

Risk Assessment of Rockfall Hazards on Highways

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ABSTRACT: With the rapid development of the west regions in China, a great number of highways are being or will be built in western mountainous regions. Rockfalls constitute a major hazard in numerous adjacent rock cuts or steep natural rock slopes along these highways. Based on the concept, the connotations, extensions and characteristics of rockfall are discussed and the triggering mechanism is analyzed. The previous relative rockfall rating systems widely accepted are introduced. Based on the Italian modified rockfall hazard rating system, the weights of all categories used to assess rockfall risk are introduced to enhance the major categories and weaken the minor categories. On the basis of the expert investigation, the weight vector can be calculated through analytic hierarchy process method. An application of the modified method to a rock cut slope of Shuifu-Maliuwan highway in Yunnan Province was developed. The heavy annual rainfall and high rockfall frequency with great weights affect this studied slope very much. Rockfalls may cause a large amount of casualties and traffic accidents or interruptions, as well as damage in this interval. Therefore, for this rock cut slope, the analysis shows that the risk is unacceptable and should be reduced using urgent remedial measures.

1 INTRODUCTION

Transportation systems such as highways and railways are vulnerable to rockfall wherever they cut across or skirt along mountains, ridges and similar topographic features(e.g. Bunce et al., 1997; Brawner and Wyllie, 1975; Hungr et al. 1999). In the recent years, there are a great number of highways which are being or will be built in western mountainous regions in China. And with the rapid development of the west regions, more demands to develop civil infrastructure (especially, highways) in mountainous regions will increase the number of rock cuts and slopes greatly. Under this topographic condition, rockfalls pose a considerable risk to traffic safety along these highways.

As the analysis above, Hoek (1996) states that the number of people killed by rockfalls tends to be of the same order as the people killed by all other forms of slope instability combined. Furthermore, according to Badger and Lowell(1992), 45 percent of unstable slope problems are rockfall related. Fig 1 shows a rock cut slope on a mountainous road in the west regions of China. Obviously, it is necessary to analyze the rockfalls hazards and assess the risk so that we can prioritize rockfall hazard mitigation.

2 ROCKFALL HAZARD

A rockfall is defined as a rock mass that has detached from a steep slope or cliff, along a surface on which little or no shear displacement occurs, and descends most of its distance through air (Hoek and Bray, 1981). Once a rock block detached from the steep slope or cliff, it will drop, bounce, roll or slide along the slope surface at a high speed, which can cause a hazard to the highway or vehicles. A potential rockfall can be either rock blocks cut by discontinuities and free

faces, or boulders and big macadams on soil slope or talus slope surface. Rockfall hazard is that a rock block falls into the area where there are human activities or constructions and causes damage to human. Especially, in mountainous region, rockfall hazard poses a considerable risk to traffic safety along the highways.



Fig.1 A rock slope on a mountain road in the west regions of China.

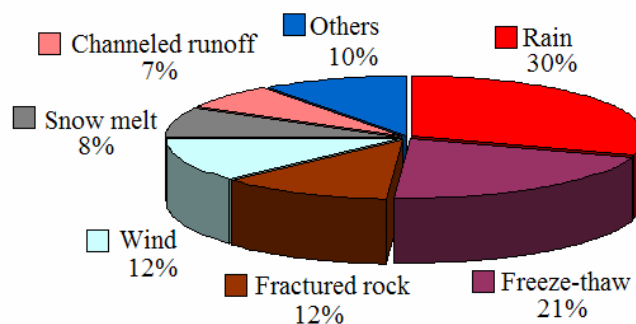


Fig.2 the main causes of rockfalls and their percentages in California

Rockfall can be caused by many factors, including unfavorable rock structure (discontinuities), adverse ground water related conditions, poor blasting practices during original construction or reconstruction, climatic changes, weathering and tree levering (Brawner,1994). McCauley and others (1985) performed a comprehensive study of rockfalls that have occurred along California state highways. They studied about 308 rockfalls and found that there are fourteen causes of rockfalls, and about 68% of those are found to be water-related. Fig.2 shows the main causes and their percentages.

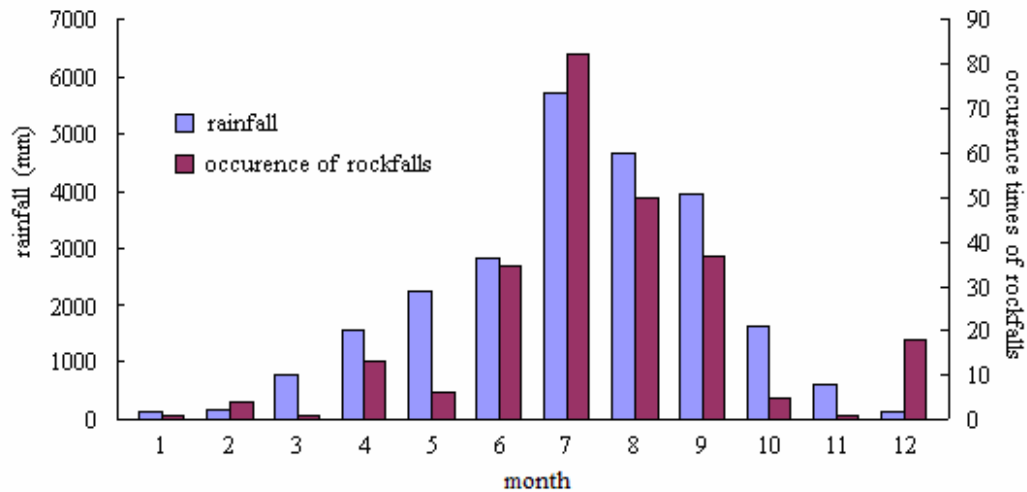


Fig.3 The relationship between rainfall and occurrence of rockfall per month from 1965~1983

In different regions, the causes of rockfalls are similar. However, the main causes are not same. For example, in the mountainous region of Chaotian-Guanyinba section on Baoji-Chengdu railway of China, the percentage of rain cause is much higher than others. Fig.3 shows the relationship between the rainfall and the occurrence times of rockfalls from 1965 to 1983 (Xueqing Su, 1991).

3 RELATIVE ROCKFALL HAZARD RATING SYSTEM

Relative rating systems are used to cost-effectively evaluate large areas for identification of the most problematic slopes. Based on the early work on relative slope rating, Pierson (1990) developed the Oregon Rockfall Hazard Rating System. Budetta P. (2004) modified the rockfall hazard rating system developed by Pierson et al. And similar systems have been developed by other organizations.

3.1 Oregon Rockfall Hazard Rating System

The Oregon State Highway Division developed a Rockfall Hazard Rating System (RHRS) based on an evaluation of 9 different categories. This system is widely accepted. The 9 categories include the rockfall hazard factors (slope height, geologic character, volume of rockfall/block size, climate and presence of water on slope and rockfall history) and the vehicle vulnerability factors (ditch effectiveness, average vehicle risk, percent of decision sight distance, roadway width). In this method, an exponential scoring graph is used. The resulting total score is the sum of every category, which can assess the degree of the rockfall risk along highways.

One of the categories is ditch effectiveness. It indicates the ability to prevent falling rock from reaching the highway. In estimating the ditch effectiveness, the Ritchie's design chart shown in Fig.4 is introduced to determine required width and depth of rock catch ditches in relation to the height and slope angle of the slope.

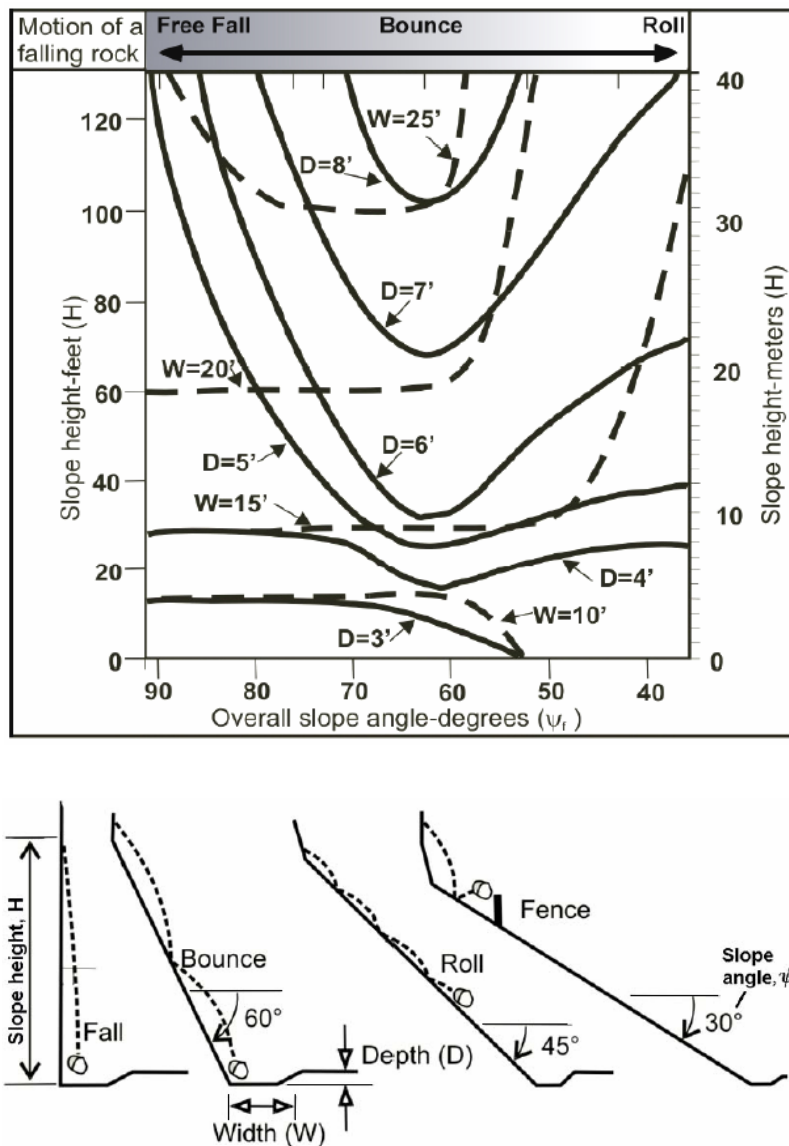


Fig.4 Ritchie's design chart for determining required width (W) and depth (D) of rock catch ditches in relation to height (H) and slope angle (ψ) of hill slope.

Table 1 Summary sheet of Italian modified Rockfall Hazard Rating System

Category	Rating criteria and score			
	Points 3 (3^1)	Points 9 (3^2)	Points 27 (3^3)	Points 81 (3^4)
Slope height	7.5m	15m	22.5m	>30m
Ditch effectiveness	Good catchment: properly designed according to updates of Ritchie's ditch design chart + barriers	Moderate catchment: properly designed according to updates of Ritchie's ditch	Limited catchment: wrongly designed design chart	No catchment
Average vehicle risk	25% of the time	50% of the time	75% of the time	100% of the time

Percent of decision sight distance	Adequate site distance, 100% of design value	Moderate site distance, 80% of design value	Limited site distance, 60% of design value	Very limited site distance, 40% of design value
Roadway width	21.5m	15.5m	9.5m	3.5m
Slope Mass Rating (SMR)	80	40	27	20
Block size	30cm	60cm	90cm	120cm
Boulder volume	26 dm ³	0.21 m ³	0.73 m ³	1.74 m ³
Volume of rockfall per event	2.3m ³	4.6m ³	6.9m ³	9.2m ³
Annual rainfall and freezing periods	h=300mm or no freezing periods	h=600mm or short freezing periods	h=900mm or long freezing periods	h=1200mm or long freezing periods
Rockfall frequency	1 per 10 years	3 per year	6 per year	9 per year

3.2 Italian modified RHRS

Budetta P. modified the RHRS developed by Pierson et al.. He considered that some qualitative categories make the appraisals too much subjective and rough, and not concrete enough. Therefore, in this modified method, the ratings for the categories “ditch effectiveness”, “geologic characteristic”, “volume of rockfall/block size”, “climate and water circulation” and “rockfall history” have been rendered more easy and objective. Table 1 gives a summary of the scores for different categories included in the classification.

In the modified method, the Romana’s Slope Mass Rating (SMR-Romana, 1991) for slope instability hazard evaluation is introduced to improve the estimate of the geologic characteristics. SMR is obtained from RMR (Rock Mass Rating by Bieniawski, 1989) by subtracting a factorial adjustment factor depending on the joint – slope relationship and adding a factor depending on the method of excavation. The basic equation is

$$SMR = RMR - (F_1 \cdot F_2 \cdot F_3) \cdot F_4 \quad (1)$$

where F_1 is a factorial depending on parallelism between joints and slope face strikes; F_2 refers to joint dip angle in the planar mode of failure, measuring the probability of joint shear strength; F_3 reflects the relationship between the slope face and joint dip; F_4 is an adjustment factor for the method of excavation.

4 THE MODIFIED ROCKFALL HAZARD RATING SYSTEM

The Oregon Rockfall Hazard Rating System is one of the most widely accepted systems in rockfall hazard assessment. However, as Budetta P. says, there are some categories which are qualitative and may lead to appraisals too much subjectively and rough. In addition, in this system, the weights of all the categories are considered to be equivalent. Obviously, their influences on the potential rockfall are different. Therefore, the weights of the categories which are used to assess the rockfall risk should be different, not to mention that the system will be applied to the problematic slopes in different areas.

Table 2 Exponential functions for the score computations.

Category	Equation
Slope height (H)	$y=3^{H/7.5}$
Average vehicle risk (AVR)	$y=3^{AVR/25}$
Decision sight distance (%Da)	$y=3^{(120-Da)/20}$
Roadway width (Lc)	$y=3^{(27.5-Lc)/6}$
Slope mass rating (SMR)	$y=3^{80/SMR}$
Block size (Db)	$y=3^{Db/0.3}$
Volume of rockfall per event (V _{fall})	$y=3^{V_{fall}/2.3}$
Annual rainfall (h)	$y=3^{h/300}$
Rockfall frequency (f)	$y=3^{1+(0.334 \cdot f)}$

The method introduced in this paper is based on the Italian modified RHRS. The weights are introduced to all categories in order to enhance the major categories and weaken the minor ones. Furthermore, the introduction of weights can make this system have a comprehensive application. The first step in this modified method is scoring the categories. The exponential function $y = 3^{f(x)}$ shown in table 2 can represent the expressions that best fit the data in table 1. Using this modified method, the point-scores can be determined as Table 2 shown. This step is similar to Italian modified RHRS.

The second step is determining the weights of all categories. The weights can be calculated through analytic hierarchy process (Qiyuan Jiang et al. 2003).

First, the importance of all categories can be approximated by using pairwise comparisons through expert investigation. The matrix of weight ratios is defined as follows:

$$W_{ij} = \begin{pmatrix} 1 & w_1/w_2 & w_1/w_3 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & w_2/w_3 & \cdots & w_2/w_n \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \cdots & 1 \end{pmatrix}_{n \times n} \quad (2)$$

Then, the consistency of original comparisons values should be checked. In order to check the consistency, the consistency ratio (CR) should be introduced as follows:

$$CR = \frac{\lambda_{\max} - n}{(n-1) \cdot RI} \quad (3)$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix; n is the number of all categories; RI is random consistency index, and when $n=9$, $RI=1.45$. If $CR < 0.1$, the comparisons values satisfy consistency and the corresponding eigenvector with $\lambda_{\max}$ can be considered as the weight vector. Otherwise, it need be rejudged. Once the weight vector is gained, the obtained points of every category are

$$P_i = \alpha_i \times p_i \quad (i=1, 2, \cdots, n) \quad (4)$$

where p_i is the score, α_i is the weight of this category. The total points are:

$$P = n \times \sum_{i=1}^n P_i \quad (5)$$

where n is the number of categories.

Once the total score is obtained, we can identify whether the slope is particularly hazardous or not and whether it requires urgent remedial works or further detailed study.

5 AN APPLICATION

Shuifu-Maliuwan Highway locates in the adjacent area of the Yungui Plateau and Liangshan mountain of Sichuan Province, which is in northeast of Yunnan Province. The total length of this line is 135.325 km.

The topographic condition is complex and steep in the studied area. Owing to Yanshan and Himalayan tectonic movement, the tectonic deformation is heavy. There are many high mountains, steep gorges with heavy erosion, rapid rivers and saw-cuts everywhere. Along the highway, rockfalls often occur and constitute a major hazard. It is observed that the high rock cut and natural outcrops above the highway generate rockfalls. And in the studied area, the groundwater replenishment mainly depends on the local rainfall and the rivers are replenished by the springs.

The studied slope lies on the interval from K92+80 to K92+200. Mudstones and sandstones outcrop with bedding planes dipping about 25°~30° north-northeast. There is no water seep found on the slope. The vegetations on the slope are heavy. There are many joints which are discontinuous and oriented favorable. However, the rock mass is much fractured and heavily weathered. The size of the average rockfall is approximately 30 cm in diameter. However, there is no catchment here. There is an average of about 10000 vehicles estimated per day passing this site. The posted speed limit is 60km/h along the highway. The photograph of the studied area and the stratigraphic section are shown in Fig.5.

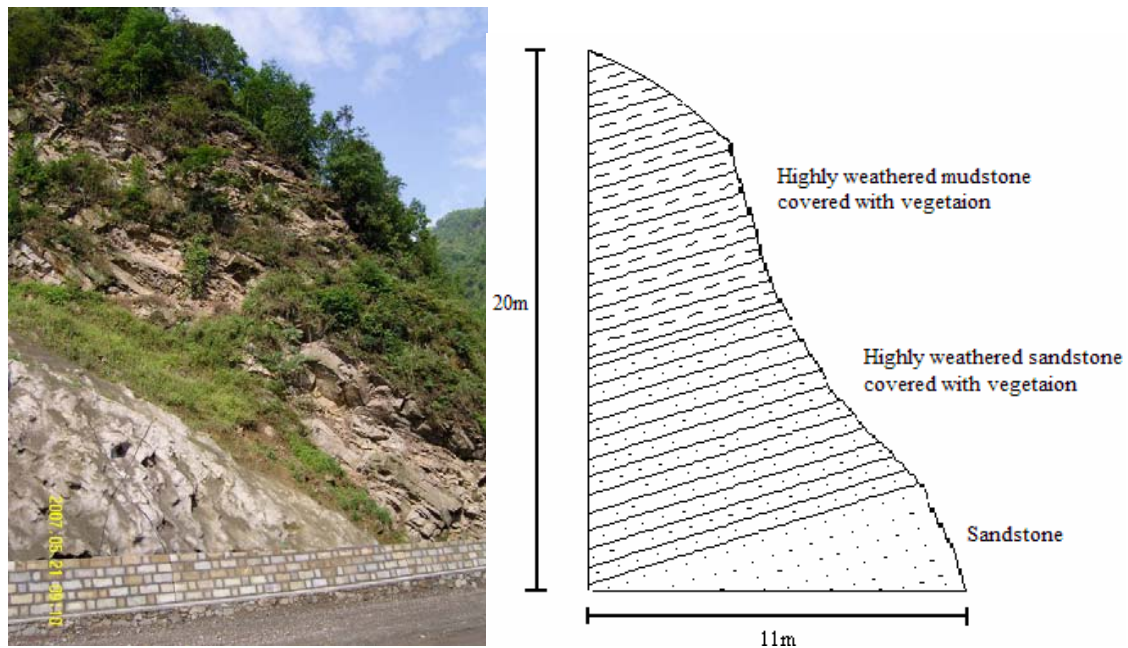


Fig.5 Photograph of the studied area and the stratigraphic section

The slope is about 20m high, the score are 18 points according to Table 2.. There is no catchment for catching the rockfall, therefore, the score of ditch effectiveness is determined to 81 points.

The average vehicle risk (AVR) is obtained by

$$AVR = (ADT \cdot SL) / PSL \cdot 100\% \quad (6)$$

where ADT is the average traffic per hour (vehicle/hour); SL is the hazard slope length (km); and PSL is the posted speed limit (km/h). According to the equation above, the score of AVR are 38 points.

Decision sight distance (DSD), one of the categories, represents the length of highway a driver needs in order to make a complex or instantaneous decision. The percent of DSD is obtained by

$$PDSD = (ASD / DSD) \cdot 100\% \quad (7)$$

where ASD is the actual sight distance (km). 3 points are assigned to this category according to the field investigation.

The road width is 11.25m including the shoulders, therefore, the score are 20 points. According to the site survey, the SMR is about 30; 3 points are assigned to this category consequently. Furthermore, 3 points are assigned to the category “Block size” because the average block size is about 30cm in diameter.

According to the historical data, the intensity of local rainfall is much heavier. The average annual rainfall is about 1184mm; therefore, the score is determined to 76 points. According to the statistical data, rockfall occurs about 9 times per year; therefore, the score are 81 points.

Based on the analysis above, the scores are shown in Table 3 as follows:

Table 3 the scores of the application example

Category	Value	Rating
Slope height	20m	18
Ditch effectiveness	No catchment	81
Average vehicle risk	83%	38
Percent decision sight distance	100%	3
Roadway width	11.25m	20
Slope Mass Rating (SMR)	30	19
Block size	0.30m	3
Annual rainfall	1184mm	76
Rockfall frequency	9 per year	81

After computing the rating value of this slope, the weights should be obtained subsequently. Based on the expert investigation method and analytical hierarchy process method, the matrix of weight ratios is computed as:

$$W = \begin{pmatrix} 1 & 2 & 2 & 2 & 2 & 1/2 & 1 & 1/2 & 1/3 \\ 1/2 & 1 & 1/2 & 1 & 1 & 1/4 & 1/2 & 1/4 & 1/5 \\ 1/2 & 2 & 1 & 1 & 2 & 1 & 2 & 1/2 & 1/2 \\ 1/2 & 1 & 1 & 1 & 2 & 1/3 & 1/2 & 1/4 & 1/5 \\ 1/2 & 1 & 1/2 & 1/2 & 1 & 1/2 & 1/2 & 1/3 & 1/4 \\ 2 & 4 & 1 & 3 & 2 & 1 & 2 & 1 & 1 \\ 1 & 2 & 1/2 & 2 & 2 & 1/2 & 1 & 1/3 & 1/3 \\ 2 & 4 & 2 & 4 & 3 & 1 & 3 & 1 & 1 \\ 3 & 5 & 2 & 5 & 4 & 1 & 3 & 1 & 1 \end{pmatrix} \quad (8)$$

The maximum eigenvalue of the matrix is $\lambda_{\max} = 9.3026$, the corresponding eigenvector is

$$\alpha = (0.100, 0.046, 0.099, 0.058, 0.050, 0.160, 0.081, 0.190, 0.216) \quad (9)$$

The value of CR is calculated as:

$$CR = \frac{\lambda_{\max} - n}{(n-1) \cdot RI} = \frac{9.3026 - 9}{8 \times 1.45} = 0.026 < 0.1 \quad (10)$$

Therefore, the eigenvector α can be considered as the weight vector. Based on analysis above, according to the equation (4,5), the total score are 411 points. It is observed that the heavy annual rainfall and high rockfall frequency with great weights affect this studied slope very much. Consequently, this slope is identified for urgent remedial action.

6 CONCLUSIONS

The weight of every category for assessing the rockfall risk is different obviously. Therefore, it is necessary to introduce the weights so that the major categories can be enhanced and the minor categories can be weakened. Furthermore, according to the specific circumstances of different slopes in different areas, the weight of every category is also variable. Hence, the introduction of weights can make this system have a comprehensive application.

Through the application, the slope is identified for urgent remedial action. It can be seen that the modified rating system with weights of all categories is reasonable and feasible. And the analytic hierarchy process method based on expert investigations for determining the weight vector is feasible. However, further applications are needed to better check its suitability for rockfall risk assessment along roads.

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