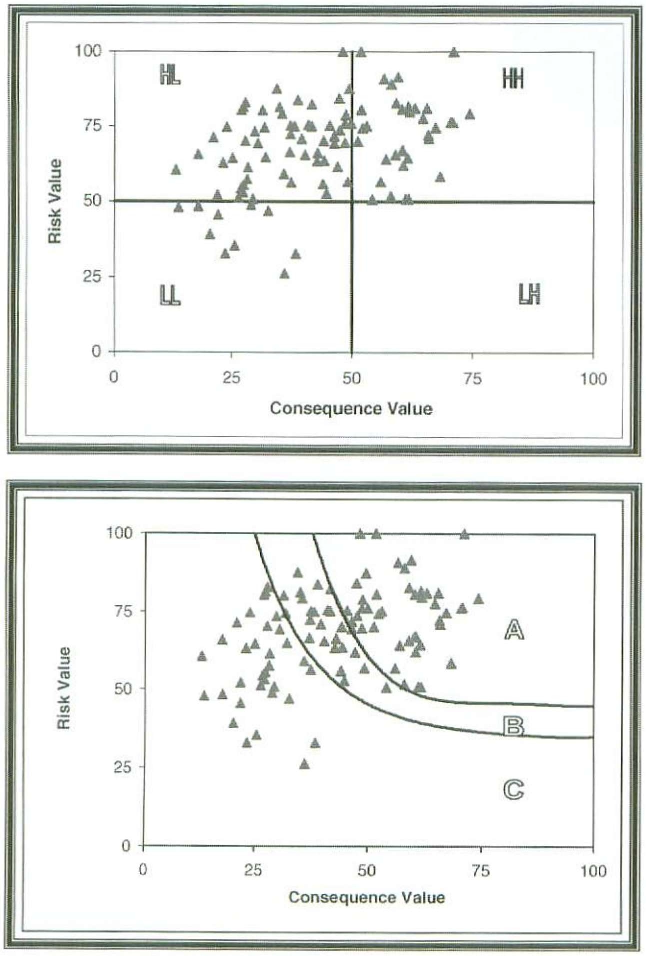


Figure 3. An example of a risk–consequence diagram for rock cuts from a section of Highway 63. Top: Diagram for the risk/quadrant data. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence. Bottom: Diagram for the zoned data. A = High-hazard zone, B = moderate-hazard zone, and C = low-hazard zone.

Table 2. *MORFH RS factors and range of ratings/values (1 ft = 0.3048 m; 1 cf = 0.0283* m^3*; 1 mph = 1.6 kmph).*

	Class No.	Value
A. Risk Factors		
1. Slope height*	—	0–60 ft
2. Slope angle*	—	0–90°
3. Rockfall instability**	0–4	—
4. Weathering factor***	0–8	—
5. Strength of intact rocks***	0–4	—
6. Face irregularity***	0–4	—
7. Face looseness***	0–4	—
8. Block size*	—	0.1–5 ft
9. Water on face***	0–4	—
B. Consequence Factors		
1. Ditch width*	—	0–15 ft
2. Ditch volume*	—	0–30 cf/ft
3. Expected rockfall quantities*	—	0–40 cf/ft
4. Slope angle*	—	20–90°
5. Shoulder width*	—	0–12 ft
6. Number of lanes*	—	1–4 lanes
7. Average daily traffic**	—	0–20,000 cars/day
8. Average vehicle risk**	—	*(calculated from)*
Speed limit	—	40–70 mph
Hazard rock cut length	—	100–600 ft
9. Decision sight distance*	0–4	—
10. Block size*	—	0.1–5 ft
C. Adjustment Factors/Risk		
1. Adversely oriented discontinuities***	0–4	—
2. Karst effect***	0–4	—
D. Adjustment Factors/Consequence		
1. Ditch capacity exceedance****	—	*(calculated)*
2. Ditch shape*	0–3	—

*Factors that can be determined from video images.
**Factors that can be made available by MODOT.
***Factors that require on-site qualitative assessment.
****Factor that is internally calculated.

Slope Stability Probability Classification

The slope stability probability classification system (Hack et al., 2003) is based on the probabilistic assessment of independently different failure mechanisms in a slope. The three steps include the exposure rock mass, the reference rock mass, and the slope rock mass.

Table 3. *Slope height risk rating (1 ft = 0.3048 m).*

Slope height (ft)	10	20	30	40	50	60
Risk rating	2	4	6	8	10	12

Table 4. *Slope angle risk rating.*

Slope angle	30°	40°	50°	60°	70°	80°	90°
Risk rating	0	2	4	6	8	10	12

The factors that the system depends on are intact rock strength, discontinuity orientation, and discontinuity condition, with some correction factors, such as weathering and method of excavation to convert the data of exposed rock mass to reference rock mass.

This system cannot be applied to the raveling type of failure and deals with risk factors only (does not consider consequence).

Tennessee Rockfall Hazard Rating System

The Tennessee Department of Transportation has also modified the Oregon RHR system. An important innovation is that they have developed a protocol to use a mobile Palm Pilot platform for field-based input and analysis (Bellamy et al., 2003).

How to Improve the Efficiency and Effectiveness of Classification/Rating Systems

Although the use of a classification system significantly improves the efficiency of evaluating rock cuts, there are two areas where efficiency improvements can be made: first, by rapidly identifying which rock cuts need detailed assessment using classification systems; second, by rapidly measuring some of the parameters needed for the system, such as SH and SA, ditch width (DW), and capacity, etc. The efficiency improvement can be made using digital video imaging of rock cuts and scaled measurements of features on the images.

MISSOURI ROCKFALL HAZARD RATING SYSTEM: A NEW METHOD FOR RATING THE ROCK CUT BY USING RISK–CONSEQUENCE FACTORS

Concept

A rock cut rating system has been developed for Missouri highways, the Missouri Rockfall Hazard Rating System (MORFH RS), which can be used by MODOT (Missouri Department of Transportation) to cost-effectively determine a priority of maintenance for rock cuts. This approach is taken to safeguard the motoring public and to reduce the risk of vehicle damage and traffic delays as a result of rockfalls.

Table 5. *Slope angle consequence rating.*

Slope angle	20°	30°	40°	50°	60°	70°	80°	85°	90°
Consequence rating	0	12	10	6	3	2	4	12	0

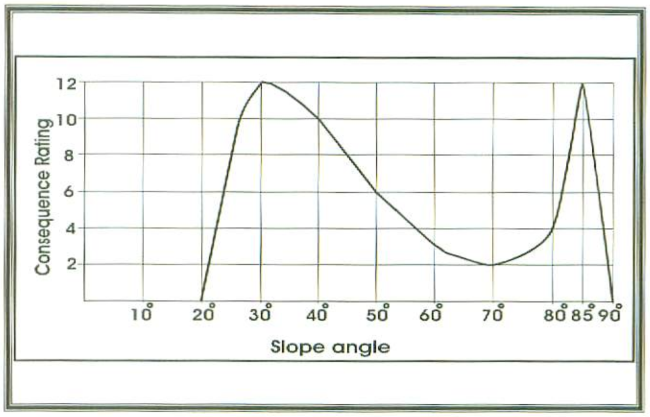


Figure 4. Consequence rating as a function of slope angle (SA) based on CRSP (Colorado Rockfall Simulation Program) analysis. SAs of approximately 30° tend to be high consequence (because of rolling and bouncing of large boulders) and SAs of approximately 85° tend to be high consequence (because of bouncing of small blocks off the face and onto the highway).

A three-phase approach to mitigating rockfall hazards is proposed, which seeks to use resources efficiently:

1. Identification (over the entire road network) of potentially problematic rock cuts, using mobile digital video logging.

Table 6. *Rock face instability risk rating.*

Rock Face Instability	Class No.	Description	Risk Rating
Completely unstable	4	Rocks often fall in this area; there is considerable evidence for frequent rockfall in the ditch and from maintenance records; severe rockfall events are common	12
Unstable	3	Rocks fall sometimes; the rockfalls will occur frequently during certain times of the year, but will not be a significant problem during other times; significant rockfalls have occurred in the past	9
Partially stable	2	Rocks fall occasionally; rockfalls can be expected several times per year; usually during storms	6
Stable	1	Very few rocks fall during the year; only during severe storms	3
Completely stable	0	No rocks fall; no historical or physical evidence for any rockfall in the area	0

Table 7. *Weathering factor risk rating.*

Weathering Factor	Class No.	Description	Risk Rating
High	4	Major erosion features; many overhanging areas along the rock cut; differential erosion is widespread along the rock cut	24
Moderate	3	Some erosion features; differential erosion features are large and numerous	18
Low	2	Minor differential erosion features appear widely distributed; differential erosion is limited	12
Slightly	1	Few differential erosion features; erosion rate is very low	6
Fresh	0	No evidence for weathering; the walls are smooth and fresh	0

2. Characterization and prioritization of remediation (for the potentially problematic rock cuts identified in phase 1) using a purpose-designed RHR system.
3. Detailed analysis and design methodologies for final remediation (for the prioritized rock cuts identified in phase 2).

A major efficiency of this approach comes from rapid, low-cost screening of problematic areas, leaving most of the resources for the task of detailed characterization, design, and implementation of final remedial measures on slopes deemed to be high priority.

This paper and research specifically addresses the first two phases. Phase 3 methodologies have been well-established elsewhere and are widely implemented.

Table 8. *Strength of intact rock risk rating (1 psi = 6.895 kPa).*

Strength Of Intact Rock	Class No.	Description	Risk Rating
Very strong rock	4	Many blows of a hammer needed to fracture the rock (>14,500 psi)	0
Strong rock	3	Several blows needed to fracture the rock (>7,250 psi)	3
Moderately strong rock	2	A firm blow needed to fracture the rock (>3,630 psi)	6
Weak rock	1	Can indent the rock with a pick (>725 psi)	9
Very weak rock	0	Can crumble the rock by hand (<725 psi)	12

Table 9. *Face irregularity risk rating.*

Face Irregularity	Class No.	Description	Risk Rating
Very highly irregular face	4	There are many joints and overhanging features; irregular features everywhere throughout the site; the face is stepped everywhere	12
Highly irregular face	3	Much of the face is irregular and there are many joints and stepped faces	9
Moderately irregular face	2	There are many irregular areas in the face	6
Slightly irregular face	1	There are some irregular areas along the face	3
Smooth face	0	Very smooth face	0

Video Logging and Computer-Scaled Video Measurement

Video Logging

A digital video-logging system (Figure 1) described previously (Maerz et al., 2003) is being used as a screening tool to identify problematic highway rock cuts. A specific subset or the entire highway network can be video-logged using a video camera equipped with GPS (global position system) coordinate overlays. Trained geotechnical engineers or geologists can review the video footage at a computer workstation to identify problematic cuts and then decide which sites warrant investigation that is more detailed. This would call for making measurements on the images.

Measurements on Scaled Video

The same images that are used for video logging can also be used to measure some of the parameters required

Table 10. *Face looseness risk rating.*

Face Looseness	Class No.	Description	Risk Rating
Very highly loose material	4	The face is completely covered by loose blocks	12
Highly loose material	3	Much of the face is covered by loose blocks	9
Moderately loose material	2	Some of the face is covered by loose blocks	6
Lowly loose material	1	Little of the face is covered by loose blocks	3
No loose material	0	There are no loose blocks on the face	0

Table 11. *Block size risk rating (1 ft = 0.3048 m).*

Block Size	Description	Risk Rating
Massive	Blocks are large and average joint spacing is 5 ft	0
Moderately blocky	Average block size is 2.5 ft	4
Very blocky	Average block size is 1 ft	8
Completely crushed	Intact rock has the character of crushed run aggregates; joint spacing is <0.5 ft	12

Table 13. *Water on face risk rating.*

Water on Face	Class No.	Description	Risk Rating
Dry	0	No water on the face	0
Damp	1	Some evidence of water on the face	3
Wet	2	Significant water on the face	6
Dripping	3	Water drips from face	9
Flowing	4	Water flows from face	12

for the rating system (Maerz et al., 2003). Measurements can be made on single images without extensive vehicle instrumentation and modifications. Although not as accurate as manual measurements in the field, the measurements are sufficiently accurate to provide input data for a RHR system. At the University of Missouri–Rolla (UMR), a prototype of such a system has been developed (Figure 2).

The system uses the video-logging hardware (including a simple camera setup), scale calibration, and appropriate identification of object endpoints to enable quick and easy measurements. Typical measurements include SHs, lengths, and angles; and DWs, depths, and volumes. Manual measurements were made to verify the accuracy of the video measuring system at 17 locations along state highways (Maerz et al., 2003). Examples of measurement errors are given in Table 1. Average errors, defined as the percentage difference between manual and image measurements, were found to be less than 10 percent.

Risk vs. Consequence Rating System (MORFH RS)

The new Missouri rating system is predicated on separating risk of failure from consequence of failure (Figure 3). Although other rating systems may consider both risk and consequence of failure factors, they tend to lump risk and consequence together. This is incorrect because some parameters affect risk and consequence in different ways. For instance, the larger the block size (BS), the lower the risk of failure, but the higher the consequence of failure. Alternatively, a vertical slope would present the highest risk of failure but a lower consequence with adequate catchment area; and a 30° slope would present the highest consequence for large rolling blocks and an 85° slope would have the highest consequence from small bouncing blocks.

Table 12. *Block size consequence rating (1 ft = 0.3048 m).*

Block Size	Description	Consequence Rating
Massive	Blocks are large and average joint spacing is 5 ft	12
Moderately blocky	Average block size is 2.5 ft	8
Very blocky	Average block size is 1 ft	4
Completely crushed	Intact rock has the character of crushed run aggregates; joint spacing is <0.5 ft	0

In any case, separating risk and consequence is useful because it may be possible to concern ourselves only with high-risk, high-consequence rock cuts. Low-risk rock cuts need not worry us because there is small chance of failure, and low-consequence cuts need not worry us because the fallen rock is not likely to reach and affect the highway traffic.

THE MORFH RS

MORFH RS in a Nutshell

The MORFH RS includes 23 factors (Table 2), including 9 factors for risk, 10 factors for consequence, 3 adjustment factors, and 1 internally calculated value. These factors have been organized into risk and consequence categories, and identified based on how the factors are evaluated:

1. SH, SA, DW, ditch depth, shoulder width (SW), BS, ditch capacity, and expected rockfall quantity (ERFQ) can often be measured on computer-scaled video images of rock cuts in the office.
2. Weathering, face irregularities (FI), face looseness (FL), strength of rock face, water on the face, and design sight distance are descriptive and need field evaluation.
3. Average daily traffic (ADT), number of lanes (NOL), and AVR are obtained from MODOT records or calculated for each section of road.
4. Conditional parameters, such as adversely oriented discontinuities (AOD), karst features, ditch capacity

Table 14. *Ditch width consequence rating (1 ft = 0.3048 m).*

Ditch width (ft)	0	5	10	15
Consequence rating	12	8	4	0

Table 15. *Ditch volume consequence rating.*

Ditch volume (ft^3/ft)	0	5	10	15	20	25	30
Consequence rating	12	10	8	6	4	2	0

exceedance, and the effect of bad benches are reflected in a conditional ditch shape (DS) parameter.

For each parameter, the input value is either an actual measurement or one of an assigned class value between 0 and 4 units (in increments of 0.5 units), based on the descriptive examples in Tables 16 through 27. In each case, the measurement/value is translated to a rating, typically between 0 and 12. Each set of ratings, both risk and consequence, are added and normalized to a percentage. Conditional ratings are simply added to either the risk or consequence rating.

MORPH RS Parameter Descriptions and Values

Slope Height

The SH category (Table 3) evaluates the risk associated with the height of a slope. High slopes have a greater risk of failure than low slopes. Measured from video images or estimated in the field, vertical SH should be taken from the pavement level up to the highest point on the rock slope from which rockfall may be expected. If rocks are coming from the natural slope above the cut, the cut height plus the additional SH (vertical distance) should be used.

Slope Angle

The SA is measured from video images or estimated in the field. This angle is important because the risk of failure is greater as the SA is increased (Table 4).

On the other hand, the angle of the slope affects the trajectory of falling rock. Thus, the consequence rating of the SA (Table 5) is different from the risk rating. From CRSP (Colorado Rockfall Simulation Program) studies (Pfeiffer and Higgins, 1990), it was determined that rock falling off vertical cuts tends to fall into and be contained in the ditch, whereas SAs of approximately 30° result in large boulders hitting the road surface because of rolling. SAs of 85° result in small blocks bouncing off the face and onto the highway. This is a non-linear relationship, as illustrated in Figure 4.

Table 16. *Ditch volume consequence rating (alternate) (1 ft = 0.3048 m).*

Modified ditch width (ft)	0	10	20	30
Consequence rating	12	8	4	0

Table 17. *Ditch shape consequence rating.*

Ditch Shape	Flat (0°)	Slight Back Slope (1V:8H; 7°)	Moderate Back Slope (1V:6H; 9°)	Large Back Slope (1V:4H; 14°)
Class no.	3	2	1	0
Consequence rating	12	8	4	0

Rock Face Instability

This parameter summarizes a critical combination of factors leading to instability of the rock cut, determined from the observations of previous failures, evidence of blocks in the ditch, and loose blocks on the face of the rock cut (Table 6).

Weathering Factor

Both physical and chemical weathering increase the instability of slopes by weakening the rock. Erosion features include weak zones that ravel over time and unsupported rock units that fall as a result of undercutting by differential erosion. Because of the significance of weathering processes in Missouri rockfalls, the rating for weathering is double that of the other parameters (Table 7).

Strength of Intact Rock

The compressive strength of the rocks on the face is an important predictor of the durability of the slope (Bieniawski, 1984; Table 8).

Table 18. *Expected rockfall quantities (ERFQ) consequence rating ($1\ ft^3 = 0.02832\ m^3$; 1 ft = 0.3048 m).*

ERFQ	Description	Consequence Rating
>40 ft^3 per linear foot	The face is completely loose and the expected volume of falling rocks will be approximately 40 ft^3/ft	12
30 ft^3 per linear foot	Most of the face is loose and the expected volume of falling rocks will be 30 ft^3/ft	9
20 ft^3 per linear foot	Many areas of the face are loose and the expected volume of falling rocks will be 20 ft^3/ft	6
10 ft^3 per linear foot	Few areas on the face are loose and the expected volume of falling rocks will be 10 ft^3/ft	3
<5 ft^3 per linear foot	There is no expected rockfall (there are no loose materials on the face)	0

Table 19. *Shoulder width consequence rating (1 ft = 0.3048 m).*

Shoulder width (ft)	0	3	6	9	12
Consequence rating	12	9	6	3	0

Face Irregularity

FI is an indicator of unstable slopes and is based on a descriptive scale (Table 9).

Face Looseness

FL is also an indicator of unstable slopes. It is based on an estimate of the number of open discontinuities visible in the face and the "looseness" of rock blocks in the face (Table 10).

Block Size

Generally, in rock masses, a small BS is inherently less stable (and has a larger risk of failure) than a larger BS (Table 11). BS also affects the consequence factor in a different way, because large moving blocks have greater kinetic energy than smaller ones, meaning they will travel further down the inclined slope and cause more damage to the road and vehicles (Table 12). BS is a function of the distribution of discontinuities on the slope, or of the damage caused by blasting.

Water on Face

The presence of water pressures in rock masses is perhaps the most important precursor for instability in a rock slope. Many rockfalls occur after a period of particularly heavy rainfall. Sometimes, rainfall may not be the main factor but may act as the final trigger. Water in conjunction with freeze–thaw cycles contributes to the weathering and instability of rock slopes. This factor is a descriptive factor (Table 13) and can be inferred by observing water seeping from the face (observations must be 2 to 3 days after rainfall) or by observing permanent water stains on the slope face.

Ditch Effectiveness (DW; DV; DS)

Ditch effectiveness includes three parameters contributing to the consequence factors: DW, ditch volume (DV), and, optionally, DS. The first two parameters estimate the probability of rock reaching the traveled portion of the highway for vertical cuts; the last is for sloped cuts and cuts with bad benches (bench conditions that are likely to contribute to rock reaching the road). The effectiveness of a ditch is measured by its ability to restrict rockfall from reaching the roadway. Under normal circumstances (slopes greater than 85° without bad benches), DW and DV are used (Tables 14 and 15).

Table 20. *Number of lanes (NOL) consequence rating.*

NOL	One lane	Two lanes	Three lanes	Four lanes
Consequence rating	12	6	3	0

Table 21. *Average daily traffic consequence rating.*

Average daily traffic	5,000 cars/day	10,000 cars/day	15,000 cars/day	20,000 cars/day
Consequence rating	3	6	9	12

If the slope is less than 85° or if bad benches are detected, the DW rating is modified and the DS parameter is added to the rating system (Tables 16 and 17).

Expected Rockfall Quantities (ERFQ)

This factor estimates the maximum anticipated volume of the rocks that will fall down from the face, including from multiple failures. ERFQ is determined by measuring or estimating the area of the face that is unstable and estimating the depth of loose zone (this depth may possibly be determined based on FL and depth of overhang; Table 18).

Shoulder Width (SW)

Available SW is the width of shoulder (paved or unpaved) that is available to accommodate fallen rock if the ditch area is filled to capacity. If the width is small, the chance of fallen rocks reaching the highway will be higher (Table 19).

Number of Lanes (NOL)

If the highway has only one lane, then the ability for the driver to avoid fallen rocks is very low (Table 20). On the other hand, if there are multiple lanes, the driver has a better opportunity to avoid the fallen rocks by swerving to an adjacent lane (Table 20).

Table 22. *Average vehicle risk consequence rating.*

Average Vehicle Risk	Percent of Time Vehicle Will Be in the Rock Cut Zone	Consequence Rating
Low risk	25%	3
Medium risk	50%	6
High risk	75%	9
Very high risk	100%	12

Table 23. *Decision sight distance consequence rating.*

Decision Sight Distance	Class No.	Description	Consequence Rating
Very limited	3	Distance is very small and there are many vertical and horizontal curves on the roads; vegetation obscures falling rock	12
Limited	2	There are some curves and obstacles on the road, not giving the driver enough time to perceive that there are fallen rocks on the road	8
Moderate	1	There are few curves and obstacles and the driver can control the vehicle easily because falling or fallen rocks are visible	4
Adequate	0	The road is completely straight without any obstacles or curves and the driver can see the entire rock face and road at any time	0

Average Daily Traffic (ADT)

Traffic densities (vehicles/day) vary considerably from highway section to highway section. This factor is important because the consequence of rockfall increases with increasing traffic (Table 21). ADT values can be found for Missouri highways on the MODOT website.

Average Vehicle Risk (AVR)

The AVR is a measure of the number of vehicles present in the hazard zone at any given time, or, when a fractional quantity, of the percentage of time that a vehicle is present in the rockfall hazard zone. This percentage is obtained by using a formula based on cut length, ADT, NOL, and the posted speed limit through the hazard zone:

$$\mathrm{AVR\%} = \frac{\mathrm{ADT\ (cars/day)} \times \mathrm{cut\ length\ (miles)} \times 100\%}{\mathrm{Posted\ speed\ limit\ (miles/hour)} \times \mathrm{NOL}}$$

A rating of 100 percent means that, on average, at least one or more vehicles can be expected to be within the hazard section at all times. Care should be taken to measure only the length of rock cut where rockfall is a problem; overestimating lengths will strongly skew the formula results. It is possible to obtain values greater than 100 percent with this formula. This equation is a modified equation from the one that is used by rockfall hazard rating system (RHRS) (Pierson and Van Vickle, 1993). AVR consequence rating is given in Table 22.

Table 24. *Adversely oriented discontinuities risk rating.*

Adversely Oriented Discontinuities	Favorable	Fair	Unfavorable	Very Unfavorable
Class no.	0	1	2	3
Dip angle of discontinuity towards road	<20, 90°	20–45°	45–65°	65–90°
Consequence rating	0	4	8	12

Table 25. *Karst effect discontinuities risk rating.*

Karst Effect	Class No.	Consequence Rating
Non-carbonate rocks (igneous, sandstone)	0	0
Carbonate rocks that could possibly have karst features but are not evident on the rock cut face	1	3
Karst features that appear on the rock cut face; width is 50 ft; filled by boulders and cobbles or undercut with weak materials	2	6
Karst features that appear on the rock cut face; width is 100 ft; filled by boulders and cobbles with weak materials	3	9
Karst features that appear on the rock cut face; width is 150 ft; filled by boulders and cobbles with weak materials	4	12

Decision Sight Distance (DSD)

The DSD is a measure of the distance/reaction time from a hazard zone that a driver is first able to recognize the hazard, either fallen rock on the highway or falling rock on the slope, and take action. Sight distance, as prescribed by the American Association of State Highway and Transportation Officials (American Association of State Highway and Transportation Officials, 1990), is the shortest distance at which a 6-in. (15-cm) high object on the road is continuously visible to a driver.

Throughout a rockfall section, the sight distance can change appreciably. Horizontal and vertical highway curves, along with obstructions, such as rock outcrops and roadside vegetation, can severely limit a driver's ability to see an object on the road. In this system, a descriptive method is used to characterize the DSD (Table 23).

Adversely Oriented Discontinuities

This parameter is an attempt to deal with the effect of the discontinuities that have an orientation that might

Table 26. *Ditch capacity exceedance consequence rating.*

ERFQ/DV	1	2	3	4
Rating value	0	5	10	15

Table 27. *Bad bench calculation (1 ft = 0.3048 m).*

Bench present?	Yes/No (if yes, look at the bench and faces above the bench)			
	Score	4	2	0
Faces above bench	Weathering	High	Low	Fresh
	Face irregularity	High	Moderate	Smooth
	Face looseness	Large	Moderate	No
Bench characteristics	Bench width	Narrow, <5 ft	Moderate, 15 ft	Wide, >20 ft
	Rock on the bench	Large amount	Moderate	None
	Slope of the bench	Toward road	Horizontal	Back slope

Total score: __ (if greater than 12, then bench is considered "bad")

contribute to sliding of rock toward the highway (Table 24). Although a simplification, the steeper the dip-angle with respect to the highway, the higher the risk of failure (sub-vertical and sub-horizontal discontinuities are not common in Missouri).

Karst Effect

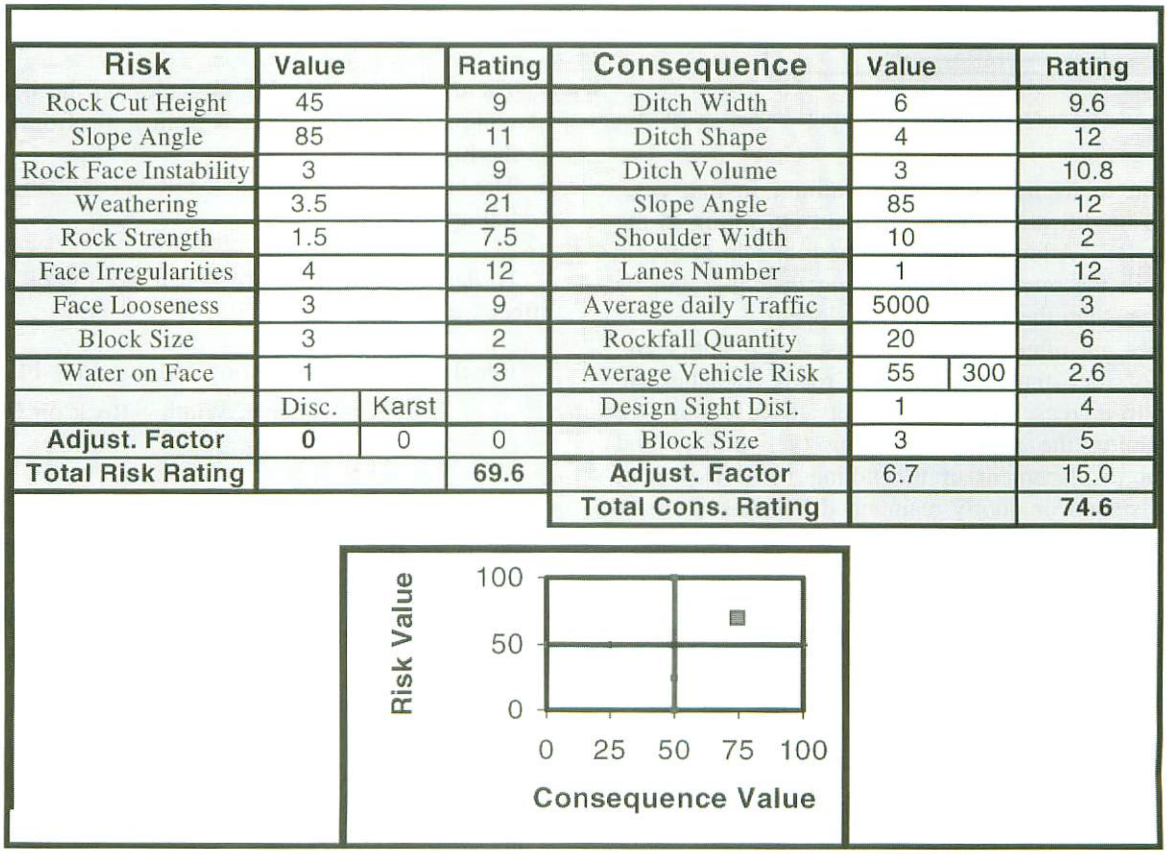
Karst features, typically filled sinkholes, are very common along the Missouri highways. The most important factor is the material types or fills, which could be cemented material or easily eroded materials. If the karst features (sinkholes) are filled by well-cemented materials, these cuts are treated as normal cuts without adding any adjustments. If the sinkholes are filled by materials that can easily weather, a karst adjustment is used (Table 25).

Ditch Capacity Exceedance (ERFQ/DV)

Ditch capacity exceedance is the ratio of ERFQ/DV. Calculated internally, it is a very important factor that is used to determine whether the capacity of the ditch will be exceeded (Table 26). The value of the ditch capacity is an internal calculation arrived at by dividing the ERFQ by the DV.

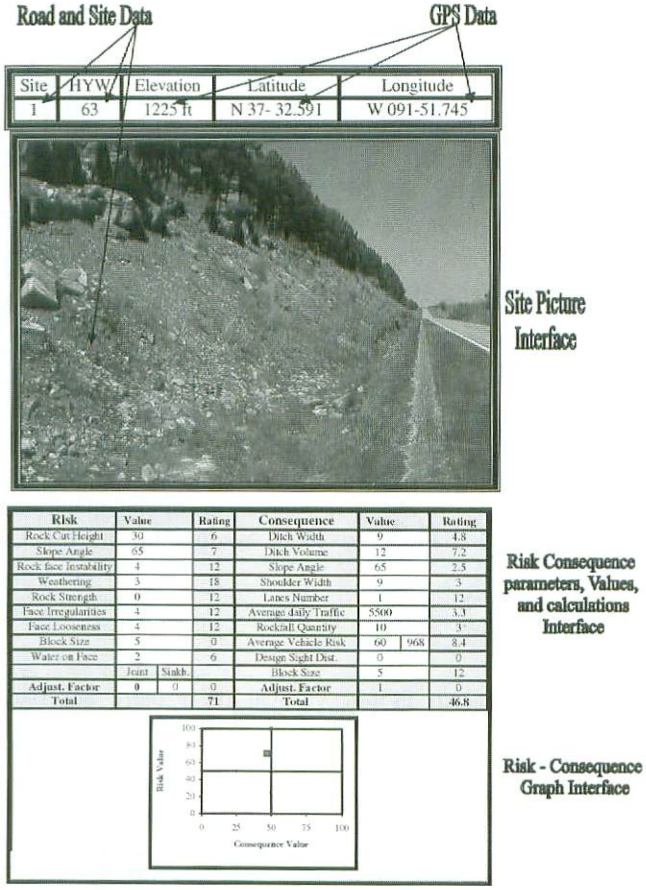
Bench-Effect Calculation

If the rock cut is not vertical or if there are bad benches, falling rock will tend to have a horizontal



Risk	**Value**		**Rating**	**Consequence**	**Value**		**Rating**
Rock Cut Height	45		9	Ditch Width	6		9.6
Slope Angle	85		11	Ditch Shape	4		12
Rock Face Instability	3		9	Ditch Volume	3		10.8
Weathering	3.5		21	Slope Angle	85		12
Rock Strength	1.5		7.5	Shoulder Width	10		2
Face Irregularities	4		12	Lanes Number	1		12
Face Looseness	3		9	Average daily Traffic	5000		3
Block Size	3		2	Rockfall Quantity	20		6
Water on Face	1		3	Average Vehicle Risk	55	300	2.6
	Disc.	Karst		Design Sight Dist.	1		4
Adjust. Factor	**0**	0	0	Block Size	3		5
Total Risk Rating			**69.6**	**Adjust. Factor**	6.7		15.0
				Total Cons. Rating			**74.6**

Figure 5. Microsoft Excel–based rating chart. The unshaded fields are manually entered; the shaded fields represent calculated values. The risk–consequence graph is automatically produced. Everything on the page is recalculated each time a new value is entered.



Site	HYW	Elevation	Latitude	Longitude
1	63	1225 ft	N 37- 32.591	W 091-51.745

Risk	Value		Rating	Consequence	Value		Rating
Rock Cut Height	30		6	Ditch Width	9		4.8
Slope Angle	65		7	Ditch Volume	12		7.2
Rock face Instability	4		12	Slope Angle	65		2.5
Weathering	3		18	Shoulder Width	9		3
Rock Strength	0		12	Lanes Number	1		12
Face Irregularities	4		12	Average daily Traffic	5500		3.3
Face Looseness	4		12	Rockfall Quantity	10		3
Block Size	5		0	Average Vehicle Risk	60	968	8.4
Water on Face	2		6	Design Sight Dist.	0		0
	Joint	Sinkh.		Block Size	5		12
Adjust. Factor	**0**	0	0	**Adjust. Factor**	1		0
Total			71	**Total**			46.8

Figure 6. Single page report to show the results of the evaluation.

component to its trajectory when falling. In that case, there is a modification to the DW and DS rating in the MORFH RS. Additionally, if a bad bench effect is determined, the overall SA (including benches) will be used, rather than the vertical bench slope.

Benches are often used to decrease the quantity and velocity of rock that falls onto the roads. Benches are designed to increase the level of safety from falling rock by containing the rock or reducing the velocity and horizontal displacement of the falling rock. However, poorly designed or poorly maintained benches decrease the level of safety.

Benches are beneficial if:

1. The benches are clean with no accumulated material that would act as a ramp to enable rock from above to bounce or roll off the ramp.
2. Rock faces *above* the first bench are in good condition (little weathering, AOD, or loose materials).
3. The benches are horizontal or they have a back slope so the fallen rock will be retained on the bench.
4. There are soft materials on the bench, such as clay, shale, sand, or gravel, that will absorb the energy of the falling rock.
5. There are trees or other obstacles on the bench that will prevent the falling rock from above from reaching the highway.
6. The bench is wide enough that it will contain all of the falling rock.

Table 28. *MORFH RS preliminary rating.*

Factor	Detailed Assessment Triggered **IF** There Is:
Weathering/Karst	1. A highly weathered rating on the video image, **OR** 2. Any indication of karst (voids, filled sinks), **OR** 3. Any significant differential erosion (cut back voids, overhangs), **OR**
Face irregularity/face looseness	1. A highly irregular face or a moderately irregular face high on the cut, **OR** 2. A highly loose face or a moderately loose face high on the cut, **OR**
Fallen rock in the ditch or on the cut	A significant amount of loose rock visible in the ditch, **OR**
Ditch effectiveness	Very low ditch effectiveness (too small, too narrow), **OR**
Adversely oriented discontinuities	Indication of adversely oriented discontinuities, **OR**
Bench(es)	Presence of bench(es)
	NO detailed assessment is triggered **IF** there is:
Slope Height (SH)	1. SH <10 ft, **OR** 2. The SH is less than the width of the ditch plus the shoulder

To determine whether the bench has a good or a bad effect we use this formula:

$$\begin{aligned}\text{Bench Value} = {} & \text{Weathering Value} + \text{FI} + \text{FL} \\ & + \text{Bench Width} + \text{Rock on Bench} \\ & + \text{Bench Slope},\end{aligned}$$

where each parameter is rated 0, 2, or 4. If the Bench Value is greater than 12, then the bench is considered "bad," and the aforementioned modification to the DW and DS ratings are used in the MORFH RS. Table 27 is used to make the bad bench determination.

MORPH RS Internal Calculations

The MORFH RS calculations are best described with the use of the Microsoft Excel rating chart of Figure 5. The shaded fields represent calculations, only the unshaded fields need to be filled in (in a newer version of RockSee, an extension of the software, calculations are all handled internally and only ratings have to be entered).

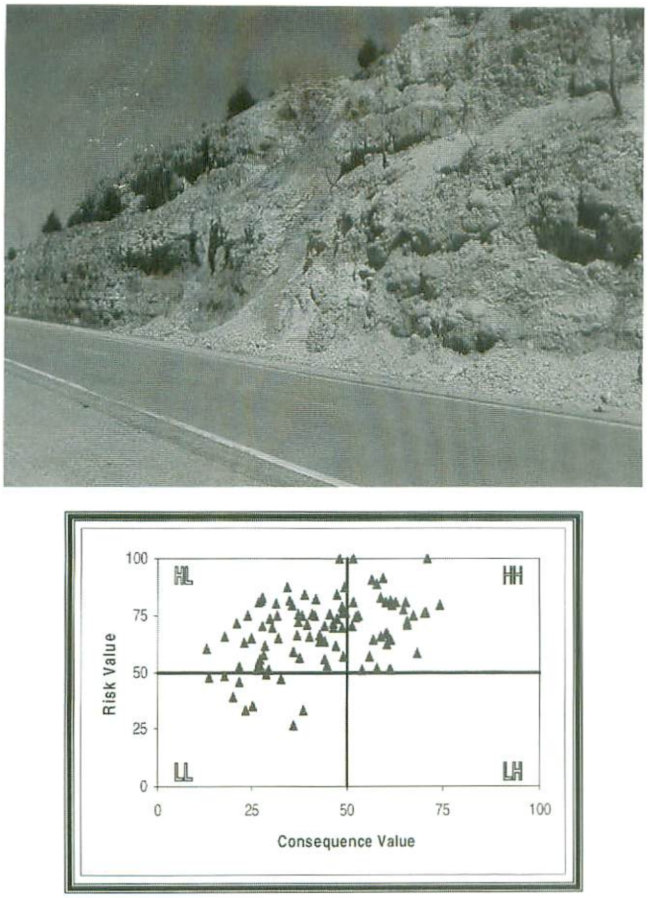


Figure 7. Top: Typical Highway 63 rock cut showing a filled sink that is raveling. Bottom: Risk–consequence diagram for the data from Highway 63. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence.

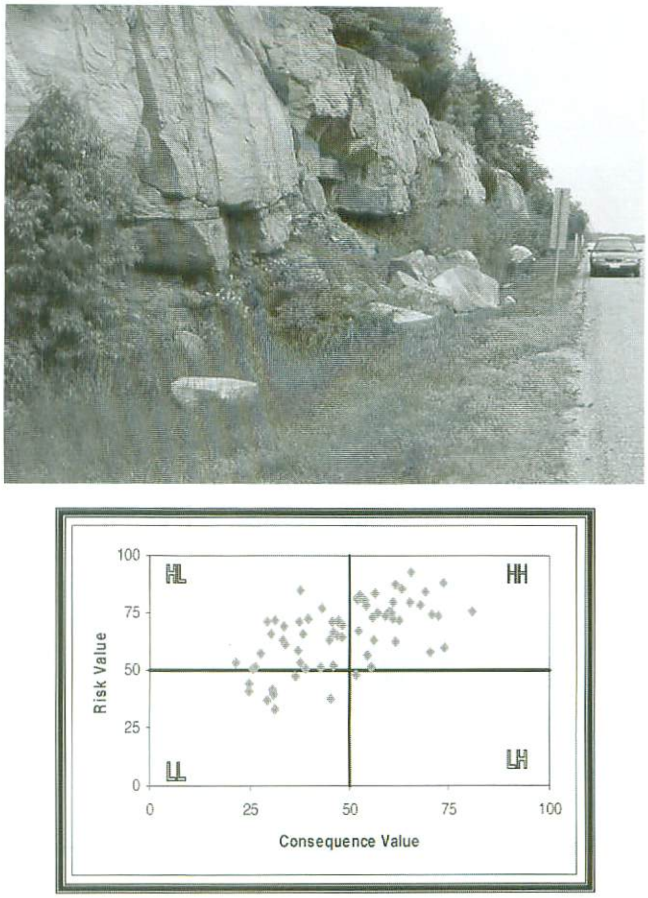


Figure 8. Top: Typical Highway 44 rock cut showing large fallen blocks of sandstone. Bottom: Risk–consequence diagram for the data from Highway 44. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence.

Risk Side

For risk evaluation, a rating of 0–12 is calculated (0–24 for weathering, weighted double because of its importance) for the nine basic parameters, from the input values according to the formulas described in "MORPH RS Parameter Descriptions and Values." The values of all nine parameters are summed, and normalized to produce a risk rating between 0 and 100.

The adjustment factors (if non-zero) are also calculated on a scale of 0–12, according to the formulas described in "MORPH RS Parameter Descriptions and Values." These values are simply added to the risk rating; the maximum risk rating is 100.

Consequence Side

On the consequence side, a rating of 0–12 is calculated for the 10 basic parameters (DS is only used for non-vertical slopes, or if bad benches are found), from the input values according to the formulas described in "MORPH RS Parameter Descriptions and Values." The values of all parameters are summed, and normalized to produce a consequence rating between 0 and 100.

The adjustment factor is internally calculated on a scale of 0–15, according to the formula described in "MORPH RS Parameter Descriptions and Values." This value is simply added to the consequence rating; the maximum consequence rating is 100.

MORPH RS Presentation of Results

Figure 6 shows the output results from the MORFH RS analysis, including an image, a risk–consequence graph, and identification/location of the cut.

MORPH RS Preliminary Ratings

The MORFH RS requires a preliminary assessment or screening rating to determine whether a full rating is required for a given rock cut. The criteria here is that the

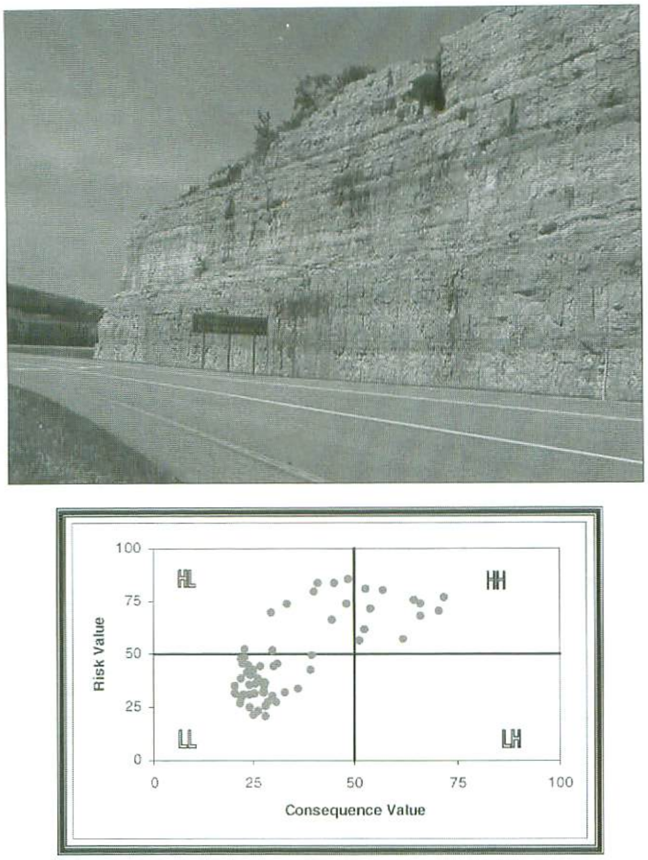


Figure 9. Top: Typical Highway 65 rock cut showing a new well-designed rock cut. Bottom: Risk–consequence diagram for the data from Highway 65. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence.

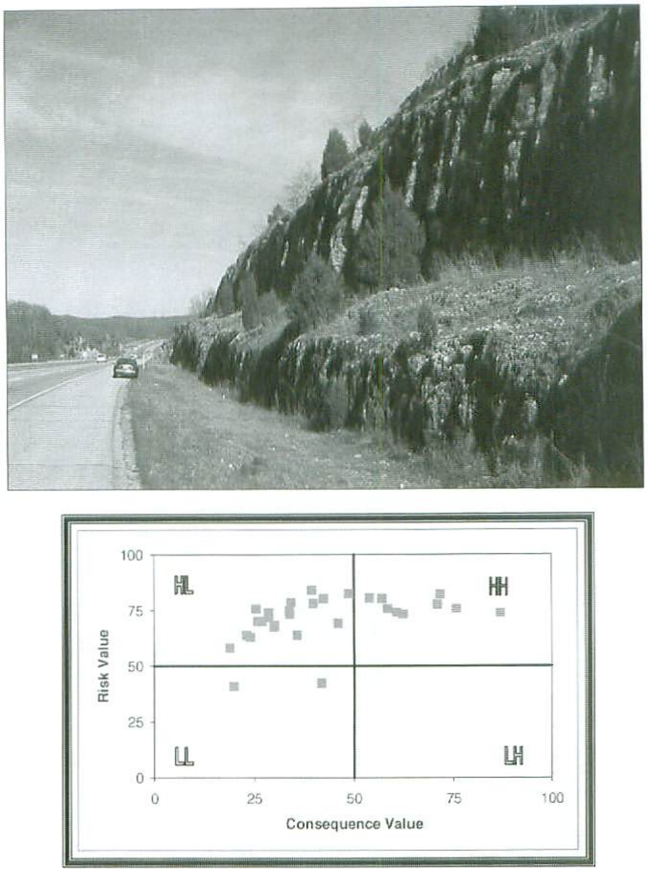


Figure 10. Top: Typical Highway 54 rock cut showing badly designed and maintained benches. Bottom: Risk–consequence diagram for the data from Highway 54. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence.

preliminary rating must be simple, quick, qualitative, and it must be done from the video log. If there is any doubt, the conservative assumption should be to do a full rating. The following factors are used (any one of these can trigger the requirement for a full rating):

1. Weathering/karst evidence
2. FI/FL
3. Fallen rock in the ditch or on the cut.
4. Ditch effectiveness.
5. AOD.
6. Presence of benches.

The algorithm to determine whether a full rating is required is given in Table 28.

RESULTS OF ANALYSIS FOR SELECTED SECTIONS OF MISSOURI HIGHWAYS

Analyses were conducted on various highways in Missouri. In all, over 300 rock cuts were analyzed. Individual rock cuts were selected to test and stress the analysis system, representative cuts were used, and no effort was made to include all of the cuts that are present along those stretches of highway.

Highway 63 from Licking to Columbia, Missouri

Figure 7 shows the results for 101 sites that were studied along Highway 63. This section of highway contains older rock cuts in carbonate rock with many deep-filled sinks or highly discontinuous sandstone along a two-lane highway. The distribution of the data shows that the data fall in three zones: high risk–high consequence, high risk–low consequence, and low risk–low consequence. Significantly, there are many sites in the high risk–high consequence section and relatively few in the low risk–low consequence section.

Highway 44 Between St. Louis and Springfield, Missouri

Figure 8 shows the results for 70 sites that were studied along Interstate Highway 44. This section of highway contains older rock cuts in carbonate rock with some filled sinks and sandstone rock with large BSs, along a four-lane interstate highway. The distribution of the data shows that the data fall in three zones: high risk–high consequence, high risk–low consequence, and low risk–low consequence. Significantly, there are many sites in the high risk–high consequence section and relatively few in the low risk–low consequence section.

Highway 65 Between Springfield and Branson, Missouri

Figure 9 shows the results for 60 sites that were studied along Highway 65. This section of highway contains many recent well-designed, high rock cuts, in carbonate rock with near-surface dissolution features along a four-lane highway. Significantly, there are many sites in the low risk–low consequence section and relatively few in the high risk–high consequence section.

Missouri Highway 54

Figure 10 shows the results for 30 sites that were studied along Highway 54. This section of highway contains older rock cuts in carbonate rock with many deep filled sinks along a two-lane highway. Significantly, there are many sites in the high risk–low consequence section and relatively few in the high risk–high consequence section.

Other Highways: 30, 55, 8, 110, 61, 72, 67, and Route W

Figure 11 shows the results for 33 sites that were studied along Highways 30, 55, 8, 110, 61, 72, 67, and Route W. Rock types include carbonates, sandstones, granites, and rhyolites.

Analysis

Figures 12 and 13 show the comparison between risk–consequence values for the different highways. Most of the rock cuts on highways other than 65 have a risk rating greater than 50 percent. On the other hand, most rock cuts along Highway 65 have a risk rating of less than 50 percent. On the consequence side, most of the highways cuts have consequence values that center around 50 percent, although Highways 65, 55, and 54 cuts have consequence ratings that are much lower.

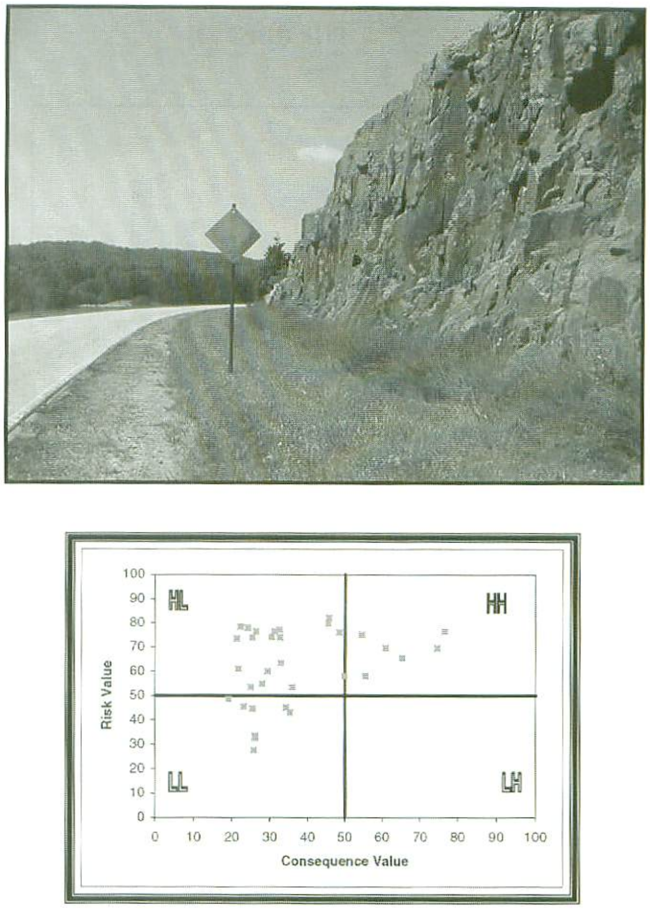


Figure 11. Top: Typical rock cut in rhyolite. Bottom: Risk–consequence diagram for the data from other highways. LL = low risk–low consequence; HL = high risk–low consequence; HH = high risk–high consequence; and LH = low risk–high consequence.

MORFH RS VERIFICATION

Sensitivity analysis of the MORFH RS system was done by checking the errors both in making measurements on the images and in rating errors.

Image Measurement Errors

To test the measuring system, 17 locations were selected along state highways, and manual measurements of road widths, DWs and ditch depths, and SHs and SAs were conducted using tape measures, measuring rods, and a range-finding clinometer. Measurement errors are described in Table 1. Errors, defined as the percentage difference between manual and image measurements, on average were found to be less than 10 percent.

Rater Errors

Ten sites from Highway 63 between Rolla and Jefferson City were selected to test how MORFH RS

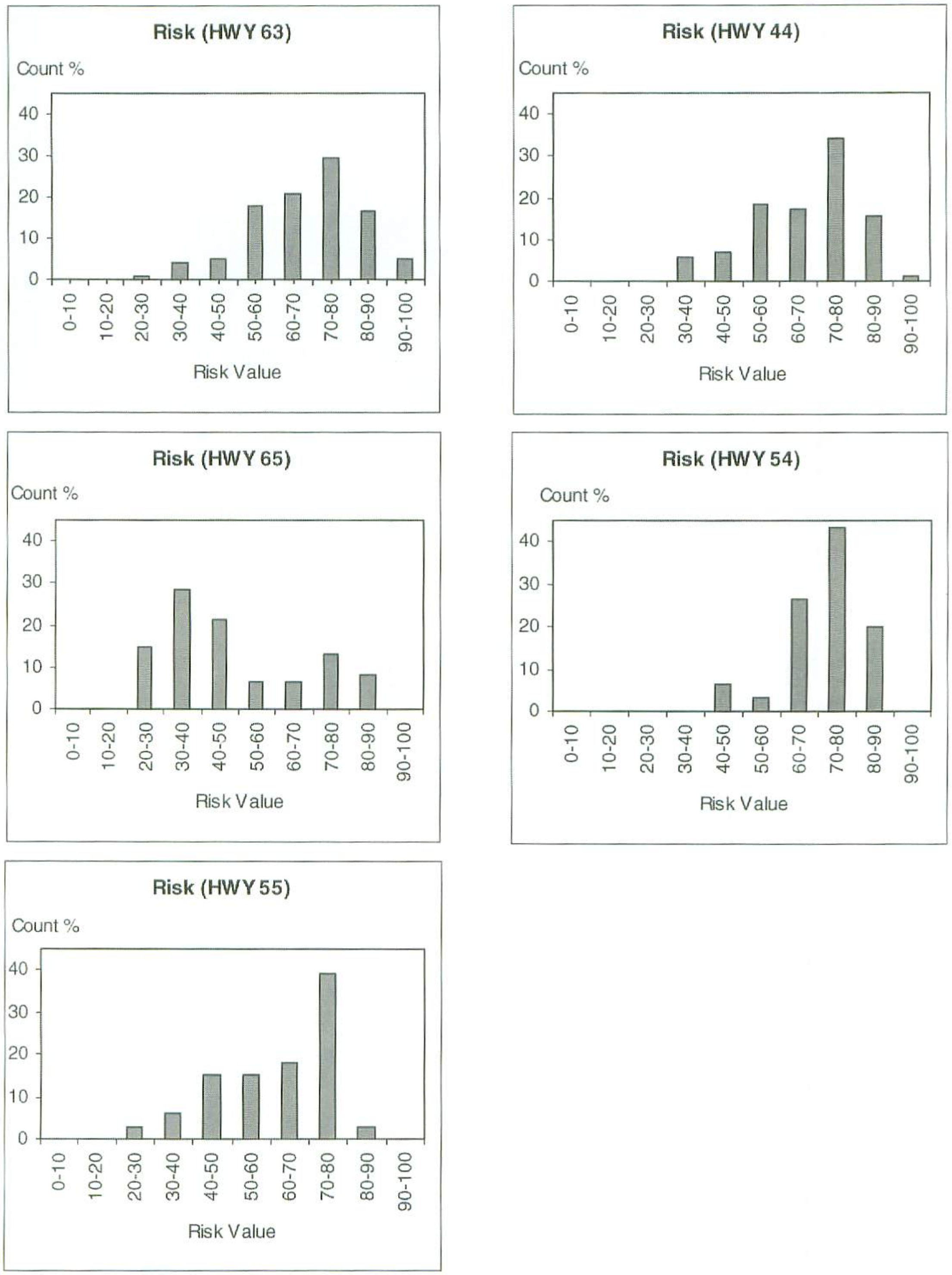


Figure 12. Comparison between risk values for the different highways (all data shown).

responds to different users (rated parameters only). In all, 12 different raters, including the authors, MODOT personnel, and UMR geological engineering graduate students rated the cuts. The raters were represented by civil engineers, geological engineers, geologists, and technicians. Other than the authors, raters received approximately 30 minutes of training and were given manuals with rating descriptions and example pictures for each rating. Figures 14, 15, and 16 show the results. It is clear that the results are tightly clustered; how-

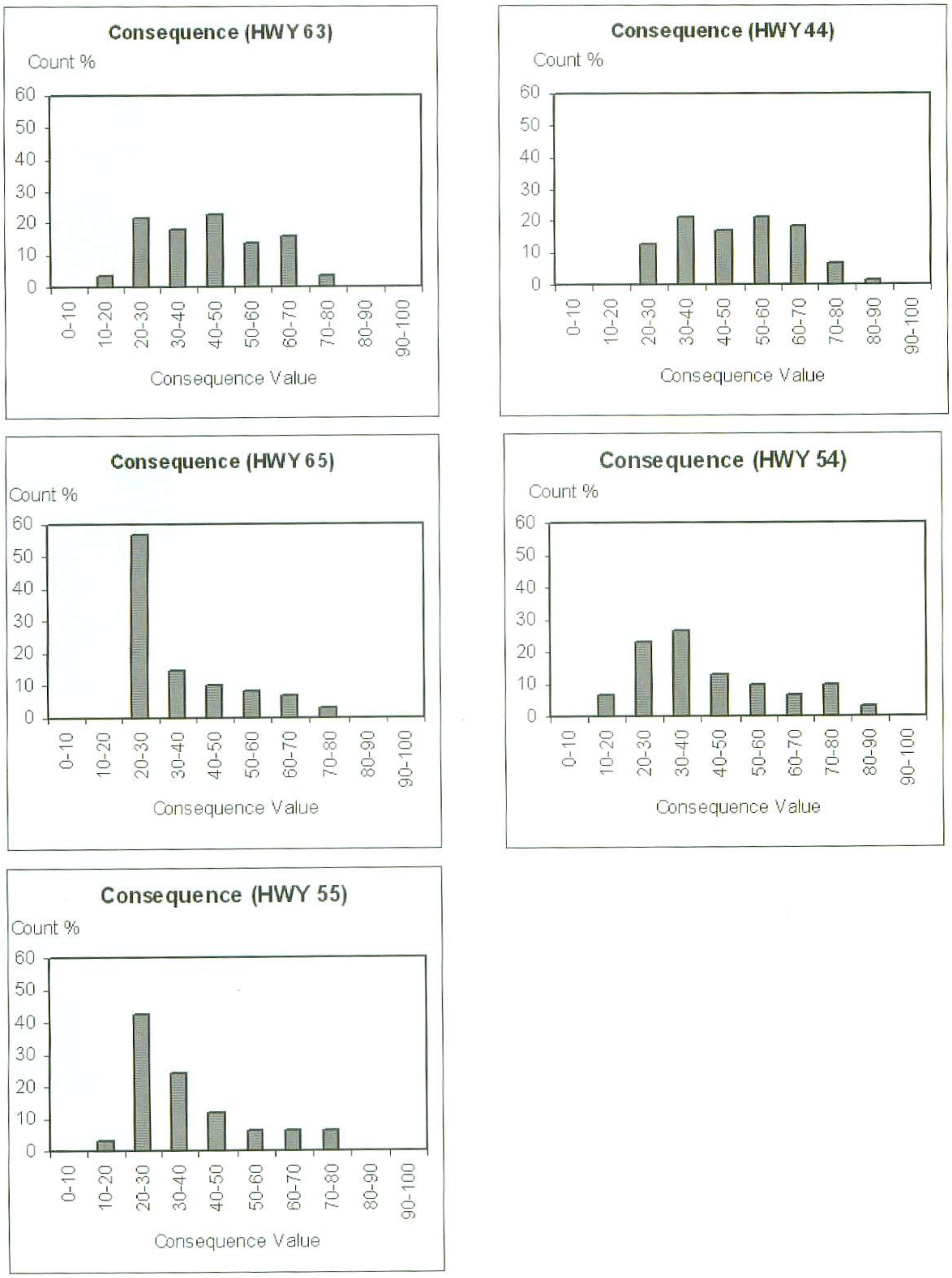
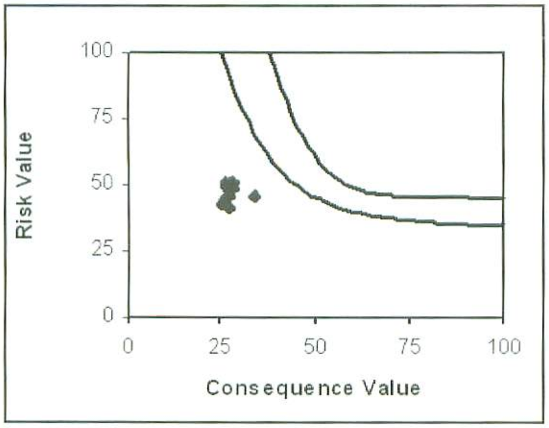
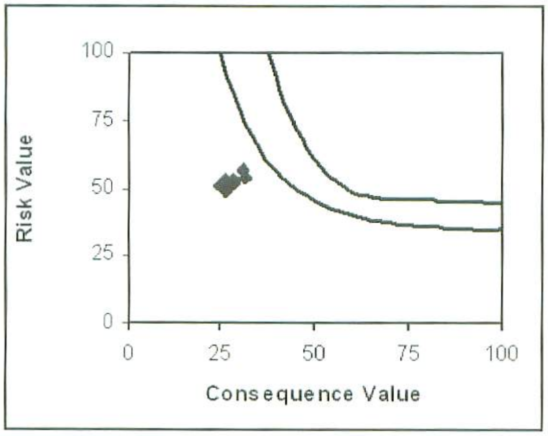


Figure 13. Comparison between consequence values for the different highways (all data shown).



Data for Site 35

Image for Site 35



Data for Site 28

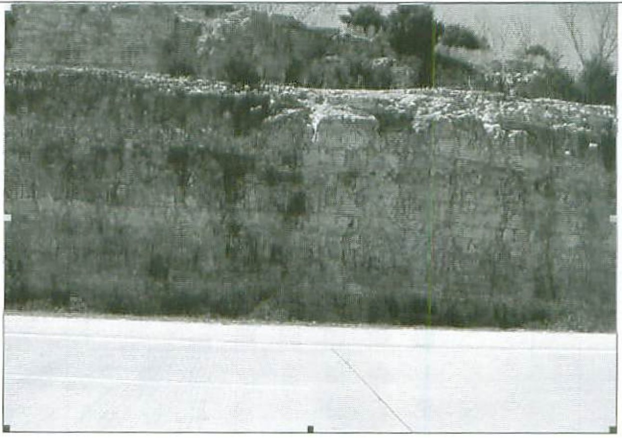
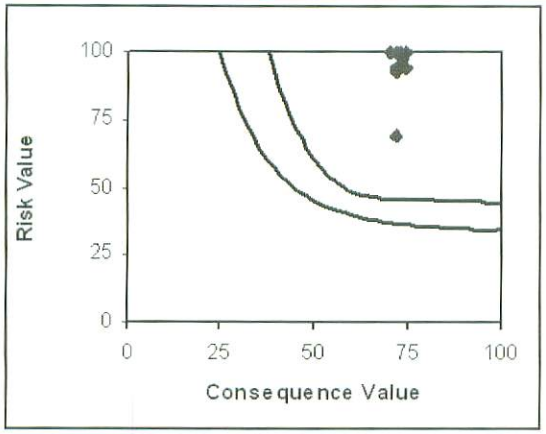


Image for Site 28



Data for Site 29

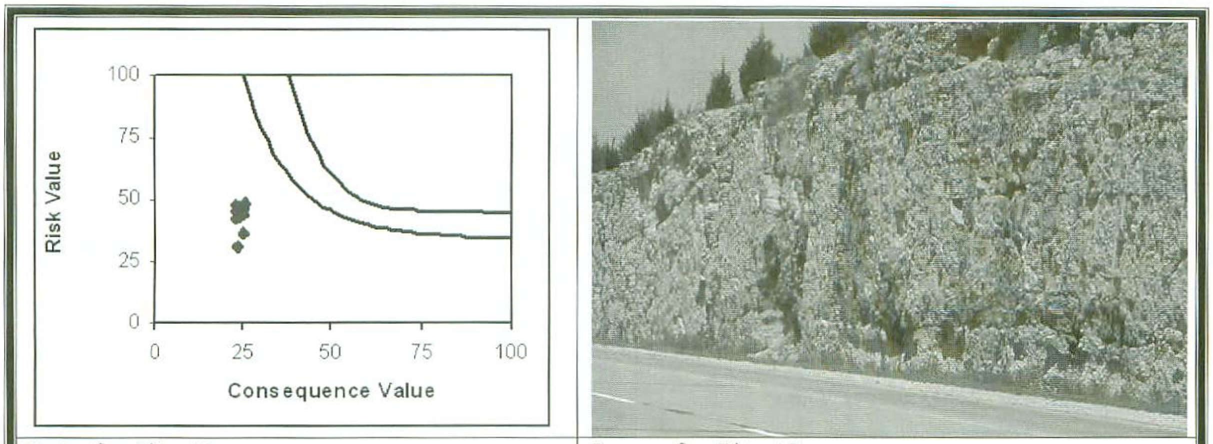
Image for Site 29

Figure 14. Risk–consequence plots, 12 raters for each site.

ever, there is a difference of approximately 5–8 percent for both risk and consequence for one of the raters. It may be that the 30 minutes of training time was not enough to make all the personnel familiar with the system.

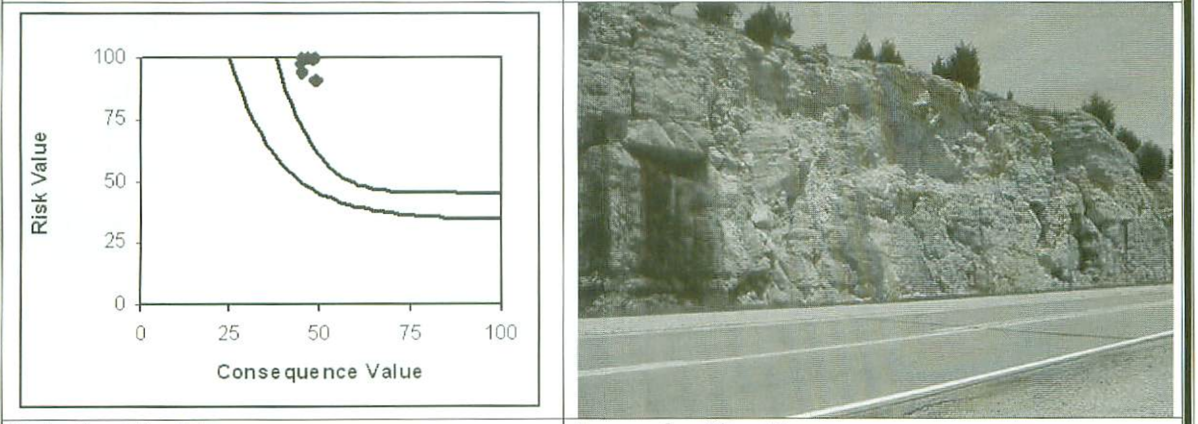
SUMMARY AND CONCLUSIONS

A proactive solution to rockfall prevention has been proposed by the authors for use by MODOT, by developing and implementing the MORFH RS, de-



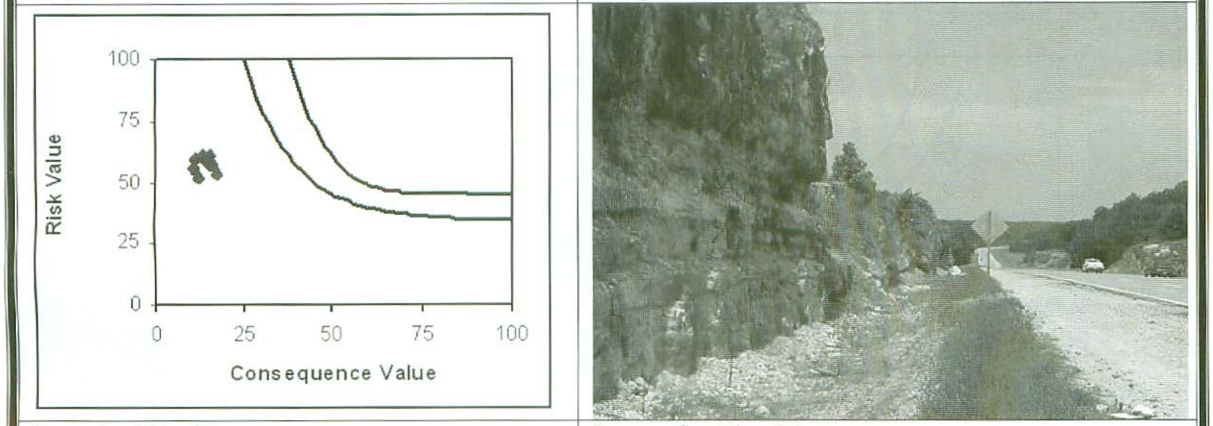
Data for Site 43

Image for Site 43



Data for Site 47

Image for Site 47



Data for Site 54

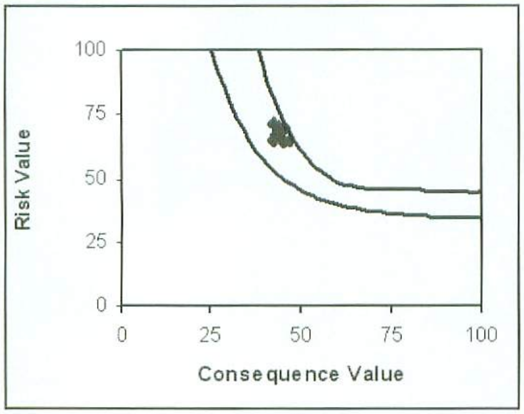
Image for Site 54

Figure 15. Risk–consequence plots, 12 raters for each site.

signed for Missouri highways to cost-effectively determine the need and priority of maintenance on rock cuts.

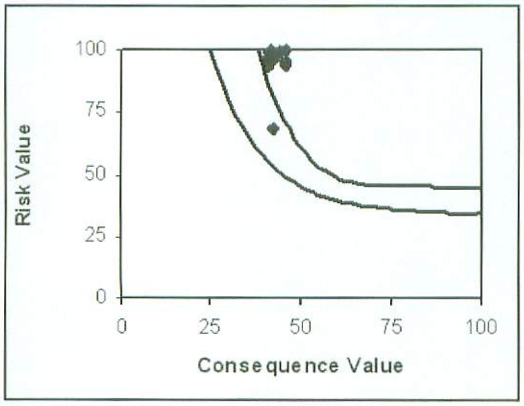
In MORFH RS, risk of failure and consequence of failure factors are given equal weight and isolated from each other. This allows factors that influence risk and consequence in opposite ways to be correctly assessed. It also allows the flexibility of more effectively determining the priority of remediation.

MORFH RS dramatically lowers costs by: 1) identifying the most potentially problematic rock cuts, by using mobile digital video logging, and 2) making measurements of some of the parameters on the video images using the RockSee program.



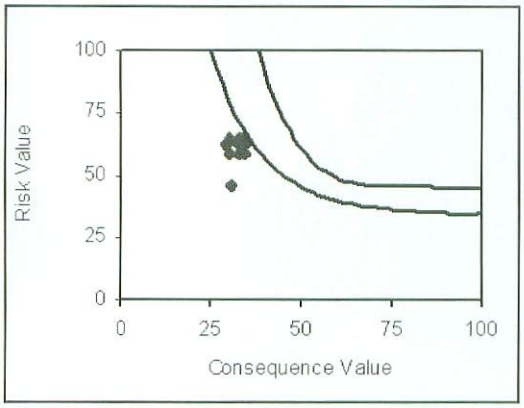
Data for Site 56

Image for Site 56



Data for Site 57

Image for Site 57



Data for Site 71

Image for Site 71

Figure 16. Risk–consequence plots, 12 raters for each site.

Parameters for MORFH RS were selected that were deemed meaningful and/or relatively easy to measure or estimate, and were assigned to either a risk or consequence category or both.

MORFH RS has been tested on approximately 300 sections of Missouri highways. The system was tested and modified many times, using the same rock cuts. The system was verified by quantifying potential errors in the video measurements and by a rating comparison of MODOT and UMR personnel on 10 rock cuts along Highway 63.

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