Evaluation of Hazardous Area of Falling Rocks Using Digital Elevation Model

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Abstract

We have developed a method to extract hazardous area of rockfall, using digital elevation model; DEM. Our proposed method consists of three components: an estimation of the distribution of rock-outcrops, a search of pathways of falling rocks from the estimated rock-outcrops, and an evaluation of the reach probability of falling rocks. The rock-outcrops distribution is estimated from topographic characteristics calculated using the DEM, as reported in a previous paper. The pathways of falling rocks are searched on the DEM with assumption that falling rocks move to the direction of the maximum downward gradient. The reach probability of the falling rocks is evaluated using an existing rockfall simulation. The rock-outcrops distribution, the pathways and the reach probability are shown on a geographical information system as a rockfall hazard map. This hazard map is helpful for screening of rock-outcrops to investigate and for planning of measures against a rockfall disaster.

Keywords: hazard map, rockfall, pathway search, reach probability, DEM

1. Introduction

Travel distances and travel paths of falling rocks are ones of the most important factors for considering the hazard and risk (Bridearu and Roberts, 2015). A reach probability that is the probability of reaching of a falling rock to some interest site is desirable information to plan measures against a rockfall disaster. Especially for lineal long structures, e.g. railways and road, that are accompanied with many slopes, the reach probability would be helpful to find the section where the hazard of the rockfall is higher in the extensive area.

Many methods to estimate rockfall hazard and risk have been proposed. Some methods are qualitative (e.g. Abbruzzese et al., 2009) and others are quantitative (e.g. Agliardi et al., 2009; Copons et al., 2009). Mavrouli et al. (2014) conducted a comprehensive review about it. These methods consider mechanisms of rockfall at rock-outcrops, post failure movements of falling rocks. Worthiness exposed for the falling rocks is additionally considered to evaluate risks. However, there is no method, where an estimation of a distribution of rock-outcrops and evaluation of the reach probability from the rock-outcrops are integrated.

Our proposed method consists of three components as shown in Fig.1: an estimation of the distribution of rock-outcrops, search of pathway of falling rock from each rock-outcrop, and evaluation of the reach probability using rockfall simulation on two dimensional sections along the pathways. We have already developed a method of the estimation of the distribution of rock-outcrops according to indices calculated using DEM. This part was reported by Hasegawa and Ohta (2015).

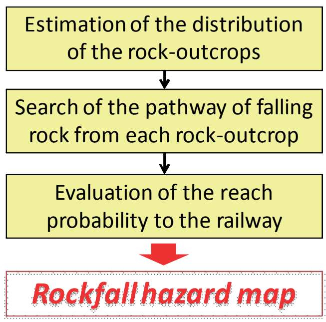

Figure 1. The process of the proposed method to evaluate hazardous area of rockfall

In this research, firstly, we develop a method of the pathway search using DEM. Secondly, we apply an existing rockfall simulation to evaluate the reach probability on two dimensional section along every pathway. Finally, we map the reach probabilities using a geographical information system; GIS.

2. Method

2.1 Studied area and high resolution DEM

The studied area is a hill up to around 250m in elevation, where sedimentary rocks of the Late Cretaceous are distributed. Rock-outcrops are observed on slopes of the hill, and railway, road and houses exist along the base of the hill. In this study, we treat the railway as a target of disaster mitigation.

We created a high resolution DEM with 1m mesh from three dimensional data obtained by airborne LiDAR at Dec. 2010.

2.2 Estimation of the distribution of rock-outcrops

We adopt the method reported in Hasegawa and Ohta (2015) to estimate the distribution of rock-outcrops. Hasegawa and Ohta (2015) revealed that a slope angle and a curvature of ground surface calculated using DEM were discriminative indices whether rock-outcrop existed or not, based on a statistical analysis between characteristics of ground surface and distributions of rock-outcrops confirmed by field investigation.

The summary of the estimation method is as follows.

(1) Calculation of slope angle and curvature

Slope angle s and curvature c of ground surface are defined as

$$s = \mathrm{Arctan}\left\{\left(\frac{z(i+1,j)-z(i-1,j)}{2d}\right)^2 + \left(\frac{z(i,j+1)-z(i,j-1)}{2d}\right)^2\right\}^{\frac{1}{2}} \quad (1)$$

and

$$c = \frac{z(i+1,j)+z(i-1,j)-2z(i,j)}{d^2} + \frac{z(i,j+1)+z(i,j-1)-2z(i,j)}{d^2} \quad (2)$$

, where $z(i,j)$ is the elevation of the cell (i, j) of the DEM, i and j are cell numbers along x-axis and y-axis, and d is the width of the cell as shown in Fig.2. The curvature c is spatially-smoothed.

(2) Estimation of the distribution of rock-outcrops

A cell is classified as the rock-outcrop cell if the characteristics of the cell satisfy the both conditions,

$$s > 50 \text{ deg.} \quad (3)$$

and

$$c < 0 \text{ m}^{-1} \quad (4)$$

. These conditions are derived from the results of the statistical analysis (Hasegawa and Ohta, 2015). The condition shown as Eqn.(3) is corresponding to common slope angles of rock-outcrops. The condition shown as Eqn.(4) means that the ground surface is convex at a rock-outcrop.

2.3 Searching of pathways of falling rocks

The pathways of falling rocks are analyzed with the assumption that a falling rock moves in the direction of maximum downward gradient; DMDG. The gradient g is defined as

$$g = \frac{z_{no} - z(i,j)}{d} \quad (5)$$

and

$$g = \frac{z_{nd} - z(i,j)}{\sqrt{2}d} \quad (6)$$

, where z_{no} is the elevation of an orthogonal neighbor cell of the cell (i, j) where a falling rock exists, and z_{nd} is that of a diagonal neighbor cell (Fig.2). The arrow A shown in Fig.3 represents the DMDG.

If two or more DMDG-s are analyzed from one cell, for example the arrows B and C shown in Fig.3, we save all DMDG-s as possible direction of pathway. Hence, more than one pathway may be obtained from

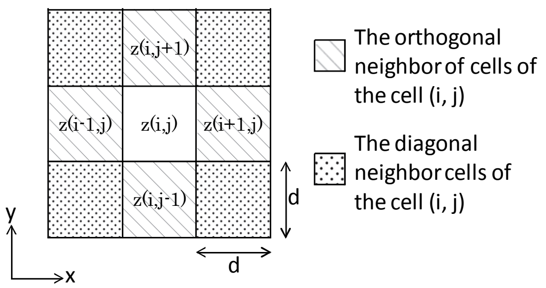

Figure 2. Numbering of DEM cells.
Z(i,j) is the elevation of the cell (i, j)

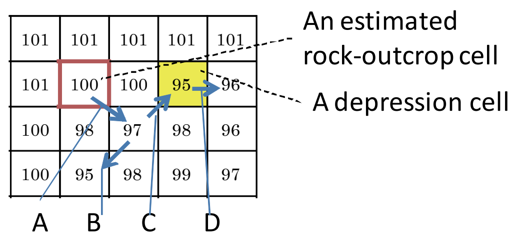

Figure 3. An example of the pathway search using DEM.
Values in each cell are elevations (m). A detail explanation of the arrows A, B, C and D is on the text.

Table 1. Set values for the rockfall simulation

Area or target	Property		Set value
On pathway	Friction coefficient	average	0.48 [1]
		standard deviation	0.06 [1]
	Reflection coefficient in vertical direction	average	0.58 [1]
		standard deviation	0.26 [1]
	Reflection coefficient in horizontal direction	average	0.77 [1]
		standard deviation	0.17 [1]
	Critical velocity for changing of the motion of the falling rock from rolling and slipping to jumping	average	8.5 m/s [1]
		standard deviation	2.5 m/s [1]
Falling rock	Diameter		1 m
	Mass		170 kg
Simulation settings	Number of trials on each pathway		100 times
	Time step in the simulation		0.05 s

[1]: Values for gravelly talus, obtained by a case study (Japan Road Association, 2002)

an estimated rock-outcrop cell. In the case shown in Fig.3, two pathways are obtained.

If a falling rock trap in depressions of DEM, i.e. if the elevations of the surrounding eight cells are higher than that of the cell where the rock exists, we assume the rock moves in the direction of minimum upward gradient; DMUG, only if the gradient is less than 10 deg. because falling rocks may leap ridges of ground surface in practical cases. The arrow D shown in Fig.3 is an example of the DMUG.

2.4 Evaluation of reach probability

To evaluate the reach probability, we conduct an existing rockfall simulation (Yoshida et al., 1991), to which the Monte Carlo method is applied. This simulation analyzes the movement of a falling rock on a two-dimensional vertical cross-section, and outputs the trajectory of the falling rock in each trial of the Monte Carlo simulation. The friction coefficient and the reflection coefficient between the falling rock and ground surface, and the critical velocity for changing of the motion of the falling rock from rolling and slipping to jumping, are automatically set for each trial as the occurrence probabilities of these parameters obey the normal probability distributions.

We project the searched pathway of falling rock onto the two-dimensional vertical cross-section of the rockfall simulation although the pathway is generally skewed. The parameters required for the simulation are set as shown in Table.1.

From the trajectories of falling rocks in all trials, reach probability p from the l-th rock-outcrop via the m-th pathway to point x is evaluated by

$$p_{lm}(x) = \frac{N_{reached}}{N_{trial}} \times 100 \tag{7}$$

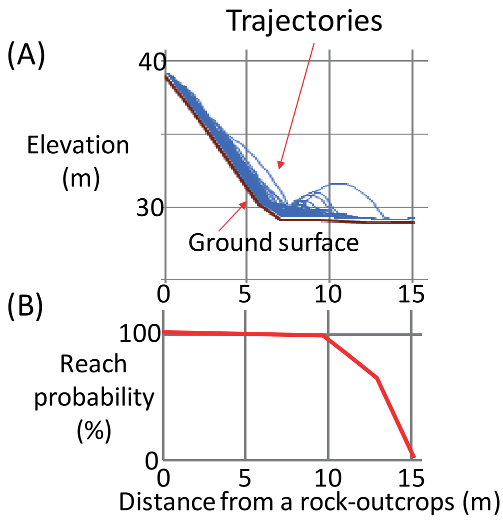

Figure 4. Example of the evaluation of reach probability using the Monte Carlo type rockfall simulation.

(A): Trajectories of falling rocks calculated in trials of the rockfall simulation. (B): The reach probability evaluated from the trajectories.

, where N_{trial} is the number of total trials and $N_{reached}$ is the number of trials in which the falling rock reached or passed point x. An example of the evaluation of reach probability is shown in Fig.4. We set N_{trial} as 100 times.

In this study, the pathway search and the rockfall simulation are executed for the estimated rock-outcrops within 100m of a railway line.

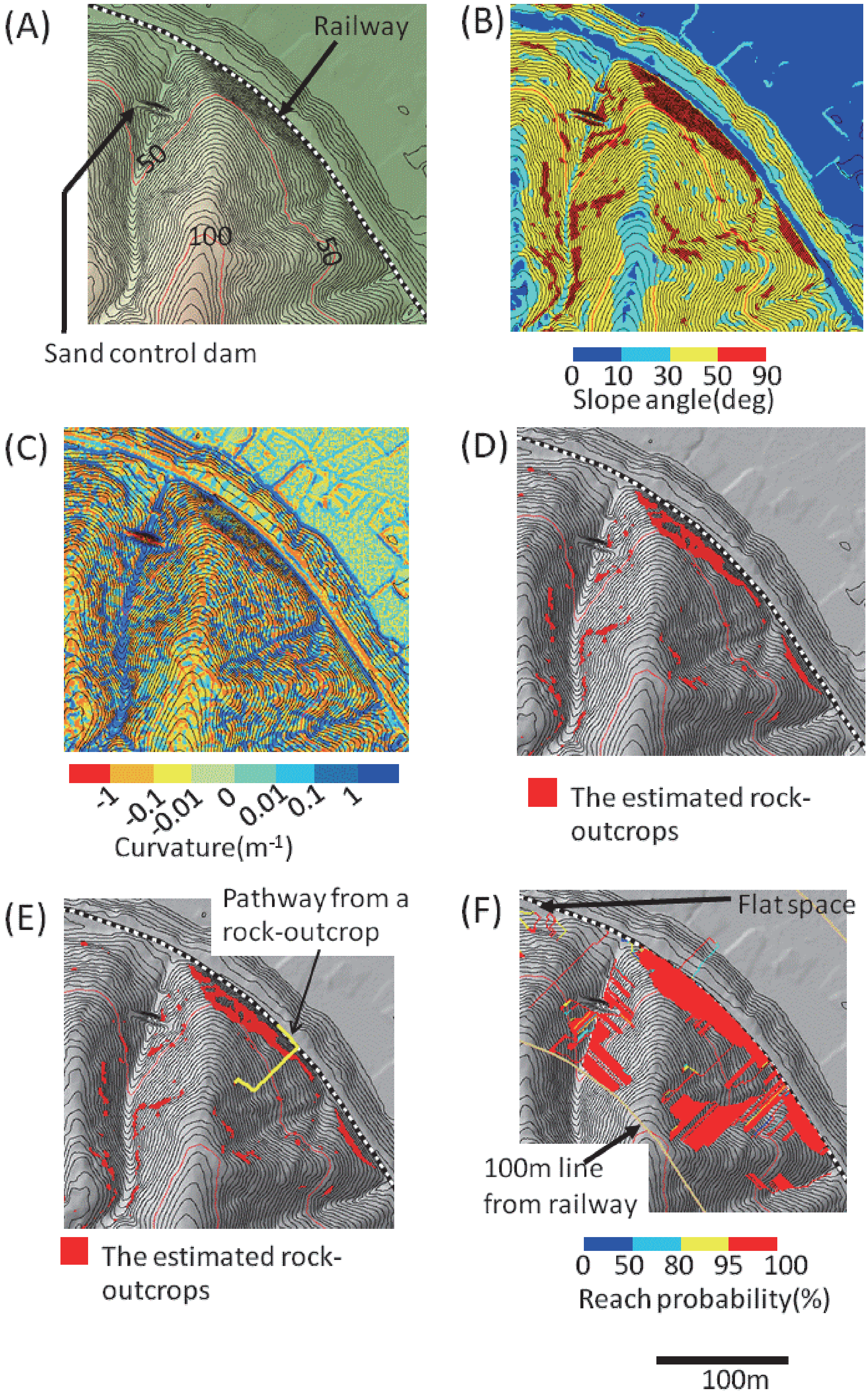

Figure 5. (A): Topological map using the DEM with 10m interval contours. (B) and (C): Distribution of the slope angle and the curvature calculated using the DEM. (D): Distribution of the rock-outcrops estimated. (E): An example of the pathway. (F): The reach probability of falling rocks from the estimated rock-outcrops within 100m from the railway.

2.5 Mapping of the reach probability

The reach probability is mapped using a geographical information system; GIS. Additionally, the extracted rock-outcrops and the pathways are also mapped.

3. Results and discussions

The rock-outcrops distribution (Fig.5(D)) is estimated using the DEM (Fig.5(A)) by the conditions eqn.(3) for the slope angle (Fig.5(B)) and eqn.(4) for the curvature (Fig.5(C)). Some estimated rock-outcrops exist on the slopes facing the railway.

The pathways from the estimated rock-outcrops within 100m from the railway are successfully analyzed using the DEM. Some pathways extend to the railway (Fig.5(E)).

The reach probability is evaluated and plotted on GIS as shown Fig.5(F). Some falling rocks will reach to the railway with 100% possibility. Others are evaluated to stop at a sand control dam on a valley or flat space.

Users can use this map as a tool to select rock-outcrops which technician should survey earlier in many rock-outcrops along railways. Moreover, this map enables users to find the sections where the reach probability is high, and helps users to make a decision where they should construct measures prior to other region.

The probability of the occurrence of rockfall, however, is not considered on the proposed method. It is a future issue to incorporate the occurrence probability.

4. Conclusion

We propose a new method to evaluate the reach probability of falling rock using DEM. This method consists of three components: estimation of the distribution of rock-outcrops, search of pathway of falling rock from each rock-outcrop, and evaluation of the reach probability using an existing rockfall simulation. Using this method, we successfully evaluate the reach probability and made a rockfall hazard map. This hazard map will be helpful for screening of rock-outcrops to investigate and for planning of measures against rockfall disasters.

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References

Abbruzzese, J.M., Sauthier, C. and Labiouse, V. (2009): Considerations on Swiss methodologies for rock fall hazard mapping based on trajectory modeling, *Nat. Hazards Earth Syst. Sci.*, Vol. 9, pp. 1095-1109.

Agliardi, F., Crosta, G.B and Frattini, P. (2009): Integrating rockfall risk assessment and countermeasure design by 3D modeling techniques, *Nat. Hazards Earth Syst. Sci.*, Vol. 9, pp.1059-1073.

Bridearu, M-A. and Roberts, N.J. (2015): Mass Movement in Bedrock, In: Shroder, J.F. (eds.) *Landslide hazards, risks, and disasters*, pp. 43-90, Elsevier.

Copons, R., Vilaplana, J.M. and Linares, R. (2009): Rockfall travel distance analysis by using empirical models (Sola d' Andorra la vella, Central Pyrenees), *Nat. Hazards Earth Syst. Sci.*, Vol. 9, pp.2107-2118.

Yoshida, H., Ushiro, T., Masuya, H. and Fujii, T. (1991): An Evaluation of Impulsive Design Load of Rock Sheds Taking into Account Slope Properties, *Journal of structural engineering. A.*, Vol. 37A, pp. 1603-1616. (In Japanese with English abstract)

Hasegawa, A. and Ohta T. (2015): An Estimation Method of the Distribution of Rock-Outcrops Using DEM, *Proc. Of Annual Meeting of Japanese Society of Engineering Geology*, now printing. (In Japanese)

Japan Road Association (2002): Reference Materials to the Handbook for the Rockfall Measures, p.295. (In Japanese)

Mavrouli O.-C., Abbruzzese, J., Corominas, J. and Labiouse, V. (2014): Review and Advances in Methodologies for Rockfall Hazard and Risk Assessment, In: Van Asch, T., Corominas, J., Greiving, S., Malet, J.-P., Sterlacchini, S. (eds.) *Mountain Risks: From Prediction to Management and Governance*, pp.179-199. Elsevier.