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ORIGINAL PAPER

Development, justification, and verification of a rock fall hazard rating system

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Abstract The Missouri Rock Fall Hazard Rating System (MORFH RS) was recently developed for the State of Missouri. It is a system that separates the risk of failure from the consequences of failure factors, thus allowing better assessment of the hazards of rock falls. Efficiency is gained by video logging of highway rock cuts from vehicles moving at highway speeds, pre-screening of rock cuts from video images, making some of the measurements needed for the rating system on digital images, and using GPS receivers to collect field data and GIS to organize all the data. This paper describes the rationale behind the parameters selected for the system using factor analysis and other methods and the verification of the system through sensitivity studies and multiple rater tests. Simulations of remediation techniques were applied to recognize the most effective methods for remediation.

Keywords Rock fall · Hazard · Rating · Risk · Consequence

Résumé Le système d'évaluation de l'aléa de chute de blocs dans le Missouri (MORFH SR) a été récemment développé pour l'état du Missouri. Ce système distingue le risque de rupture des conséquences des facteurs de rupture, permettant ainsi une meilleure évaluation des aléas de chute de blocs. L'efficacité du système réside dans l'utilisation de panoramas vidéo des déblais rocheux d'autoroute réalisés à partir de véhicules se déplaçant à grande vitesse, la réalisation de pré-enregistrements des déblais rocheux à partir d'images vidéo, l'acquisition de mesures nécessaires au système d'évaluation à partir d'images numériques et l'utilisation de capteurs GPS pour rassembler les données de terrain et d'un système SIG pour traiter ces données. Cet article décrit le raisonnement développé à partir des paramètres sélectionnés pour le système d'évaluation, utilisant l'analyse factorielle et d'autres méthodes et vérifiant le système à travers des études de sensibilité et de multiples tests. Des simulations de techniques de limitation des risques ont été réalisées pour identifier les méthodes les plus efficaces.

Mots clés Chute de blocs · Aléa · Evaluation · Risque · Conséquence

Introduction

A new rock cut rating system called the Missouri Rock Fall Hazard Rating System (MORFH RS) has been designed for Missouri highways to enable the Missouri Department of Transportation (MODOT) to cost-effectively determine the need for and priority of maintenance on rock cuts, to safeguard the motoring public, and also to reduce the risk of vehicle damage and traffic delays as a result of rock falls. A new system was needed in Missouri because existing classification systems have not been developed with Missouri rock cuts in mind; these tend to be low but highly weathered, with special problems related to highly weathered filled sink holes. The system is described extensively in Maerz et al. (2005) and is summarized in Appendix 1.

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A three-phase approach to mitigating rock fall hazards is used:

1. Potentially problematic rock cuts are identified using mobile digital video logging at highway speeds (Fig. 1). This is used as a screening tool to identify problematic highway rock cuts. A specific subset or the entire network of highways is video logged, using a video camera equipped with GPS (global position system) coordinate overlays. Trained engineers or geologists can review the video footage at a computer workstation in their office to identify problematic cuts and then decide which sites warrant more detailed investigation.
2. The rock cuts singled out for detailed investigation in phase 1 are characterized and prioritized according to the MORFH RS using a combination of measured and rated parameters. Measurements made on the video

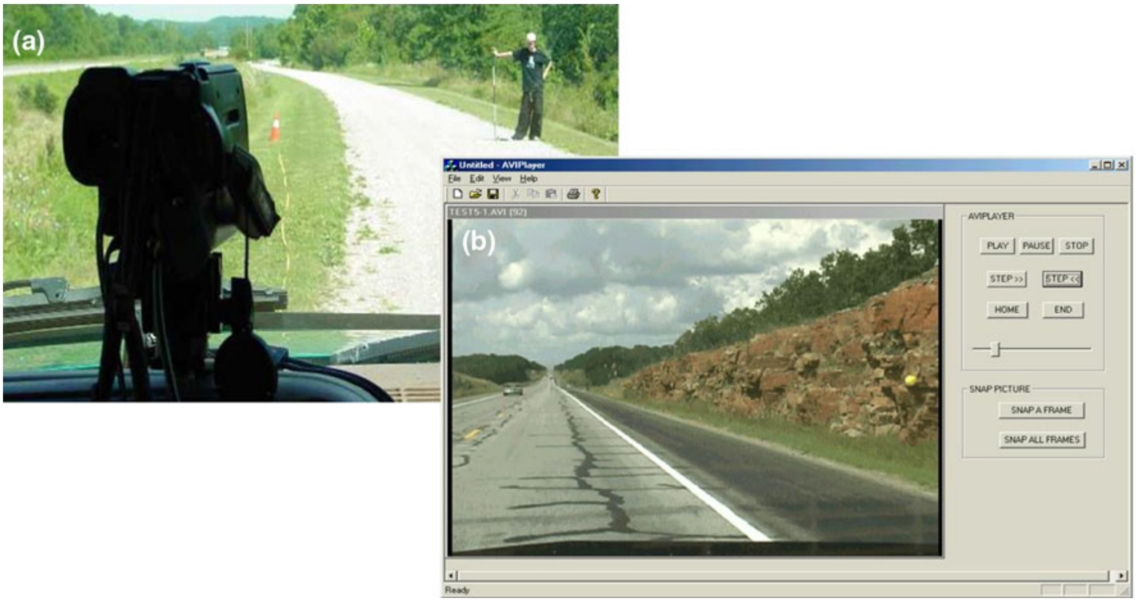
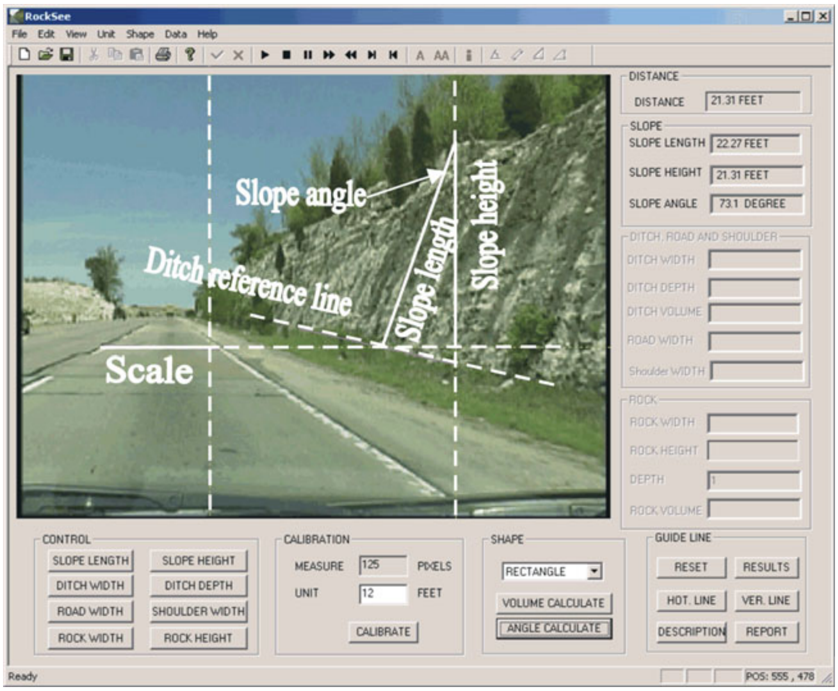


Fig. 1 Digital camcorder mounted on vehicle dashboard, used for video logging (**a**) and acquiring the images needed for scaled measurements (**b**)

Fig. 2 An example of the RockSee measurement of slope height and angle. *Dotted lines* are constructs, *solid lines* are measurements (1 foot = .3 m)



DISTANCE
DISTANCE 21.31 FEET
SLOPE
SLOPE LENGTH 22.27 FEET
SLOPE HEIGHT 21.31 FEET
SLOPE ANGLE 73.1 DEGREE
DEPTH 1
CALIBRATION
MEASURE 125 PIXELS
UNIT 12 FEET
SHAPE
RECTANGLE
POS: 555, 478

images (Fig. 2) using the computer code RockSee (Youssef et al. 2007) include slope heights, face lengths, and angles; ditch widths, depths, and volumes; and potential loose rock volumes. Parameter ratings are made from both viewing the video images and from field inspection. These include weathering, strength, face looseness, face irregularity, block size, and others.

3. Rock cuts singled out in phase 2 for remediation can undergo detailed analysis and design methodologies.

The new Missouri rating system is predicated on separating risk of slope failure from consequence of failure (Fig. 3). While other rating systems may consider both factors, they tend to lump them together. This is inherently problematic as some parameters affect risk of failure and consequence of failure in different ways. For instance, the larger the block size, the lower the risk of failure but the higher the consequence of failure. Or, a 90° slope could present the highest risk of failure, while a 30° slope might present the highest consequence from large rolling blocks and an 85° slope from small bouncing blocks. In addition, separating risk and consequence is useful, because it may be that only high risk, high consequence rock cuts merit consideration for remediation. Low-risk rock cuts may not be of concern because there is smaller chance of failure, and low consequence cuts may not be of concern because the fallen rock is not likely to reach and/or affect highway traffic.

Rating systems for applications similar to this abound in the literature and in practice. Often the selection of parameters for the system, and their arrangement, seems quite arbitrary. This paper describes how the hazard rating system was developed. The innovative techniques to select parameters, rating values, and interactions are described, as well as some of the verification studies.

Location Information	Site Number	Highway Name			
	55	63			
GPS Information	Elevation	Latitude	Longitude		
	800 ft	N 38 20.234	W 91 33.678		
RISK FACTORS	Value	Rating	CONSEQUENCE FACTORS	Value	Rating
Rock cut height	22.0	4.4	Ditch Width	11.4	2.8
Slope angle	90.0	12.0	Ditch Volume	14.8	6.1
Rockfall history	1.5	4.5	Slope Angle	90.0	0.0
Weathering	1.5	9.0	Shoulder width	15.8	0.0
Strength of intact rock	3.0	3.0	Expected rockfall quantities	5.0	1.5
Face looseness	2.0	6.0	Number of lanes	1.0	4.0
Face irregularity	1.0	3.0	Average daily traffic	5500.0	3.3
Block size	2.5	3.1	Average vehicle risk	14.5%	1.7
Water on face	1.0	3.0	Design sight distance	0.0	0.0
	Joint Sinkh	Joint Sinkh	Block size	2.5	3.3
Adjust factors	0.0 1.0	0.0 4.0	Adjust factor	0.4	2.2
Total		52.0	Total		24.9

Fig. 3 Single page report to show results of evaluation using RockSee

Selection of factors and rating values for the system

Introduction

The selection of parameters (factors) for any classification system is a balancing act; they should be both useful in the context of characterizing the rock cut but simple to understand and to rate. Several rock fall hazard rating systems are in use in North America and elsewhere, including Utah (Pack and Boie 2002); New Hampshire (Fish and Lane 2002); New York (Hadjin 2002); Washington (Ho and Norton 1991); Tennessee (Bellamy et al. 2003; Vandewater et al. 2005), and the RHRON system developed in Ontario Canada by Franklin and Senior (1987). The most widely implemented system is the Rockfall Hazard Rating (RHR) System developed by the Oregon Department of Transportation (Pierson and Van Vickle 1993). Some of these parameters were retained for the MORFH RS system, while others were not, and new ones added:

1. In order to be able to separate risk of failure from consequence of failure parameters it was important to include parameters that describe the likelihood of slope failure and those which describe the potential harm should such a failure take place.
2. Some factors were added, removed or modified to take account of the specific geological environment specific to Missouri and similar states where rock cuts are relatively smaller but are often in weaker rock.
3. To take into account the proposal to measure parameters from scaled video images.

In addition, parameter selection considered the principles of making the classification system accurately characterize the rock cut, while keeping it simple and intuitive.

For each parameter or factor, a rating scale had to be determined, whether linear or non-linear, bounded or unbounded, and conditions or measurements assigned to each of the ratings. Factor analysis was used to determine that there was no redundancy among the selected parameters.

Factors

The MORFH rating system includes 23 factors, organized into nine factors for risk of failure, 11 factors for consequence of failure and three adjustment factors (two for risk and one for consequence).

The Risk factors are

1. Slope Height.
2. Slope Angle.
3. Rock Face Instability.
4. Weathering.
5. Strength of Intact Rock.
6. Face Irregularities.
7. Face Looseness.
8. Block Size.
9. Water on Face.
10. Adversely Oriented Discontinuities (Adjustment Factor), and
11. the Karst Effect (Adjustment Factor).

The Consequence factors are

1. Ditch Width.
2. Ditch Shape.
3. Ditch Volume.
4. Slope Angle.
5. Shoulder Width.
6. Number of Lanes.
7. Average Daily Traffic.
8. Expected Rock Fall Quantity.
9. Average Vehicle Risk.
10. Decision Sight Distance.
11. Block Size, and
12. the Ditch Capacity Exceedence (Adjustment Factor).

Each of these factors was selected because it independently contributed to characterizing the rock cut risk or consequence of failure. Two factors (Slope Angle and Block Size) appear in both the risk of failure and consequence of failure categories, but with different rating criteria. On the risk side, the nine ratings on a scale of 0–12 (0–24 for weathering) are added together and normalized on a scale of 0–100 to form a risk rating. On the consequence side, the ten ratings on a scale of 0–12 are added together and normalized on a scale of 0–100 to form a consequence rating. Adjustment factors (also on a scale of 0–12), are simply added to the risk or consequence rating after normalization. Note that Ditch Capacity Excedence is an internally calculated factor; it has a rating value of (0–15), and requires no additional user input.

Ratings selection for each factor

To derive the ratings for each factor, the following approach was generally used:

1. Determine the minimum and maximum value of each factor, where measurements are ordered descriptive rankings. For example, slope heights were taken to range between 0 and 100 ft (0 and 30.5 m). Slopes heights above 60 ft (18.3 m) are rated at the maximum value.
2. Assign a relationship between the range of the factor and the rating range (0–12). The relationship could be non-linear if supported by theoretical considerations or

simulations. In the absence of such evidence, a linear relationship was used.

Slope Height (SH)

As a rule, the higher the rock cut the greater the risk of failure. Hoek and Bray (1981) present a generalized empirical relationship between slope height and factor of safety against failure. Although the Hoek and Bray relationship is non-linear, a linear approach was adopted because the slope heights are relatively small and fall in a linear range. In MORFH RS slopes are rated between 0 and 12 for heights of 0 to 60 ft (18.3 m). Slopes above 60 ft (18.3 m) are rated at the maximum value of 12.

Slope Angle (SA)—risk rating

As a rule, the steeper the rock cut the greater the risk of failure. Slopes are rated between 0 and 12 for slope angles of 30 to 90°. Slopes below 30° are rated at the minimum value of 0.

Slope Angle (SA)—consequence rating

The consequence aspects of slope angle pertain to the likelihood that falling rock will reach the highway. At very low slope angles, loose rock will not move down the slope while rocks falling off vertical slopes will fall vertically and, assuming an adequate ditch with sufficient capacity, will fall harmlessly into the ditch and not reach the highway. Between these extremes, however, there is the potential for falling rock to bounce or roll onto the highway.

For this analysis, the Colorado Rockfall Simulation Program (CRSP; Jones et al. 2000) was used to determine the effective slope angles with the greatest potential for falling rock to reach the highway. In the simulations, a constant slope height of 60 ft (18.3 m) was used while the slope angle and block size of the falling rock was varied. The percentage of blocks passing the ditch line was recorded. In this analysis a flat ditch has been assumed and the ditch line is located 20 ft (6.1 m) from the base of the cut. The results of this analysis for one example are described in Table 1 and Fig. 4. From Fig. 4 it can be concluded that

1. for a block 4–5 ft (1.2–1.5 m) in diameter the most critical slope angle is 30°;
2. for a block 3 ft (.9 m) in diameter, 40 and 85° slope angles are critical; and
3. for blocks 1–2 ft (.3–.6 m) in diameter, 85° is critical.

The overall results (Fig. 5) indicate that for large blocks, slope angles of 30–35° result in the greatest number of blocks reaching the highway, probably as a result of rolling. For small blocks, the greatest number of blocks reaching the highway occurs at about 85°, probably as a result of bouncing. Based on these data, a non-linear relationship between slope angle and consequence rating was established (Fig. 5).

Table 1 Number of rocks passing the ditch line from a 60 (feet) slope as a function of block size and slope angle (°) using CRSP

Block size (ft)	20°	30°	40°	50°	60°	70°	80°	85°
5	12	39.2	33.8	22.8	14.6	4.4	5	3
4	2	29.6	28.2	15.8	11.6	6.8	6	8.8
3	0	15.8	22.2	14.6	10.4	6.8	9.2	26.8
2	0	1	10	11.8	8.8	10	10	45.4
1	0	0	1	2.8	7.2	13.6	12.8	55.8

1 foot = .3 m

Rock Face Instability (RI)

Rock face instability is an attempt to describe the historic instability of the rock cut. Ideally this would be done using maintenance records, but these are often hard to obtain and in practice it is a matter of observing the ditch for fallen rock. In MORFH RS this is a descriptive ranking in five categories: Completely stable; Stable; Partially stable; Unstable; and Completely unstable, corresponding to ratings between 0 and 12.

Weathering Factor (WF)

This factor is determined by the presence of erosion and differential erosion features on the face of a rock cut (e.g. overhangs). The RHR system (Pierson and Van Vickle 1993) uses two factors: differential erosion features and difference in erosion rate. MORFH RS uses a single descriptive factor, but incorporates both degree of erosion and differential erosion in the description. Because of the importance of the weathering, this factor has been assigned double the weighting of the other factors. In MORFH RS this is a descriptive ranking of weathering in five categories: Fresh; Slightly; Low; Moderate; and High (weathering), corresponding to ratings between 0 and 24.

Strength of Intact Rock (SOIR)

The most common method for describing the strength of the intact rock is the uniaxial compressive strength (UCS). In classification systems it is common to estimate compressive strength using simple field evaluations. The International Society for Rock Mechanics suggests using a pocket knife and geological hammer to estimate strength

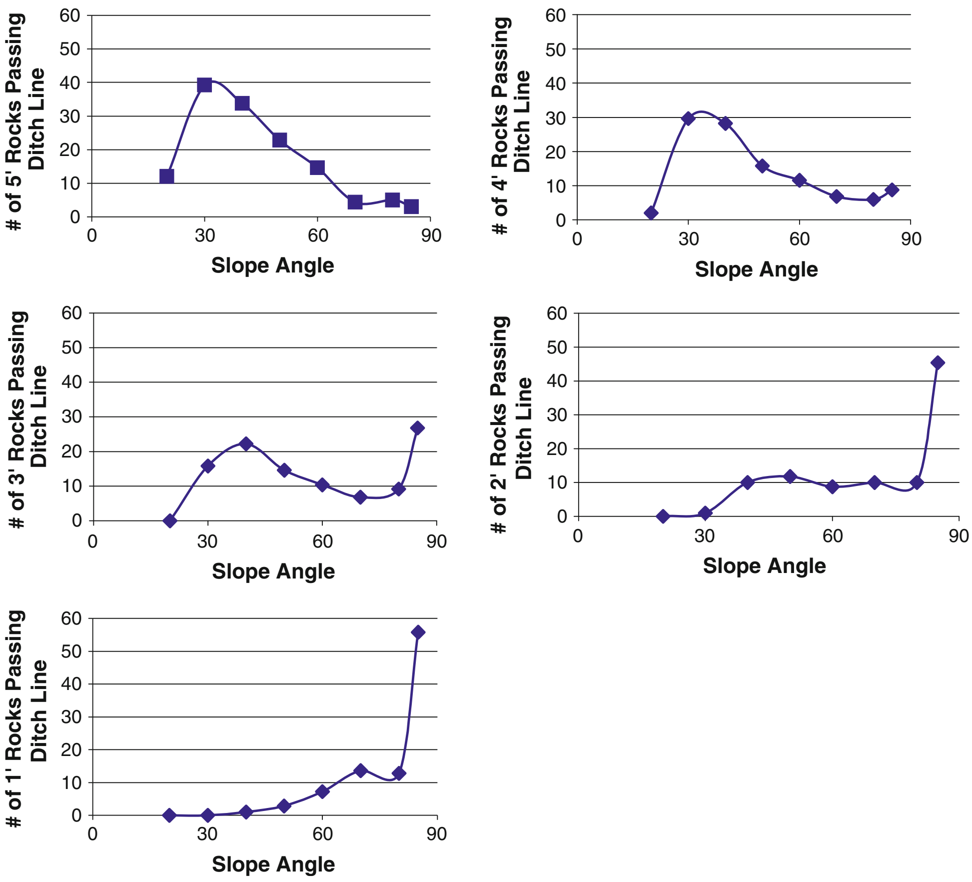


Fig. 4 Graphical relation between the numbers of blocks passing the ditch line from a 60-ft slope as a function of block size and slope angle (°) using CRSP

(ISRM 1978). A similar scheme is proposed by the Geological Society Engineering Group Working Party (1995). MORFH RS used a scheme based on practices in which a hand hammer was used. Table 2 shows the relationship between estimated UCS in psi and the rating. This is a descriptive ranking in five categories: Very weak; Weak; Moderately strong; Strong; and Very strong (rock), corresponding to ratings between 0 and 12. From Table 2 it is obvious that there is non-linear relationship between UCS and the rating.

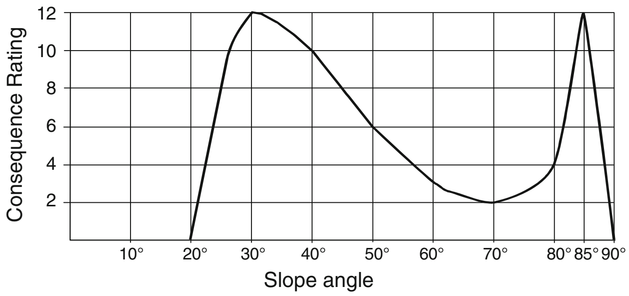


Fig. 5 Consequence rating as a function of slope angle. Slope angles of about 30° tend to be high consequence (because of rolling of large boulders) and slope angles of about 85° tend to be high consequence (because of bouncing of small blocks off the face and onto the highway)

Face Irregularities (FI)

Face irregularity is associated with instability on rock cuts (Franklin and Senior 1987) whether because of poor blasting or ongoing raveling failures. In MORFH RS this is a descriptive ranking in five categories: Smooth; Slightly irregular; Moderately irregular; Highly irregular; and Very highly irregular (face), corresponding to ratings between 0 and 12.

Face Looseness (FL)

Face looseness can be described by the number of open joints that are visible on the face and their apertures (Franklin and Senior 1987). In MORFH RS this is a descriptive ranking in five categories: Not loose; Low volume loose; Moderate volume loose; High volume loose; and Very high volume loose (material), corresponding to ratings between 0 and 12.

Block Size (BS)—risk rating

As a rule the larger the block size in a rock mass the more stable that rock mass will be (Franklin and Dusseault 1989). RHRON (Franklin and Senior 1987) uses block size

Table 2 Intact rock strength classification categories (MODOT Classification)

Rock strength	Description	R
Very strong rock	>14,504 psi, many blows by the hammer needed to fracture the rock	0
Strong rock	7,252–14,504 psi, several blows to fracture the rock	3
Moderately strong rock	3,626–7,252 psi, A firm blow needed to fracture the rock	6
Weak rock	725–3,626 psi, can indent the rock with a pick	9
Very weak rock	145–725 psi, can crumble by hand	12

1 psi = 6.9 kPa

in this context. A non-linear relationship between block size and risk rating was adapted for MORFH RS, because it is likely that the greater change in risk with block size will be observed at the low end of the block size range (Fig. 6).

Block Size (BS)—consequence rating

As a function of kinetic energy, the larger the block size the more energy and destructive potential a rolling rock block will have, and the less it will be impeded by frictional and other resisting forces. RHRS (Pierson and Van Vickle 1993) uses block size in this context. A non-linear relationship is used in MORFH RS, because larger blocks will have a disproportional potential for damage (Fig. 7).

Water on Face (WOF)

The presence of water in a rock mass, either in the form of flow as an agent of erosion or in the form of pressure or reduced effective stress, is arguably the most important factor in a slope. On the other hand, it is also one of the most difficult tasks to assess and quantify without extensive field investigations, especially on the water pressure side. Consequently, most rating systems simplify this to a descriptive rating. MORFH RS uses a method similar to the RHRON system (Franklin and Senior 1987) and has a descriptive ranking in five categories: Dry; Damp; Wet; Dripping; and Flowing, corresponding to ratings between 0 and 12.

Adversely Oriented Discontinuities (AOD)

This factor is an adjustment factor, as it is not often necessary in the relatively flat-lying sedimentary rocks of Missouri. It considers all types of discontinuities that could be formed due to different processes such as stress relief, faulting, tectonic activity etc. Categories were determined using sensitivity analyses performed using limiting equilibrium analysis and also from the data from Hoek and Bray (1981) which considers the variation of the factor of safety with the angle of the discontinuities. Table 3 shows the relationship between rating and the categories of discontinuities.

Karst Effect (KE)

This factor is an adjustment factor developed for MORFH RS. Missouri highway cuts often penetrate collapsed (filled) sinkholes. The collapsed materials are generally weak, weathered, fine-grained weakly cemented materials. In MORFH RS this is a descriptive ranking in five categories: Non-carbonate rock; No evidence of karst; 50 ft (15.2 m)

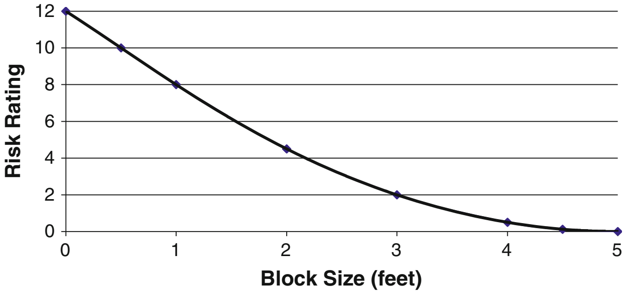


Fig. 6 Risk rating as a function of block size (1 foot = .3 m)

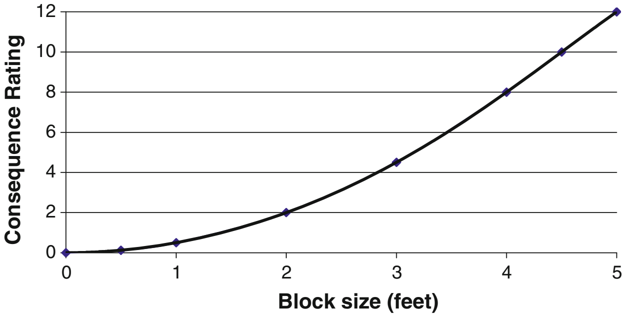


Fig. 7 Consequence ratings as a function of block size (1 foot = .3 m)

Table 3 The relationship between rating and the categories of discontinuities

	Favorable	Fair	Unfavorable	Very unfavorable
Dip angle of discontinuity	<20	20–45	45–65	65–90
Rating	0	4	8	12

of karst; 100 ft of karst (30.5 m); and 150 ft (45.7) of karst (materials present) corresponding to ratings between 0 and 12.

Ditch Width (DW)

The design criteria for ditch width was determined by requiring 99% retention of the falling rock based on slope height and ditch shape. Pierson et al. (2001) proposed improvements to the Ritchie's criteria (1963) based on an extensive research program in which over 11,000 rocks were rolled off a variety of slopes. Pierson et al. (2001) mentioned that higher slopes and flatter catchment areas produce rock fall roll out distances that are more widely scattered. Higher slopes in general produce larger average roll out and impact distances. Large roll out distances are possible when a falling rock's translational momentum is changed into rotational momentum by impacting the slope, especially if the rock strikes near the base of the cut slope.

In this study the modeled ditch shapes were Horizontal (no ditch), 1:6 slope down to the face and 1:4 slope down to the face. The results are shown in Fig. 8, which indicates that for a vertical slope up to 60 ft (18.3 m) high, a ditch width of 18 ft (5.5 m) is adequate as long as the ditch is not horizontal. This is because the blocks will tend not to roll away horizontally after dropping vertically. For inclined slopes (75 and 65°) under the same circumstances a ditch width of 30–35 ft (9.1–10.7 m) is required. (Pierson et al. 2001)

In MORFH RS ditch widths are rated between 0 and 12, for widths of 0–15 ft (0–4.6 m) for vertical slopes and 0–30 ft (0–9.1 m) for non-vertical slopes, including vertical slopes with benches.

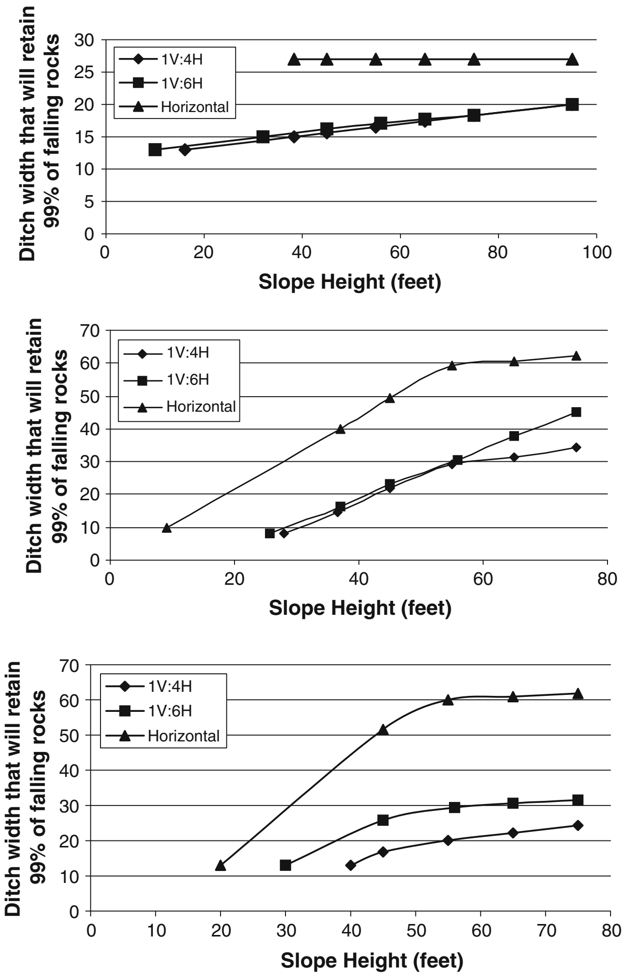


Fig. 8 Ditch width that will retain 99% of falling rock as a function of slope height and ditch shape for vertical slopes (*top*), 75° slopes (*middle*) and 63° (*bottom*) (1 foot = .3 m)

Ditch Volume (DV)

This factor is used for vertical slopes. The effectiveness of a ditch volume is measured by its ability to prevent falling rock from reaching the roadway. This depends on several factors such as ditch width, depth, and shape, as well as the anticipated quantity of rock fall. In this study, the largest ditch size was set to 30 ft^3/foot (linear foot of slope) (2.8 m^2/m) and the rating values were assigned from 0 to 12 in an inverse linear relationship with a ditch volume 0 to 30 ft^3/foot (2.8 m^2/m). The rating will be 0 if the ditch volume is 30 ft^3/foot (2.8 m^2/m).

Ditch Shape (DS)

This factor is used for non-vertical slopes (or benched slopes with inadequate benches) to deal with the rolling and bouncing blocks that land with horizontal momentum. Ditch shape here refers to the ability of the ditch to prevent falling and rolling rocks reaching the highway, in the case of horizontal rock trajectories. If the ditch is flat or has a low back slope angle the blocks may reach the highway, while if it has a large back slope the blocks are likely to bounce and roll back towards the rock face. The parameter classification comes from the ditch design manual (Pierson et al. 2001) and is modified to cover most categories that occur along Missouri rock cuts (Table 4).

Table 4 The relationship between the consequence rating and ditch shape

Ditch shape	Flat	Slight back slope (1 V:8H) 7°	Moderate back slope (1 V:6H) 9°	Large back slope (1 V:4H) 14°
Rating	12	8	4	0

Shoulder Width (SW)

Available shoulder width is the paved or unpaved width 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 high. Shoulder widths from 0 ft (no shoulder) to 12 ft (3.6 m) were used, corresponding to a rating from 0 to 12 in a linear relationship.

Number of Lanes (NOL)

The greater the number of lanes available, the more opportunity a driver has to swerve out of the path of rocks or debris. A non-linear relationship is used here because the utility in moving from 1 to 2 lanes is more significant than moving from 2 to 3 lanes in terms of the driver's ability to avoid both fallen rock on the road and other vehicles. This relationship was established in consultation with MODOT personnel (Fig. 9).

Average Daily Traffic (ADT)

Using available traffic data (MODOT 2000) it was determined that for the highways in question, the appropriate number of cars per day should be 500 to 20,000. A linear relationship between consequence rating and ADT was established (Table 5).

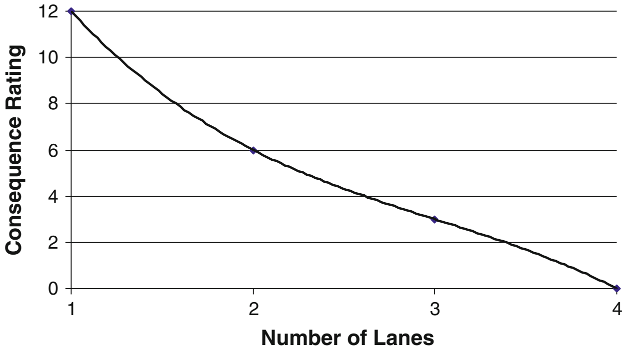


Fig. 9 Consequence rating as a function of number of lanes

Table 5 The relationship between consequence rating and average daily traffic

ADT	>500 cars/day	5,000 cars/day	10,000 cars/day	15,000 cars/day	20,000 cars/day
Rating	0	3	6	9	12

Expected Rock Fall Quantity (ERFQ)

The expected rock fall quantity is the volume of material expected to fall from the rock cut face, which must be contained in the ditch over the interval between ditch cleanings. This factor depends on the instability of the rock cut face, discontinuities on the face, and discontinuity orientations (favourable or unfavourable), presence and size of sinkholes, and height of the rock cut. It is determined by visual estimation of the quantity per linear foot (.3 m) based on the area of the hazard face and the depth of loose materials; or by using RockSee to measure areas and depths where overhangs can be measured. This parameter is set to be from 0 ft^3 (0 m^3) for a clean smooth face to about 40 ft^3 (1.1 m^3) or more for the problematic areas. The 40 ft^3 (1.1 m^3) value will be rated 12. Typically, in a loose filled sinkhole, or if there are adversely oriented discontinuities on the face, the maximum rating of 12 is used.

Average Vehicle Risk

Equation 1 below is a modified version of the one used by RHRS (Pierson and Van Vickle 1993), with the addition of a term representing the number of lanes:

$$\mathrm{AVR\%} = \frac{\mathrm{ADT(cars/day)} \times \mathrm{slopelength(miles)} \times 100\%}{\text{Posted speed limit (miles/hour)} \times \text{ number of lanes}} \quad (1)$$

In MORFH RS, a consequence rating between 0 and 12 is calculated for an AVR between 0 and 100%.

Decision Sight Distance (DSD)

The decision sight distance is the length of roadway in feet in which a driver can visually recognize obstacles on the road and make an instantaneous driving decision in response. It is the greatest distance along a roadway that an object, such as a fallen rock, is continuously visible to the driver, affected by horizontal and vertical curves along with visual obstructions such as rock outcrops and roadside vegetation.

In MORFH RS a visual determination of the decision sight distance is made, depending on different factors such as curvatures on the roads and the presence of trees, and other visual obstacles, corresponding to rating values set from 0 to 12.

Ditch Capacity Exceedence (ERFQ/DV)

This factor is an adjustment factor that is simply a ratio of the Expected Rock Fall Quantities over the Ditch Volume and results in a consequence rating of 0–15 for a ratio of 1:1 to 4:1.

Suitability analysis for the system factors

Suitability of factor analysis

Multivariate statistical analyses for the MORFH RS factors can indicate the relative contribution of each of these factors to the degree of hazard within a defined rock cut section. The analyses are based on the presence or absence of stability phenomena within these sections. Factor analysis is a technique for examining the interrelationships among a set of variables (Afifi and Clark 1996; Afifi et al. 2004). The major emphasis is placed on obtaining easily understandable factors that convey the essential information contained in the original set of variables. In the initial stage of development, all of the risk and consequence parameters of the MORFH RS are included in the factor analysis and a principal axis factoring method with varimax rotation is selected. Two tests have been performed to investigate the validity of factor analysis with the given factors.

The Kaiser–Meyer–Olkin (KMO) test measures the sampling adequacy and is a statistic which indicates the proportion of variance in the variables which is common variance, i.e., which might be caused by underlying factors. High values (close to 1.0) generally indicate that a factor analysis may be useful with the available data. If the value is less than .50, the results of the factor analysis probably will not be very useful. In this case of MORFH RS, KMO values are .857 and .585 for risk and consequence variables, respectively (Table 6); these results indicate that factor analysis is very useful for this model.

Bartlett's Test of Sphericity measures the significance of the relationships between the factors (the parameters will help each other). Very small values of significance (less than .05) indicate the suitability of using factor analysis in the system. A value higher than .10 may indicate that the data are not suitable for factor analysis. For the model it was found that the significance level for both risk and consequence variables was less than .0001 (Table 6). Based on these results for KMO and significance level, it was found that factor analysis seems to be a useful method to analyze the suitability of the system.

Table 6 KMO and Bartlett's test for Risk and Consequence variables

	Risk	Consequence
Kaiser–Meyer–Olkin measure of sampling adequacy	.857	.585
Bartlett's test of sphericity		
Approx. χ^2	1593.062	1203.812
Df	36	66
Sig.	.0001	.0001

Factor analysis for risk of failure variables

The next step in the analysis is to determine if there are any factors that do not fit the assumptions of the factor analysis model. The Measure of Sampling Adequacy (MSA) has to be above .50; however, if the value is less than .50 the factor will not contribute much to the analysis. If there is too little variability in a factor, e.g., the slopes are all 50 ft high, then the slope height would not be a useful factor. Or if karst features are not present in most of the cases, then Karst Effect is not a useful variable.

The anti-image matrix (Table 6) contains the negative partial correlations between factors. Small values indicate that the variables are relatively free of unexplained correlations. Most or all values off the diagonal should be small. Each value on the diagonal of the anti-image correlation matrix shows the Measure of Sampling Adequacy (MSA) for the respective item. The anti-image matrix of the initial 11 variables for risk was analyzed. The results showed that both Adversely Oriented Discontinuities and Karst Effect did not fit into the structure of the remaining variable. An iterative variable removal scheme was applied based on the rules of Anti-Image Matrices. The best solution is found after the second pass with the removal of Adverse Discontinuities and Karst Effect, where the Kaiser–Meyer–Olkin Measure of Sampling Adequacy is increased from .837 to .857. As a result, Adversely Oriented Discontinuities and Karst Effect were removed from the basic calculation, but added as risk of failure adjustment factors. The results of the nine remaining factors are shown in Table 7.

Factor analysis for consequence of failure variables

In the same way a factor analysis was applied to the consequence factors. The anti-image matrices for the initial 12 consequence variables (where ditch volume and ditch shape were used at the same time) (Table 8) reveals that Average Daily Traffic, Expected Rock Fall Quantity and Ditch Capacity Exceedence are the three variables that have values a little less than .5. As this is the first iteration pass of the system it was decided to include these parameters in order to see the effects of these variables before and after their removal. After the removal of Average Daily Traffic, Expected Rock Fall Quantity and Ditch Capacity Exceedence the Kaiser–Meyer–Olkin Measure of Sampling Adequacy is increased from .585 to .625, which is not a major change.

As a result, Average Daily Traffic and Expected Rock Fall Quantity were retained in the system because their values in the anti image correlation are .475 and .496, respectively, which are both quite close to .50 thresholds. However, the Ditch Capacity Exceedence was removed

Table 7 The Anti-Image correlation matrix of nine risk variables

	SH	SA	RFI	We	SF	FI	FL	BS	WOF
Slope Height (SH)	**.669**[a]	−.002	−.074	−.007	−.110	.153	−.014	−.298	.006
Slope Angle (SA)	−.002	**.849**[a]	−.001	−.101	−.081	.041	.103	−.006	.009
Rock Face Instability (RFI)	−.074	−.001	**.844**[a]	−.394	.179	−.135	−.548	.038	.066
Weathering (We)	−.007	−.101	−.394	**.856**[a]	.496	−.064	−.034	.075	−.128
Face Strength (SF)	−.110	−.081	.179	.496	**.885**[a]	.022	.032	.087	.072
Face Irregularity (FI)	.153	.041	−.135	−.064	.022	**.930**[a]	−.333	.041	−.033
Face Looseness (FL)	−.014	.103	−.548	−.034	.032	−.333	**.857**[a]	−.042	.079
Block Size (BS)	−.298	−.006	.038	.075	.087	.041	−.042	**.571**[a]	−.168
Water on Face (WOF)	.006	.009	.066	−.128	.072	−.033	.079	−.168	**.539**[a]

Bold values are those used in the Bartlett's Test of Sphericity

[a] Measures of Sampling Adequacy (MSA)

Table 8 The Anti-Image correlation matrix of 11 consequence variables

	DW	DS	DV	SA	SW	NL	ADT	ERQ	AVR	DSD	BS
Ditch Width (DW)	**.581**[a]	−.040	−.867	−.046	−.139	−.226	.190	−.169	.176	.019	−.095
Ditch Shape (DS)	−.040	**.681**[a]	.088	.505	−.021	−.042	.010	−.035	−.075	−.070	.093
Ditch Volume (DV)	−.867	.088	**.581**[a]	.070	.108	.190	−.264	.052	−.017	.065	.005
Slope Angle (SA)	−.046	.505	.070	**.626**[a]	−.090	−.026	−.109	−.057	.189	.237	.112
Shoulder Width (SW)	−.139	−.021	.108	−.090	**.569**[a]	−.064	.156	−.048	−.056	.053	−.093
Number of Lanes (NL)	−.226	−.042	.190	−.026	−.064	**.516**[a]	−.759	−.119	.113	.054	.095
Average Daily Traffic (ADT)	.190	.010	−.264	−.109	.156	−.759	**.475**[a]	.103	−.257	−.133	−.045
Expected Rockfall Quantity (ERQ)	−.169	−.035	.052	−.057	−.048	−.119	.103	**.496**[a]	−.141	−.124	−.133
Average Vehicle Risk (AVR)	.176	−.075	−.017	.189	−.056	.113	−.257	−.141	**.701**[a]	.020	.005
Decision Sight Distance (DSD)	.019	−.070	.065	.237	.053	.054	−.133	−.124	.020	**.782**[a]	.073
Block Size (BS)	−.095	.093	.005	.112	−.093	.095	−.045	−.133	.005	.073	**.649**[a]

Bold values are those used in the Bartlett's Test of Sphericity

[a] Measures of Sampling Adequacy (MSA)

and added as an adjustment factor for the consequence side where its SAM is .43, which is close to .50.

Verification techniques

Evaluation of RockSee measurement errors

Measurements of some of the parameters used in MORFH RS are made on video images using the RockSee program. A series of test measurements were conducted to evaluate the accuracy of the RockSee measuring system. Twelve test sites were measured. For each site, video measurements and corresponding manual measurements were made. The error percentage (Table 9), defined as the percentage differences between manual and image measurements, on average was found to be less than 9% in all cases. Errors of this magnitude are acceptable for the purpose of input to a classification system.

Table 9 The average error percent due to measurement values

Parameter	Error percentage	Parameter	Error percentage
Ditch Width	6.0	Cliff Height	3.9
Ditch Depth	8.6	Shoulder Width	7.6
Slope Length	4.2	Road Width	2.7
Slope Angle	2.7	Rock cut length	4.7

These measurements do have a high variability, with a few errors above 10%, and occasional errors of up to 30–40% when, for instance, mis-locating the edge or the bottom of a ditch due to the obscuring effect of vegetation.

Sensitivity analysis (ratings)

Sensitivity Analysis (SA) is the study of how the variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation, and of how the given model depends upon the information fed into it (Saltelli et al. 2000; Saltelli 2002). The aim of sensitivity analysis is to estimate the rate of change in the output of a model with respect to changes in model inputs. Such knowledge is important for (a) evaluating the applicability of the model, (b) determining parameters for which it is important to have more accurate values and (c) understanding the behavior of the system being modeled. In this work two different types of sensitivity analyses were conducted. (1) Local Sensitivity Analysis (LSA), which determines the effect of the variation in each input factor when the others are kept at some constant level. (2) Global Sensitivity Analysis (GSA)—the effects of variation in the inputs when all input parameters are allowed to vary over their ranges.

Changing one parameter at a time

In this analysis one factor at a time is varied and the effect of this factor on the risk and consequence value is observed. The base ratings for the analysis are given in (Table 10). For the measurable factors the error percent introduced into the analysis was determined by previous studies on RockSee errors (Table 11). For the rated factors a change of 1.5 and 3 on the rating scale was used, while a change of 3 and 6 was used for weathering factor (Table 12). (As an example, an error of 3 (on a scale of 0–12) is the difference between a highly irregular face and a moderately irregular face).

Table 10 Base measurements sample for the sensitivity analysis (1 foot = .3 m)

	Measurement value	Rating
Risk factors		
Rock Cut Height	30 ft	
Slope Angle	70°	
Rock Fall Instability		9
Weathering		6
Rock Face Strength		2
Face Irregularities		3
Face Looseness		6
Block Size	3 ft	
Water On Face		12
Consequence Factors		
Ditch Width	9 ft	
Ditch Volume	13.5 cu ft/ft	
Slope Angle	70°	
Shoulder Width	12 ft	
Number of Lanes		3
Average Daily Traffic	5,500 car/day	
Rock Fall Quantity	30 cu ft/ft	
Average Vehicle Risk	500 ft	
Design Sight Distance		3
Block Size	3 ft	

Table 11 Sensitivity analysis error percentage of measurable factors used

	Change in the rating (%)
Risk Factors	
Slope Height	±.41
Slope Angle	±.68
Consequence Factors	
Ditch Width	±.84
Ditch Volume	±3.35
Slope Angle	±.21
Sholulder Width	±1.26

From these analyses, it is clear that the effect of the error values for measurable parameters on the sensitivity of the rating system (Risk of failure and Consequence of failure values) is typically very small, except for ditch volume which is a little higher because it is calculated from two parameters (ditch depth and ditch width) so both error values compound. For the descriptive parameters the error range is small, about ±2.5% for 1.5 rating value and ±5% for 3 rating value, with the exception of the weathering parameter, which is twice as high. Weathering has twice the weight of the other parameters because there are two main factors which affect the weathering: differential erosion and weathering rate (Table 12).

From these analyses it is obvious that errors (other than weathering) in any parameter will have a negligible effect

Table 12 Sensitivity analysis results; error percentage of rated parameters

Risk Factors	Percent (%) of the change in Risk Rating, 1.5 rating error	Percent (%) in change in Risk Rating, 3 rating error
Rock Fall Instability	±2.58	±5.17
Rock Face Strength	±2.58	±5.17
Face Irregularities	±2.58	±5.17
Face Looseness	±2.58	±5.17
Water On Face	±2.58	±5.17
Risk Factors	Percent (%) of the change in Risk Rating, 3 rating error	Percent (%) in change in Risk Rating, 6 rating error
Weathering	±5.17	±10.35
Consequence Factors		
Decision Sight Distance	±3.56	±6.92

on the total rating. However, if there is a systematic error in all of the parameters at once the overall MORFH RS rating may be seriously skewed. For that reason the rock cut evaluations have to be done by an experienced person. However, if the errors are normally distributed (some negative, some positive) the overall effect will be small.

Changing all the parameters simultaneously

Table 13 shows the results of introducing a ±1.5 rating error in all descriptive factors (Strength, Face Irregularity, Face Looseness, Block Size, Water On Face, and Decision Sight Distance) and a ±3 rating error for Weathering, as well as the ±errors related to the RockSee measurements. However, the Number Of Lanes, Average Vehicle Risk, Average Daily Traffic, and Expected Rock Fall Quantity are kept constant, because these are not likely to be subject to errors, or the error is difficult to quantify.

These values show that the actual percent of errors, if all the descriptive parameters change, will be ±21% for the risk side and ±11% for the consequence side. This error is on the high side, so it is important that raters are well trained and do not try to deliberately or accidentally impart systematic bias in their ratings.

Rater field trials

To evaluate the effect of rater errors, field trials were conducted by asking multiple raters to rate a common set of sites. Ten raters were asked to participate: 4 MODOT personnel, 4 graduate students from the Geological Engineering Department at the University of Missouri Rolla and the authors Maerz and Youssef (who each rated the cuts twice). Ten sites along Highway 63 between the city of Rolla and Jefferson City were selected. In this analysis the measurable factors using RockSee were pre-determined. All of the raters were engineers, except one, a geologist. All raters were given 30 min of training and given a field manual which gave descriptions of each parameter/rating as well as type pictures for each rating.

The results were reported in Maerz et al. (2005). With the exception of a single rater results were always between 2–5% for both risk and consequence. With the addition of that other rater, the error increases to 5–8%. Perhaps the training time was not enough to make that particular rater familiar with the system and how to rate the different parameters. Comparing the results for Maerz and Youssef as they rated the same sites twice on different occasions, the error was less than 2%. These results suggest that MORRH RS can be very consistent between trained raters.

Table 13 Percent change in total rating value with errors due to RockSee measurements and all other factors

	Original Rating	Range of ratings with errors	Average change	Rating variation percentage
Risk value	48.3	38.3–58.5	±10.2	±21
Consequence value	46	41.2–52	±5.4	±11.7

Evaluation of remediation practices on MORFH RS

There are many methods used to reduce the effect of rock falls from the rock cut faces along the highways. These include

1. Scaling to remove loose rock,
2. improving the capacity of the ditch to hold fallen rocks, including enhancement with fences and barriers,
3. supporting the rock cut so that it will not fail or so that failed blocks will not reach the highway, and
4. blasting the rock cut so that loose rock is removed and additional storage space is created at the base of the slope.

There are some other methods used for physical restraint of rock falls. If it is accepted that it is not possible to detect or to prevent all rock falls, then methods for restraining those rock falls which do occur must be considered (Hoek 2000).

MORFH RS simulated remediation methods

The effect of different Repair/Remediation/Maintenance treatments on the rating system were simulated, assuming parameter ratings based on what the face might be like after maintenance. Three methods were simulated: Scaling, ditch improvements, and cutting (blasting) back the slope.

Scaling

Scaling is a way to remove loose, overhanging, and unstable materials from the rock face. There are many methods for scaling from manual to mechanized. Scaling is, however, typically a temporary solution, as block loosens up over time. The effects of scaling were simulated by a significant decrease of the following factors: (1) Face Instability, (2) Face Looseness, (3) Face Irregularity, and (4) Expected Rock Fall Quantity; as well as a partial decrease of Karst Effect and Adversely Oriented Discontinuities. The Ditch Capacity will increase.

Ditch improvements

Increasing the ditch capacity is a very good method used to decrease the consequence rating (decrease the number of falling rocks from reaching the highways). These include widening the ditch, increasing its depth, increasing the back slope of the ditch, and using a shoulder fence or jersey barrier to increase ditch capacity. A layer of gravel to absorb the energy of falling rocks should cover the base of this ditch, and a sturdy barrier fence can be placed between the ditch and the roadway. The location of the barrier fence can be estimated by means of a rock fall analysis such as that used to calculate the trajectories. The criterion for the minimum distance between the toe of the slope and the rock fence is that no rocks can be allowed to strike the fence before their kinetic energy has been diminished by the first impact on the gravel layer in the rock trap. Ditches, however, need to be maintained, and lose rock removed on a periodic basis. The effects on the ratings are shown by increasing the effectiveness of the following factors: (1) Ditch Width, (2) Ditch Volume, (3) Ditch Shape, (4) Ditch Effectiveness, and (5) Ditch Capacity.

Cutting back (Blasting) the slope

Cutting back the slope, typically by blasting will have a particularly large benefit on the rating system, especially when a good perimeter blasting technique replaces earlier poor blasting technique. This is, however, typically a more costly solution than the other two. The effects on the ratings are shown in the following factors changes. The negative effects of the following factors will decrease: (1) Face Instability, (2) Face Irregularity, (3) Face Looseness, (4) Weathering, and (5) Expected Rock Fall quantity, as well as a partial decrease of the Karst Effect and Adversely Oriented Discontinuities. On the other hand, there is an increase in the positive effect of the following factors: (1) Ditch Width, (2) Ditch Volume, (3) Ditch Shape, and (4) Ditch Capacity.

Analysis of MORFH RS simulated remediation methods

The remediation simulation consisted of applying the aforementioned adjustments to the parameters appropriate to the three different remediation techniques, for all the 300 Missouri rock cuts that were rated as part of this study. Figure 10 shows the "as is" risk consequence rating for those rock cuts.

Figures 11, 12, and 13 show the results of simulating scaling, ditch modification, and trim blasting, respectively. The results show that blasting is the best method to decrease the risk and consequence, but it is the costliest method. The scaling method is also very effective, but is likely to be a shorter-term solution. Improving the effectiveness of the ditch is also shown to be effective, and this is probably the most cost-effective solution.

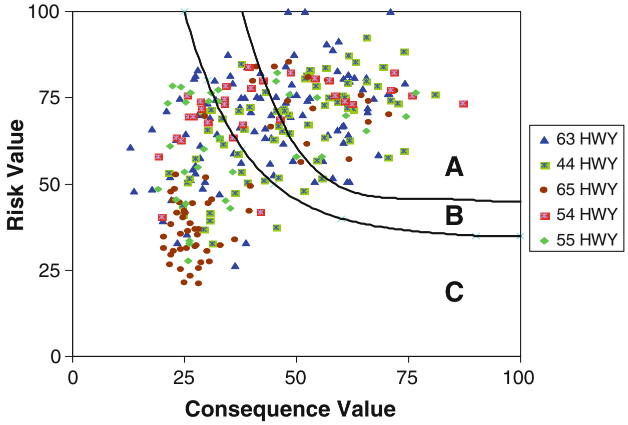


Fig. 10 Risk Consequence diagrams before applying remediation technique. Field "A" represents the rock cuts in most need of remediation; field "B" marginal need; field "C" no need

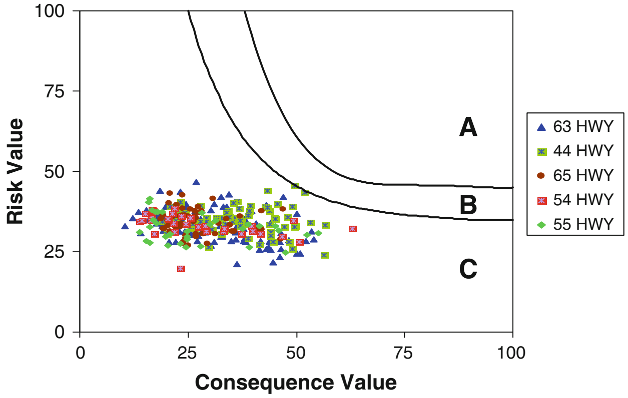


Fig. 11 Risk Consequence diagrams after scaling. Field "A" represents the rock cuts in most need of remediation; field "B" marginal need; field "C" no need

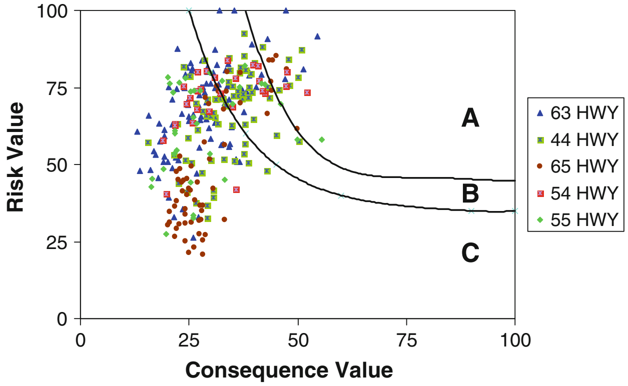


Fig. 12 Risk Consequence diagrams after ditch modification. Field "A" represents the rock cuts in most need of remediation; field "B" marginal need; field "C" no need

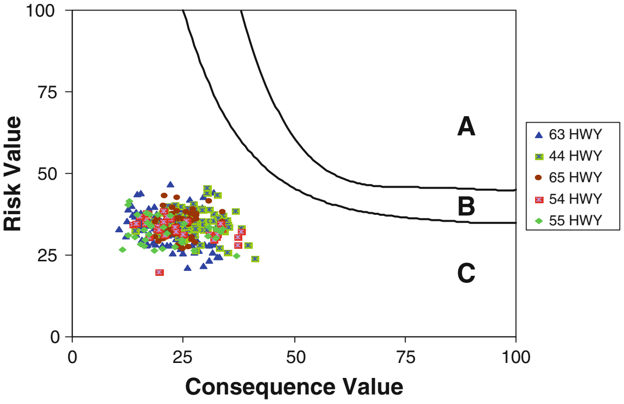


Fig. 13 Risk Consequence diagrams after excavation. Field "A" represents the rock cuts in most need of remediation; field "B" marginal need; field "C" no need

Summary and conclusions

MORFH RS is an efficient system for rating rock cuts because it utilizes fully mobile video imaging technology to do video logging of the highway and to identify and screen rock cuts with potential problems for possible study. In addition, many of the required parameters can be measured on the digital images acquired from the video logs. MORFH RS is designed to provide a relative rating to give clear and objective priorities to rock cut maintenance, so that the highways can be made safer and legal due diligence is achieved for DOTs. The system uses simple to measure/estimated parameters.

MORFH RS borrowed from both the Rockfall Hazard Rating System (RHRS) developed by the Oregon Department of Transportation and the Ontario Canada system (RHR ON) in the parameters used. However, necessary innovations included

1. Separation of Risk and Consequence parameters to determine the potential of the rock to fall (risk of failure) and the potential of these falling rocks to reach the highways and damage both vehicles and highways (consequence of failure);
2. adding, removing, and modifying some factors due to the geological environment in the State of Missouri to make the system more simple and effective in use;
3. using video logging for screening rock cuts and measuring many of the factors required to rate the rock cuts, thus saving time and money.

A number of tests have been performed to investigate the validity of factor analysis with the given variables. Kaiser–Meyer–Olkin, which measures the sampling adequacy, gives values of .857 and .585 for risk and consequence variables, respectively, indicating that factor analysis is very useful for this model. For the model it was found that the significance level for both risk and consequence variables are less than .0001. Based on these results of KMO and significance level it was found that factor analysis seems to be a useful method to analyze the suitability of the system. Factor analysis testing was conducted on the system to select the most reliable variables for both the risk and consequence parts. The results showed both "Adversely Oriented Discontinuities" and "Karst Factor" do not fit into the structure of the remaining variables for the risk side. Consequently, they are added to the system for risk adjustment factors, because they are not present at every rock cut. On the consequence side, Average Daily Traffic and Expected Rock Fall Quantity were retained in the system despite the fact that their values in the anti-image correlation are slightly below .50 (.475 and .496, respectively). However, the Ditch Capacity Exceedence was removed and added to the adjustment factor for the consequence side because its value in the anti-image matrix was .43, well below .50.

Sensitivity testing was conducted on the system by considering both the measured parameters and the rated ones. For the measured properties, the errors in measurement were quantified using RockSee and manual measurements on the field. These errors were then introduced into MORFH RS, as a worst-case scenario. It was concluded that these errors were typically negligible and the system was insensitive to these errors. On the other hand, the variability in rating on the MORPH RS final values was considered. It was determined that with few exceptions, the errors were low; the few high errors indicating perhaps that more training needed to be done.

To verify the effectiveness of the system, different raters were used to rate the same rock cuts, including personnel from the Missouri Department of Transportation, graduate students from the Geological Engineering Department at the University of Missouri-Rolla, and the authors. From these results it was found that the MORFH RS is very consistent even when performed by different raters with very little training. The difference of ~5 to 8% for both risk and consequence for one rater may be because the training time was not enough to make that particular rater familiar with the system and how to rate the parameters.

Finally, to demonstrate the effectiveness of remediation techniques, the effects of scaling, ditch enhancement, and trim blasting were simulated by changing the ratings of individual parameters. By applying different remedial measure to the data for 300 rock cuts in Missouri highways, it was obvious that MORFH RS is a very effective technique to determine the best method of remediation. The results show that the best method to decrease both risk and consequence is the trim blasting method; the scaling method will decrease the risk but only partially decrease the consequence while the ditch effectiveness method will decrease the consequence only.

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