Prioritization Framework for Rockfall Countermeasures for Rock-Cut Slopes for Rural Roads

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Abstract: Rockfalls can have devastating consequences to motorists and road facilities. Over time, countermeasures have been considered technically viable to mitigate these events. Rockfall hazard assessment is one of the options to identify feasible countermeasures, including designs, based on engineering-related data analysis. Of the attempts to enhance the fundamentals and practices of efficient and reliable rockfall hazard assessment, a few of the past contributions were devoted to developing holistic approaches that can identify the best design option by prioritizing technically viable countermeasures. These measures are based on multidimensional aspects such as construction cost and time, complexity, safety, and aesthetics. This paper presents a novel holistic prioritization framework to evaluate the cost-effectiveness of feasible design options for rockfall countermeasures, focusing on rural local road rockfall applications. The framework is composed of three main steps, including rockfall hazard assessment, prioritization, and sensitivity analysis. The processes of the proposed framework are well-demonstrated in this paper through an actual case study in West Virginia. The unique feature of the framework lies in a sensitivity analysis that provides decision-makers with a statistical inference of the confidence level in choosing the top-ranked design option. This paper also presents a synthesis of the evaluation criteria necessary to prioritize the countermeasure design options identified through a rockfall hazard assessment. Herein, the applicability of the sensitivity analysis approach was further expanded to quantitative measures obtained through standard scaling techniques. **DOI: 10.1061/(ASCE)CO.1943-7862.0002139.** *© 2021 American Society of Civil Engineers.*

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Introduction

Roads in mountain regions often require hillside rock-cut slopes to facilitate road construction (Maerz et al. 2015). Steep rock slopes are subject to rockfalls emanating from both natural forces (e.g., freeze-thaw cycles of water, intense rainfall, and root penetration) and human activities (e.g., undercutting of rock slopes and traffic) (Guzzetti and Reichenbach 2010). The risk of rockfall cannot be eliminated (Lan et al. 2007), and rockfall accidents generally progress rapidly (Volkwein et al. 2011). Road stakeholders are understandably concerned about the risk of rockfalls resulting in traffic disruptions and injury/death to vehicle users (Mignelli et al. 2013; Verma et al. 2019). Therefore, road sections located within a rockfall hazard zone require suitable rockfall countermeasures that can be either active or passive (Lambert and Bourrier 2013). Active design is intended to mitigate the risk of rockfalls through prevention work at rockfall sources, while passive design focuses on protecting the at-risk road structures from rockfall events.

Rockfall countermeasures are designed after analyzing rockfall hazards, including the susceptibility, magnitude, runout, and exposure of the rockfall (Crosta et al. 2015; Pradhan and Fanos 2017). The best rockfall countermeasure among the various design alternatives is the one that offers optimal prevention and control of rockfall. The decision-making for an appropriate rockfall countermeasure considers various aspects pertaining to the location (e.g., social, economic, and environmental) to identify the most cost-effective solution. However, Mignelli et al. (2013) found that very few frameworks are dedicated to comparing and prioritizing the cost-effectiveness of different design alternatives based on the multidimensional aspects. The main focus of existing studies is on rockfall hazard assessment to evaluate the potential consequences of rockfall events, stating that the assessment results should support the prioritization of countermeasure selection (Raetzo et al. 2002; Fell et al. 2005, 2008; Volkwein et al. 2011; Toe et al. 2018; Strada et al. 2020). Another possible reason for the deficiency in prioritization-related research is the lack of recognition that the choice of a rockfall countermeasure as the final stage of the risk management process relies on the decision of the road administrative authorities and professionals (Popescu et al. 2015; Mavrouli et al. 2018). Furthermore, the previous frameworks and methods integrated factors related to the technical (engineering) aspects, such as the site geological and geotechnical conditions, to develop and prioritize rockfall countermeasure alternatives along with other aspects. For example, Mignelli et al. (2013) considered the design aspect (e.g., geological/geotechnical residual risk and the excavated rock or soil disposal) as one decision criterion to choose a suitable rockfall protection alternative. Crosta et al. (2015) used the technical and economic issues to choose the optimal countermeasures for rockfall protection. Huber and Woodard (2018) insisted that determining a rockfall protection system for each site should depend on a number of factors, including the anticipated size and trajectory of the rockfall. However, such approaches may underestimate the importance of factors related to technical issues in the multicriteria analysis to evaluate different solutions that rely on conflicting criteria.

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This paper presents a novel holistic prioritization framework to evaluate the cost-effectiveness of feasible design options of rockfall countermeasures identified as a result of rockfall hazard analysis. Our research focus is on rural local roads adjacent to rockfall-prone slopes because local road agencies are often lacking resources and risk management processes to adequately handle rockfall hazards (Anderson et al. 2018). Furthermore, the framework is more suitable for local road agencies, as the use of rockfall avoidance measures, such as tunnels and roadway realignment, are not applicable for low-volume access roads (Andrew et al. 2011). This paper demonstrates the proposed framework by applying it to an actual local access road in the state of West Virginia. The theoretical bases for the case study are the analytical hierarchy process (AHP) to determine the relative weights of the multiple prioritization criteria and the sensitivity analysis method suggested by Triantaphyllou and Sánchez (1997). The primary contribution of this paper is the novel prioritization framework consisting of three main steps: rockfall hazard assessment, prioritization, and sensitivity analysis. In particular, the sensitivity analysis of the framework provides decision-makers with probabilistic insight into their final decision on the best countermeasure. This paper also provides a synthesis list of the evaluation criteria specific to prioritizing rockfall countermeasure alternatives for rural local roads. Our findings are the scholarly contribution to expanding the existing theoretical knowledge, albeit with limitations in sensitivity analysis for the quantitative measures driven from the standard scaling methods.

Synthesis of Prioritization Factors for Rockfall Countermeasure Evaluation

Table 1 summarizes the criteria suggested in the past studies to select the most suitable rockfall countermeasure option. The factors from the technical and economic perspectives are the basic considerations for the best decision on feasible rockfall countermeasures offered by previous highway rockfall-related studies such as Mignelli et al. (2013), Frattini et al. (2014), Crosta et al. (2015), Popescu et al. (2015), and Strada et al. (2020). The technical issues considered were the suitability of rockfall countermeasures through rockfall hazard assessment and their structural capacity to withstand the dynamic impacts of rocks falling due to their specific geometric characteristics. Therefore, consideration of the technical issues can basically provide risk-based design rankings for rock slopes (Pine and Roberds 2005). Criteria such as design, function, engineering feasibility, anticipated size and trajectory of rockfall, and acceptable risk level, along with the conditions of the roads and slopes in Table 1, can be regarded as similar because they aim to develop feasible rockfall prevention and protection measures. The economic issues involve the cost-benefit evaluation of countermeasure design alternatives. Cost-benefit analysis is typically used to determine whether the design options obtained from the technical considerations are viable economically (Ortiz et al. 2019). The costs are derived from the required design, construction, and maintenance, as well as safety-related expenses during operation (i.e., countermeasure lifetimes). The benefits are related to the advantages of rockfall protection or prevention measures, such as avoiding property damage and loss of life (Andrew et al. 2011). Benefits can be tangible/intangible and quantitative/qualitative.

Table 1. Rockfall countermeasure selection criteria in references

Reference	Criteria for rockfall countermeasure selection
Mignelli et al. (2013)	Economic, environmental, design, transport (road management), and social criteria
Andrew et al. (2011)	Debris-collection catchment area, aesthetics, and periodic maintainability
Grošic et al. (2009)	Delivery of rockfall countermeasures and assembling
Nippon Koei (2007)	Function, durability, construction ease, construction cost, maintenance requirements, and conditions of roads and slopes
Crosta et al. (2015)	Technical and economic issues
Popescu et al. (2015)	Engineering feasibility, economic feasibility, legal/regulatory conformity, social acceptability, and environmental acceptability
Huber and Woodard (2018)	Anticipated size and trajectory of rockfall, site constraints, cost, and maintenance
Frattini et al. (2014)	Technical efficiency and cost-benefit analysis
Strada et al. (2020)	Acceptable risk level, tolerability over time, and economic and social benefits
Granger et al. (2019)	Constructability, construction safety, aesthetics, durability, and maintenance

In addition to the two basic technical and economic criteria, additional criteria suggested for multicriteria decision-making approaches include environment-related concerns, maintainability, durability, and construction complexity (Nippon Koei 2007; Grošic et al. 2009; Andrew et al. 2011; Mignelli et al. 2013; Popescu et al. 2015; Huber and Woodard 2018; Granger et al. 2019; Strada et al. 2020). The environmental criterion considers the landscape change for aesthetics and the adverse impacts on the environment during construction and operation. Maintainability focuses mainly on the removal of debris accumulated in debris-collection catchment areas periodically. Andrew et al. (2011) specifically mentioned the environmental and maintainability criteria as the limitations for the most common protective measures (e.g., mesh/cable nets and barriers/fences). Durability is related to structural tolerability to withstand the force of rockfall during service life; thus, the higher the durability, the longer the service life. Construction complexity addresses the ease of delivering the components of rockfall barrier systems and assembling the systems on construction sites under various constraints. Social acceptability, transport (road management), construction safety, and legal/regulatory conformity were addressed by a few studies (Mignelli et al. 2013; Popescu et al. 2015; Granger et al. 2019).

Rockfall Countermeasure Prioritization Framework

The main steps for the proposed rockfall countermeasure prioritization framework as illustrated in Fig. 1 are (1) rockfall hazard assessment to provide feasible rockfall countermeasures; (2) multicriteria evaluation, resulting in the priorities of the countermeasure alternatives; and (3) sensitivity analysis for the certainty level in choosing the top-ranked alternative over the second-ranked alternative. The detail of each step is discussed in the following subsections.

Step 1: Rockfall Hazard Assessment

Rockfall hazard assessment involves field investigation for data collection and a geotechnical analysis through simulation model calibration and analysis by utilizing a rockfall simulation program. The data to be collected mainly include rock slope geometric parameters, rockfall quantities, and debris extents. In the geotechnical analysis, simulation model calibration is conducted to ensure accurate analysis results by adjusting the range of input values (e.g., the tangential coefficient of friction resistance and the normal coefficient of restitution) for simulation based on the data obtained

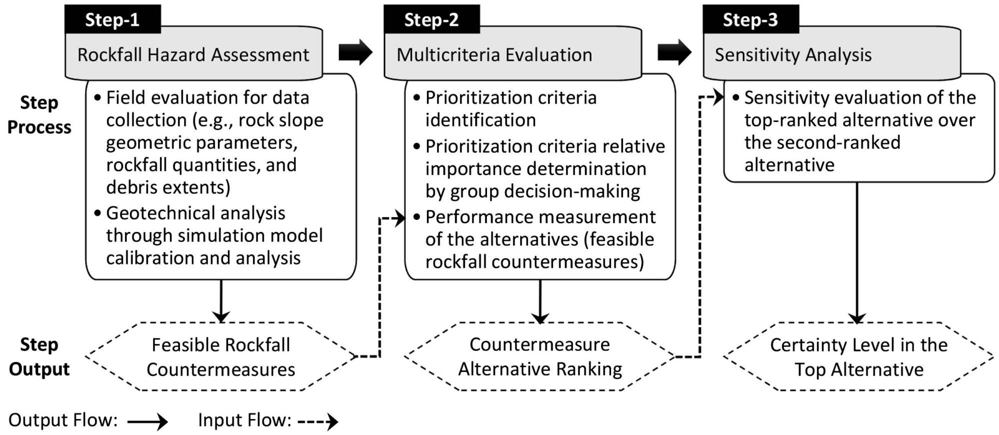

Fig. 1. Rockfall countermeasure prioritization framework with the outcome at each step.

through a field investigation. The simulation model analysis generates different models for the analysis based on the various possible rockfall debris patterns, velocities, bounce heights, and kinetic energy for different rock sizes. Finally, the rockfall hazard assessment proposes feasible rockfall countermeasures for further evaluation to prioritize them for final decision-making.

Step 2: Multicriteria Evaluation

Multicriteria evaluation involves four elements: (1) the alternatives, (2) the criteria, (3) the relative importance of each criterion, and (4) the performance measurement of the alternatives with respect to the criteria. Table 2 summarizes the criteria that we suggest local transportation agencies use to prioritize rockfall countermeasures. However, it should be clearly noted that local agencies can consider any evaluation criteria that they see as the best fit for practical application of the presented prioritization framework. The criterion based on the technical aspects is not a part of the prioritization criteria, as the rockfall hazard assessment generates feasible alternatives that were previously qualified to accommodate the technical issues expected from rockfall-prone slopes. The relative importance of each criterion is determined by group decision-making, where a judgment is based on the opinions of different individuals or groups, such as elected officials, government administrators, citizen groups, and business leaders, representing different views.

As the ultimate performance of the alternatives for the qualitative criteria primarily relies on the inputs from design, engineering, and construction management professionals, an r-point rating scale (e.g., 5-, 7-, or 10-point scale), which is commonly used to measure qualitative descriptions, is employed. The quantitative criteria for evaluating alternatives are estimated based on their unit measures. The different unit measures of the quantitative criteria need to be converted into the r-point rating scale of the qualitative criteria to create integrated weighted sums for the individual alternatives. Based on the facts that the number of rockfall countermeasure alternatives is generally small and the normal probability distribution of the quantitative criteria is considered the most likely situation, two conversion procedures are suggested as follows:

- The numeric values of the design options for each quantitative criterion are processed to percentiles, using the student's t-distribution.
- The percentiles are then multiplied by r of an r-point rating scale used for qualitative criteria.

Table 2. Prioritization criteria and descriptions

Prioritization criteria	Description
Cost	Countermeasure installation and maintenance costs
Time	Countermeasure installation time
Aesthetics	Quality of visual appearance
Complexity	Difficulties of material procurement and construction
Durability	Lifetime maintaining the original functionality of proposed design options
Safety	Ability to prevent debris from landing on the road
Maintainability	Ease of removal and installation of sections of the wall for repair and cleaning

Step 3: Sensitivity Analysis

Sensitivity analysis, which is the last step of our prioritization framework, provides a confidence level in choosing the top-ranked alternative over the second-ranked alternative. Sensitivity analysis is based on the approach introduced by Triantaphyllou and Sánchez (1997) and statistical analysis using the student's t-distribution. The details of these approaches are presented in the following subsections.

Theoretical Backgrounds of the Sensitivity Analysis Approach

The sensitivity analysis approach determines the minimum changes in the most critical criterion and scale, which is referred to as the performance measure in Triantaphyllou and Sánchez (1997). The most critical criterion is defined as the criterion that changes the priorities of two alternatives by the smallest change in its current weight. The definition of the most critical scale is similar to the most critical criterion but involves scales that are assigned to evaluate alternatives in terms of criteria instead of criteria weights. The smallest change can be computed in relative terms, which are the changes over the current weights or scales in percentages. That is, there are two alternatives, A_i and A_j ($i, j \in M$ and $i < j$; M = a set of alternatives), and the ranking A_i is higher than A_j. When $\delta_C(W_k/A_iA_j)$ denotes the minimum change in the current weight W_k of criterion C_k ($k \in N$; N = a set of criteria) to reverse the priority order of A_i and A_j, $\delta_C(W_k/A_iA_j)$ is computed by

$$\delta_C(W_k/A_iA_j) = \frac{WS_j - WS_i}{a_{j,k} - a_{i,k}} \tag{1}$$

where WS_i and WS_j = weighted sums of A_i and A_j; and $a_{i,k}$ and $a_{j,k}$ = scales assigned to A_i and A_j for criterion k. The absolute value of $\delta_C(W_k/A_iA_j)$ is required to be smaller than the absolute value of W_k to be feasible. Then, any feasible $\delta_C(W_k/A_iA_j)$ is computed to the relative term δ'_C (W_k/A_iA_j) of the minimum change by

$$\delta'_C(W_k/A_iA_j) = \frac{\delta_C(W_k/A_iA_j)}{W_k} \times 100(\%) \tag{2}$$

The most critical criterion is the criterion with the smallest $|\delta'_C(W_k/A_iA_j)|$ value. On the other hand, the most critical scale is determined by Eqs. (3)–(5)

$$\delta_S(a_{i,k}/A_iA_j) = \frac{WS_i - WS_j}{W_k} \tag{3}$$

$$\delta'_S(a_{i,k}/A_iA_j) = \frac{\delta_S(a_{i,k}/A_iA_j)}{a_{i,k}} \times 100(\%) \tag{4}$$

$$\text{Critical Normalized Scale} = \min \delta'_S(a_{i,k}/A_iA_j) \tag{5}$$

where $\delta_S(a_{i,k}/A_iA_j)$ = minimum change in $a_{i,k}$ to reverse the ranking of A_i and A_j; and δ'_S $(a_{i,k}/A_iA_j)$ = relative term of the minimum change. The relative change δ'_S $(a_{i,k}/A_iA_j)$ should be less than 100% to be feasible. The details in deriving Eqs. (1) and (5) are presented in Triantaphyllou and Sánchez (1997).

This sensitivity analysis approach is effective in identifying the most critical weight and scale and the minimum changes required to reverse two alternatives. However, in cases where the scales are converted from any quantitative values using standard scaling techniques based on statistical measures, such as means and standard deviations, we found that the minimum change in the most critical scale would not make the rankings of A_i and A_j equal. Therefore, an additional solution-seek process was required to find an optimal scale that makes the rankings at least equal and the change in the associated quantitative value of the most critical scale. An example to clarify this process is presented in "Results and Discussion" section.

Confidence Level for Minimum Changes

The student's t-distribution is similar to the normal distribution and is useful for a smaller number of data samples, which is approximately less than 30 (Tong and Zhang 2012; Robinson 2016; Kwak and Kim 2017). A confidence interval in statistics is interpreted as a range of values that includes the population mean at a certain confidence level. Confidence intervals become wider for higher confidence levels. The calculation of a confidence interval involves a sample mean ($\bar{X}$), sample standard deviation (SD), sample size (n), and t-value given the degree of freedom ($\nu = n - 1$) and a confidence level (1-α; α = significance level). The event, which reverses the rankings of A_i and A_j $(i < j)$, occurs when the current weight of the most critical criterion decreases or the current value of the most critical scale increases, assuming that higher scales are preferred. Therefore, the confidence levels for the change in the most critical criterion and scale can be derived from the lower (L) and upper limit of a population mean (U), as seen in Eqs. (6) and (7), respectively. The L and U can be found at $|\delta_C(W_k/A_iA_j)|$ and $\delta_S(a_{i,k}/A_iA_j)$

$$L = \bar{X} - t_{\nu,\alpha} \times \frac{SD}{\sqrt{n}} \tag{6}$$

$$U = \bar{X} + t_{\nu,\alpha} \times \frac{SD}{\sqrt{n}} \tag{7}$$

Application of Rockfall Countermeasure Prioritization Framework

Site Background

The case study involved a rock-cut slope prone to rockfall risk that was constructed in the late 1990s in order to build a local access road to an industrial complex in West Virginia. The access road was built along a narrow strip of land in a mountainous area, which necessitated a cut in the hillside with a backslope of about 60°. For approximately 20 years, the road encountered only small rockfalls from the hillside. However, in late 2017, a massive rockfall occurred, during which a section of wall [approximately 12.2 m (40 ft) wide, 9.1 m (30 ft) tall, and 0.9 m (3 ft) thick] slipped, blocking the entire road. There were two distinct issues that needed to be resolved: (1) small rocks falling from the top of the face (near the original topsoil) or along the face due to localized variations in the sandstone layer of the slope and (2) the risk of large slips of the entire sandstone layer.

Rockfall Hazard Assessment for Feasible Countermeasure Options

The field evaluation examined the basic profile of the rock-cut slope. The rock was visually classified as a hard sandstone rock that had parallel planes approximately 30.5 cm (12 in.) thick with sand-filled bedding planes. The measurements of the debris patterns indicated rock slabs roughly 30.5 cm (12 in.) thick with a critical width by length ranging from 0.3 m × 0.3 m (1 × 1 ft) to 1.8 m × 1.8 m (6 × 6 ft) in the planar surface area. The field evaluation also observed that the average size of the rocks was 0.9 m × 0.9 m (3 × 3 ft). The total number of rocks for the simulation was assumed at 300 with a rock density of $2.5\ \text{g/cm}^3$ $(155\ \text{lb./ft}^2)$. The geotechnical analysis used the two-dimensional Colorado Rockfall Simulation Program (CRSP) to determine the behaviors of the rockfalls, such as the potential kinetic energy, rockfall velocity, and bounce height. CRSP generally requires three major input variables: (1) surface roughness, (2) tangential coefficient, and (3) normal coefficient. Surface roughness is a function of the irregularity of the surface and how much the slope angle may vary within the radius of the rock. The tangential coefficient of frictional resistance determines how much the rock velocity is slowed during the impact parallel to the slope. The normal coefficient of restitution measures the change in the velocity normal to the slope after impact compared to the normal velocity before impact. The rigidity of the slope surface determines the normal coefficient. The two-dimensional CRSP is known to be very sensitive to the ranges of input values of these variables. Thus, the simulation model calibration was conducted, starting with the initial values of the variables assumed through the field evaluation, which finally culminated in the calibration ranges for the least sensitive trends of the input variables. As the next step, the simulation model analysis tested a few model cases, considering the various rockfall behaviors. As a result, the following four feasible design options were recommended as the rockfall countermeasures: (1) soldier pile wall system and precast concrete lagging materials, (2) rock bolting, (3) shotcrete techniques, and (4) posttensioned masonry walls (PTMW).

Multicriteria Evaluation for Prioritization

Given the main feasible design options that resulted from the rockfall hazard assessment, the rock bolting and shotcrete techniques were further detailed in the three combinations of rock bolt, shotcrete, and rock bolt + shotcrete, considering steel rock bolts.

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Table 3. Quantitative prioritization criteria measures and scales

Design option	Criterion									
	C_1			C_2						
	\$/year	P (%)	Scale	Year	P (%)	Scale	C_3	C_4	C_5	C_6
A_1	10,364	79.68	3.98	0.29	41.66	2.08	3.60	4.00	4.60	4.60
A_2	151,952	42.52	2.13	0.30	36.56	1.83	2.80	3.20	2.40	3.40
A_3	155,543	41.48	2.07	0.11	87.82	4.39	3.00	4.80	3.40	4.20
A_4	309,641	10.94	0.55	0.41	13.26	0.66	2.80	3.20	4.00	4.00
A_5	6,053	80.46	4.02	0.20	80.77	4.04	3.80	3.20	3.60	2.00

Note: A_1 = soldier piles + precast concrete lagging; A_2 = steel rock bolts; A_3 = shotcrete; A_4 = steel rock bolts + shotcrete; A_5 = PTMW; C_1 = EUAC; C_2 = time; C_3 = aesthetics; C_4 = complexity; C_5 = safety; and C_6 = maintainability.

Consequently, the multicriteria evaluation for prioritization was conducted for a total of five design options: soldier piles + precast concrete lagging (A_1); steel rock bolts (A_2); shotcrete (A_3); steel rock bolts + shotcrete (A_4); and PTMW (A_5). The rating system used to evaluate the design options for the prioritization criteria in Table 2 was a five-point Likert scale: very good (5), good (4), fair (3), poor (2), and very poor (1). The five-point scale was directly applied to the qualitative criteria (aesthetics, complexity, safety, and maintainability), relying on the engineering judgments from the case project owners and the researchers involved in this project. On the other hand, the quantitative criteria (cost, time, and durability) were estimated according to the numeric values in consultation with the project engineers, contractors, and material/equipment vendors, as well as referring to the 2018 Building Construction Costs with RSMeans Data. The cost and durability criteria were combined into the equivalent uniform annual cost (EUAC), which is a useful measure for the life-cycle cost comparison of alternatives with different lifetimes. The numeric values were then converted into five-point scales for the weighted sums with qualitative criteria.

As given in Table 3, a total of five subjective inputs for each of the qualitative criteria were obtained and averaged for the design options (e.g., A_1–A_5). Table 3 also gives the numeric values, percentiles, and converted scales for the quantitative prioritization criteria. For example, the average and standard deviation of the EUAC measures were \$126,711/year and \$125,526/year, respectively. The t-value of A_1 was $-0.927[= (10{,}364 - 126{,}711)/125{,}526]$, and its percentile was 79.68% (= 100% − 20.32%) from the t-value table, applying the degree of freedom at four because less cost is better. Finally, the percentile was multiplied by 5 to translate into the five-point scale. The scales for the other design options were similarly calculated for both quantitative criteria.

The priority evaluation employed AHP for the weighted sums of the design options. AHP analysis is a structured technique to determine weights based on the relative importance among evaluation factors through pairwise comparison (Yoon et al. 2009). The AHP worksheet, as shown in Fig. 2, was distributed to the four professionals to collect their AHP inputs, and the average weights of the evaluation criteria were determined as follows: cost = 0.201, time = 0.067, aesthetics = 0.047, complexity = 0.066, durability = 0.179, safety = 0.230, and maintainability = 0.210. As the cost and durability criteria were managed through EUAC, the weights of the two criteria were combined to 0.380 for EUAC. Table 4 summarizes the scales and weighted sums of the design options. The final weighted sums were relatively high for design option A_1 (soldier piles + precast concrete lagging), followed by A_5 (PTMW), A_3 (shotcrete), A_2 (steel rock bolts), and A_4 (steel rock bolts + shotcrete).

Introduction

- This worksheet is designed to prioritize the cost and benefit elements using the analytic hierachy process (AHP) which is a structured technique for organizing and analyzing complex decisions.
- In the AHP analysis, the comparison matrix (Table 2) is established by doing a pairwise comparison of the various elements based on a predetermined relative scale shown in Table 1.
- The diagonal entries of the comparison matrix (Table 2) are equal to 1.0 because the elements being compared are the same.
- The entries in the lower triangular matrix are reciprocals of the entries in the upper triangular matrix.

Instructions

Step-1. Select a cell in the upper triangular matrix that you want to provide a pairwise comparison scale. Ex) For the row for cost in Table 2, suppose that you consider cost has weak importance compared to time, then you provide 3.

Step-2. Click on the button-down button on the right side of the cell.

Step-3. Select one relative importance from the list.

Step-4: Once you complete the pairwise comparison, press 'Consistency Ratio' button below to check the consistency of your inputs.

Step-5: If the consistency ratio > 0.1, check the scales you provided and repeat Step-4.

Step-6: If consistency ratio ≤ 0.1, save your AHP evaluation and send it back to us.

Table 1. Analytics Hierarchy Process (AHP) Comparison Scale

Scale	Degree of Preference	Definition
1	Equally	Equal importance of elements
3	Moderately	Weak importance of one element over another
5	Strongly	Strong importance of one element over another
7	Very Strongly	Demonstrated or very strong importance of one element over another
9	Extremely	Absolute importance of one element over another
2,4,6,8	Intermediate	Intermediate values between two adjacent degrees of importance
Reciprocals	Opposites	Inverse comparison

Table 2. Comparison Matrix Consistency Ratio (≤ 0.1):

	Cost	Time	Aesthetics	Complexity	Durability	Satety	Maint.
Cost	1						
Time		1					
Aesthetics			1				
Complexity				1			
Durability					1		
Satety						1	
Maint.							1

Note: Maint. - Maintainability

Fig. 2. AHP worksheet to determine the criteria weights.

Table 4. Scales and weighted sums of the design options

Design option	Criterion, C_k (weight, W_k)						
	C_1	C_2	C_3	C_4	C_5	C_6	
	(0.380)	(0.067)	(0.047)	(0.066)	(0.230)	(0.210)	
	Scale, S						Weighed sum, WS
A_1	3.98	2.08	3.60	4.00	4.60	4.60	4.11
A_2	2.13	1.83	2.80	3.20	2.40	3.40	2.54
A_3	2.07	4.39	3.00	4.80	3.40	4.20	3.20
A_4	0.55	0.66	2.80	3.20	4.00	4.00	2.36
A_5	4.02	4.04	3.80	3.20	3.60	2.00	3.44

Table 5. Calculations for the most critical criterion and performance measure

Criticality	Minimum change	Criterion, C_k					
		C_1	C_2	C_3	C_4	C_5	C_6
Criterion	$\delta_C(W_k/A_1A_5)$	−16.750	−0.342	−3.350	0.838	0.670	0.258
	Feasibility	n/f	n/f	n/f	n/f	n/f	n/f
Scale	$\delta_S(a_{1,k}/A_1A_5)$	1.76	10.00	14.26	10.15	2.91	3.19
	$\delta'_S(a_{1,k}/A_1A_5)$	44.2%	480.8%	396.0%	253.8%	63.3%	69.4%
	Feasibility	f	n/f	n/f	n/f	f	f

Note: f = feasible; and n/f = nonfeasible.

Sensitivity Analysis for the Most Critical Criterion and Scale

As the sensitivity analysis of the prioritization framework in this paper aimed to provide a certain level for the decision on the top-ranked alternative, the variables i and j in Eqs. (1)–(5) were replaced by 1 and 5, which were the highest- and second highest–ranked design options, as given in Table 4. The scales and weighted sums of A_1 and A_5 in Table 4 were applied to Eqs. (1) and (3) to compute $\delta_C(W_k/A_iA_j)$ and $\delta_S(a_{i,k}/A_iA_j)$, which then were evaluated for feasibility. Table 5 includes the computation results for the pair of A_1 and A_5.

In Table 5, f and n/f stand for feasible and nonfeasible, respectively. n/f is used for the absolute values of the minimum changes that were greater than the corresponding weights W_k for $\delta_C(W_k/A_1A_5)$ and used for $\delta'_S(a_{1,k}/A_1A_5)$ exceeding 100%. That is, the minimum change required for the weight of C_2 (i.e., W_2) was computed as

$$\delta_C(W_2/A_1A_5) = \frac{WS_5 - WS_1}{a_{5,2} - a_{1,2}} = \frac{3.44 - 4.11}{4.04 - 2.08} = -0.342 \quad (8)$$

The minimum change for C_2 was not feasible because its absolute value was not less than the value of W_2, 0.067

$$Abs(\delta_C(W_2/A_1A_5)) = 0.342 \not< W_2 = 0.067 \quad (9)$$

As none of the absolute values of the criteria minimum changes were less than the weights, the relative terms of the minimum changes for the criteria were not computed. On the other hand, as displayed in Table 5, the minimum changes in the relative terms for $a_{1,1}$, $a_{1,5}$, and $a_{1,6}$ were feasible. For example, the minimum change required for $a_{1,1}$ at C_1 was

$$\delta_S(a_{1,1}/A_1A_5) = \frac{WS_1 - WS_5}{W_1} = \frac{4.11 - 3.44}{0.380} = 1.76 \quad (10)$$

$$\delta'_S(a_{1,1}/A_1A_5) = \frac{\delta_S(a_{1,1}/A_1A_5)}{a_{1,1}} \times 100(\%) = \frac{1.76}{3.98} \times 100(\%) = 44.2\% \quad (11)$$

The minimum change $\delta_S(a_{1,1}/A_1A_5)$ was feasible, as its relative value $\delta'_S(a_{1,1}/A_1A_5)$ was less than 100%. The scale $a_{1,1}$ was the most critical scale, which reversed the priority order between A_1 and A_5 by the smallest change, among other minimum changes in the scales $a_{1,5}$ and $a_{1,6}$.

Results and Discussion

The sensitivity analysis results indicated that the decision-making on A_1 was completely stable (i.e., 100% confident) over A_5 when the subjective inputs on the criteria weight values were considered. In other words, there was no chance of reversing the priority rankings between A_1 and A_5 by adjusting any of the criteria weights, given the scales. For the most critical scale $a_{1,1}$, a change from 3.98

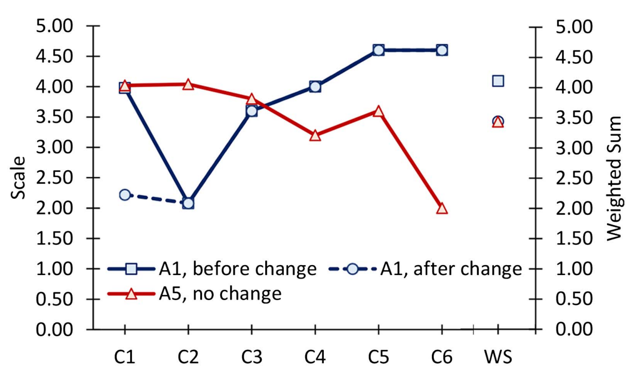

Fig. 3. Variations in the scores at C_1 and WS.

by 44.3%, which decreased $a_{1,1}$ by 1.76 from its current scale to 2.22, made the priority of A_5 at least equal to A_1. Fig. 3 illustrates the variations in the scales at C_1 before and after decreasing the initial $a_{1,1}$ to $a^*_{1,1}$, which set the weighted sums WS of A_1 and A_5 equal at 3.44. Any further decrease from the scale $a^*_{1,1}$ would make A_5 preferred over A_1.

However, as the minimum change in the most critical scale was driven by the scale that was converted from the percentile in the student's t-distribution, the increase in the numeric value for the minimum change caused the reestimation of the scales of A_2–A_5, which made the WS of A_1 and A_5 unequal. That is, the EUAC of A_1 associated with the changed scale of 2.22, which was equivalent to 44.4% (= 2.22/5) in the t-distribution, was $176,003, considering the EUACs of A_2–A_5 were unchanged. The increase in the EUAC of A_1 reestimated the scales of the other alternatives as the mean and standard deviations (STED) were changed due to the increase, as displayed in Table 6. The reestimated scales along with the scales of C_2–C_6 in Table 4 generated the modified weighted sums of the alternatives. Fig. 4 shows the changes in the weighted sums (WS) of A_1 and A_5 computed based on the initial scales (A_1–3.98 and A_5–4.02), the scale required by the minimum change in the most critical scale (A_1–2.22 and A_5–4.02), and the scales reestimated by the increased EUAC of A_1 (A_1–3.44 and A_5–4.02).

As a result, the solution-seek process was conducted to find a EUAC increase at a scale that made the WS of A_1 and A_5 equal. The EUAC for A_1 was $149,300, which was converted to a scale of 2.59, considering the mean of $154,498 and the standard deviation of $107,401. Given the statistical measures, the percentile of A_5 for the EUAC of $6,053 was 88.05% in the t-distribution, which was equivalent to a scale of 4.40. Table 7 gives the equal WS of A_1 and A_5 calculated from the reestimated scales.

The increased EUAC for A_1 was the upper limit required for A_1 to maintain its higher priority over A_5. Thus, the application of Eq. (7) was required to determine the confidence level to choose A_1 as the final design option in consideration of the uncertainty in the cost overrun. The use of Eq. (7) involved the minimum sample size of two and a standard deviation. However, the EUAC estimation for the design options in this paper was made by one individual using the cost data collected from various sources, such as the contractors, material and equipment vendors, and reference books. Therefore, the confidence levels for the upper limit of the EUAC at A_1 were sought in various scenarios that assumed sample sizes ranging from 2 to 5 and standard deviations incrementing by 5% from 5% to 50% of the mean EUAC. Table 8 gives the confidence levels computed for each of the scenarios. The results indicate that the decision-making on design option A_1 had at least a 98.8% confidence level over the second-best design option A_5, given the conditions of the number of cost estimators and cost overruns.

Table 6. Reestimated C_1 scales due to the increase in the EUAC of A_1

Design option	C_1 before applying the minimum change to A_1			C_1 after applying the minimum change to A_1		
	$/year	P (%)	Scale	$/year	P (%)	Scale
A_1	10,364	79.68	3.98	176,003	44.40	2.22
A_2	151,952	42.52	2.13	151,952	52.74	2.64
A_3	155,542	41.48	2.07	155,542	51.49	2.58
A_4	309,641	10.94	0.55	309,641	11.84	0.59
A_5	6,053	80.46	4.02	6,053	88.67	4.43
Mean	126,710	—	—	159,838	—	—
STED	125,526	—	—	107,741	—	—

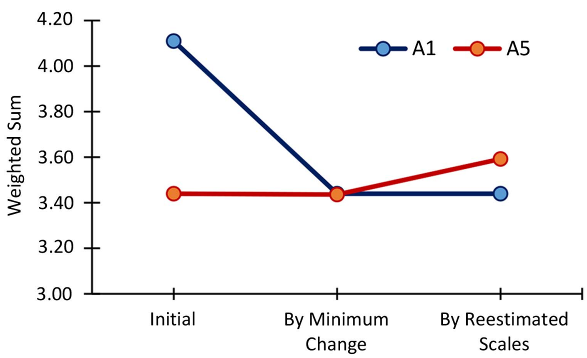

Fig. 4. Changes in the WSs between A_1 and A_5.

Table 7. Scales and weighted sums of the design options

Design option	C_1 (0.380)	C_2 (0.067)	C_3 (0.047)	C_4 (0.066)	C_5 (0.230)	C_6 (0.210)	Weighed sum, WS
	Criterion, C_k (weight, W_k) — Scale, S						
A_1	2.59	2.08	3.60	4.00	4.60	4.60	3.58
A_5	4.40	4.04	3.80	3.20	3.60	2.00	3.58

Table 8. Confidence levels at various scenarios of sample sizes and standard deviations

Sample size	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
	Standard deviation in % of mean EUAC — Confidence level (%)									
2	100.00	100.00	100.00	100.00	100.00	99.29	99.17	99.05	98.93	98.81
3	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
4	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
5	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Conclusions

Rockfalls can have devastating consequences to road facilities and vehicle users. Finding the most cost-effective rockfall countermeasures has been a constant concern for tax revenue-dependent public transportation agencies. The fundamentals of the novel framework for rockfall countermeasures in this paper are applicable to any transportation agency. However, as the need for rockfall countermeasures exists more often on low-volume roads in rural areas, this paper specifically addresses its use for local road applications. The presented framework consists of three major steps: (1) rockfall hazard assessment to generate multiple rockfall countermeasure alternatives, (2) multicriteria evaluation for prioritization, and (3) sensitivity analysis. This paper presents a synthesis list of rockfall countermeasure evaluation criteria found through a literature review. The uniqueness of this framework can be found in the application of sensitivity analysis in the decision-making process. The ability to quantify a confidence level for local road agencies to select the best alternative is the main advantage of using the presented prioritization framework over conventional prioritization methods. That is, while conventional methods show the list of prioritized rockfall countermeasure alternatives in a way that may cause a decision-maker stress and uncertainty in choosing the top-ranked alternative to implement, the presented framework provides the decision-maker with the confident inference of the choice that is also communicable with other involved stakeholders. The sensitivity analysis of the framework employs the approach suggested by Triantaphyllou and Sánchez (1997) due to its practical use for prioritization methods based on weighted sums and AHP. However, the applicability of the original approach was further extended for cases that consider quantitative measures obtained through standard scaling techniques, which is the scholarly contribution of this paper to advance the theoretical knowledge.

The presented prioritization framework was well-demonstrated with an actual case study in West Virginia, which confirmed that the framework was able to provide a sense of certainty to decision-makers about the top-ranked alternative. Nevertheless, we recommend the following future work to continue its development. First, while the holistic prioritization framework presented in this paper is applicable to any evaluation criteria, there is a need for a more comprehensive literature review to identify prioritization criteria and research to validate them for practicality by conducting an extensive survey among local transportation agency professionals. Second, to enhance the practicability of the presented prioritization framework, the development of a computational application that integrates the steps for multicriteria evaluation and sensitivity analysis could be beneficial for those in charge of making final decisions for real-world rockfall countermeasure construction projects. Finally, although it is not likely to have a quantitative evaluation criterion with a probability distribution other than normal, the methods to convert alternative values for the criterion to percentiles and to compute confidence levels for minimum changes easily can be customized by adopting the percentile and confidence level equations relevant to the probability distribution.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. Available data sets include (1) raw data collected for the evaluation criteria and AHP and (2) all data sets used to generate the tables and figures in the paper.

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