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`*Research Article*

Rockfall hazard analysis based on the concept of functional safety with application to the highway network in South Korea

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Abstract:

Numerous rockfall incidents involving infrastructure damage and loss of life have been reported along roads in mountainous terrain. Previous studies have used quantitative risk assessment approaches to identify the level of rockfall risk. However, appropriate quantitative indicators that are able to describe time-varying risk have not yet been developed. This study aims to develop a rockfall risk mitigation method based on reliability concepts, to classify rockfall data, to model the probability of rockfall occurrence, and to estimate the magnitude of risk reduction through mitigation measures. A synthetic measure of rockfall risk is proposed, which allows to compare directly and quantitatively the rockfall risk for different cut slopes under unmitigated and mitigated conditions. The proposed methodology can estimate the risk reduction obtained by using mitigation measures, such as introducing protections barriers, their periodic maintenance, and horizontal coverage ratio. This methodology was applied to 20 years of rockfall data collected by the Korea Expressway Corporation from 1215 artificial cut slopes along the highway network in South Korea. The rockfall frequency was analyzed based on the inventory data, and a rockfall hazard mitigation strategy was demonstrated by using the suggested methodology for the case study. It was shown that appropriate mitigation strategies, based on number of protection barriers, interval of periodic maintenance, and horizontal coverage ratio, can be devised to reduce the risk of different artificial slopes below a target failure probability. The approach shown in this study can provide insights into ways of improving overall risk management to prevent losses by rockfall.

Keywords: Rockfall hazard, Rockfall mitigation, Risk management, Time-varying risk, Reliability, Common cause failure

1 Introduction

Vast databases on natural hazards and their effects on infrastructure systems have been built in various regions with extensive observation networks as part of the current efforts to manage the risks posed by natural disasters (UNISDR 2004). However, additional research is needed to understand how the collected inventory data can be systematically managed, efficiently processed, and used in practical applications for managing risk from natural hazards and reducing losses and damages (Cutter and Emrich 2005; Soeters and Van Westen 1996). For rockfall hazard, it is often difficult to obtain data from sources other than cases of accidents that directly cause harm to people (Budetta 2004; Chau et al. 2003; Dussauge et al. 2003), and it is also challenging to find examples of classification and recording systems. Nonetheless, various rockfall incidents causing infrastructure damage and loss of life have occurred, e.g., along roads in mountainous terrain, in quarries, and in residential villages located near cliffs (Badger and Lowell 1992; Flügel et al. 2015; Guzzetti 2000; Yarahmadi et al. 2014). Transportation corridors (such as roads and railways) that are built on mountainous terrain are vulnerable to rockfall due to the lack of adequate countermeasures along cut slopes due to the lack of adequate countermeasures along cut slopes (Hungr et al. 1999). For example, 1215 artificial cut slopes in the Korean highway network have been listed and managed by the Korean Expressway Corporation (KEC), which is the public company operating and managing most of highways constructed in South Korea, and more than 1030 rockfall events have been recorded between 1998 (initial year of data collection) and 2017 (KEC 2018).

Although rockfall is caused by multiple factors and its mechanism are not fully understood, rockfall is known to be triggered by rainfall, snow, freezing and thawing, wind storms, spring runoff, earthquakes, roots of plants enlarging joints, and/or human activities (Guzzetti et al. 2003). Rockfall can be initiated by detachment of rock fragments from bedrock slopes due to slope movement and weathering, which results in fracturing of vulnerable parts of rock joints (Crosta & Agliardi, 2004; Duncan 1996; Evans & Hungr, 1993). However, the cause and timing of fracturing can rarely be identified, and a time lag may occur between an extreme weather event, such as intense rainfall, and a subsequent rockfall event (Hong et al. 2007). Therefore, mitigation measures are needed to prevent accidents, e.g., by installing physical protection barriers and/or other nonstructural solutions in areas where rockfall is likely to occur (Bertrand et al. 2012).

Mitigation measures such as barrier fences (Peila and Ronco 2009), retaining nets (Peila et al. 1998), and ground embankments (Peila et al. 2007) can be installed to reduce the risk posed by rockfall hazard. However, these measures cannot be installed in all potentially vulnerable areas due to economic, environmental, and technical limitations. Therefore, the installation of mitigation measures for cost-effective protection should reflect a prioritization and selection of design level based on a hazard assessment and an appropriately quantified risk assessment (Bell and Glade 2004; Corominas et al.

2005; Fell et al. 2008; Raetzo et al. 2002). In addition, regular maintenance and continuous surveillance of mitigation measures are also important for reducing rockfall hazard. For example, immediate maintenance is required to ensure the expected protective performance after rockfall events, since retention capacity may be weakened, and corrosion defects must be controlled to guarantee structural strength (Peila and Ronco 2009; Volkwein et al. 2011). Negligence of reasonable maintenance can be a legal issue: for example, in Canada, the provincial authorities have been found to bear the liability of maintenance to prevent loss of life from rockfall hazard (Bunce et al. 1997).

Previous studies have investigated quantitative risk assessment approaches to evaluate the risk exposure of infrastructure near unstable slopes (e.g., through analyses of rockfall event inventories and data on road conditions and weather), and to generate estimated probabilities of rockfall events used to grade hazard levels (Budetta 2004; Crosta and Agliardi 2003; Lan et al. 2007). Advanced approaches based on three-dimensional computational simulation of rockfall trajectories (e.g., examining path, height, and potential stop positions) and kinetic energy distribution have been proposed for rockfall hazard assessment and design of mitigation measures such as rockfall protection barrier, embankment, and shelters (Crosta et al., 2015). However, appropriate quantitative safety indicators that are able to describe time-varying risk have not yet been developed, and the quantitative risk reduction achievable by installing mitigation measures has not been fully investigated in the existing literature. The European Technical Approval Guideline (ETAG) 027 regarding rockfall protection kits (EOTA 2008) provides a method to test the performance of rockfall protection and some information about maintenance, but this method represents a design guideline for rockfall protection net fences rather than a guideline for a complete maintenance and management plan of transportation systems subject to rockfall hazard. The ISO 31000:2009 standard on risk management (ISO 2009) provides general principles and guidelines for managing risk by an organization; however, the standard does not specify customized practices that fit for rockfall risk management.

Peila and Guardini (2008) evaluated the risk on a road affected by rockfall hazard. Their study was later further developed into a quantitative rockfall risk management method that reflects the characteristics of traffic (Mignelli et al. 2012). Using event tree analysis, Mignelli et al. (2012) showed that the level of risk was reduced by protective measures, but did not include a quantitative assessment of how additional mitigation measures or periodic maintenance would change risk. Several qualitative and semi-quantitative rockfall hazard assessment methods have been developed and are applied worldwide, such as the Rockfall Hazard Rating System and its local modifications, or the Rockfall Hazard Assessment Procedure used in Northern Italy (Ferrari et al. 2016). These heuristic approaches are commonly used for rapid assessment of rockfall hazard over large areas, as they avoid computationally expensive simulations; however, they generally lack objectivity and are characterized by low accuracy (Ferrari et al. 2016). Research is still needed to develop accurate and efficient rockfall risk models that are able to estimate time-varying risk, to evaluate the risk reduction obtained through additional mitigation measures, and to assess the influence of maintenance activities by using typically-available data (i.e., data that are commonly collected in everyday practice) on slope stability.

In the industrial sector, standards regarding functional safety based on reliability engineering, such as IEC 61508 by the International Electro-Technical Commission, have been developed to manage the probabilistic risk of safety devices throughout the safety life cycle (IEC 2003). Functional safety is the ability of a safety-related system or other risk reduction measure to perform its intended actions to achieve a safe status of its targeted equipment, and the concept is fundamentally applicable to all industrial sectors (ISA 2002). In addition, a number of reliability and risk analysis approaches has been developed for design and management of civil engineering, structural, and critical infrastructure systems (Faber and Stewart 2003; Guikema 2009). The definition of functional safety has been broadened to include organizational and human safety functions, which can reduce the probability of hazardous events in a system, and the extended concept has been used for accident investigations in workplaces (Harms-Ringdahl 2009). Applying the concept of functional safety to analyze natural hazards data in civil engineering applications can help to assess the exposure risk in a quantitative manner and to develop new risk mitigation strategies (Lee and Lee 2018).

The purpose of this study is to develop a method of classifying rockfall hazard data based on reliability concepts, to model the probability of rockfall occurrence, and to estimate the magnitude of risk reduction achievable through additional mitigation measures and periodic maintenance. As a case study, the rockfall data collected by the KEC from artificial cut slopes along the highway network of South Korea are investigated. Using these rockfall data collected for over 20 years, the occurrence rate for different cut slopes is classified in detail and analyzed to identify the cut slopes with the highest rockfall hazard. The effects of additional protections barriers, periodic maintenance, and coverage ratio are also compared in a quantitative manner. Other possible mitigation measures are also discussed, by identifying data that are not available at the present time, but that could be included in further data collection in the future to assess the effectiveness and limitation of additional mitigation measures.

2 Methodology

2.1 Classification of rockfall inventory data

A classification scheme for rockfall inventory data is proposed based on grouping rockfall events into three major categories based on the severity of the rockfall event consequence. In particular, the proposed rockfall hazard assessment methodology focuses on assessing and mitigating the risk of rockfall reaching the road surface and affecting the functionality of the road network. As such, a rockfall classification scheme is needed that can use the minimum amount of information typically collected by companies or agencies managing roads and highway systems, and that can relate this information to probabilistic input to be used in the rockfall hazard assessment procedure. Therefore, the proposed rockfall inventory data classification scheme includes the following three categories of rockfall events: (1) rockfalls that are large enough to reach the road surface even in the presence of barriers (referred to hereinafter as "dangerous damaging failures" and described by the annual frequency λ_{DD}), (2) rockfalls that are large enough to reach the road surface in unmitigated conditions but that can be stopped by a mitigation system, such as protective barrier or fence (referred to as "dangerous non-damaging failures" and described by the annual frequency λ_{DN}), and (3) rockfalls that are too small to reach the road surface and conditions corresponding to incipient failure such as cracks or fractures observed on slopes (referred to as "safe failures" and described by the annual frequency λ_S). The dangerous damaging and dangerous non-damaging failures can be also grouped into a class of dangerous failures, described by the annual frequency $\lambda_D = \lambda_{DD} + \lambda_{DN}$. The proposed classification of the rockfall data is presented in Table 1 and was adapted from the definition of failure modes introduced in IEC 61508 (IEC 2003), which distinguishes between dangerous and safe failures.

Table 1 Classification scheme of rockfall inventory data

Annual frequency	Description	Example of rockfall inventory data
λ_{DD}	Dangerous damaging failure	Rockfall occurred and rock material reached the road surface
λ_{DN}	Dangerous non-damaging failure	Rockfall occurred and rock material was stopped by rockfall protection barriers
λ_S	Safe failure	Incipient failures (i.e. cracks or fractures) were identified on a slope during inspection

The adopted classification is consistent with rockfall volume distributions that have been developed for artificial slope to describe the relative frequency of rockfall events of different sizes and consequences and that is often obtained by fitting historical data to an inverse power law (Santana et al., 2012). Fig. 1Figure 1 shows the conceptual relation between an annual cumulative frequency vs. rockfall volume curve and the annual frequencies used in the proposed classification. In particular, the annual frequency for dangerous damaging rockfalls, λ_{DD}, corresponds to the frequency of rockfall volumes larger than a specified (but often unknown) volume V_2 beyond which the rockfalls will reach the road surface even when a barrier is placed on the artificial slope; whereas the annual frequency for dangerous non-damaging rockfalls, λ_{DN}, corresponds to the frequency of rockfall volumes between V_1 and V_2, for which the rockfalls are large enough to reach the road if the slope is left unprotected but not large enough to overcome a barrier placed on the artificial slope. The annual frequency for safe rockfalls, λ_S, corresponds to the frequency of rockfalls that are too small to reach the road even without a barrier, or to incipient failures detected on the artificial slope but for which no rockfall has been yet observed. It is noted here that an accurate value for λ_S is difficult (if not impossible) to measure; thus, this quantity is not directly employed in the calculations required by the proposed methodology. In fact, the definition of safe failures is used here only to identify and exclude from the risk calculations those rockfall events that have no consequences in terms of road functionality. Those failures include incipient failures, cracks, and fractures that are identified on artificial slopes during inspection and that could be related to future rockfall events. The proposed methodology could be extended to include in a more explicit form this information to develop additional preventative actions; however, this potential development is considered outside the scope of this study.

It is important to note that the proposed rockfall event classification is able to incorporate the information provided by rockfall volume frequency curves (as the proposed annual frequencies can be easily calculated from these curves), but it does require such detailed information when it is not readily available. This property represents an advantage in terms of practicality of the proposed methodology when compared to more complex approaches that require the use of rockfall volume frequency curves.

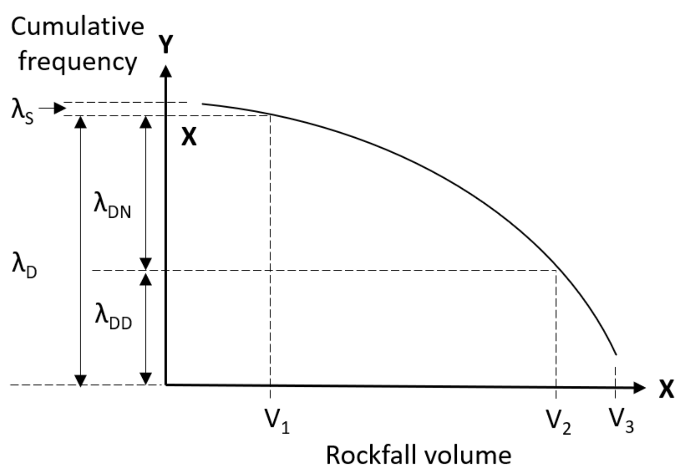


Fig. 1 Conceptual diagram of the relation between rockfall volume distribution and event frequency based on the proposed rockfall classification scheme

2.2 Probability of rockfall occurrence and rockfall risk under unmitigated conditions

The probability of rockfall occurrence over time is defined here based on the concept of reliability. In this study, the reliability of the system, $R(t)$, corresponds to the probability of safe operation of the highway transportation system subject to rockfall hazard, whereas the failure probability of the same system is given by $F(t) = 1 - R(t)$. The considered failure limit state is rockfall of rock material on the roads. By assuming that the rate of rockfall is constant over time and that each rockfall event is independent from previous rockfall events (Daley and Vere-Jones 2003), i.e., the rockfall events at each slope are described by a Poisson process, the time-dependent failure probability for a given slope without any mitigation measure can be expressed as

$$F_{\mathrm{U}}(t) = 1 - e^{-\lambda_{\mathrm{D}} \cdot t} \quad (1)$$

where F_{U} denotes the unmitigated instantaneous rockfall probability, $\lambda_{D} = \lambda_{DD} + \lambda_{DN}$ is the rate of occurrence of dangerous rockfall, and *t* denotes time. It is noted that the Poisson assumption is used here because existing data are insufficient to suggest other potentially more realistic distributions for rockfall events. However, this assumption could be easily modified based on new data that better describe the physical characteristics of rockfall events. In addition, the rockfall rates used in this study were obtained by averaging the recorded numbers of rockfalls observed over a relatively long period of time, with individual events that were sufficiently rare to justify at least in an approximate manner the assumption of independence between subsequent events.

In order to identify a simple quantitative risk measure that can be used to compare synthetically different slopes in a given database, the concept of average failure probability over a specified time interval (ISA 2002) can be introduced. In particular, for slopes without any mitigation measure, the unmitigated failure probability averaged over the design life time, T_{DL}, is referred to as unmitigated rockfall failure probability, $P_{f,\mathrm{U}}$, and is defined as

$$P_{f,\mathrm{U}}(T_{\mathrm{DL}}) = \frac{1}{T_{\mathrm{DL}}} \int_{0}^{T_{\mathrm{DL}}} F_{\mathrm{U}}(t) \cdot \mathrm{d}t \quad (2)$$

Once a rockfall risk level is identified as acceptable or desirable, the unmitigated rockfall failure probability can be directly used to identify dangerous slopes that require the use of mitigation strategies, as well as to prioritize intervention on the most dangerous slopes within a given database or portfolio.

2.3 Probability of rockfall occurrence and rockfall risk under mitigated conditions

When the unmitigated rockfall failure probability is higher than the acceptable rockfall risk level, different mitigation strategies can be implemented to reduce this risk and to operate highway networks safely with respect to rockfall hazard. In particular, protective barriers and periodic maintenance are commonly employed to mitigate the rockfall risk of an unstable cut slope. Assuming that a set of *n* barriers are deployed at a given cut slope, and that the rate of failure of the *i*-th barrier can be represented as a Poisson process with occurrence rate equal to λ_i $(i = 1, \ldots, n)$, the time-dependent mitigated failure probability for a given slope can be estimated as

$$F_{\mathrm{M}}(t) = F_{\mathrm{U}}(t) \cdot \prod_{i=1}^{n} \left(1 - e^{-\lambda_i \cdot t}\right) \quad (3)$$

The barrier failure rates, λ_i, depend on the barrier strength, the mass of detached rock, and the distance traveled by the rock material from the detachment point to the barrier. Whenever available, accurate values of λ_i should be used, e.g., obtained as a result of three-dimensional trajectory analysis or from detailed rockfall inventory data recorded using photogrammetric surveys and/or three-dimensional laser scanning techniques. However, without loss of generality but at the price of accuracy, approximate λ_i

values can also be used. Under the reasonable assumptions that all barriers have the same strength and are distributed at equal distances along the height of the slope, this failure rate can assume values contained between two limit cases, i.e.:

$$\frac{\lambda_{\mathrm{DD}}}{n} \leq \lambda_i \leq \lambda_{\mathrm{DD}} \tag{4}$$

in which the upper-bound value ($\lambda_i = \lambda_{\mathrm{DD}}$) implies that a rockfall that induces failure of a barrier will also induce failure of all the other barriers between the rockfall detachment and the road, whereas the lower-bound value ($\lambda_i = \frac{\lambda_{\mathrm{DD}}}{n}$) accounts for the reduction in impact energy due to the reduction in the distance traveled by the rock material before hitting a given barrier.

Similar to the considerations made for an unmitigated cut slope, a quantitative measure of the rockfall probability for a mitigated slope is needed in order to support decision-making. Based on functional safety consideration (IEC 2003; Goble and Cheddie 2005), the following simple model is proposed to evaluate the rockfall failure probability for a cut slope for which multiple barriers and periodic maintenance are implemented:

$$P_{f,\mathrm{M}}(T_{\mathrm{DL}}, T_{\mathrm{I}}, CR) = CR \cdot \frac{1}{T_{\mathrm{I}}}\int_0^{T_{\mathrm{I}}} F_{\mathrm{M}}(t) \cdot \mathrm{d}t + (1 - CR) \cdot \frac{1}{T_{\mathrm{DL}}}\int_0^{T_{\mathrm{DL}}} F_{\mathrm{U}}(t) \cdot \mathrm{d}t + CR \cdot \left(1 - e^{-\lambda_{\mathrm{DN}} \cdot T_{\mathrm{R}}}\right) \tag{5}$$

in which $P_{f,\mathrm{M}}$ denotes the average mitigated failure probability, T_{I} is the maintenance interval (i.e., the interval between two subsequent inspections and repairs of the barrier system), *CR* is the horizontal coverage ratio of the barriers (i.e., the portion of the cut slope length protected using barriers), T_{R} is the repair time of damaged barriers. The average mitigated failure probability is the sum of the failure probabilities corresponding to the following three statistically independent events: (1) the failure of the barriers in the protected portion of the cut slope (which depends on the maintenance interval); (2) the rockfall in the unprotected portion of the cut slope (which depends on the design life time); and (3) the rockfall happening during repair of the protective barriers, which would have been prevented by the presence of barriers. When $CR = 1$ (100% coverage) and $T_{\mathrm{R}} = 0$ (i.e., the repair time is negligible when compared to the maintenance interval), Eq. (5) reduces to the following simpler form:

$$P_{f,\mathrm{M}}(T_{\mathrm{I}}) = \frac{1}{T_{\mathrm{I}}}\int_0^{T_{\mathrm{I}}} F_{\mathrm{M}}(t) \cdot \mathrm{d}t \tag{6}$$

Figure 2 illustrates the unmitigated and mitigated rockfall probabilities obtained using Eq. (1) through Eq. (5), as defined in the proposed methodology.Fig. 2) Figure 2(a) shows the unmitigated instantaneous rockfall probabilities, F_{U}, and the corresponding unmitigated rockfall failure probabilities, $P_{f,\mathrm{U}}$, for different values of λ_{D} and a design life time $T_{\mathrm{DL}} = 25$ years. Lower values of λ_{D} produce significantly lower values of F_{U} and $P_{f,\mathrm{U}}$.Fig. 2 Figure 2(b) shows the mitigated instantaneous rockfall probabilities, F_{M}, and the corresponding mitigated rockfall failure probabilities, $P_{f,\mathrm{M}}$, for different numbers of protection barriers, *n*, for $T_{\mathrm{I}} = T_{\mathrm{DL}} = 25$ years, $T_{\mathrm{R}} = 1$ month, $CR = 100\%$ and λ_{DD}

= λ_{DN} = 0.2. Increasing the number of barriers decreases the values of F_M and $P_{f,M}$, but every subsequent barrier has a smaller effect than the previous one.Fig. 2 Figure 2(c) plots the mitigated instantaneous rockfall probabilities, F_M, and the corresponding mitigated rockfall failure probabilities, $P_{f,M}$, for different maintenance intervals, T_I , with T_{DL} = 25 years, T_R = 1 month, n = 1, CR = 100%, and λ_{DD} = λ_{DN} = 0.2. It is observed that the use of shorter maintenance intervals is a very effective approach to reduce $P_{f,M}$, because it effectively resets F_M to values corresponding to short operation times, for which F_M assumes relatively low values.Fig. 2 Figure 2(d) plots the mitigated rockfall failure probability, $P_{f,M}$, for different values of coverage ratios, CR, and maintenance intervals, T_I, with T_{DL} = 25 years, T_R = 1 month, n = 1, and λ_{DD} = λ_{DN} = 0.2. $P_{f,M}$ is a linear function of CR and tends to $P_{f,U}$ when CR tends to zero.

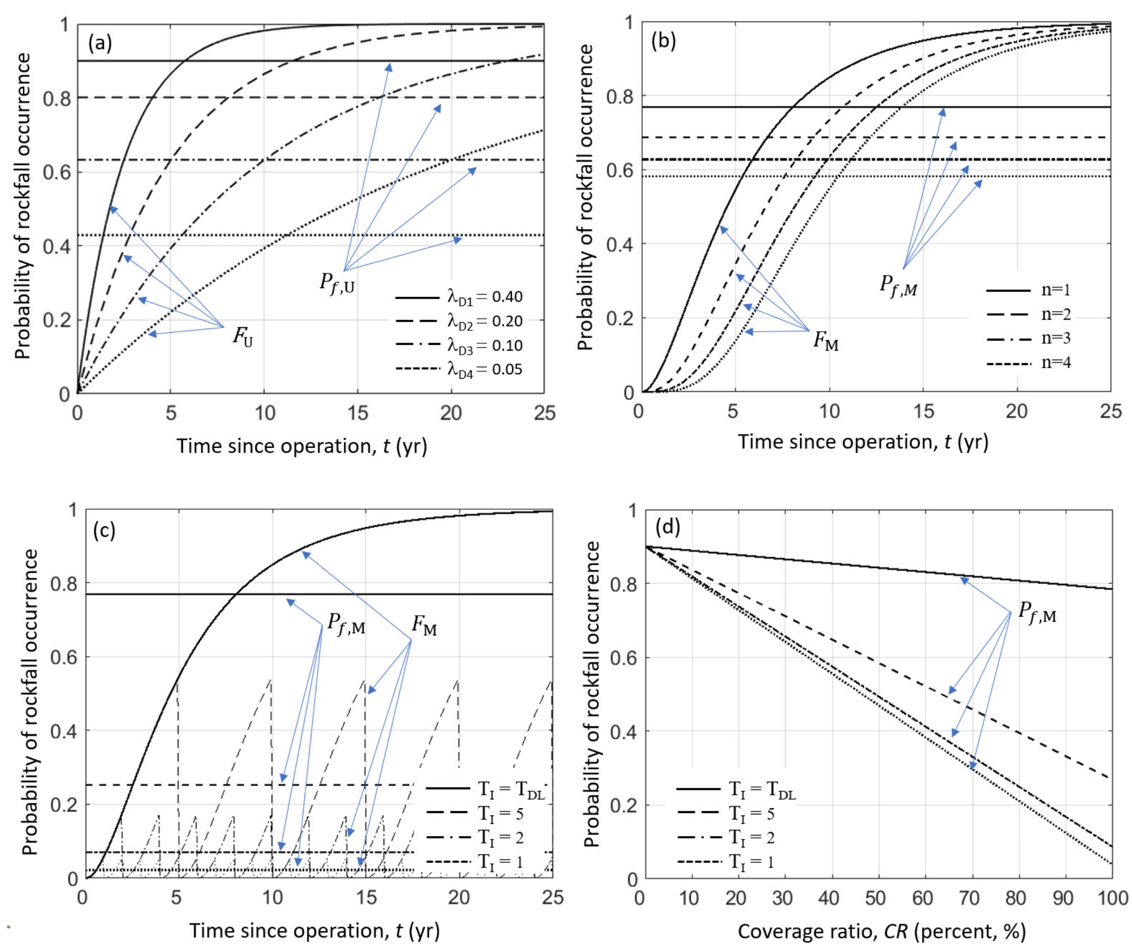
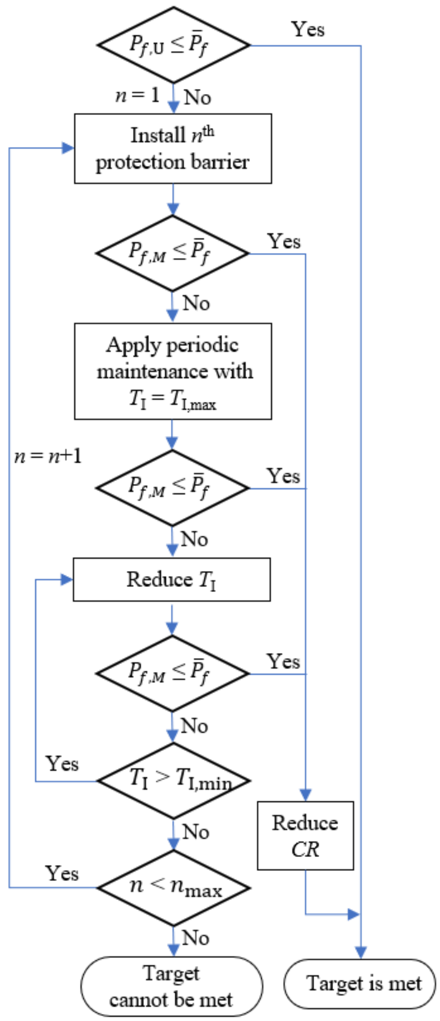


Fig. 2 Rockfall probability model: (a) unmitigated instantaneous rockfall probability, F_U, and unmitigated rockfall failure probability, $P_{f,U}$, for different values of λ_D; (b) mitigated instantaneous rockfall probability, F_M, and mitigated rockfall failure probability, $P_{f,M}$, for different numbers of protection barriers, n; (c) mitigated instantaneous rockfall probability, F_M, and mitigated rockfall failure probability, $P_{f,M}$, for different maintenance

intervals, T_{I}; and (d) mitigated rockfall failure probability, $P_{f,\mathrm{M}}$, for different values of coverage ratios, CR, and maintenance intervals, T_{I}.

2.4 Proposed methodology for selection of rockfall mitigation strategy based on protection barriers

The probabilistic framework developed in Sections 2.1 through 2.3 can be used to select an appropriate rockfall mitigation strategy based on protection barriers for any given artificial slope and specified target failure probability. Three design variables are considered in this study and are applied sequentially in order to efficiently decrease the failure probability of a given slope below the target failure probability: (1) installation of protection barriers and selection of the number of barriers (n), (2) application of periodic maintenance and selection of corresponding maintenance interval (T_{I}), and (3) change of coverage ratio (CR). The flowchart in Figure 3 shows the proposed procedure to select these three design variables for a target failure probability, $\bar{P}_f$. The proposed selection methodology also allows the definition of the following design constraints: design life time (T_{DL}), repair time duration (T_{R}), minimum coverage ratio ($CR_{\min}$), maximum number of protective barriers ($n_{\max}$), and minimum and maximum maintenance time intervals ($T_{\mathrm{I,min}}$ and $T_{\mathrm{I,max}}$, respectively). The specific values of the target failure probability and of the design constraints can be selected by the appropriate stakeholders and decision-makers depending on their specific needs and available technology, thus making the proposed framework as general and flexible as possible.



1) Calculate $P_{f,\mathrm{U}}$ using λ_D and Eqs. (1) and (2).
   a) If $P_{f,\mathrm{U}} \le \bar{P}_f$, no protection is needed.
   b) If $P_{f,\mathrm{U}} > \bar{P}_f$, set $n = 1$ and install the 1st protection barrier with CR = 100% and no maintenance.

2) Calculate $P_{f,\mathrm{M}}$ using $\lambda_i = \lambda_{\mathrm{DD}}$ and Eqs. (3) and (5).
   a) If $P_{f,\mathrm{M}} \le \bar{P}_f$, reduce CR until $P_{f,\mathrm{M}} = \bar{P}_f$ or $CR = CR_{\min}$. No additional protection is needed.
   b) If $P_{f,\mathrm{M}} > \bar{P}_f$, apply periodic maintenance with $T_\mathrm{I} = T_{\mathrm{I,max}}$.

3) Calculate $P_{f,\mathrm{M}}$ using Eqs. (3) and (5) and considering periodic maintenance.
   a) If $P_{f,\mathrm{M}} \le \bar{P}_f$, reduce CR until $P_{f,\mathrm{M}} = \bar{P}_f$ or $CR = CR_{\min}$. No additional protection is needed.
   b) If $P_{f,\mathrm{M}} > \bar{P}_f$, reduce T_I until $P_{f,\mathrm{M}} \le \bar{P}_f$ or $T_\mathrm{I} = T_{\mathrm{I,min}}$

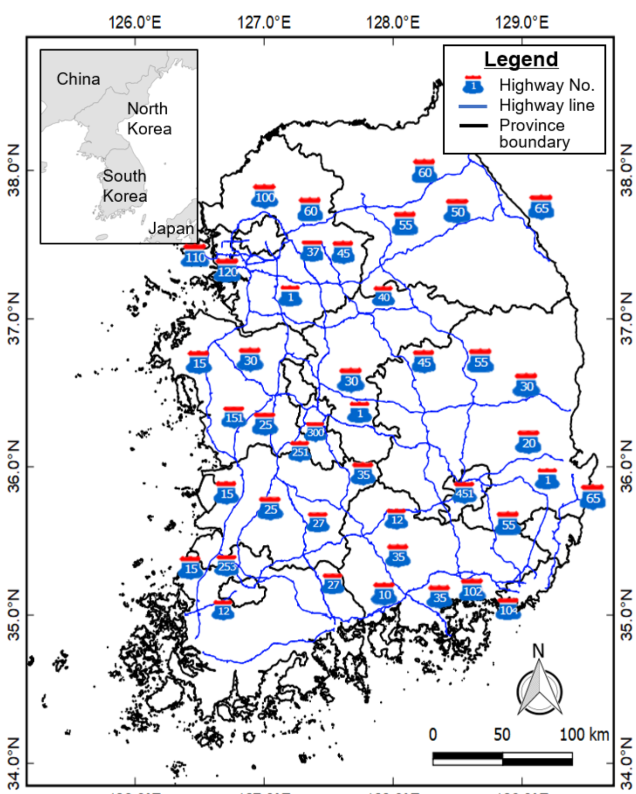
4) Calculate $P_{f,\mathrm{M}}$ using Eqs. (3) and (5) and considering periodic maintenance.
   a) If $P_{f,\mathrm{M}} \le \bar{P}_f$, reduce CR until $P_{f,\mathrm{M}} = \bar{P}_f$ or $CR = CR_{\min}$. No additional protection is needed.
   b) If $P_{f,\mathrm{M}} > \bar{P}_f$ and $T_\mathrm{I} = T_{\mathrm{I,min}}$, check n:
      i) If $n < n_{\max}$, set $n = n + 1$, install another protection barrier, and go back to step #2.
      ii) If $n = n_{\max}$, the target failure probability cannot be achieved under the selected design constraints.

Fig. 3 Flowchart of proposed methodology for selection of rockfall mitigation system.

3 Case study

The rockfall inventory data provided by the KEC were used to perform a rockfall frequency analysis and to demonstrate the proposed rockfall hazard mitigation methodology. The rockfall data includes records of rockfall events along a total of 26 routes in the South Korean highway network. The differences in the operation time of the different routes (i.e., the time during which a specific highway route has been in operation after being built) were taken into account to identify the rockfall occurrence rate. In particular, the observation time for the rockfall probability calculation varied between 7 and 20 years, depending on the operation time of each specific route. Figure 4 shows the highway network operated by KEC in South Korea and number of slopes analyzed for the case study. In this application example, no attempt was made to correct for omissions, under-counting, or over-counting of rockfall events. It is noted here that the likelihood of under-counting rockfall events increase for decreasing rockfall volumes. Within the proposed methodology, this issue is mitigated by the fact that the information corresponding to λ_S (which is most likely to be inaccurate) is not used. However, the accuracy issue could still affect the estimated values of λ_{DN} and should be further investigated in future studies.

The fields of the dataset used in this study and provided by KEC included event date, approximate location on the highway network, qualitative description of the rockfall event (i.e., reached road surface, blocked by barriers, or crack/fractures), suspected cause (intensive rain, thawing, weathering, etc.), approximate location of detaching within the slope (upper and lower half of the slope, or initial, middle, and final third of the cut with respect to the direction of traffic), rockfall volume, and slope width affected by rockfall. However, the information regarding rockfall volumes and the slope width affected by the rockfall events was incomplete, could not be verified independently, and was not supported by supplementary documentation. The dataset did not include information on the consequences of the rockfall events, on the level of damage for the barriers, or on whether multiple detachments happened at the same time. It is noted here that, even with all these limitations, the available information was still sufficient to calculate meaningful rockfall frequencies to be used in the proposed methodology.



Highway No.	No. of unstable cut slopes recorded	Total distance (km)
1	112	416.1
10	59	106.8
12	49	217.3
15	152	336.6
20	41	105.9
25	29	82
27	37	117.8
30	79	171
35	105	215.3
37	7	31.1
40	15	127.4
45	93	301.7
50	119	234.4
55	95	406.2
60	2	150.2
65	63	254.4
100	40	128
102	8	17.9
104	4	20.6
110	17	70
120	2	13.4
151	38	61.4
251	26	54
253	13	42.5
300	3	20.9
451	7	30

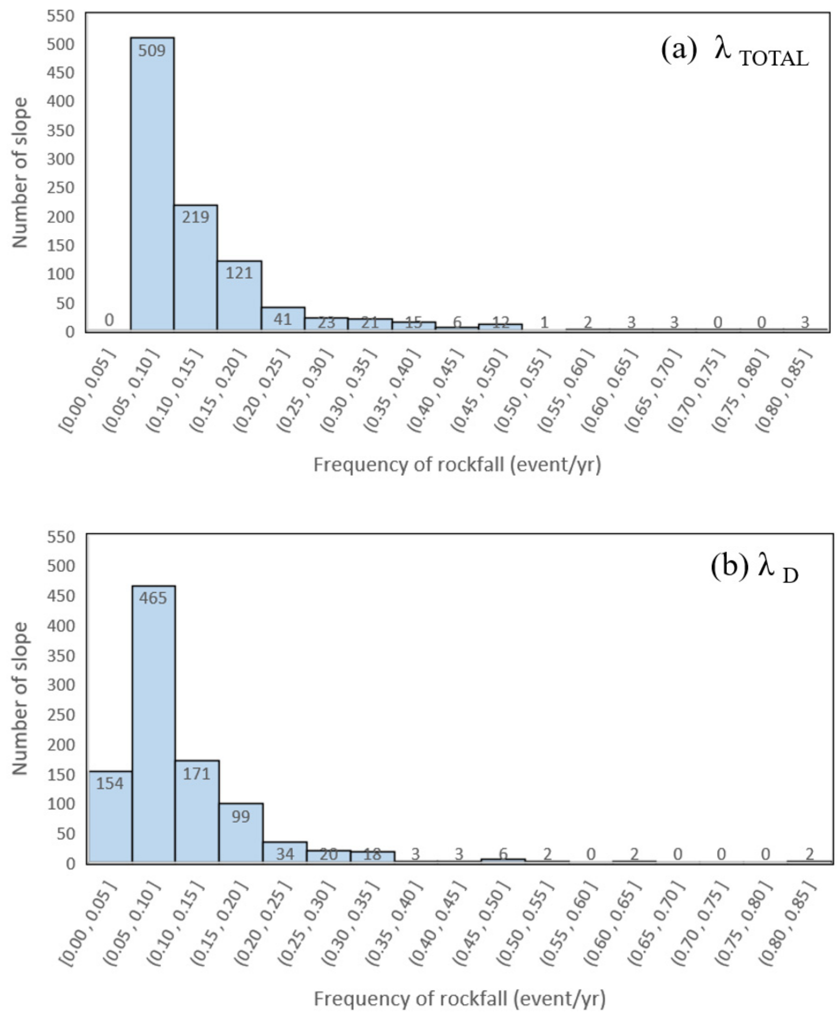
Fig. 4 Highway network in South Korea considered in the case study

The rockfall inventory data were aggregated for each individual slope. However, due to the sensitive political situation with North Korea, basic information on the artificial slope (such as geographic coordinates, length, and grade) is considered classified and was not shared with the authors. Thus, even though commonly rockfall frequency data is expressed in units of event/(yr · km) (Corominas and Moya, 2008), the rockfall frequency data in this study is expressed in units of event/yr. However, the proposed methodology is able to overcome this issue as it requires a low level of detail in the data and can use a synthetic measure of rockfall frequency integrated over the length of the slope. It is also observed that most of the slopes along the South Korean highway networks are generally similar in length, as most of them have a length contained between a few to several hundred meters. Therefore, the rockfall frequencies for individual artificial slopes can be reasonably described by using an event/yr unit of measure.

3.1 Frequency analysis

Figure 5 shows the rockfall occurrence rates based on the proposed rockfall rate classification and obtained from the rockfall inventory data of 1215 artificial cut slopes along the South Korea’s highway network. In particular, Fig. 5(a) shows the histogram of the total rockfall yearly rate, $\lambda_{TOTAL} = \lambda_{DD} + \lambda_{DN} + \lambda_{S}$, which represents the annual rate of occurrence of any rockfall event. The results reported in Figure 5Fig. 5(a) indicate that every slope had at least some rockfall events during the considered observation time of 20 years (in fact, no slope falls within the lowest frequency range with an annual rate lower than or equal to 0.05). Fig. 5 Figure 5(b) shows the histogram of the yearly rate of occurrence of dangerous rockfall, $\lambda_{D} = \lambda_{DD} + \lambda_{DN}$, and Fig. 5(c) shows the histogram of the yearly rate of occurrence of dangerous damaging rockfall, λ_{DD}. For all three quantities, the largest number of slopes fall within the range of 0.05 to 0.10 events per year, followed by a clear decrease of the number of slopes for increasing yearly rates. As expected, the number of slopes in the lowest frequency range increases from λ_{TOTAL} (with zero slopes) to λ_{D} (with 154 slopes) to λ_{DD} (with 262 slopes). It was found that at least one or more rockfalls reached the road surface in 979 slopes out of the 1215 artificial cut slopes considered in this study.

Fig. 6 Figure 6 plot the scatter diagrams showing the relationships between the different rockfall rate classification groups used to classify the rockfall inventory data. In particular, Fig. 6(a) and Fig. 6(b) shows the relationship between λ_{TOTAL} and λ_{DD} and between λ_{D} and λ_{DD}, respectively. These scatter diagrams show the relative distribution of unstable slopes with different types of rockfall. The number of slopes in which rockfall failures caused critical damage to the functionality of the road can be distinguished from the proportion of failures that only increased the probability of rockfall through incipient failures or small-scale falls. The slopes corresponding to data points positioned closer to the vertical axes in Figure 6 are those with a greater frequency of small-scale rockfall stopped by protective barriers greater than the frequency of critical failures reaching the road surface. In contrast, the slopes corresponding to data points positioned closer to the diagonals in Figure 6 includes those in which more slope failures led to rockfall reaching the road and damaging its function. It is observed that λ_{DD} and λ_D have a stronger correlation ($R^2 = 0.80$) than λ_{DD} and λ_{TOTAL} ($R^2 = 0.43$). This result shows the consistency of the data used in this case study and was expected because the events corresponding to λ_{DD} are a subset of the events corresponding to λ_D, which in turn are a subset of the events corresponding to λ_{TOTAL}.



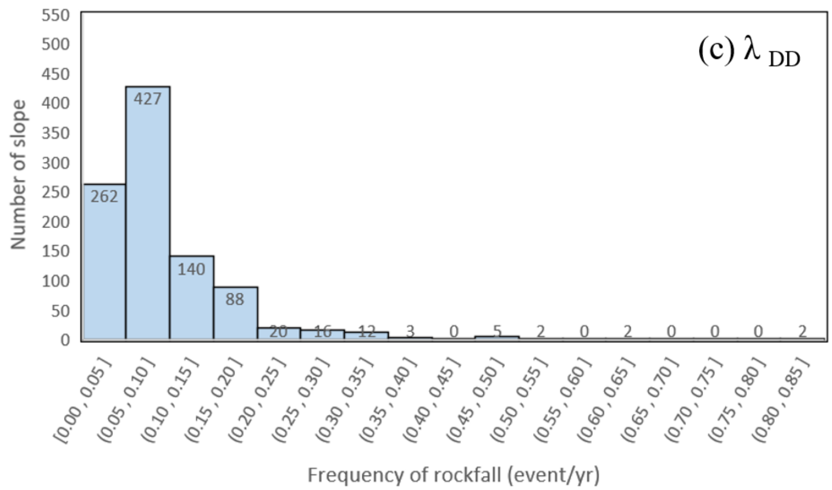


Fig. 5 Histogram of number of slopes with given rockfall frequencies for: (a) λ_{TOTAL}, (b) λ_{D}, and (c) λ_{DD}.

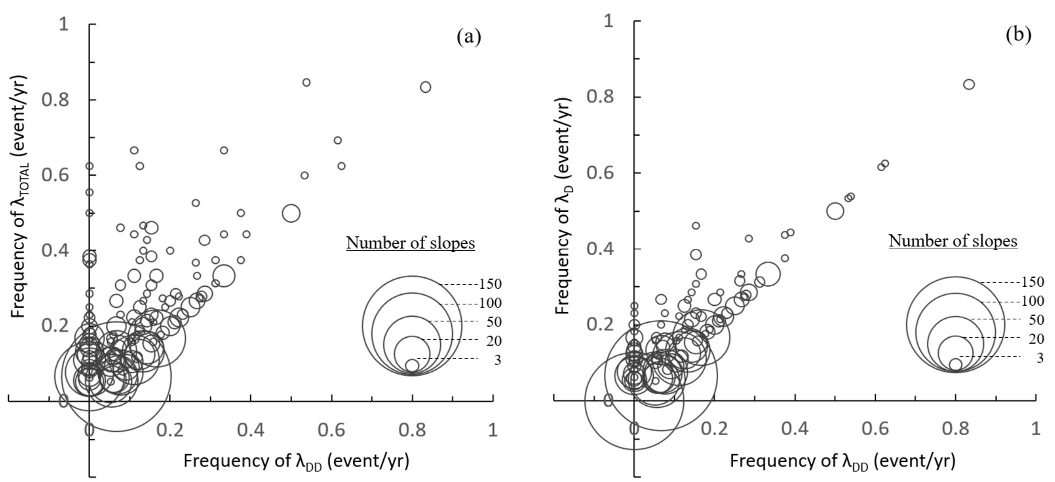


Fig. 6 Scatter diagrams showing the relationships between the rockfall frequencies for:(a) λ_{DD} and λ_{TOTAL}, and (b) λ_{DD} and λ_{D}.

Due to the absence of data and of an appropriate model to describe accurately the barrier failure rates for the specific application considered here, this study assumed the worst case scenario $\lambda_i = \lambda_{\mathrm{DD}}$ identified by Eq. (4) in all calculations performed hereinafter.

3.2 Selection of rockfall mitigation strategy

Based on the results of the rockfall frequency analysis, the unmitigated rockfall failure probability was calculated for all slopes listed in the dataset. According to the ETAG 027, the design life time for an artificial cut slope and its protection devices is assumed to be 25 years when installed appropriately in normal conditions (EOTA 2008). The target failure probability was assumed equal to 0.30, i.e., $\bar{P}_f = 0.30$. The following values were assumed for the other design variables: repair time duration T_R = 1 month, minimum coverage ratio CR_{min} = 50%, maximum number of protective barriers n_{max} = 3, maximum maintenance time interval $T_{I,max}$ = 5 years, and minimum maintenance time interval $T_{I,min}$ = 2 years.

For the case study considered here, all slopes were classified into four groups based on the corresponding unmitigated rockfall failure probability for T_{DL} = 25 years, i.e.: Group 1 with $P_{f,U} < 0.50$, which includes 533 slopes; Group 2 with $0.50 \leq P_{f,U} < 0.75$, which includes 509 slopes; Group 3 with $0.75 \leq P_{f,U} < 0.90$, which includes 158 slopes; and Group 4 with $P_{f,U} \geq 0.90$, which includes 15 slopes, as shown in Table 2. Within each group, the slope with the highest value of λ_D was further investigated to select the appropriate rockfall mitigation strategy to meet the target rockfall failure probability of 0.30. In addition, the slope with the highest value of λ_{DD} in Group 3 (i.e., with $0.75 \leq P_{f,U} < 0.90$) was also investigated because it did not coincide with the slope having the highest value of λ_D. Figure 7(a) plots the unmitigated instantaneous rockfall probability for all slopes, F_U. Figure 7(a) also highlights the unmitigated instantaneous rockfall probability for the slopes with the highest values of λ_D within each of the four groups previously identified, and it plots the corresponding unmitigated rockfall failure probabilities, $P_{f,U}$, as well as the target failure probability.

Table 2 shows the selected mitigation strategies for the different slopes in the different groups and the corresponding mitigated rockfall failure probabilities. For Group 1 ($P_{f,U} < 0.50$), the highest value of λ_D is 0.063 event/yr, and the corresponding unmitigated rockfall failure probability is $P_{f,U}$ = 0.492 which is higher than the target safety level, $\bar{P}_f = 0.30$. By applying the proposed methodology described in section 2.4, the selected rockfall mitigation strategy requires one protection barrier, with a periodic maintenance interval $T_I = T_{I,max}$ = 5 years and a coverage ratio CR = 50%, which provides a mitigated failure probability $P_{f,M}$ = 0.260.

In Group 2 ($0.50 \leq P_{f,U} < 0.75$), the highest value of λ_D is 0.154 event/yr, and the corresponding $P_{f,U}$ is 0.746. By applying the proposed methodology, the selected rockfall mitigation strategy requires one protection barrier, with a periodic maintenance interval $T_I = T_{I,max}$ = 5 years and a coverage ratio CR = 75%, which provides a mitigated failure probability $P_{f,M}$ = 0.273.

In Group 3 ($0.75 \leq P_{f,U} < 0.90$), the highest value of λ_D is 0.385 event/yr, with λ_{DD} = 0.154 event/yr and λ_{DN} = 0.231 event/yr. For this slope, $P_{f,U}$ = 0.896. Since the value of λ_{DD} is equal to that of the worst-case scenario considered for Group 2, the selected rockfall mitigation strategy is very similar to the one selected for the previous case, i.e., one protection barrier is required with periodic maintenance of T_I = 5 years and coverage ratio CR = 90%, which provides a mitigated failure probability $P_{f,M}$ = 0.293. For Group 3, the slope with the highest value of λ_D did not coincide with the slope with the highest value of λ_{DD}. Thus, in order to test the proposed methodology for this type of situation, the slope in Group 3 with the highest value of λ_{DD} = 0.375 event/yr (for which λ_{DN} = 0 event/yr, λ_D = 0.375 event/yr, and $P_{f,U}$ = 0.893) was also investigated. The selected mitigation strategy requires one protection barrier with a periodic maintenance interval T_I = 4 years and a coverage ratio CR = 100%, which yields a mitigated rockfall failure probability $P_{f,M}$ = 0.281.

In Group 4 ($P_{f,U} \geq 0.90$), the highest λ_D is 0.833 event/yr, with a corresponding $P_{f,U}$ = 0.952. By using the methodology described in section 2.4, the first protection barrier is installed, and periodic maintenance is required. A periodic maintenance of $T_I = T_{I,max}$ = 2 years with a coverage ratio of CR = 100% yields a mitigated rockfall probability of $P_{f,M}$ = 0.320, which does not satisfies the target failure probability. Thus, a second protection barrier is required. The final recommended mitigation strategy includes two protection barriers, periodic maintenance with T_I = 2 years, and coverage ratio CR = 100%, which yields a mitigated rockfall probability of $P_{f,M}$ = 0.209.

Fig. 7 Figure 7(b) illustrates the different steps of the proposed methodology when applied to the slope from Group 3 with λ_{DD} = 0.375 event/yr. The solid lines represent the unmitigated instantaneous rockfall probability, F_U, and the corresponding unmitigated failure probability $P_{f,U}$ = 0.893. The dash-dot lines represent the mitigated instantaneous rockfall probability, F_M, and the corresponding mitigated failure probability $P_{f,M}$ = 0.840 when using one protection barrier but no periodic maintenance. Finally, the dotted lines represent the mitigated instantaneous rockfall probability with periodic maintenance, F_M, and the corresponding mitigated failure probability $P_{f,M}$ = 0.281 when using one protection barrier with a periodic maintenance interval T_I = 4 years, and a coverage ratio CR = 100%.

Table 2 Mitigated rockfall failure probability with conceptual barrier design options

Slope group	Range of $P_{f,U}$	Number of slopes	λ_D (event/yr)	λ_{DD} (event/yr)	$P_{f,U}$	n	T_I (yr)	CR (%)	$P_{f,M}$
1	$P_{f,U} < 0.50$	533	0.063	0.063	0.492	1	5	50	0.260
2	$0.50 \leq P_{f,U} < 0.75$	509	0.154	0.154	0.746	1	5	75	0.273
3	$0.75 \leq P_{f,U} < 0.90$	158	0.385	0.154	0.896	1	5	90	0.293
			0.375	0.375	0.893	1	4	100	0.281
4	$P_{f,U} \geq 0.90$	15	0.833	0.833	0.952	2	2	100	0.209

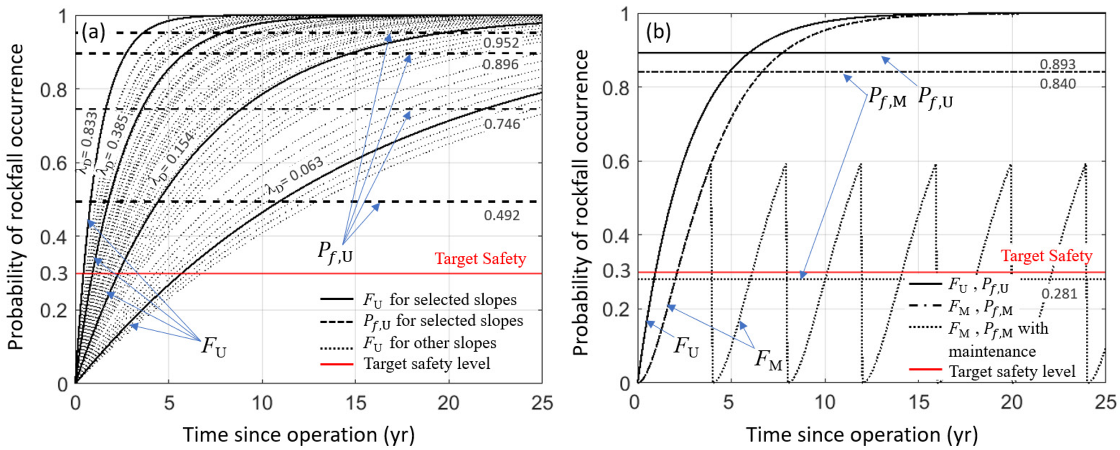


Fig. 7 Selection of rockfall mitigation strategy: (a) unmitigated instantaneous rockfall probability, F_U, for the slopes in the case study, and unmitigated failure probability, $P_{f,U}$, for the selected slopes (T_{DL} = 25 yr); (b) mitigated instantaneous rockfall probability, F_M , and mitigated rockfall failure probability, $P_{f,M}$, for the slope belonging to Group 3 with $\lambda_D = \lambda_{DD}$ = 0.375 event/yr (T_{DL} = 25 yr, T_I = 4 yr, n = 1, T_R = 1 month, CR = 100%)

4 Discussion

The proposed methodology for selecting an appropriate rockfall mitigation strategy is based on several assumptions and has some limitations due to the lack of sufficient data to better model some aspects of the rockfall phenomenon. In this section, we present a brief discussion of possible improvements and additional approaches that could be used to further advance the proposed methodology.

4.1 Improved modeling of protection barrier effectiveness

The proposed probabilistic framework to assess the risk of rockfalls requires a better evaluation of the barrier failure rates, λ_i. As discussed in section 2.3, this failure rates depend on the barrier strength, the mass of detached rock, and the distance traveled by the rock material from the detachment point to the barrier. This information is typically not available. Appropriate models could and should be developed to better inform the proposed model with appropriate values of λ_i for a given combination of protection barrier and cut slope characteristics, as well as to develop approaches to systematically and efficiently decrease the values of λ_i to improve the effectiveness of a given protection barrier. As part of these models, the use of three-dimensional (3D) trajectory simulation models would increase the accuracy with which rockfall hazard mitigation systems could be assessed and designed (Agliardi et al. 2009; Frattini et al. 2008; Guzzetti et al. 2003; Jaboyedoff et al. 2005); however, more accurate descriptions of the point of origin and measurements of rockfall volumes must be recorded in the inventory data to allow the development of realistic 3D trajectory simulation models (Bourrier et al. 2009).

4.2 Integrated efforts to prevent losses from rockfall

Since rockfall is generally considered an infrequent cause of fatal accidents, management efforts to reduce rockfall risk could be seen as relatively less significant than corresponding efforts for other natural disasters, such as landslides or flooding. However, initial failures of unstable slopes, which are directly related to rockfall failure rates, may precede a massive rock slope failure (Evans et al. 2006). Therefore, monitoring and management activities to prevent further collapse could be strengthened once a precursory phenomenon such as rockfall or fracture on an unstable slope is detected. Improving the recording procedures and establishing a rockfall hazard rating system should be considered as an important starting point for applying quantitative risk assessment for a variety of other hazards (Bunce et al. 1997; Corominas et al. 2014).

Rockfall classification schemes for artificial cut slopes along highways before have been previously developed and can be used as a basis for a rockfall hazard rating system (Pierson and Vickle 1993). Furthermore, after appropriate rockfall risk assessment, including an analysis of the damage severity on the element at risk and a consideration of its vulnerability, shifting of land-use zoning or the use of engineering solutions to protect infrastructure could be suggested as alternative mitigation measures to reduce the rockfall hazard for areas estimated to exceed a tolerable risk level (Copons et al. 2005). An integrated framework, including a systematic rockfall inventory, rockfall hazard rating, and rockfall risk assessment supported by a physics-based and/or mechanics-based model of rockfall, needs to be implemented with periodic maintenance planned on the basis of risk indicators. This integrated management effort will be an effective and efficient approach to prevent unwanted losses caused by rockfall. It is observed here that an integrated management effort could be also applicable to natural slopes, by dividing these slopes into homogenous portions for which data collection of rockfall events can be conducted. However, for natural slopes, obtaining stable rockfall failure rates may require data collection over significantly bigger slope segments for a significantly longer time than those typically needed for artificial slopes, which could make the data collection phase prohibitively expensive.

4.3 Further research needed for comprehensive rockfall risk assessment

In this study, the frequency of rockfall events, the probability of rockfall occurrence, and how rockfall events affect functional safety on the highway network were analyzed without consideration of the consequences due to rockfall. However, the rockfall consequences on the highway infrastructure must be included in a comprehensive rockfall risk assessment. The present study provides a rigorous probabilistic framework to estimate the time-dependent and average probability of rockfall occurrence including the effects of periodic maintenance and coverage ratio, based on a detailed frequency analysis of rockfall hazard using the concept of functional safety. Beyond this study, data on the volume and mass of rock materials could be analyzed to produce a vulnerability curve of the distribution of rockfall volume according to frequency. The outcome of such an analysis could be used as another index to determine resource allocation for rockfall risk management.

Precise monitoring of rockfall using light detection and ranging (LiDAR) devices could allow the acquisition of precise measurements of the volume and location of falling rocks (Rosser et al. 2007). Doing so would provide accurate data on the relationship between magnitude and frequency, which is known to follow a power-law distribution for rocks larger than a certain size (Dussauge-Peisser et al. 2002). In addition, the effects of traffic patterns on vulnerability can be included in subsequent rockfall risk assessments. Highway user information regarding the average speed of vehicles, traffic volume, and types of passenger vehicles could be used to conduct a more detailed rockfall risk assessment (Budetta 2004). Finally, an improved design strategy could be developed based on initial costs and total costs of different mitigation components, e.g., by optimizing the designed mitigation strategy with respect to total costs measured over the design life time of a given artificial cut slope or even for an entire dataset of slopes.

5 Conclusions

The aim of this study was to develop a general probabilistic framework based on a rigorous rockfall frequency analysis to estimate the potential reduction in the probability of rockfall occurrence resulting from a mitigation strategy based on number of protection barriers, interval of periodic maintenance, and slope horizontal coverage ratio. The proposed framework was applied to the case study of rockfall along the highway network of South Korea, demonstrating how the rockfall occurrence rates can be systematically classified and how the risk reduction effects of different mitigation measures can be quantitatively estimated. This study also proposed an operation method to select an appropriate mitigation strategy for any given artificial cut slope based on available rockfall frequency rates. Future research supported by a more detailed rockfall inventory could include additional effects, such as probability of large rock avalanche, novel protection barrier systems, and alternative mitigation strategies. The approach used in this study can serve as the basis for a systematic classification of rockfall hazard data. Furthermore, the results provide insights into ways of improving overall risk management considering mitigation measures and maintenance activities, with the ultimate goal of preventing losses by rockfall. Further investigation is needed to extend the proposed methodology to include the assessment and mitigation of rockfall-induced losses and to use effectively more detailed data, such as full rockfall volume frequency curves, when available.

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