The development of a strategic slope management system for use in South Africa

R.C.Leyland
CSIR Built Environment, Pretoria, South Africa

ABSTRACT: Despite some preliminary developments for Slope Management Systems (SMS) for the South African Road Network, no functional SMS has been implemented. Slopes along important strategic routes are generally not monitored and only maintained on a reactive basis. This application of remedial measures after failures occur often results in disruptions to the flow of traffic. The USA is the leading implementer of Rock Hazard Rating Systems (RHRS) and bases these systems on qualitative methods that follow a heuristic approach. The first state wide RHRS was developed in Oregon and awarded scores to various categories that contribute to rockfalls and the potential impact thereof on traffic. This RHRS has been adopted by 18 different states either unchanged or modified to suit the local conditions. Unstable slopes need to be reassessed every 2 years, or before maintenance budget allocations, to allow for the RHRS inventory to be updated and mitigation plans to be made. There is, however, limited literature available on comprehensive SMS's that incorporate both rock and soil slopes. Following a comprehensive literature review the modified Colorado Department of Transport RHRS was found to be a suitable starting point for the development of a SMS for South Africa. As the system contains no rating methodology for soil slopes, appropriate rating criteria have been incorporated into the proposed South African system. Other modifications include the removal of variables considered unimportant in South Africa and the variables concerned with the risk to lives of motorists. The proposed method is intended to be applied on an iterative basis with initial basic observations of all slopes along a route and proceeding to different levels of reassessment on specific slopes based on the identification of high risk slopes. The method has been used on major road links of an important strategic nature within South Africa to asses its suitability.

1 INTRODUCTION

1.1 *Current South African slope management*

The acceptance that one cannot prevent landslides but could predict their occurrence and properly manage their effects is vital to the concept of providing safe roads in areas where topography necessitates the construction of road cuts. Currently no formal requirements are dictated by any authorities regarding the monitoring and maintenance of road cuts after construction. The last formal publication on road cutting management in South Africa was in 1995 and this only stated that monitoring should, in its simplest form, consist of regular visual inspection during which staff should be able to identify potentially unstable features such as tension cracks or unexpected water flows (NITRR, 1995).

In 1992 a preliminary framework for a local Slope Management System was developed by Hall & Knottenbelt (1992) and this was later used as the basis for the development of a SMS for the South African Roads Network (SRK/ASCH, 1999). This SMS, however, proved to be too detailed and complex and therefore impractical for the resources available to the South African road authorities at the time. No formal SMS has therefore been implemented in southern Africa yet, although records of slope problems on certain roads are used to facilitate periodic monitoring. According to Paige-Green (1997) the major barrier to the implementation of a SMS is that such systems lack early returns and require a large initial data collection effort. It has therefore been proposed that a SMS be run on an iterative process in that it should begin with basic observations on all slopes and then proceed to different levels of reassessment on specific slopes based on the potential of failure (Paige-Green, 1997, SRK/ASCH, 1999).

The current situation is therefore that slopes along important strategic routes are not always maintained or monitored on a proactive basis but rather on a reactive basis. This results in remedial measures only being applied after failure of slopes has occurred often with serious disruptions to the flow of traffic.

1.2 *International slope management systems*

The majority of slope management literature originates from the USA with limited work from other areas. An example of a non-USA system is that presented by McMillan and Matheson (1997) which consists of an initial Hazard Index assessment (Potential for Failure x Consequences of Failure) to identify slopes that require further attention followed by a Hazard Rating assessment (Probability of Failure x Consequences of Failure) of slopes identified as significant hazards in the first step. The hazard index assessment is intended to be a very rapid assessment (approximately 30 minutes per slope) while the hazard rating assessment is a comprehensive investigation requiring in excess of a full day to perform.

After numerous debris flows that occurred in Scotland during August 2004 caused significant damage to road infrastructure, studies were initiated to identify options to review side slopes on the road network, outline mitigation measures and management strategies and ultimately lead to the development of a system for network review and mitigation measure assignment (Winter et al. 2005). These methodologies are, however, all focused on debris slope management. Winter et al. (2005) noted that road network management authorities have to consider multiple different slope failure types (i.e. rock, soil, debris) within their jurisdiction and as such the results of any specific assessment criterion needs to be directly comparable with that of others so as to avoid confusion between results.

SMS's developed in the USA are generally only rock hazard rating systems as apposed to comprehensive SMS's. One exception is the "Unstable Slope Management System" (USMS) proposed in Washington State that prioritises slopes for mitigation work (Paige-Green, 1997, Ho & Norton, 1991, Badger & Lowell, 1992 and Ho & Knutson, 1994). After the inception of the USMS in Washington Sate, unstable slopes were reviewed by regional maintenance and materials offices every 2 years before the following biennial budget cycle (Lowell & Morin, 2000). This practice allowed for the inventory to be updated before mitigation plans are made and the result is that more than 2,500 slopes are currently in the inventory (Lowell & Morin, 2000).

Woodard (2004) provides a summary of all the rock hazard rating systems that have been developed in the United States. One of the factors that is commonly included in the rating of a slope is the effectiveness of ditches to prevent falling rock material reaching the road. The majority of SMS's employ the Ritchie (1963) ditch criteria as benchmarks against which the effectiveness of the existing ditch is gauged. The Oregon Rockfall Catchment Area design guide (Pierson et al. 2001 in Woodward, 2004:15) consists of a series of charts comparing slope height, slope angle, catchment angle, catchment width and roll out distance of the rocks. These charts are used to design new catchment areas or evaluate existing ones (Woodward 2004). According to Woodward (2004) the Oregon Rockfall Catchment Area design guide was intended to build and improve upon the Ritchie ditch criteria.

2 ROCK HAZARD RATING SYSTEM DEVEOPMENT IN THE USA

The first state wide RHRS was developed by Oregon and was based on a system published by Wyllie (1987), which introduced an exponential rating system that scored various categories that contribute to rockfall and their impact on traffic (Russel et al. 2008). The Oregon RHRS categorizes rockfall potential and the hazard to traffic based on the parameters, which are given scores ranging from 3, 9, 27, and 81, with higher scores indicating a condition more likely to promote rockfall or traffic disruption. It is important to note that these numerical rating systems are not predictive models and a higher-rated slope will not necessarily fail before a lower-rated slope (Lowell & Morin, 2000).

The Oregon RHRS was then adopted by 18 different states, either as is or as modified versions thereof (Bateman, 2003 in Russel 2008:3). The Colorado Dept. of Transport (CDOT) modified Oregon's RHRS to provide detailed ratings of highway stretches within the state that had frequent rockfall problems and in 1994 the Colorado Rockfall Hazard Rating System (CRHRS) was implemented (Andrew, 1994 in Russel et al. 2008:4). The CRHRS was modified in 1997 to include ditch catchment, decision site distance and average daily traffic and again in 2003, replacing average daily traffic with average vehicle risk (Russel et al. 2008).

Ohio is characterized by flat lying sedimentary rock and the dominant mode of rockfall is the result of differential erosion of less resistant units. Based on this, the Ohio DOT included slake durability tests on the weaker units to help predict rockfall potential in susceptible areas (Russel et al. 2008). The Ohio DOT also incorporated a comparison between actual ditch dimensions and Ritchie's recommended design to determine the ditch effectiveness (Shakoor, 2005; Ritchie, 1963 in Russel et al. 2008:5).

New York state modified the Oregon system by creating three main factors (Geologic Factors, Section Factors and Human Exposure Factors) that were collectively multiplied to establish the Total Relative Risk (TRR) for each slope. The Geologic Factor considers two types of slope separately: Crystalline rock slopes (considering continuity, number and dip of discontinuities) and Sedimentary rock slopes (considering dip of bedding planes/discontinuities and the degree of undercutting due to differential erosion (NYDOT, 1996 in Russel et al. 2008:9)). The Section Factor is a ditch dimension comparison with Ritchie's ditch design criteria (NYDOT, 1996; Ritchie, 1963; NYDOT, 2003 in Russel et al. 2008:9). The Human Exposure Factor is a measure of the likelihood of a traffic accident due to a rockfall. A Risk Reduction factor was added to the New York system for use on slopes where mitigation measures were employed.

The Missouri DOT uses a rating system based on rating risk-of-failure and consequence-of failure under two separate categories to allow independent assessment of risk and consequences (Maerz &Youssef, 2004). The Colorado Rockfall Simulation Program was used to simulate rock behavior due to "bad benches" and incorporated this into the determination of adequate ditch dimensions using the Ritchie design criteria (Maerz, et al. 2005 in Russel et al. 2008:12).

Russel et al. (2008) concluded that numerous important factors that contribute towards rockfall potential are not considered by most state DOT's and numerous new rating methodologies were identified by them. These include:

- Slope Angle: the Colorado Rockfall Simulation Program (CRSP) showed how rocks rolling down 30° slopes are likely to reach the roadway and rocks detaching from cuts around 85° are likely to bounce off the face and land in the roadway (Maerz et al. 2005). A consequence rating thus increases as the slope angle decreases from 70° to 30°.
- Ditch shape: an appropriate ditch shape is an important factor for effective rockfall catchment (Ritchie, 1963; Badger & Lowell, 1992; Maerz et al. 2005). A ditch of suitable depth and width is inadequate if the off-shoulder slope is too shallow and simply acts as a ramp (Ritchie, 1963).
- Geological conditions: these contribute the most to rockfall potential (Flatland, 1993; Szwiliski, 2002) and should be weighted more than the other parameters (Flatland, 1993, Vandewater et al. 2005).
- Discontinuity Conditions: The number and spacing of discontinuity sets (Vandewater et al. 2005; Senior, 1999; Maerz et al. 2005; Romana, 1988; Nichol & Watters, 1983; Mazzoccola & Hudson, 1996) discontinuity aperture (Senior, 1999; Maerz et al. 2005; Romana, 1988; Mazzoccola & Hudson, 1996), physical and chemical weathering (Flatland, 1993; Maerz et al. 2005; Eliassen & Ingraham, 2000; Barrett & White, 1991; Ritchie, 1963) and cohesion and friction along discontinuity surfaces (Piteau, 1970; Flatland, 1993; Mazzoccola & Hudson, 1996) were identified as those that largely control stability within a rockmass.

- Block-in-Matrix Material: Erosion of the matrix soil (within glacial deposits, debris flow deposits, colluvium, etc.) and successive ravelling of the larger blocks contribute to excessive rockfall reaching roadways (Vandewater et al. 2005; Maerz et al. 2005; Miller, 2003).

Russel et al. (2008) modified the CRHRS by removing subjective terminology and replacing scoring parameters with either numerical values or more descriptive terminology. The parameters identified above were also included in the modified system proposed by them. The system contains four separate categories that contribute to rockfall hazard (slope character, climatic conditions, geologic conditions, and discontinuity conditions). Slope types with fewer parameters have weightings to compensate. A separate category is scored for risk, and is based on traffic conditions.

3 SOIL SLOPE CLASSIFICATION

Rock slope failures are mostly based on the assumption that geological features (e.g. bedding planes and joints) divide the rock into separate masses and the failure path is defined by one or more of these discontinuities. However, soil, fills and extremely highly jointed rock masses with no strongly defined structural pattern exist and failure surfaces generally follow the path of least resistance. The simple and common method of determining the stability of such materials is by the use of "circular failure charts" (Duncan, 1996). The use of such charts requires that the groundwater flow conditions, unit weight, friction angle and cohesion of the material are known or can at least be estimated. The factor of safety (FOS) of a slope decreases with an increase in slope angle, slope height and/or unit weight of material, Increases in the cohesion and friction angle cause an increase in the FOS. The charts however are coupled with many assumptions and when these are not met (e.g. soil properties vary within the slope) the use of the charts is no longer valid. In such cases analytical approaches based on slices such as Bishop's, Janbu's or the Morgenson and Price method are applied.

All these methods are, however, not feasible for use during preliminary slope hazard management stability investigations as sample collection and laboratory analyses are usually required to determine the needed parameters. The stability of such a slope and the potential effect of a failure thereof can, however, be qualitatively estimated by other factors that are easily measured.

As noted by Gavin & Xue (2010) the development of a wetting front within a slope reduces the near surface suctions and reduces the shear strength of the soil. Wetting front development also depends on factors such as initial water content and rainfall intensity and infiltration. The initial conditions depend on soil type, water table and antecedent rainfall (Gavin & Xue, 2010) which are generally not readily available or easily collected, while infiltration depends on, among others, slope angle, vegetation type, rainfall intensity and rainfall duration (Gavin & Xue, 2010).

4 PROPOSED SMS FOR SOUTH AFRICA AND IMPLEMENTATION THEREOF

4.1 *Introduction*

The modified CRHRS presented by Russel et al. (2008) was used as a starting point for the development of an SMS for South Africa. The modified CRHRS is considered to be an improvement on the original CRHRS which itself was an improvement of the Oregon system developed as the first statewide SMS. The system is, however, not a comprehensive SMS as it contains no rating methodology for soil slopes, common in South Africa as a result of deep weathering and thick residual soils. Soil slope rating criteria were therefore incorporated. The soil slope scoring system of the Washington State Department of Transport's Unstable Slope Management System (Lowell & Morin, 2000) was not suitable for use in the proposed system as it does not contain a similar level of definition as that required by the modified CDOT RHRS for rock slopes. A preliminary soil slope rating methodology based on new field parameters was therefore derived.

The modified CRHRS's "Annual Freeze Thaw Cycles" parameter was omitted as this is irrelevant for South African slopes. The proposed SMS was also developed to consider the economic effects of slope failures resulting from road closures and to neglect the risk to motorists which resulted in the replacement of all traffic parameters. An obvious modification of the system was the conversion of units to equivalent metric units.

The proposed system was implemented on two alternative routes that form part of South Africa's national route from the economic hub of Johannesburg to the Lowveld region. This route is a vital link between South Africa and the Mozambican capital city and port of Maputo and carries in excess of 8500 vehicles per day. The two routes are similar in total length (60.7-62.9 km) and have similar total lengths within cut (12.5-14.5 km).

Any slopes containing more than one material type that poses a rockfall hazard (e.g. Crystalline rock and Block in matrix) were rated separately for both slope types and the higher of the two scores (most prone to failure) was used to classify the slope. Notes were also collected on the effectiveness of current mitigation features as these are required for post scoring analyses and decisions.

4.2 *Slope character parameters*

4.2.1 *Slope height*

The modified CRHRS neglected slopes less than 15 m in height, but steep cuts located adjacent to the road can still cause significant obstruction should they fail. No minimum slope height is therefore included in the proposed system. The maximum slope height measured was 65.8 m and the minimum was 3.2 m.

The modified CRHRS required that if rockfall hazards exist high up on the slope beyond the cut, the total slope height is measured and if only the cut slope is being rated, the maximum height of the cut is considered. This process was followed during this study but was not always possible. Some slopes can be seen to most definitely have extended back slopes beyond the road reserve but these are often covered in dense vegetation and not easily measured with the laser range finder used during field investigations. In such cases the height of the cut slope or slope within the road reserve was measured.

4.2.2 *Slope failure frequency*

As no comprehensive rockfall/landslide data set was available for the investigated routes this parameter was scored using subjective estimates of how often such events occur based on material accumulated behind retaining structures/in ditches, damage to retaining structures (walls, mesh, etc), age of retaining structures and slope vegetation cover. Of the 90 slopes rated more than half (55%) were rated as having more than 2 years between failures, while 25% were rated as having failures every 1-2 years. This seems to be reasonable as the route is not know for excessive slope failures.

4.2.3 *Average slope angle score*

For rock slopes where the slope angle affects the trajectory of falling rocks the scores based on the research conducted by Maerz et al. (2005) were retained. For soil slopes a different scoring system with increasing score with increasing slope angle was used. This is required as steeper soil slopes are more prone to having daylighting relict discontinuities and therefore to failure.

If a slope failure hazard was present above the cut face the cut slope angle and the natural slope angle above the crest should be measured and recorded. The measurement that posed the higher hazard to the roadway was used to score the slope angle. Soil slopes had slightly lower slope angles (average 45°, maximum of 70°) than other slopes (average of 53°, maximum 80°).

4.2.4 *Launching features*

This parameter required no modification and the majority of slopes had minor or no launching features (an indication of good road cut construction and finishing). Crystalline rock slopes generally had higher surface variations and this is probably due to stable rock masses not being excavated with methods that yield smooth faces (eg, pre-split blasting) due to cost implications. Soil slopes generally did not have high ratings for this parameter. Only large benches can act as launching features for Soil slopes as the smaller features will form part of the failed mass. It may therefore be necessary for this parameter to be rated differently for Soil slopes to prevent the consistent low scores assigned to these.

4.2.5 *Ditch catchment*

The modified CRHRS rated both the ditch dimension effectiveness and the ditch shape effectiveness and used the higher of the two scores. The ditch dimension effectiveness rating requires the comparison of ditch dimensions with the dimensions required based on slope geometry. The ditch shape effectiveness is, however, easily rated during rapid field assessments (Table 1) and as such only this was considered in the proposed South African system.

The modified CRHRS also automatically assigns a worst case score to slopes with worst case launching features score. The proposed system rejected this as the presence of launching features is accounted for in the previous parameter. This parameter therefore rates the effectiveness with which a ditch will catch any rock that may reach it.

Table 1. The Points assigned to various catchment ditch slope angles (Russel et al. 2008)

Ditch shape effectiveness	3 points	9 points	27 points	81 points
Off-shoulder slope	>30° or barrier	21°-30°	11°-20°	<10°

Ditches capable to arresting a large falling rock may not prevent a sliding mass of soil from reaching the road and it is therefore required that this parameter is modified for Soil slopes. It is proposed that the next development stage considers the soil retaining abilities of barrier or ditches separately, based on different criteria. Very few slopes were given scores below worst case scenarios as no purpose-built ditches were noted and only some slopes had barriers installed.

4.3 *Climatic conditions*

4.3.1 *Annual precipitation*

No modifications were made to this parameter and precipitation was determined using available data sources in a GIS. The route investigated straddles the contact area between the high rainfall (>850mm) areas along the escarpment and the high lying, intermediate rainfall areas (500-850mm) and therefore all slopes were rated in one of these two categories.

4.3.2 *Seepage/water*

As seasonal differences occur, this parameter was rated subjectively based on evidence of seepage (e.g. water marks or streaks and zones of discoloration (Russell et al. 2008)). 92% of the slopes were rated as dry despite the high rainfall location. This is counter intuitive but despite investigations being done during the rainy season most slopes did not show any signs of seepage. Some Soil slopes were, however, very damp and had evidence of shallow water tables that included hydrophilic vegetation above the crest and subsurface drains installed at their toes to keep pavement layers dry. One slope had active seepage at its toe.

4.3.3 *Aspect*

Slope aspect was introduced by Russel et al. (2008) not only to account for differences in annual freeze/thaw cycles experienced by different aspect slopes but also as aspect has an influence of the establishment of vegetation on a slope. South facing slopes (north facing in the southern hemisphere) experience more solar radiation during the day which results in higher evaporation rates, drier soils and therefore less vegetation. Such slopes are exposed and susceptible to surface runoff and higher erosion and sedimentation rates. This all increases the potential for debris flows and mass wasting events. In South Africa freeze thaw cycles are seldom experienced but the parameter was retained due to the vegetation effects.

The aspect of slopes was determined accurately using a GIS. Where slopes where present on both sides of the road the slopes were rated based on the least favorable aspect. It is, however, envisaged that this parameter could potentially be removed as in addition to freeze thaw cycles not playing a significant role in the degradation of slopes in a sub-tropical location the effects of vegetation are accounted for by the vegetation parameters in Block in Matrix and Soil slope ratings.

4.4 *Sedimentary rock slope geological conditions*

4.4.1 *Degree of undercutting*

Differential erosion and weathering in various lithologies can result in undercutting and associated failures. The parameter accounts for undercutting present at the time of investigation only. Twenty three slopes were rated as Sedimentary rock slopes and most of these received very low scores for this parameter.

4.4.2 *Jar slake*

This parameter accounts for the potential for undercutting to develop due to weaker sedimentary units (e.g. shale) being interbedded with a more competent units (e.g. sandstone). Slake durability is the most relevant parameter to quantify this (Shakoor, 2005 in Russel et al. 2008:38) and Santi (2006, in Russel et al. 2008:38) proposed the use of a simple 30 minute jar slake test during field investigations. During the implementation of the proposed system no jar slake tests were performed but a subjective estimate of slake durability was performed by investigation of the exposed surfaces of weaker units (usually clearly evident).

65% of Sedimentary slopes had best possible scores which show that the investigated sedimentary strata generally are not susceptible to slaking. Some strata did, however, appear slakable and as such maximum scores were assigned in places.

4.4.3 *Degree of interbedding*

The number of weak inter-beds and their corresponding thicknesses contribute to rockfall hazards (Vandewater et al. 2005 in Russel et al. 2008:38). This parameter therefore accounts for the influence that slakable units will have on the total slope stability if slaking occurs.

Most slopes had few weak beds and generally thin beds. Once again, however, the full range of possible ratings was encountered.

4.5 *Crystalline rock slope geological conditions*

4.5.1 *Rock character*

As with Sedimentary rock slopes, lithological variation is expected to contribute to rockfalls occurring in Crystalline rock slopes. All but one of the 25 Crystalline rock slopes had a massive rock character (lowest score). This is expected in an area were excessive faulting and folding has not occurred.

4.5.2 *Degree of overhang*

This parameter accounts for undercutting present at the time of investigation and is rated identically to degree of undercutting in Sedimentary rock slopes. 60% of the slopes had no or less than 0.25 m of overhang and a further 36% had overhangs of 0.25-0.5 m.

4.5.3 *Weathering grade*

This parameter takes into account the degree of weathering of the intact rock, not the weathering grade along the surfaces of discontinuities. The worst case rating of “core stones” was retained although this rating is problematic in that core stones indicate that the rock mass has been weathered to a residual soil with only the cores of the original rock blocks still being intact and classified as rock. Such a slope will therefore fail as either a Block in matrix slope or a Soil slope and not as a Crystalline rock slope. This parameter may be altered to highly weathered in future and “core stone” slopes rated as Block in matrix slopes only.

All grades of weathering were observed within the slopes investigated. Of the two “core stone” Crystalline rock slopes rated as both rock and Block in matrix slopes one received a higher score as a rock slope while the other a higher score for Block in matrix.

4.6 *Discontinuities*

4.6.1 *Block size/volume*

Rockfall events can be characterized by either single blocks or by a volume of material of varying sizes depending on which seems to occur most frequently or is most likely to occur at a given site. Block size/volume scores for the investigated slopes were well distributed amongst the different classes.

4.6.2 *Number of joint sets*

Russel et al. (2008) included this parameter to account for the increased amount of avenues that exist for water infiltration and physical and chemical weathering to occur if multiple joint sets are present. The number of joint sets was easily investigated during visual inspection. 66% of slopes rated had two or more joint sets and 11% had only one joint set.

4.6.3 *Continuity and dip*

Originally called "Persistence and Orientation" by Russel et al. (2008) this parameter is included due to the obvious effect that joint orientation has on slope stability. The majority of slopes investigated had at least one joint set that daylighted/dipped out of the slope and as such received one of the two higher scores.

4.6.4 *Aperture*

This parameter accounts for the increased chance of water infiltration, frost wedging and associated ravelling that occur with increasing space between apertures.

Half of the slopes rated had a joint aperture of more than 5 mm on at least one of the joint sets and 34% of slopes were rated as "closed" joint aperture. The dominance of these two extreme classes over intermediate classes is possibly related to the fine division between classes. Joints that appear closed from a distance may in fact have an aperture of 0.1-1 mm on closer inspection and similarly those that appear slightly more than 5 mm apart may in fact be just less than 5 mm apart. It is not feasible during such an investigation to actually measure joint sets individually and as such this parameter's scores may have to be reinvestigated to make them easier to estimate and classify in the field.

4.6.5 *Weathering*

The strength of discontinuity surfaces has a major influence on the mechanical strength properties thereof and therefore on that of the entire rock mass (Russel et al. 2008). The weathering of joints seemed to be easier to distinguish as a good range of ratings was obtained.

4.6.6 *Surface texture*

This parameter is estimated by observation of discontinuity surfaces and was relatively easy to perform. The full range of scores was not observed as no slickensided joints were seen. All of the other three possible classes received between 29 and 34% of the slopes' ratings.

4.7 *Block in Matrix slope geological conditions*

4.7.1 *Block size*

Scores should be subjectively assigned and not based on the largest blocks in the slope, but rather given to the largest blocks that are likely to become unstable (Russel et al. 2008). The sizes of the blocks in each class were increased with the result that a piece of rock in a Block in matrix slope will get a lower score than if it was a block in a rock slope. Block in matrix slopes are more likely to have single blocks failing at any time while rock slopes will generally have rock falls with more than one rock. Since the proposed method is focused on the economic effect of rock falls due to road closures and repair costs it is necessary that the isolated failures associated with blocks in Block in matrix slopes consists of larger blocks than the rock slope failure blocks in rock masses for the same score. A full range of block sizes was observed in the 37 slopes rated as Block in matrix slopes.

4.7.2 *Block shape*

Most Block in matrix slopes had either "Blocky" or "Blocky to angular" block shapes but all classes of block shape were observed. Rounded and smooth blocks were not only limited to Crystalline rock slopes weathered to core stones but were generally slopes that consisted of residual materials from igneous rocks. This is generally to be expected in South Africa where transported soils are generally thin and as such colluvium or non-indurated glacial deposit slopes are uncommon.

4.7.3 *Vegetation*

Vegetation generally stabilizes Soil slopes and Block-in-matrix slopes by reducing the amount of erosion of the matrix materials (Miller, 2003; Anderson et al. 1999; Arndt et al. 2003 in Russel et al. 2008:54). Block in matrix and Soil slopes are therefore rated in identical ways. The Soil and Block in matrix slopes encountered on the investigated route generally all had some vegetation cover. The climate in the area is, however, such that vegetation will cover any area relatively quickly after it has been exposed.

4.8 *Soil slope geological conditions*

4.8.1 *Block size*

The determination of Soil slope block size is somewhat arbitrary as an estimate of the soil volume that could potentially fail is not straight forward. The scoring system used is based on how much soil will be on the road if a worst case failure occurred and how large that amount would be relative to the road width. As a preliminary scoring system the "block size" of the Soil slope is calculated as a thickness of soil that will cover the entire road if the failed soil mass is evenly distributed over the entire road width (Fig. 1). The quantity of the failed mass is calculated using Equation 1 with the variables defined in Figure 1. Equation 1 essentially includes the calculation of the triangular volume (T), ¾ of T (F, as an estimate of the amount of soil that will be mobilized) and the bulking of the soil volume due to dilation during failure (S). Nicoletti & Sorriso-Valvo (1991 in Cruden & Varnes, 1996:43) suggest an average dilation of 33% for soil during failure. Finally this volume is divided by the road width to arrive at a value for average thickness of the material across the road per metre of width. The road width is defined as the entire width of the pavement and any additional area between the toe of the slope and the pavement. The proposed calculation results in a general overestimation of the volume of material that would fail and a gross overestimation if a translational slip failure were to occur rather than a rotational slip failure.

In the proposed method no consideration is taken of the length of the cut slope. A cut 1 km long that has the same slope dimensions as a 100m long slope will obviously cause a much more significant failure if the entire length fails and as such this will have to be incorporated as the methodology is refined.

$$X = \frac{1\frac{1}{3}\left(\frac{3}{4}\left(\frac{1}{2}\cdot H\cdot\left(\frac{H}{Tan\theta}\right)\right)\right)}{W} = \frac{\left(\frac{H^2}{2\,Tan\theta}\right)}{W} \qquad (1)$$

4.8.2 *Tension crack*

The presence of a tension crack above the crest of a slope is an indication that soil movement is occurring and if filled with water additional lateral forces act on the soil mass. The tension crack parameter was not easy to investigate in the field due to either steep slopes or dense vegetation making it time consuming or impracticable to reach the crest. Slopes on which the crest was not investigated were therefore assigned the lowest score. Only one slope was seen to have evidence of a tension crack or at least some form of depression behind its crest. This area was also characterized by surface seepage and covered in thick vegetation.

The inclusion of this parameter may have to be revised and if retained will result in additional time required to complete investigations. The extra observations made by gaining access to the crest of every slope may, however, be beneficial to identifying other parameters.

4.8.3 *Structures/bedding*

Translational slip failures are more likely to occur if a discontinuity in soil properties exists. This could either be a hard rock stratum below the soil or a relict structure such as a bedding plane or clay layer within a soil mass. The majority of Soil slopes had no structures and those with structures generally had highly variable weathering or rapidly changing geological features as some areas consisted of almost unweathered rock and others of residual soils.

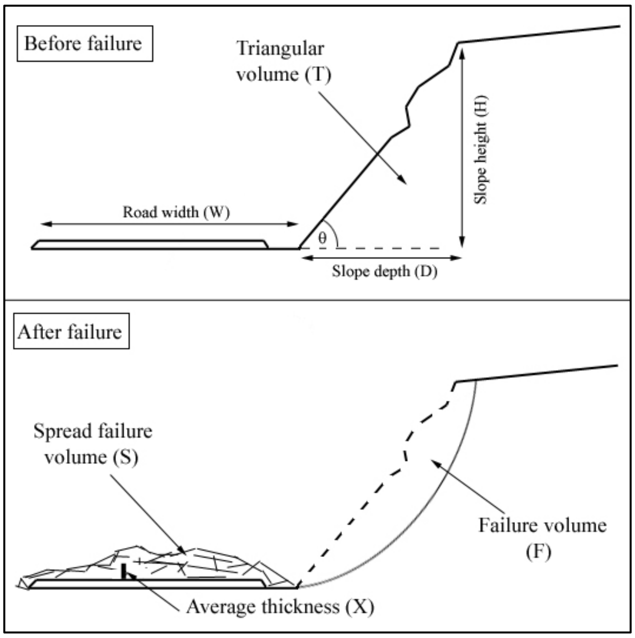

Figure 1. Schematic representation of Soil slope failure and variables required for block size calculation.

4.9 *Economic factors*

The proposed method includes a parameter similar to the 1997 CDOT's RHRS rating for average daily traffic (Russel et al. 2008) which is relevant as it will affect the total economic costs associated with the road being closed due to a landslide. Both routes carried equal traffic and as such were assigned the same score.

The "detour availability" is similar to the Washington State Department of Transportation's Unstable Slope Management System (Lowell & Morin, 2000) but scored slightly differently as it is based on the capacity of the available detour and not the length thereof. If even a short detour was not capable of carrying the large amounts of traffic then the additional time vehicles spend in traffic would increase the economic effects greatly. In addition to this if a tertiary road was used as a detour it would not be designed for the high traffic levels and as such would be damaged rapidly. This would result in additional maintenance costs for the roads authority responsible for the road. Both routes were assigned equal scores as they are similar capacity roads and function as detours for each other.

5 RESULTS AND DISCUSSION

A wide range of slope scores was obtained during the investigation. As seen in Table 2 the range of the values is over 700 with an average slope score of 457. On average the Block in Matrix slopes obtain the highest scores while the Soil slopes have the lowest average score. The highest overall score was assigned to a Sedimentary rock slope. The low average Soil slope score is potentially inaccurate as the Soil slopes also have the lowest maximum and minimum rating and are therefore more consistently being rated with lower scores than the other slope types. This may be indicative of greater care being taken with the design of Soil slopes, as they have generally been better understood in the past.

When the fifteen slopes with the highest scores are considered with respect to the effectiveness of mitigation measures installed some useful management data is obtained. Six of these slopes have mitigation measures (including wire mesh and gabion walls) that are acceptable and in a good condition. Six of the slopes had measures that were either damaged or not sufficient to mitigate the effects of potential failures. These slopes required minor, but vital, attention that would not require significant expenditures. These included repairing wire mesh damaged by previous failures, repairing gabion walls that were tilting (a potential hazard on there own) and increasing the height of some barriers.

Table 2. Summary of slope ratings obtained.

Slope type	Maximum rating	Minimum rating	Average rating
Sed. Rock slope	945	237	467
Cryst. Rock slope	855	273	491
Block in matrix	819	309	531
Soil	564	209	337
All	945	209	457

Finally four of the slopes were assessed as requiring urgent attention as mitigation measures were either absent or significantly inadequate. Two of these slopes had significant catch walls but due to previous failures these had become filled and were therefore now acting as launch features. One such wall had been constructed only along a section of a cut. Although this section was visibly less stable than the remainder of the cut and had recently failed a similar failure just beyond the wall would result in significant road closures and repair costs. Another slope had a large catch wall but was a steep Block in matrix slope and as such a falling block may be launched over this wall. Wire mesh would be a more effective mitigation measure for this slope.

None of the fifteen worst slopes were Soil slopes and this again indicates that the Soil slope parameters need revision.

6 CONCLUSIONS

Although the use of the modified CRHRS presented by Russel et al. (2008) did not require major changes, some significant adaptations were made for use in South Africa. These include the addition and removal of parameters to make the method suitable for current needs and conditions. The most significant addition is that of parameters to evaluate the hazard level of Soil slopes.

The implementation of the system on a national route was simulated and resulted in useful information that can be used to develop slope management activities within road authorities. The method will, however, need to be validated further. A significant amount of validation of the proposed SMS may be possible if a workshop hosting experts that are familiar with specific routes is held. Here the methodology could be presented to concerned parties and in return the experts could identify the accuracy of the assessments on their relevant sections based on long term experience of those slopes (Winter et al. (2005)).

Numerous future refinements have been identified of which the most important are:

- The development of a risk reduction factor that will modify scores based on mitigation measures
- Comprehensive development of the Soil slope scoring system
- Testing the feasibility/necessity of jar slake testing in the field
- Consideration of cut lengths

7 ACKNOWLEDGEMENTS

This paper is published with the permission of the Executive Director, CSIR Built Environment. The input of Dr P Paige-Green in initiating this research and providing ongoing guidance is gratefully acknowledged.

REFERENCES

Anderson, S.A. King, T.J. Schloner M. 1999. Urban rockfall hazard and mitigation cost rating, in: Amandei, B. Kranz, R.L. Scott, G.A. Smeallie, P.H. *Proceedings of the 37th U.S. Rock Mechanics Symposium*, Volume 2, Rock Mechanics for Industry, pp. 1229-1234.

Andrew, R.D. 1994. *The Colorado Rockfall Hazard Rating System*, Colorado Dept. of Transportation, report number CTI-CDOT-2-94.

Arndt, B.P. Andrew, R. Herring, K. 2003. Rockfall potential along I-70 at the Georgetown Incline, in: Boyer, D.D. Santi, P.M. Rogers, W.P. *Engineering Geology in Colorado: Contributions, Trends, and Case Histories*, Association of Engineering Geologists Special Publication no. 15.

Badger, T.C. and Lowell, S.M. 1992. *Rockfall control in Washington State.* Transportation Research Record, 1343, pp 14-19.

Barrett, R.K. and White, J.L. 1991, Rockfall prediction and control: National Symposium on Highway and Railroad Slope Maintenance, *34th Annual Meeting of the Association of Engineering Geologists*, pp. 23-40.

Bateman, V. 2003. The development of a database to manage rockfall hazard: The Tennessee Rockfall Hazard Database: *2003 Transportation Research Board Annual Meeting*, 13p.

Cruden DM and Varnes, DJ. 1996. *Landslide Types and Processes*. In Turner and Schuster (Eds), *Landslides, Investigation and Mitigation*. Special Report 247. Transportation Research Board, National Research Council. National Academy Press, Washington, DC.

Duncan J.M. 1996. *Soil slope stability analysis*. In Turner and Schuster (Eds), *Landslides, Investigation and Mitigation*. Special Report 247. Transportation Research Board, National Research Council. National Academy Press, Washington, DC.

Elliasen, T.D. and Ingraham, P.C. 2000. Review, rockfall hazard rating and repair of aging interstate rock cuts in northeastern Vermont: *51st Annual Highway Geology Symposium Proceedings,* Seattle Washington, pp. 233-243.

Flatland, R. 1993. *Application of the Rockfall Hazard Rating System to the rock slopes adjacent to U.S. 50 and State Route 28 on the east side of Lake Tahoe, Nevada*. University of Nevada, Reno, M.S. Thesis, unpublished, 318 p.

Gavin, K. and Xue, J. 2010. Design Charts for the Stability Analysis of Unsaturated Soil Slopes. *Geotechnical and Geological Engngineering*. Vol. 28, no. 1, pp. 79–90.

Hall, B. and Knottenbelt, E. 1992. Towards a slope management system for roads. *Procedings of the Annual Transportation Convention* , Pretoria.

Ho, CL and Norton, SS. 1991. *Development of an Unstable Slope Management System*. Washington; Washington State Department of Transportation. (Final report WA-RD-270 1).

Ho, CL and Knutson, RA. 1994. *Pilot study of an unstable slope management system*. Washington; Washington State Department of Transportation. (Final report WA-RD-297,1).

Lowell, S. and Morin, P. 2000. Unstable slope management, Washington State: *Transportation Research News*, no. 207, pp. 11-15.

Mazzoccola, D.F. & Hudson, J.A. 1996. A comprehensive method of rock mass characterization for indicating natural slope instability: *Quarterly Journal of Engineering Geology,* Vol. 29, pp. 37-56.

Maerz, N.H. Youssef, A. Fennessey, T.W. 2005. New risk-consequence rockfall hazard rating system for Missouri highways using digital image analysis: *Environmental & Engineering Geoscience,* Vol. XI, no. 3, pp. 229-249.

Maerz, N.H. and Youssef, A. 2004. *Development of a Highway Rock Cut Rating System For Missouri Highways.* Missouri Department of Transportation Research, Development and Technology. Report number. RDT 04-009.

Miller, S.M. 2003. *Development and implementation of the Idaho Highway Slope Instability and Management System (HiSIMS).* Idaho Transportation Department, report # N03-07.

New York State Dept. of Transportation (NYDOT), 1996. *Rock slope rating procedure.* Geotechnical Engineering Bureau, report number GEM-15.

New York Dept. of Transportation (NYDOT), 2003. Geotechnical design procedure for preparing rock slope recommendations: *Geotechnical Design Procedure GDP-13,* Geotechnical Engineering Bureau.

Nichol, M.R. & Waters, R.J. 1983. Comparison and effectiveness of rockfall mitigation techniques applied by states in the U.S.A. and Canada: *Proceedings of the 20th Annual Engineering Geology and Soils Engineering Symposium, Boise, Idaho.*

Nicoletti P.G. and Sorriso-Valvo M. 1991. Geomorphic controls of the shape and mobility of Rock avalanches. *Bulletin of the Geological Society of Amreica,* Vol. 103, No. 10, pp. 1365-1373.

National Institue for Transport and Road Research (NITRR), 1995. *The investigation, design, construction and maintenance or road cuttings.* Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa.

Paige-Green, P. 1997. *A Slope Management System for Transportation Routes*. Technical report no. TR-97/005. CSIR, Division of Roads and Transport Technology, Pretoria, South Africa.

McMillan, P. and Matheson, G.D. 1997. A two stage system for highway rock slope risk assessment. *International Journal of Rock Mechanics and Mining Sciences*, Volume 34, Issue 3-4, pp. 409-427.

Pierson, L.A. David, S.A. Pfeiffer, T.J. 1994. *The nature of rockfalls as the basis for a new fallout area design criteria for 0.25:1 slopes:* Federal Highway Works Administration Report No. FHWA-OR-GT-95-05, 31p.

Piteau, D.R. 1970. *Geologic factors significant to the stability of slopes cut in rock*, in: Van Rensburg, P.W.J. Planning Open Pit Mines*: Proceedings of the Symposium on the Theoretical Background to the Planning of Open Pit Mines with Special Reference to Slope Stability,* A.A. Balkema, Cape Town, Amsterdam, pp. 33-53.

Ritchie, A.M. 1963. Evaluation of rockfall and its control: *Highway Research Board Record,* no. 17, Washington D.C. pp. 13-28

Romana, M. 1988. Practice of Slope Mass Rating (SMR) classification for slope appraisal. *Glissements de Terrain*, pp. 1227-1229.

Russell, C.P. Santi, P. Humphrey, J.D. 2008. *Modification abd Statistical Analysis of the Colorado Rockfall Hazard Rating System.* Colorado Department of Transportation Research. Report No. CDOT-2008-7.

Santi, P.M. 2006. Field methods for characterizing weak rock for engineering: *Environmental and Engineering Geoscience,*Vol XII, no. 1, pp. 1-11.

Senior, S.A. 1999. Rockfall hazard remediation along Ontario highways: *50th Annual Highway Geology Symposium, Proceedings and Field Trip Guide*, pp. 276-286.

Shakoor, A. 2005. Development of a rockfall hazard rating matrix for the state of Ohio: *The Ohio Department of Transportation Office of Research & Development Executive Summary Report.*

SRK consulting and ASCH Consulting Engineers (SRK/ASCH), 1999. *Report on the establishment of a slope management system for the South African roads network.* SRK consulting Project number E07-000-06/1.

Szwilski, A.B. 2002. *Rockfall rating evaluation and data management systems for highway and railway rock slopes*. Appalachian Transportation Institute and West Virginia Department of Transportation.

Vandewater, C.J. Dunne, W.M. Mauldon, M. Drumm, E.C. Batemann, V. 2005. Classifying and assessing the geologic contribution to rockfall hazard: *Environmental & Engineering Geoscience*, Vol XI, no. 2, pp. 141-154.

Winter, M.G. Macgregor, F. Shackman, L. 2005 (Eds). *Scottish Road Network Landslides Study.* The Scottish Executive, Edinburgh, Scotland.

Woodard, M. 2004. *Development of a Rockfall Hazard Rating Sytem Matrix for the State of Ohio*. PhD dissertation. Kent State University, Department of Engineering Geology, Kent Ohio.

Wyllie, D.C. 1987. Rock slope inventory: *Proceedings, Federal Highway Administration Rockfall Mitigation Seminar,* FHWA Region 10, Portland Oregon, 25 p.