

Highway Rock Cut Stability Assessment in Rock Masses Not Conducive to Stability Calculations

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Abstract

Ensuring the stability of highway rock cuts requires an evaluation of the structure of the rock. Failures usually initiate and follow pre-existing discontinuities rather than break through intact rock. Rock determined to be loose or with the potential for failure must be removed or restrained in some way. Analytical calculations of potential instability can range from limiting equilibrium analysis to numerical modeling.

In many terrains the discontinuities are oriented in such a way that they contribute to create wedge, planar, or toppling failures. These are then relatively easy to analyze. In other terrains, most notably flat lying sedimentary rock with vertical jointing, the predominant failure mechanism tends to be raveling, which is typically not conducive to calculation.

This paper describes some of the techniques currently used for stability assessment, as well as speculating on future trends in analysis and data acquisition.

Introduction

The safety and convenience of the motoring public demands that highway rock cuts be made safe. Catastrophic failures of rock cuts can result in property damage, injury, and even death. Highways impeded by even small spills of rock material are in addition an inconvenience for motorists (Figure 1).

Ensuring the stability of highway rock cuts, whether new or old, requires an evaluation of the structure of the rock. Failures usually initiate and follow pre-existing discontinuities rather than break through intact rock. Thus it is the nature of the discontinuities (joints, fractures, bedding planes, faults, and other breaks in the continuity of the rock) and not of the intact rock that governs the mechanical and hydrological behavior of the rock mass (Figure 2). With a few exceptions, most of the rock masses that engineers deal with are influenced to some extent or another by discontinuities. While the understanding of the mechanical properties of intact, solid rock is well advanced in rock mechanics, the understanding of the fundamental behavior of discontinuous rock is significantly less well developed.

Planar and wedge sliding and toppling analysis and remediation

In many terrains the discontinuities are oriented in such a way that they contribute to create wedge, planar sliding, or toppling failures (Figure 3). Franklin and Senior (1997b) report that of



Figure 1. Example of rock failures causing obstructions in roadways



Figure 2. The discontinuous nature of rock masses

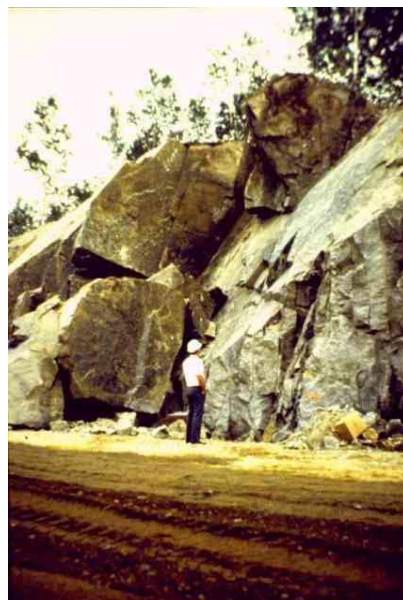


Figure 3. Example of wedge, planar, and toppling failures along road cuts.

415 analyzed cases of failure in Northern Ontario, only 33% of failures involved these mechanisms (23% toppling, 8% planar sliding, 2% wedge sliding). These failures are however easy to analyze, and can range from limiting equilibrium analysis to numerical modeling (Hoek and Bray, 1981; Piteau, 1979c; Piteau, 1979d). The mapping of discontinuity orientations is a requirement, before or after the cut has been exposed (Piteau, 1979a; Piteau, 1979b; Piteau 1979g). Rock determined to be loose with the potential for failure must be removed or restrained in some way (Piteau, 1979e). Prescribed designs for remediation and/or mitigation are easy to find (Brawner, 1994; Konya and Walter, 1991; Piteau, 1979f; Franklin and Senior, 1997a).

Raveling type failure modes

In the Northern Ontario study, 65% of the failures were of the “raveling” type (Figure 4). These included raveling (25%), overhang/undercutting failure (15%), ice jacking (14%), and rolling blocks (11%). In other terrains, most notably flat lying sedimentary rock with vertical jointing, where planar and wedge slides are unusually not found, the predominant failure mechanism being of the raveling type is even greater.

These raveling failures, whether slow, time-dependent or fast and catastrophic are much more difficult to analyze. Analytical techniques for prediction are non-effective, and remediation judgments are typically made with on-site engineering judgment of an experienced specialist, who must then balance the risk in terms of probability of failure and consequence of failure, against the cost of effective remediation. The use of empirical design and rock mass classification become important (Franklin and Maerz, 1996).

Even though no analytical tools are available for this task, other tools are available for the practitioner. One example of this is the use of empirical design and rock mass classification, as for an example the Oregon RHR (Rock fall hazard rating) system. The Colorado rock fall simulation program (CSRFP) can be used to assess the risk of falling, rolling and bouncing rocks, and to design slope angles, breaks, and ditch dimensions to mitigate the consequence of falling, bouncing and rolling rocks.

Other new technologies are available to assist in the analysis and design. Imaging software such as WipJoint can be used to analyze the structure and block size of the rock. Computer analysis, using instrumented cameras, using oblique images will in future be able to measure or estimate slope heights, slope angles, loose rock quantities and ditch capacities to help identify optimum remedial measures and help with construction specification quantities.

Empirical Design and Rock Mass Characterization

Empirical design is a design methodology that does not use formal design methods, and calculations or analytical equations or modeling or such. Instead it relies on experience and judgment of the engineer. When applied to rock cuts, an experienced engineer with considerable expertise in a particular geological terrain, will be able to use his experience to drive the design

But what of the inexperienced engineer, or the experienced engineer in an unfamiliar geological terrain? Clearly the engineer needs to rely on more than his own experience. This is where rock mass classification comes in.

Classification is defined as the formal arrangement of attributes in a hierarchy. In the case of rock engineering this means collecting data and classifying the outcrop in some meaningful way, based on parameters that are both easy to measure or classify, and are useful as predictors of rock behavior. Examples of such parameters would include block size and rock strength.

The realization of empirical design that uses not only individual experience, but also the cumulative experiences of many comes from the following principles.



Figure 4. Raveling, undercutting, and rolling failures along road cuts.

1. Description of **ground quality** by a quantitative classification system, based on parameters that are easily and universally measured.
2. Description of **ground performance** by a formal set of parameters (unsupported stand time, support requirements, bearing capacity, ease of excavation, etc.).
3. Correlation of the above 2 based on a broad spectrum of case histories, based on local or global experience.

Design schemes like this are common in the mining and tunneling industries, and are described in Singh and Goel (1999). Examples of such classification systems that include elements of design includes Deere's RQD (rock quality designation) system (Deere et al., 1969), Franklin's Size-Strength system (Franklin, 1986), Franklin's Shale Rating System (Franklin, 1983), Bieniawski's RMR (rock mass rating) system (Bieniawski, 1984), and Barton Q system (Barton et al., 1974).

In addition there are several schemes for slopes. Romana's SMR system is for rock slopes, based on Bieniawski's RMR system (Romana, 1985). The Oregon RHR (rock hazard rating) system is designed specifically for highways cuts ((Pierson and Van Vickle, 1993). The Ontario RHRON (Rock Hazard Rating ONtario) system is a modification of the Oregon system (Franklin and Senior, 1997b).

Basic Rock Mass Classification - RMR

Bieniawski's rock mass rating (RMR) was originally developed for tunneling (Singh and Goel, 1999; Bieniawski, 1998). In this system 5 basic parameters are measured or estimated in the field:

1. Uniaxial compressive strength of the intact rock,
2. RQD (rock quality designation),
3. Discontinuity spacing,
4. Condition (weathering) of the discontinuities,
5. Groundwater conditions.

Each of these parameters is rated with a value typically between 0 to 20, 0 to 15, or 0 to 30 depending on the case. The sum of these 5 ratings is the basic RMR rating, which is an evaluation of rock quality without taking into account the orientation of the discontinuities. This sum is then modified by a negative rating for discontinuity orientation. Discontinuities are rated as favorable or unfavorable in terms of strike parallel/perpendicular to tunneling direction, dip with/against direction of tunneling, and dip angle. Ratings range between 0 to -12 for tunnels.

The final RMR rating is then used to determine both unsupported stand-up time and support requirements, as a function of opening span, based on an empirical database.

Rock Mass Classification Applied to Slopes - SMR

Romana's slope mass rating (SMR) builds on the RMR system by incorporating adjustments to the basic RMR rating (Singh and Goel, 1999):

$$SMR = RMR_{basic} - (F_1 \bullet F_2 \bullet F_3) + F_4$$

where:

$$F_1 = (1 - \sin(\alpha_s - \alpha_j))^2$$

where α_s is the strike of the slope face and α_j is the strike of the critical joint (discontinuity) plane, and:

$$F_2 = \tan \beta_j$$

where β_j is the joint dip angle with respect to planar failure mode, and F_3 is a rating between 0 and -60 based on the relationship between the slope face and the dip of the discontinuity.

While these three parameters deal primarily with sliding and toppling failure mechanisms, the F_4 parameter is an adjustment factor dealing with the method of excavation (poor blasting -8, normal blasting or mechanical excavation 0, smooth blasting 8, pre-split blasting 10, and natural slopes 11).

As with RMR, the SMR value ranges between 0 and 100, and design charts can be used to infer stability, type of failure potential, and a crude estimate of the probability of failure. Suggested support designs are also available.

Rock Mass Classification For Rock Falls – RHR

The rock fall hazard rating system (RHR) was designed to proactively address the issue of rock falls for road cuts and rail lines (Pierson and Van Vickle, 1993). The system goes much further than other classification systems, in addition to looking at material properties, taking into account such diverse aspects as rock fall history, volumes of material that might fail, and the capacity of existing mitigation measures to contain that volume of rock, in a quasi-probabilistic manner. In addition, the system is useful as a screening technique, allowing high-risk slopes to be quickly identified by a preliminary rating.

The preliminary rating consists of an assessment of the slope into one of three categories, A, B, C (high, moderate, low) for two considerations: 1) Estimated potential for rock fall on roadways, and; 2) Historical rock fall activity. Typically only slopes with preliminary ratings of A are given detailed ratings.

The detailed rating system uses 10 categories with 4 nominal rating criteria and scores, although interpolations of scores between criteria are allowed. The scoring is a power progression, with score $y=3^x$ where x is a rating between 1 and 4 and allows scores of 3, 9, 27, and 81 respectively. The following are the categories:

1. Slope height (25, 50, 75, or 100 feet),
2. Ditch effectiveness (good, moderate, limited, or no catchment),
3. Average vehicle risk (vehicle present in rock fall section 25, 50, 75, or 100% of the time),
4. Sight distance (100, 80, 60, or 40% of stopping distance when viewing a 6" object),
5. Roadway width (44, 36, 28, or 20 feet including shoulders),
6. Structural condition *discontinuous rock* (discontinuous joints- favorable orientation, discontinuous joints – random orientation, discontinuous joints – adverse orientation, or continuous joint – adverse orientation),
7. Rock friction (rough –irregular, undulating, planar, clay infilling or slickensided),
or
6. Structural conditions *eroded rock* (few differential erosion features, occasional erosion features, many erosion features, or major erosion features),
7. Difference in erosion rates (small, moderate, large – favorable structure, or large – unfavorable structure),
8. Block size/volume of rock fall event (1/3, 2/6, 3/9, or 4/12 ft/cubic yards),
9. Climate and presence of water on slope (low to moderate precipitation; no freezing periods; no water on slope, moderate precipitation or short freezing periods or intermittent water on slope, high precipitation or freezing periods or continual water on slope, or high precipitation and long freezing periods or continual water on slope and long freezing periods),
10. Rock fall history (few, occasional, many, or constant falls).

All the categories are then added up, and the highest scores are deemed to have the highest priority in terms of remediation.

Rock Mass Classification For Rock Falls – RHRON

The rock fall hazard rating system, Ontario, (RHRON) is a modified version of the RHR system. It attempts to address the overemphasis on high slopes and large volumes that occur as a result of the power relationship between rating and score (Franklin and Senior, 1997a). In Ontario, with its relatively lower slopes than locations like Oregon, the RHR system was just not sensitive enough. In addition, five new parameters were added, and several parameters were re-defined.

The basic formulation for RHRON is:

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

where:

- F1=Magnitude: “How much rock is unstable?”
- F2=Instability: “How soon or often is it 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?”

For the *preliminary screening*, each of these F factors is directly rated on a scale of 0 to 9. For the *detailed rating*, each of these F factors are calculated from a number of individual ratings also on a scale of 0-9:

$$F1 = \frac{(R2 + R3 + R4)}{3}$$

$$F2_{ravelling} = \frac{(R1 + R9 + R11 + R4 + R5 + R6)}{6}$$

$$F2_{sliding} = \frac{(R1 + R9 + R11 + R5 + R6 + R8)}{6}$$

$$F2_{erosion} = \frac{(R1 + R9 + R11 + R4 + R7 + R10)}{6}$$

$$F3 = \frac{(R4 + R13 + R16 + R19)}{4}$$

$$F4 = \frac{(R17 + R18 + R19)}{3}$$

where:

R1=History of rock falls
R2=Volume of the largest potential rock fall
R3=Volume of total potential rock fall
R4=Face irregularity
R5=Face looseness
R6=Joint orientation/persistence
R7=Rock intact strength
R8=Rock joint shear strength
R9=Block size
R10=Slake durability
R11=Water table height
R12= Slope height
R13=Crest angle
R14=Ditch and shoulder width
R15=Ditch capacity
R16=Overspill potential
R17=Average vehicle risk
R18=Decision sight distance
R19=Available paved width
R20=Remediation cost

Not all ratings (R) are used in all cases and some ratings are used for different purposes entirely such as calculating cost-benefit ratios.

Rolling and Bouncing Rock - CRSP

Having identified slopes with significant failure potential, the consequences of the failure must be evaluated. One aspect of this evaluation has to be an analysis of the kinetics of the bouncing and rolling rock. Will the falling rock reach the highway? What effect will slope angles have on this? Will the rock bounce or roll into the catchment ditch and out the other side?

One way to assess this is to do some tests to evaluate this. If the roadway below a slope is closed, it is a simple matter to select 100 typical broken rock fragments and roll them from the top of the slope and record how far towards the road they travel. Of course it is not always possible to close the road below.

An interesting alternative is the Colorado rock fall simulation program (CRSP) (Figure 5). This program uses slope and rock geometry and material properties, calculating falling rock bounce height, velocity and travel distance.

While this can be used to predict the amount of road material that will reach the road, its most useful application is probably to help with design of slope angles, break in slope angles and, ditch geometry. Because rounded rocks rolling gather a great deal more energy than angular blocks sliding, the results, in terms of predicting the amount of rock reaching the roadway, should be used with caution. In addition, CRSP requires the input of a number of coefficients, which are best input empirically, based on calibrating with actual bouncing and rolling tests.

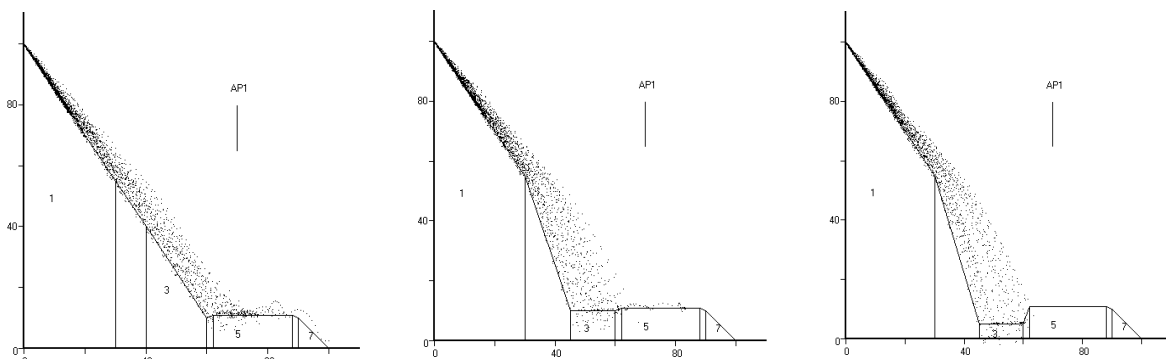


Figure 5. CRSP simulation for 100 blocks 0.4' in diameter bouncing and rolling down a slope to a roadbed. The simulation reveals that for the original geometry (left) 14 blocks reach the road surface; if the slope is cut back (center), 2 blocks reach the road surface, and if a ditch is put in place (right), no blocks reach the road surface.

Automated Measurements - WipJoint

A cursory survey of the different ratings of RHRON shows that a significant number of the parameters upon which these ratings are based are items where quantities are measured or estimated. Examples of these include slip heights, ditch capacities, block sizes, block volumes, and face irregularities. Some of these items are conducive to automated measurements such as can be done using image analysis (Franklin and Maerz, 1988; Maerz et al., 1997).

An example of an image analysis package that does exactly this is WipJoint, designed to measure blocks size and joint fabric images of rock cuts (Figure 6).

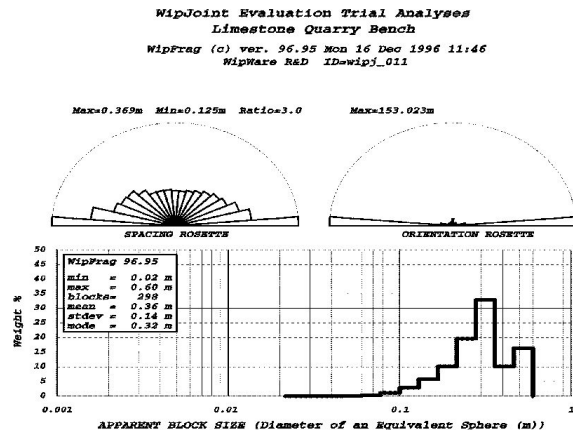
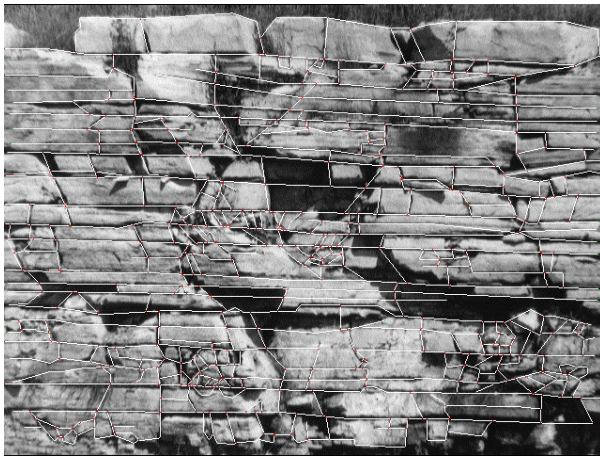


Figure 6. WipJoint image analysis of a rock cut.

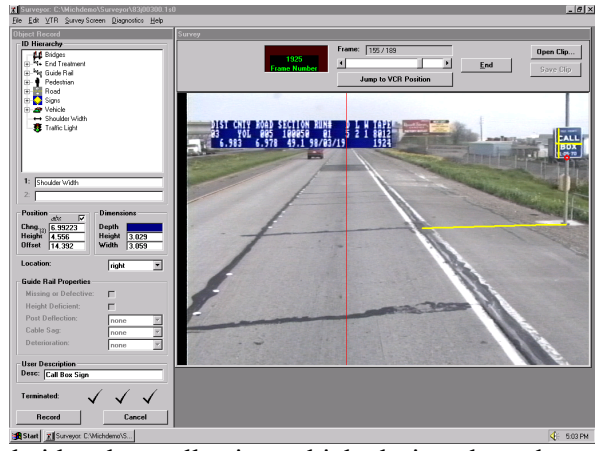
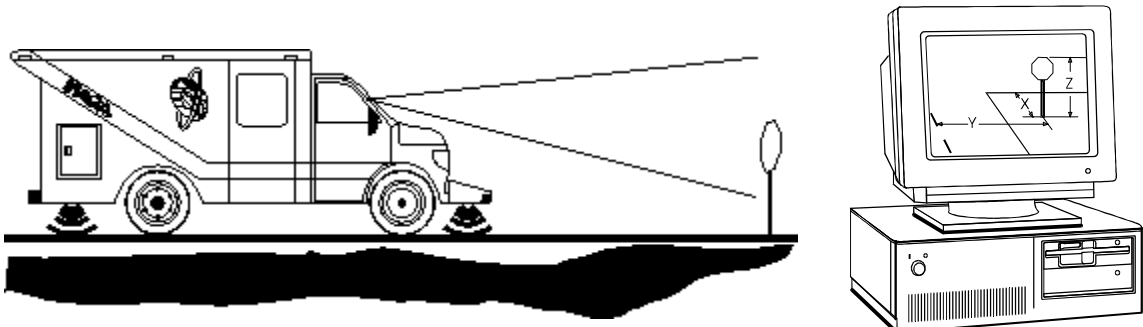


Figure 7. The ARAN system, a mobile instrumented video data collection vehicle designed to take video images at highway speeds and allow users to make measurements and create roadside inventories (Maerz and McKenna, 1999).

Future Trends - Rapid Screening and Mobile Automated Measurements

Future trends in automated measurements of rock cuts may come in the form of a mobile data acquisition system. An example of such a system is the ARAN (Automatic Road Analyzer) Surveyor System (Figure 7) (Maerz and McKenna, 1999). This system was designed to allow measurements of object dimensions, and inventorying of those dimensions. A user identifies objects and distances to be measured using mouse clicks on a computer monitor showing the video taped images. The computer then makes all necessary calculations, possible because each video frame has an associated data set that corresponds to the camera position, attitude, speed, and orientation.

This type of data acquisition would open entirely new possibilities with respect to collecting data for rock cuts.

In the first place, although video logging is not entirely new, it allows initial screening of the cuts. Often engineers spend all too much time screening road cuts, deciding which need to be further evaluated and which do not, rather than focusing on those that are clearly in need of work. A further benefit is that in addition to being a screening tool, this would provide a permanent record of the condition of the road cuts at a given point in time.

Second, the measurement capabilities can be used to measure estimated volumes of rock, slope heights, slope angles, ditch capacities and land and shoulder widths.

Finally hard copies of the video images can form “working diagrams” (Figure 8), complete with GPS (global positioning system) coordinates for establishing correct locations.



Figure 8. Simulated images demonstrating the potential to develop mobile vision based data acquisition systems for rudimentary measures such as slope heights, slope angles, loose rock quantities and ditch capacities

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