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Placement Optimization Method for Rockfall Protection Structures along a Road

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Abstract: The purpose of our study is to facilitate the effective and feasible design planning of protection structures against rockfall events. We propose a novel method for placement optimization of rockfall protection structures along a traffic road. A series of three-dimensional rockfall trajectory simulations are carried out and then the results are utilized to calculate the risk value as a product of the rockfall hazard, exposure and vulnerability of structures. The proposed method is capable of determining an optimum placement of protection structures that minimizes the total risk on the entire road, while satisfying a given budget constraint. We apply the method to a case study of an actual site to examine the results of optimized protection structures and discuss the capability of the method for risk reduction.

Keywords: Rockfall protection structures; design planning; optimization; knapsack problem.

1 Introduction

Rockfalls are frequent and widespread events, in which rock blocks tumble rapidly down a mountain slope. It is a significant natural hazard encountered on traffic roads or railways. The accidents cause serious economic losses due to not only traffic interruption, but also damage to infrastructures and vehicles (Lan et al. 2010). In addition, the recovery of them consumes extra manpower. In order to reduce those losses, analyzing the risk of rockfalls and then managing the roads at risk are certainly needed. A considerable number of studies have been made on the risk (or hazard) analysis along traffic roads or railways in terms of rockfall events. On the other hand, only a few studies among those refer to the way of risk reduction; for example, the arrangement of protection structures (Agliardi et al. 2009; Lambert et al. 2013). Although those previous studies consider some protection scenarios by the use of protection structures in the risk analysis, their effectivity and reasonability were not argued.

The present study aims to propose a framework that optimizes the placement of protection structures based on the risk analysis along a traffic road. A series of three-dimensional rockfall trajectory analyses are first carried out to determine the hazard on a target road. The value of risk is then calculated as the product of the hazard, exposure, and vulnerability (IPCC 2012). For the necessity of defining the smallest unit length of protection structures, the target road section is virtually divided into several road subsections. The change in the risk value at each road subsection caused by the placement of a protection structure is also calculated. With the results for all the road subsections, a set of protection structures that minimizes the total risk on entire road is finally determined by solving the proposed optimization problem, while a given budget constraint is satisfied. Although the proposed method can work in principle with various options to prevent rockfall accidents such as traffic regulations and fastening rock blocks to the slope, this study illustrates its capability by only one approach that proposes constructing passive protection structures for the sake of simplicity. The proposed framework was applied to a case study of actual site to examine the results of optimized protection structures and discuss their capabilities for risk reduction.

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2 Framework for Rockfall Risk Analysis and Optimization Problem for Placement of Protection Structures

2.1 Rockfall risk formalization

Moos et al. (2018) defines the rockfall risk (i.e., the cost due to the impact of rockfall events) on the structure at risk i, considering different block volumes, as

$$R_i = \sum_{j=1}^{v} \left(F_j \times P_{\mathrm{S},ij} \times W_i \times P_{\mathrm{T},i} \times \frac{1}{n_{ij}} \sum_{n_{ij}} V(I)_i \right), \tag{1}$$

where F_j is the onset frequency of volume scenario j; $P_{\mathrm{S},ij}$ is the spatial probability of propagation to the structure i in the volume scenario j, associated with the hazard; W_i is the economic value of the structure i; $P_{\mathrm{T},i}$ is the temporal probability of presence with the economic value, associated with the exposure; V_i is the vulnerability to possible impacts n_{ij} on the intensity I.

In our approach, the protection structure k that prevents rockfalls to the structure at risk i (i.e. road subsection) is incorporated into above equation as

$$R_{ik} = \sum_{j=1}^{v} \left\{ F_j \times P_{\mathrm{S},ij} \times \left(W_i \times P_{\mathrm{T},i} \times \frac{1}{n_{ij}} \sum_{n_{ij}} V(I)_{\mathrm{R},ik} + W_k \times P_{\mathrm{T},k} \times \frac{1}{n_{ij}} \sum_{n_{ij}} V(I)_{\mathrm{P},k} \right) \right\}. \tag{2}$$

This implies that excessive spending on the protection structure at a little hazardous site adversely increases the risk.

2.2 Optimization problem for placement of protection structures

After estimating the rockfall risk of all road subsections in a row with Eq. (2), we then find the most reasonable combination of sites and types of protection structures that can minimize the total risk on the road subject to a given budget constraint. This corresponding optimization problem can be defined as follows:

$$\min\ \mathrm{TR} = \sum_{i=1}^{n_{\mathrm{unit}}} \sum_{k=0}^{n_{\mathrm{prot}}} \left(a_{ik} \times R_{ik} \right), \tag{3}$$

$$\text{s.t.}\ \sum_{i} \sum_{k} \left(a_{ik} \times W_k \right) \le \mathrm{TC}, \tag{4}$$

$$a_{ik} \in \{0,1\},\ a_{ik} + a_{il} \le 1,\ \forall (k,l) \in E. \tag{5}$$

where TR is the total risk; TC is the budget constraint; a_{ik} is the decision variable that is 1 if protection structure k is placed on road subsection i, and is 0 otherwise; E is the set of incompatible pairs; n_{unit} is the number of road subsections; n_{prot} is the number of selectable protection structures. This formulation can be regarded as a variation of integer programming problem, which is known as the knapsack problem.

3 Case Study

3.1 Case site

The part of a major road in Japan was selected for analysis. It has 6,633 meters in length, mostly facing mountain slopes. Since rockfall events occur frequently due to unfavorable natural conditions, the rock blocks often hinder traffic or collide with a vehicle. Thus, the local municipality provides that traffic regulations are implemented on the road section when it heavily rains.

3.2 Rockfall trajectory simulations

3.2.1 Simulation model

The spatial probability of propagation P_{S} and the intensity I in Eq. (2) can be obtained by the results of rockfall trajectory simulations. The simulation tool we have employed here is an extended version of the lumped-mass model proposed by Ushiro et al. (2000) to three dimensions. It can predict a trajectory of a block through the succession of four basic motion types: rolling, sliding, flight, and rebound. The rebound on a slope surface is mostly modelled by restitution coefficients related to the terrain characteristics. In addition, the model considers the block mass, the incident velocity, and the penetration of the block into the soil to calculate accurately the magnitude of energy dissipation when the block collides with the slope surface. Moreover, the kinetic energy that generally represents the intensity of falling block is accounted for not only the translational velocity but also the rotational velocity, unlike many of the other lumped-mass models (Volkwein et al. 2011). In the present study, a simple spherical block is used and the density is 2,600 kg/m^3, and the spatial distribution of surface materials on the terrain is not included.

3.2.2 Terrain characterization

The terrain surface on the site is represented by an assembly of a half million triangular elements that is generated from the digital elevation data with 5 m spatial resolution available online. In order to define rockfall sources for the trajectory analysis, we first detected steep triangular elements around the road and then selected from those at random. In this study, the threshold of steepness is set at 60 degrees according to Guzzetti et al. (2003).

3.3 Risk analysis

3.3.1 Hazard and exposure

Because sufficient number of rockfall events has not been recorded on the case site, the magnitude-frequency distribution of rockfall events cannot be set up. The diameter of spherical blocks is hence provisionally defined as constant and assigned to be 0.75 m. Decadal onset frequency is also assigned provisionally to be $F = 521$. It implies that a rockfall event occurs every week for ten years. That appears to be over-estimated, but must be a plain scenario for this case study.

For the sake of simplicity, neither traffic nor people on the road are taken into account. Therefore, economic values of road subsections W_i and protection structures W_k consist only of its physical value, respectively, and P_{T} is fixed at 1. The target road is divided equally into 330 subsections with about 20 m length. Three selective types of protection structures are considered as substitutes for existing ones in our optimization problem. The dissipative capacity and the economic value per unit of those protection structures are shown in Table 1. Also, the economic value of road subsection is set be 2M yen per unit length. All those values in this study are roughly estimated, as the aim of this study case is to propose a new framework and to confirm how it works well.

Table 1. Values of different types of protection structures.

k	Structure type	Dissipative capacity (kJ)	Value per unit (M yen)
0	None	0	0
1	Fence type-1	150	0.15
2	Fence type-2	250	0.25
3	Fence type-3	750	0.75

3.3.2 Vulnerability

For each simulated trajectory across the road, the kinetic energy is output and classified into three classes of intensity; low, medium, high. Thresholds between these classes vary with object categories and types. In this study, we employ those for road subsections defined by Moos et al. (2018) such that low intensity ranges from 0 to 30 kJ, medium intensity from 30 to 300 kJ and high intensity over 300kJ. On the other hand, for protection structures, low intensity is set to range from 0 to 10% of their dissipative capacities, medium intensity from 10% to 100% and high intensity over them.

The vulnerability values V for the object categories separated by intensity classes are shown in Table 2. In addition, the obstruction by placed protection structure in front of road subsection is considered. We determined that placing a protection structure gave zero value to vulnerability of the road subsection when the intensity class for the protection structure was low or medium. If the intensity class was high, the protection structure is assumed to be broken and the road vulnerability is assessed as the same as non-protected road subsections.

Table 2. Vulnerability values of objects.

Object category	V_{obj} (low intensity)	V_{obj} (mid intensity)	V_{obj} (high intensity)
Road, Trail	0.1	0.5	1
Protection structures	0.1	0.5	1

4 Results

Figure 1a shows the results of rockfall trajectory simulations on the study site. In the same figure, the color bar on the left side represents the terrain elevation, and the black line signifies the target road. A total of 2,387 blocks run over the road from 10,000 selected sources. Figure 1b shows the histogram of the simulated trajectories intersecting the road. The vertical axis on left side is absolute frequency, and right side is relative frequency (i.e. density). Each bin of this histogram represents the road subsections and each bar representing frequency is color-coded according to the calculated kinetic energies of rock blocks. The spatial probability of propagation $P_{S,i}$ equals to the total density of *i*th bin in Figure 1b. The reliability of those results is assessed in comparison with some reports available. Then, it seems reasonable to conclude that they are qualitatively correct, since Figure 1b finds out the location of endangered road subsections, at which a large number of rock blocks or critical rock blocks assemble.

Based on this result, risk analysis and placement optimization for the three types of protection structures are performed by R, the free software for statistical computing and graphics (R Core Team 2017). That can obtain the solutions in no time. Figure 2 shows a procedure for solving the optimization problem in R. The package 'lpSolveAPI' is used to solve the knapsack problem defined by equations (3)- (5).

Figure 3 shows the result of placement optimization overwriting the figure 1b. Blue, green, and yellow markers drawn at the bottom of histogram bins represent the type of protection structures (see table 1). All those layouts were optimized through the procedure in figure 2. For comparison purpose, the noticeable subsections of two optimum solutions with different budget constraints are arranged. It costs 13.14M yen for the solution in Figure 3a, while that in Figure 3b is obtained with the budget limited to 7.5M yen (i.e. about a half of the sufficient amount). The budget cut made the degradation of the fence type or blanks at many road subsections. On the other hand, it is obvious that highly endangered road subsections took priority in terms of budget allocation over the road.

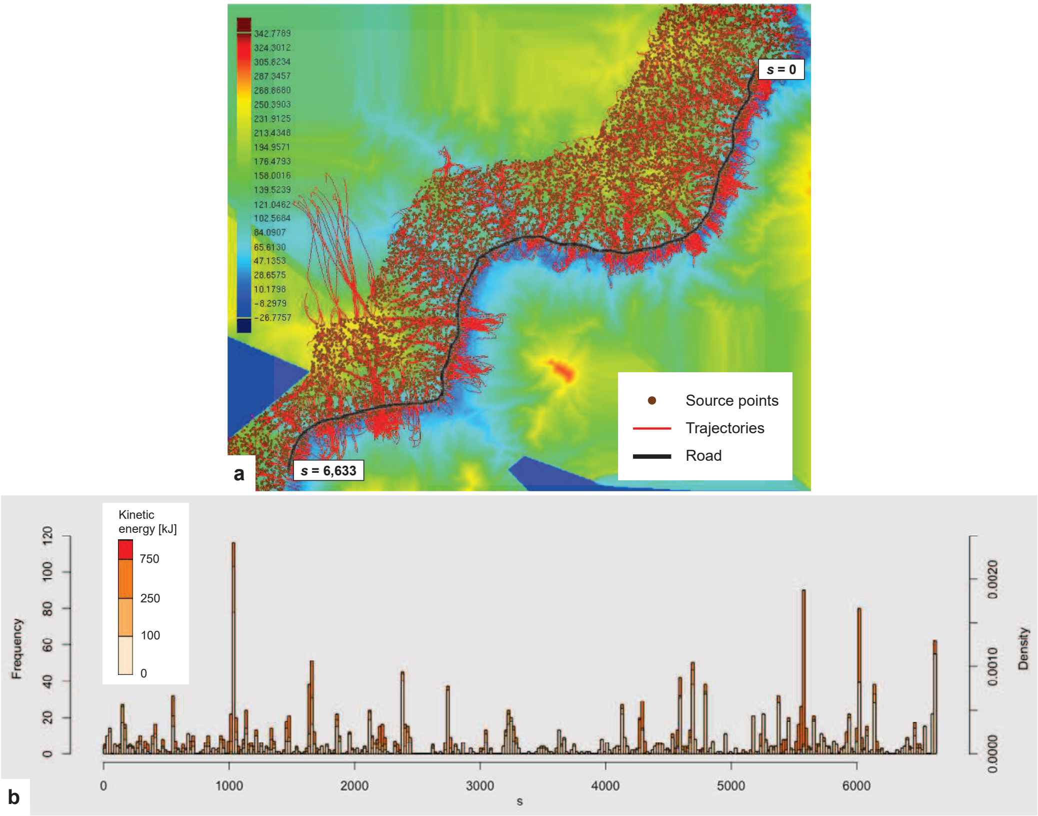

Figure 1. Simulation results: (a) Result of rockfall trajectory simulations; (b) Distribution of simulated trajectories on road.

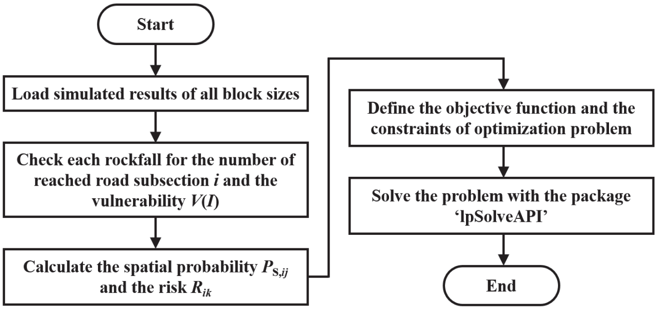

Figure 2. Procedure for solving optimization problem in R.

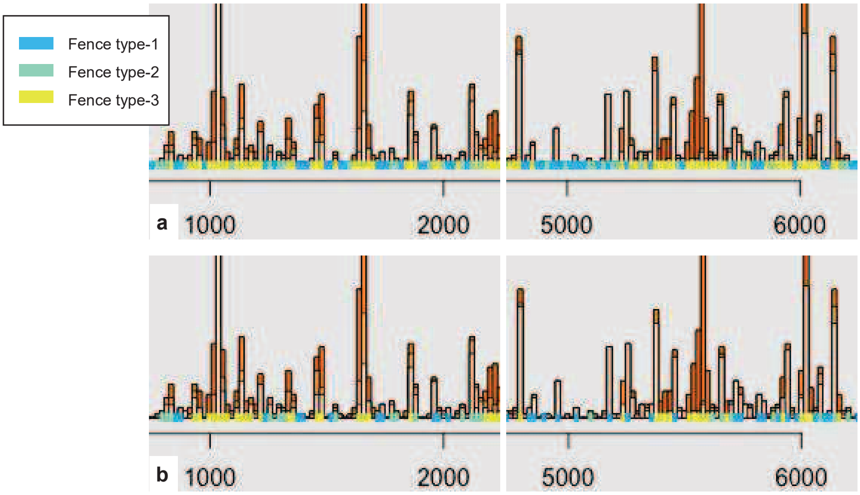

Figure 3. Optimum solutions: (a) without budget constraint; (b) with budget of 7.5M yen.

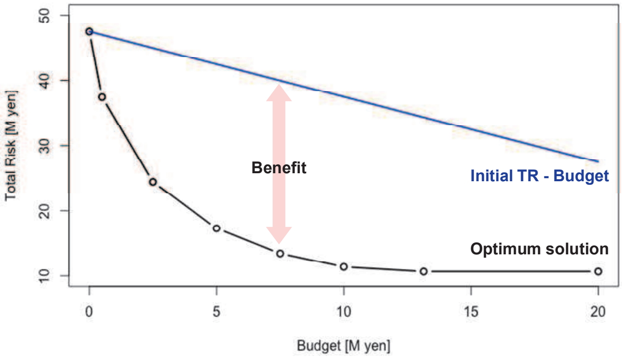

Figure 4. Optimum solutions for different budget scenarios and those amount of benefit.

Finally, we have carried out similar optimization processes for seven budget scenarios and obtained the results as illustrated in Figure 4. The blue line means the difference between the initial total risk (without any protection structures) and the given budget. When an optimum solution is positioned on the blue line, it implies that the amount of risk reduction by placed protection structures is the same as the given budget for the placement. Therefore, the benefit derived from the proposed optimization framework can be obviously defined as the gap between two curves. Figure 4 finds out that the spending on protection structures increases the benefit sharply with relatively low budget, but it turns to decrease at a certain level. This change makes us realize the redundancy of given budget for the protection scenario.

5 Conclusion

This study proposed a framework for rockfall risk analysis along a traffic road and for optimization of placing protection structures to fully reduce the risk. Firstly, the risk was defined in terms of rockfall hazard computed by the trajectory simulations, the exposure to rockfall events, and the vulnerability of structures at risk. Secondly, the optimization problem was designed to minimize the total risk on entire road within a limited budget. The proposed framework was performed for a study case of the actual site. The results lead to the conclusion that the framework enables us to obtain the most reasonable layout plan of protection structures under any given budget conditions as we had expected. However, the placement optimization presented in this paper was only to check the performance of our framework because some provisional assumptions were defined due to insufficient information. Future work should therefore include performing another case study with more reasonable assumptions.

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