A risk evaluation method of countermeasure for slope failure and rockfall with account of initial investment

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ABSTRACT: In Japan, with the asset management and the advancement of risk management research, soil structures, such as slopes, are now being taken into consideration as infrastructure properties. In order to execute effective countermeasure for slope failure and rockfall, it is necessary to quantify effects of countermeasure by numerical analysis, such as DEM rockfall simulation. And, at present, method for evaluating the initial investment in countermeasures has not yet been established. To allow for the determination of an appropriate investment, we propose a new method of calculating the investment based on slope risk in this paper.

1 INTRODUCTION

In Japan, with the development of risk management technology, earth structures, such as slopes and tunnels, are now being taken into consideration as infrastructure properties. In this framework, there are circumstances in which it is necessary to execute slope measures more efficiently. This is because local governments face strict financial limitations, while the number of dangerous slopes is increasing due to expanding road networks in mountain areas.

Slope risk management presumes the slope risk value beforehand, and supports the execution of strategic measures corresponding to the slope risk value. Some risk quantification techniques have been proposed, and in part, these have been studied increasingly for business use with GIS. However, many large problems should be addressed.

The first problem is improving the precision of slope risk quantification with slope measures. Second, the paper proposes a new method to evaluate the validity of the slope measure cost.

In this study, deal with slope failure and rock fall as a slope collapse disaster at the same time. Probability distributions are used in a mechanical stability analysis model to quantify the slope risk after each occurring mechanism is presumed. Moreover, we use the rockfall simulation DEM (Discrete Element Method) to quantify the effect of counter measures.

2 QUANITIFICATION OF SLOPE RISK

2.1 Definition of slope risk

In order to quantify the slope risk R, R is defined as follows. This shows the expected value of amount lost.

\[ R = p \times D \] (1)

where \( p \) is the probability of slope disaster, \( D \) is the amount lost due to disaster.

2.2 Calculation of occurrence probability

We indicate the calculation method for each probability in this section because the occurring mechanism is different between slope failure and rockfall.

(1) Probability of slope failure

The calculation method for slope failure probability is divided roughly into a statistical and a mechanical technique. Here, we will use the mechanical model...
that Ohtsu proposed the method which is used slope stability analysis.

In this method, first, rainfall is assumed to be an exogenous factor of slope disaster. We calculate the slope failure probability \( p_r \) from the excess probability of annual probable rainfall \( \psi(\alpha) \) in rainfall intensity \( \alpha \) and the slope failure probability \( p_f \) in case of that probable rainfall.

If it is supposed that the rainfall hazard follows the Gumbel distribution, the excess probability \( \psi(\alpha) \) will be the following.

\[
\psi(\alpha) = 1 - \exp\left\{ -e^{-a(a-b)} \right\}
\]

In this equation, \( a \) and \( b \) are constant numbers obtained from the rainfall history.

Next, it is supposed that a collapse type is infinity slope model (Fig.1) in order to calculate the \( p_f \). Then, the safety factor of the slope stability analysis is indicated as follows.

\[
F = \left( 1 - \frac{\gamma H w}{\gamma H} \right) \tan \phi + \frac{c}{\tan \theta} \frac{1}{\gamma H \sin \theta \cos \theta}
\]

where \( \gamma \) is the soil unit weight, \( \gamma_w \) is the unit weight of water, \( H \) is the thickness of the sliding layer, \( H_w \) is groundwater level, \( \theta \) is the slope angle, \( c \) and \( \phi \) are the soil strength parameters.

![Figure 1. Infinite slope model](image)

Moreover, it is necessary to relate \( \alpha \) and \( H_w \), so we decided to use Eq.(4) from reference. (JCCA kinki, 2006)

\[
H_w(\alpha) = 0.1906 \times \ln(\alpha) - 0.0635
\]

Now, to quantify slope failure probability, we calculate the probability of " \( F < 1 \)" because this shows the unstable (collapse) condition. To do this, we assume the soil cohesion \( c \) and inter friction angle \( \phi \) to be random variables according to a normal distribution as in Eq.(5). This shows the uncertainty of soil parameters in physical terms.

\[
c \sim N(\mu_c, \sigma_c), \quad \tan \phi \sim N(\mu_{\tan \phi}, \sigma_{\tan \phi})
\]

As a result, the slope failure probability \( p_f \) is calculating from the following equation.

\[
p_f(\alpha) = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\beta(\alpha)} \exp\left( -\frac{1}{2} s^2 \right) ds
\]

(6)

\[
\beta(\alpha) = \mu(\alpha) / \sigma(\alpha)
\]

Therefore, the slope failure probability \( p_f \) is as follows.

\[
p_f = -\int_0^\infty p_f(\alpha) \frac{\partial \psi(\alpha)}{\partial \alpha} d\alpha
\]

(8)

The feature of this method is that probability distribution is taken into the mechanical stability analysis model. However, it is difficult to determine the volatility of the random variable. In addition, it is necessary to note that we use a simple equation for ease of calculation, although it is known that the occurring mechanism is influenced by the saturation, groundwater level, and so on.

(2) Probability of rockfall

The occurring mechanism of rockfall is very complex and has not yet been clarified. However, the calculation method for rockfall probability is also roughly divided into a statistical and a mechanical technique. We use the mechanical model that Okimura proposed.

Fig.2 shows the cases of the overhang type and fall off type of rockfall, and the safety factor equation for each type. Then, the random variables \( c \) and \( \phi \) are taken into these equations. It is assumed that the probability from \( F \) number of falls below one (\( N' \)) is divided into the number of all trials (\( N \)) by Monte Carlo simulation.

This mechanical model is very simple, so it is easy to execute. On the other hand, it seems that endogenous factors such as geological situation and exogenous factors such as rainfall, snow, freeze-thaw, wind, and earthquakes cannot be reflected in the model. Therefore, these points will become research topics in the future.

![Figure 2. Types of rockfall](image)

2.3 Calculation of loss amount due to disaster

It this study, we define \( D \) as the sum of \( D_1 \), the personal loss; \( D_2 \), the road restoration cost; and \( D_3 \), the traffic detour loss. In addition, the loss amount is changed by whether there are existing countermeasures or not. However, this section does not deal with the effects of countermeasures; these details will be given in section 4. Collapse types,
which are needed to calculate $D_1$, are modeled as in Fig.3.

1) Personal loss, $D_1$
In case of slope failure, it called a "buried case" when sand exceeds the height of a car; the "buried case" seems to result in death, incurring the human loss $I$ (yen) in this case. The loss amount decreases linearly in relation to the reduction of the disaster level. In case of rockfall, it seems that the case of being situated "right under the falling rock" results in death, and this is calculated in the same manner as before (Fig. 3).

The number of victims is calculated from the daily traffic volume of the object road and the average number of passengers. Furthermore, the number of victims is calculated separately in relation to compact cars and large-sized cars in order to reflect the difference in the cars’ height. Incidentally, the human loss used is $I = 29,764,000$ (yen), as obtained from the survey of the Japanese Cabinet Office.

![Figure 3. Type of collapse](image)

2) Road restoration cost, $D_2$
In each case of slope failure and rockfall, we use Eq. (9) to calculate $D_2$ (Yen). This equation is a regression function between the restoration cost and the archived volume of sand $V(m^3)$ based on past disaster records. (PWRI, 2004)

$$D_2 = 9,624.6 \cdot V + 1,361,100$$ (9)

3) Traffic detour loss, $D_3$
The traffic detour loss refers to the closing of roads when slope failure or rockfall occurs, and $D_3$ consists of two kinds of loss, the "Cost loss of time" generated by increases of running time and the "Running cost loss" generated by increases in mileage. These can be calculated according to the mileage distance and the daily traffic volume.

Recovery time has a big influence on the detour loss, and Fig.4 shows relations between the recovery time $N$(days) and the collapse volume $V(m^3)$. In this study, we use the regression function as given in Eq.(10) However, it seems that extensive losses that are not reflected in the equation occur if there is no detour or the event occurs near an isolated village, so it is necessary to evaluate $D_3$ in each slope for these cases.

$$N = 0.00051 \cdot V + 0.461$$ (10)

![Figure 4. Relationship between collapse volume and recovery time](image)

3 RESULTS OF CASE STUDY

In this section, the calculations of slope risk using the above method are shown. In this paper, we set the 10 slope conditions as in Table.1. These are not real slopes, but we can assess what factors influence the results. In addition, probable rainfall is based on rainfall history for 1945-2006 in the Takayama Gifu observatory.

Table 1. Slope failure conditions

<table>
<thead>
<tr>
<th>Slope No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V(m^3)$</td>
<td>2,100</td>
<td>600</td>
<td>900</td>
<td>800</td>
<td>1,500</td>
</tr>
<tr>
<td>$\phi$ (deg.)</td>
<td>30</td>
<td>35</td>
<td>30</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>$\theta$ (deg.)</td>
<td>41</td>
<td>38</td>
<td>43</td>
<td>36</td>
<td>38</td>
</tr>
<tr>
<td>$\gamma$ (kN/m^3)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>$c$ (kN/m^2)</td>
<td>16.7</td>
<td>2.7</td>
<td>10.4</td>
<td>4.5</td>
<td>13.2</td>
</tr>
<tr>
<td>$H$ (m)</td>
<td>3.5</td>
<td>1</td>
<td>2</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Traffic volume (/days)</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
</tr>
<tr>
<td>Mix rates of large-sized car (%)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Distance of original / detour road (km)</td>
<td>20/40</td>
<td>20/40</td>
<td>20/40</td>
<td>20/70</td>
<td>10/30</td>
</tr>
<tr>
<td>Speed of original / detour road (km/h)</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
</tr>
</tbody>
</table>

Table 2. Rockfall conditions

<table>
<thead>
<tr>
<th>Slope No.</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of collapse*</td>
<td>(ov)</td>
<td>(ov)</td>
<td>(rf)</td>
<td>(rf)</td>
<td>(rf)</td>
</tr>
<tr>
<td>Weight of rock $W$ (kN)</td>
<td>12.9</td>
<td>2.76</td>
<td>6.9</td>
<td>86.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Angle of sliding surface $\alpha$ (deg.)</td>
<td>80</td>
<td>95</td>
<td>65</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Length of sliding surface $Y$ (m)</td>
<td>0.8</td>
<td>0.4</td>
<td>0.5</td>
<td>2.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Length of crack $\Delta Y$ (m)</td>
<td>0.0</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\phi$ (deg.)</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>$c$ (kN/m^2)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Traffic volume (/days)</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
<td>4,502</td>
</tr>
<tr>
<td>Mix rates of large-sized car (%)</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Distance of original / detour road (km)</td>
<td>20/20</td>
<td>20/20</td>
<td>20/20</td>
<td>20/20</td>
<td>20/20</td>
</tr>
<tr>
<td>Speed of original / detour road (km/h)</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
<td>50/30</td>
</tr>
</tbody>
</table>

* (ov)⋯Overhang Type  (rf)⋯Rock off Type
Table 3. Results of slope risk analysis

<table>
<thead>
<tr>
<th>Slope No.</th>
<th>$p_e$</th>
<th>$DA$</th>
<th>$D2$</th>
<th>$D3$</th>
<th>$D$</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0621</td>
<td>1,446</td>
<td>2,157</td>
<td>2,258</td>
<td>5,862</td>
<td>364</td>
</tr>
<tr>
<td>2</td>
<td>0.9960</td>
<td>57</td>
<td>714</td>
<td>807</td>
<td>1,578</td>
<td>1,571</td>
</tr>
<tr>
<td>3</td>
<td>0.2001</td>
<td>803</td>
<td>1,002</td>
<td>761</td>
<td>2,567</td>
<td>515</td>
</tr>
<tr>
<td>4</td>
<td>0.3384</td>
<td>0</td>
<td>906</td>
<td>1,437</td>
<td>2,343</td>
<td>793</td>
</tr>
<tr>
<td>5</td>
<td>0.1041</td>
<td>1,307</td>
<td>1,580</td>
<td>2,719</td>
<td>5,605</td>
<td>583</td>
</tr>
<tr>
<td>6</td>
<td>0.3870</td>
<td>566</td>
<td>137</td>
<td>485</td>
<td>1,188</td>
<td>460</td>
</tr>
<tr>
<td>7</td>
<td>0.4650</td>
<td>566</td>
<td>136</td>
<td>463</td>
<td>1,165</td>
<td>542</td>
</tr>
<tr>
<td>8</td>
<td>0.0200</td>
<td>566</td>
<td>136</td>
<td>976</td>
<td>1,678</td>
<td>34</td>
</tr>
<tr>
<td>9</td>
<td>0.2050</td>
<td>566</td>
<td>140</td>
<td>466</td>
<td>1,172</td>
<td>240</td>
</tr>
<tr>
<td>10</td>
<td>0.0350</td>
<td>566</td>
<td>136</td>
<td>549</td>
<td>1,252</td>
<td>44</td>
</tr>
</tbody>
</table>

Previously, there were no methods of indicating a slope risk which is expressed by the monetary value in terms of slope failure and rockfall at the same time. Now, however, we indicate that each type of slope risk can be evaluated simultaneously by the index of slope risk. Moreover, it is understood that the collapse probability by use of stability analysis that has been used does not necessarily correlate the slope risks. This is because the risk includes not only an index that shows the danger of slope collapse but also that considers the amount loss when the disaster will occur. For instance, comparing slope No.3 and No.9, the collapse probability is almost at the same level. However, it is understood that slope No.3 has double or more the risk of slope No.9 (Fig. 5).

A methodology to determine the priority level of slope measures had not been clarified. However, it is thought that these priority levels can be decided more reasonably by arranging slopes in order in terms of slope risk value. (Fig. 6) This also means that we can order slopes in terms of their impact on society. In addition, it seems that slope risk can be used as a means of determining the accountability for residents as to when slope measures will be executed under the budget reductions.

4 QUANTIFICATION OF SLOPE MEASURE EFFECT

In this section, it described how to quantify the effects of countermeasure that either exist or will be built up. In this study, it pays attention to the rockfall disaster; the effect of countermeasure is quantified by calculating a rockfall behavior using two-dimensional DEM.

4.1 Concept of DEM rockfall simulation

DEM is a numerical analysis method used to solve each element progressively in an independent motion equation. At present, this method is most commonly used for rockfall simulations, in Japan. The ground slope is an actual section of a real site, and ground surface is approximated by a single layer of some particles. Often, ground slope is expressed by particle assembly. In this study, only one layer was used because it reduces the lengthy analytical time required to calculate many cases. Details will be provided later.

Based on preliminary surveys, the location of rockfall generation was determined. To simplify calculations, rock particle was assumed to have a circular shape. Furthermore, the shape and location of countermeasure, such as a retaining wall, is set up arbitrarily. This represents the situation of how to establish a new countermeasure.

To quantify the effect of slope measure, it is necessary to judge whether the road would be struck as a result of rockfall simulation. Two cases are thought to serve as judgment standards, and are represented in Fig. 7 and Table.4. In case (B), the judgment standard is presumed to be an amount greater than the possible absorption energy of the countermeasure.
4.2 Results of DEM rockfall simulation

Analytical parameters DEM are set according to Table.5.

Table.5 Analytical parameters of DEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring constant (normal)</td>
<td>$5.0 \times 10^9$</td>
</tr>
<tr>
<td>Spring constant (shear)</td>
<td>$5.0 \times 10^9 \times \frac{1}{4}$</td>
</tr>
<tr>
<td>Damping factor (normal)</td>
<td>0.3</td>
</tr>
<tr>
<td>Damping factor (shear)</td>
<td>0.3</td>
</tr>
<tr>
<td>Coefficient of particle friction</td>
<td>0.477</td>
</tr>
</tbody>
</table>

Fig.8 represents one example of a simulation result. The solid line shows tracks of two or more falling rocks. The figure’s scales are equivalent to the actual site. In order to determine the number of times judgment standards (A) or (B) are filled, it is necessary to obtain two numbers. First, the number of times rockfall height exceeds the retaining wall height of 2.0 m; and, second, the number of times that rockfall energy exceeds the possible absorption energy of the retaining wall. To be more specific, the possible absorption energy is set at 300 kJ, and it is assumed the countermeasure is destroyed if it received more than 300 kJ of kinetic energy in the x-direction.

In this study, that number was 21; therefore, the probability of being struck by rockfall is estimated to be 55%. Next, it is necessary to calculate the risk decrease rate in order to correlate this result to the slope risk. In this case, risk decrease rate is estimated at 45%, calculated as $(100 - 55) \%$.

In addition, rockfall simulation may be used not only to examine the effects of countermeasures, but also to decide the best scale and shape for them. For instance, Fig.9 represents the results of changing the height of the retaining wall, by only 0.5 m, when exactly the same simulation as before was executed. As a result, the risk decrease rate increased to 70%.

The risk decrease rate, relative to the arbitrary scale and shape, is estimated by DEM rockfall simulation both in existing and newly measured cases.
The damage cost on the slope is generated only at the disaster points, as shown in Fig.10(Left). On the other hand, slope risk shows the expected value per year of the cost that may be generated, as shown in Fig.10(Right). In other words, it can be assumed that the slope risk is the slope's cost per year. Therefore, slope LCC can be calculated by integrating slope risks for the use period. In addition, it is possible to adjust the evaluation techniques related to investment amount that have been developed with general infrastructures by the concept of slope LCC. Therefore, slope LCC is defined as follows.

\[ LCC_N = \sum_{i=0}^{N} (1-w) \cdot R_i \left( \frac{1}{1+r} \right)^{i-1} + C_0 \]  

(11)

where \( R_i \) is the slope risk of the \( i \)th year, \( N \) is the use period, \( C_0 \) is the initial investment, \( w \) is the risk decrease rate by investment, and \( r \) is the Japanese social discount rate (4%).

The OM cost (operation and maintenance cost) is not included in Eq.(11) because we assume that slope check and research costs can be disregarded compared with slope risk. In addition, it is necessary to presume \( w \) based on the DEM simulation result indicated in section 4, because this differs depending on the type of measurement and scales in each slope.

5.2 Evaluation index of investment, \( W \)

In order to examine the amount of the investment, it is necessary to compare \( LCC' \) in case of making the initial investment (countermeasure is executed) to \( LCC \) in the case of not making it (unmeasured). If \( LCC' < LCC \), it will be judged that "It is necessary to execute the project." This means that the standard of the evaluation has to do with the relationship between both LCCs, as shown in Fig.11. Therefore, we propose a new index \( W \) as in Eq.(12) that pays attention to the ratio of both LCCs in order to simplify investment decisions.

\[ W(\%) = (1 - \frac{LCC'_{50}}{LCC_{50}}) \times 100 \]  

(12)

With the index of \( W \), the project can be judged "It is necessary to execute it" if \( W \) is positive, or can be judged "Should not execute it" if \( W \) is negative.

![Figure 10. Meaning of slope risk](image_url)

![Figure 11. Comparison of the two types of LCC (W=65%)](image_url)
Table 6. Example of investment judgment for each plan

<table>
<thead>
<tr>
<th>Measures cost</th>
<th>Non</th>
<th>Plan (A)</th>
<th>Plan (B)</th>
<th>Plan (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk decrease rate (%)</td>
<td>0</td>
<td>100</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>LCC or LCC'</td>
<td>0</td>
<td>50%</td>
<td>65%</td>
<td>90%</td>
</tr>
<tr>
<td>(500)</td>
<td>(350+250)</td>
<td>(375+175)</td>
<td>(350+50)</td>
<td></td>
</tr>
<tr>
<td>W (%)</td>
<td>-</td>
<td>+20</td>
<td>+25</td>
<td>+10</td>
</tr>
</tbody>
</table>

Table 6 shows the example of investment decisions when some measures plan is shown. The decision-maker can determine the most effective plan by choosing the plan in which $W$ has the biggest value. In this case, Plan (B) is the most effective investment plan. And, for the further discussion, we call initial investment when becoming $W=0$ "Amount of the limit investment", $C_{up}$.

5.3 Evaluation of investment amount considering the risk volatility

In the previous section, the slope risk volatility is not considered. However, it is necessary to consider the risk volatility according to passage of time in the use period when we calculate slope $LCC$. Then, we describe the investment amount evaluation in the condition of uncertainty. The risk volatility factors are shown in Table 7, but the governing factor is (C). Therefore, in this study, we assume that (C) is the only volatility factor in the future slope risk.

Table 7. Volatility factors in the future slope risk

<table>
<thead>
<tr>
<th>Volatility of probability</th>
<th>(A) Volatility of probable rainfall</th>
<th>(B) Volatility of geometrical parameter</th>
<th>(C) Volatility of traffic volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatility of loss amount</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Then, it is necessary to model the traffic volume in the future. This estimation is usually carried out according to the some scenario based on forward road planning, but this has been criticized in that there is uncertainty in prediction and a constant width in the predictive value. Because of this, we considered the annual volatility of traffic volume to be "Arithmetic Brownian motion," which is used in the field of the Financial Engineering; this is expressed using the Monte Carlo simulation. Fig. 12 shows one example of these results. In addition, the feature of the arithmetic Brownian motion is its accordance with the Markov process in that the following present term traffic volume depends only on the traffic volume before one term.

$LCC$ can be fined when the traffic volatility is given; the result is shown in Fig. 13. The result demonstrates that $LCC_{up}$ shows distribution with a certain width that centers on the mean value. Here, we consider the confidence interval of distribution to be 90%, and it is assumed that $LCC_{up}$ when the cumulative probability is 5% and $LCC_{down}$ when the cumulative probability is 95%. From this, we can calculate the "Amount of the limit for investment." With this result, the $W$ and initial investment $C_{0}$ relation are led as in Fig. 14. It can be determined whether the initial investment under examination is in the safety zone or in a dangerous zone, and the width of the middle zone generated by the uncertainty of the traffic can also be understood. For instance, if it was proposed to build newly countermeasure from 150,000 thousand yen, decision-maker can evaluated that this proposal is not economical but is not far apart from $C_{up}$. And if it was proposed more expensive plan, they might require to change this measure plan fundamentally.

From this, it is believed that the investment evaluation for uncertain conditions will become possible by the index of $W$. 

![Figure 12. Traffic volume prediction by use of "Arithmetic Brownian motion"](image)

![Figure 13. Result of Slope LCC](image)

![Figure 14. Relationship between $W$ and $C_{0}$ for decision-maker](image)
In this paper, it has been made clear that slope risk can be quantified both in terms of slope failure and rockfall when slope risk management is executed. Furthermore, it has been demonstrated that it is possible to reasonably determine the priority level of countermeasures by slope risk.

Moreover, in order to quantify the slope measure effect, rock fall simulation by DEM is an effective method. And it is able to calculate risk decrease rate of countermeasure by judging the road struck in many calculations.

We have proposed a new method for evaluating the validity of an initial investment by leveraging the index $W$ based on the concept of slope LCC. In addition, this method will be able to support decision making under uncertain conditions, as it has built in the risk volatility of traffic volume in the future.

Future tasks include determining how to treat the statistical and mechanical error margin for each model. Furthermore, the required risk precision is different in the steps of risk management as compared to those of decision-makers, so it is necessary to construct a complete system of risk management. For instance, the decisions of measuring priority level are based on relative risk evaluations; on the other hand, investment decisions are based on an absolute risk value. In this case, a high level precision is needed. Briefly, it is necessary to clarify the risk quantification technique corresponding to the necessary risk precision. In addition, in relation to the rock fall simulation DEM, etc., future research to improve its precision is necessary.

REFERENCES


