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PROPOSAL OF RISK EVALUATION METHOD FOR RAIN-INDUCED SLOPE FAILURE ON ROAD SLOPE

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ABSTRACT

It is important to prevent or mitigate road disasters, because roads support our daily life, and they play a crucial role in supporting the infrastructure for economic activities. In order to prevent or mitigate road disasters caused by slope failures, it is necessary to select dangerous slopes previously by evaluating the risk of slope failure occurrence and to take some sort of effective countermeasures to the selected slopes. In this research, we proposed the risk evaluation method for slope failure caused by rainfall on road slope. Our method could perform quantitatively evaluation by carrying out comprehensive evaluation of both the evaluation of collapse risk and the evaluation of road damage. We applied this method to an actual national road in Japan. As a result, our method was useful for a quantitative risk evaluation method for the road slope.

Key words: Risk evaluation method, road slope and rain-induced slope failure

1. INTRODUCTION

Roads support our daily life, and they play a crucial role in supporting the infrastructure for economic activities. However, road disasters caused by slope failures, rock falls and so on have occurred frequently in Japan, because it is subjected to the severe natural conditions such as heavy rainfall, steep topography, brittle geology, etc. As the road disaster, not only the primary disaster (the road suffers damage directly) but also secondary disaster (hindrance to the society and the economic activity by traffic stop) must be taken into account. In order to prevent or mitigate such road disasters caused by slope failures, it is necessary to select dangerous slopes previously from a number of road slopes and to take some sort of effective countermeasures to the selected slopes. Therefore, it is important to determine the hazard level by quantitatively estimating the risk of slope failure. From these backgrounds, Ministry of Land, Infrastructure and Transport in Japan has investigated slopes along national highways all over the country at the proportion of 1 degree in about 5 years and has selected the dangerous slopes. In this investigation, the risk of road slope was evaluated by the score table in consideration of the topographical and geological factors, which affect generating of slope failure, and the present countermeasures. However, in this score evaluation method, it seems that the risk evaluation that mechanism was fully taken into consideration did not perform and the effect of the present countermeasures were only qualitatively evaluated by field investigators. In order to evaluate the risk of road slopes, it is important to perform the

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overall risk evaluation which consists of not only the evaluation considering the collapse mechanism of whether slope failure occurs (the evaluation of collapse risk) but also the evaluation of whether to affect road when slope failure occurs (the evaluation of road damage). Moreover, the priority decision of disaster prevention countermeasure is important in order to advance the rational countermeasure projects.
In this research, we propose the risk evaluation method for slope failure caused by rainfall on road slope. This is the method of the ability to perform quantitatively evaluation by carrying out comprehensive evaluation of both the evaluation of collapse risk and the evaluation of road damage. Furthermore, we carry out priority decision using the evaluation result by this method.

2. METHODOLOGY

Fig. 1 shows the flowchart of this method.
Firstly, the data (e.g. topographic and geological conditions, distribution of potential failure layer, condition of present countermeasure, etc.) required for the risk evaluation is obtained by field investigation. Next, the evaluation of collapse risk and the evaluation of road damage are carried out, respectively. Finally, the comprehensive evaluation of both evaluation results is carried out and priority decision is carried out. Each evaluation method is described below.

Fig. 1: The flowchart of this method.

2.1 Evaluation of collapse risk

Generally, the stability or instability of slope at the time of rain is evaluated by the value of the safety factor calculated by analysis that combined the slope stability analysis according to the mechanism of collapse and the seepage analysis that simulates the infiltration of the rain in the slope. In this analysis, it is necessary to consider the uncertainty (dispersion) of input parameters because obtained result depends on the accuracy of the value of input soil parameter such as cohesion and friction angle, which are used for analysis. In addition, rainfall as trigger factor is necessary to take into consideration the local characteristic of it. Then, in this research, the risk of slope failure caused by rainfall is evaluated by the annual probability of failure, which considering the uncertainty of input soil parameter and the local characteristics of rainfall. The annual probability of failure *Pf* is calculated according to the flowchart shown in **Fig. 2**.

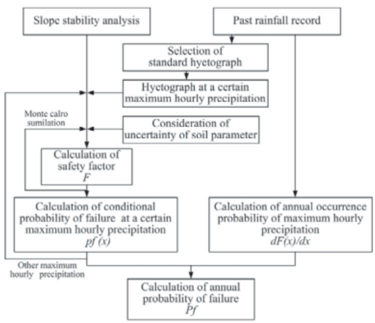

Fig. 2: The flowchart of calculation of annual probability of failure Pf.

a) Slope stability analysis model

We use multi-planar sliding surface method (Okimura, 1983) as slope stability analysis model. This analysis model is based on the limit equilibrium theory for analyzing slope stability and it is developed from a tri-planar sliding surface method (Chowdhury, 1978). This analysis model assumes the slope to be covered by

nth rectangular blocks of potential failure layer (see **Fig. 3**). The assumed sliding mass that consists of lth blocks on this slope is set up (see **Fig. 4**), and stability of the sliding mass is evaluated. The ground water level is calculated using saturated seepage model (Okimura and Ichikawa, 1985), and it is made to work as pore water pressure.

This model aims to finding the safety factor for a slopes or a segment considered hazardous. In order to achieve this, a slip surface must be defined, which is the critical for the studied site; this is, the lowest factor of safety from the analysis. The critical slip surface is found by using the distribution of potential failure layer of a given slope and the mechanical soil features of the potential slip surface.

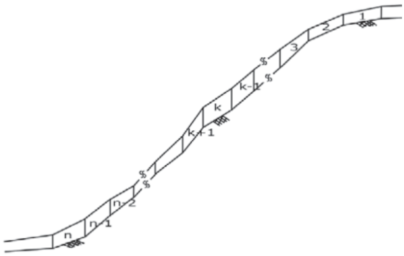

Fig. 3: nth blocks of potential failure layer on slope.

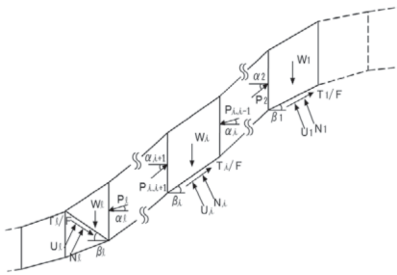

Fig. 4: Slope profile for multi-planar sliding surface method.

b) Calculation of conditional probability of failure

The conditional probability of failure *pf(x)* at a certain maximum hourly precipitation x is calculated by following procedures.

Firstly, the standard hyetograph as a basis for calculating the conditional probability of failure is decided. In this research, the standard hyetograph that actually caused slope failure in the past is selected from the past rainfall record in the site for evaluation.

Next, assumed hyetographs according to various maximum hourly precipitations are made using this standard hyetograph, respectively. When the hyetograph whose maximum hourly precipitation is x is assumed, it is made by multiplying the ratio of the maximum hourly precipitation of it to that of the standard hyetograph (x/x_{max}) by each time precipitation of the standard hyetograph (see **Fig. 5**).

Next, in order to consider uncertainty of input soil parameter, cohesion and friction angle are

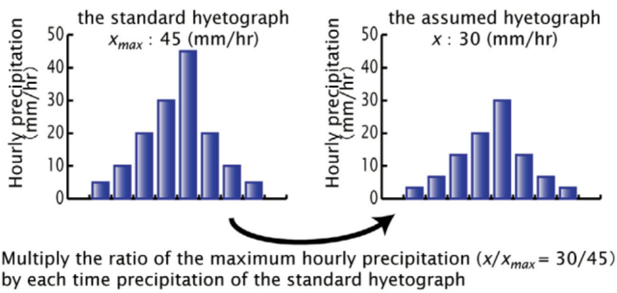

Fig. 5:An example of creating of assumed hyetograph.

dealt with as a random variable that varies in normal distribution.
Finally, the safety factor is calculated in multi-planar sliding surface method by using the assumed hyetograph whose maximum hourly precipitation is *x* and the normal random numbers of cohesion and friction angle are generated in each trial, respectively. This procedure repeats *N* times (the total number of trials) and the conditional probability of failure *pf(x)* at a certain maximum hourly precipitation *x* is calculated by following equations.

$$pf(x) = N' / N \tag{1}$$

where *pf(x)* is the conditional probability of failure *pf(x)* at a certain maximum hourly precipitation *x, N'* is the number of times that safety factor *F* is less than 1.0, N is the total number of trials.

By the same procedure, the conditional probabilities of failure at other maximum hourly precipitation are calculated.

c) Calculation of annual occurrence probability of maximum hourly precipitation
Using past rainfall record at the area for evaluation, the probability that a certain maximum hourly precipitation will be observed in a year (annual occurrence probability of maximum hourly precipitation) *dF(x)/dx* is calculated by following procedures.
Firstly, the probability distribution of maximum hourly precipitation in a year is defined. In general, as a probability distribution of the maximum value in a year such as maximum hourly precipitation in a year, Gumbel distribution (extreme value distribution) is applied (Kanemaru and Takasao, 1983). In this research, Gumbel distribution is applied, too. The probability distribution function of Gumbel distribution is shown in the following equation.

$$f(x) = exp(- exp^{-y}) \tag{2}$$
$$y = a\,(x - b) \tag{3}$$

where *f(x)* is the probability distribution function in which maximum hourly precipitation in a year is less than x (nonexceedence probability distribution function), a and b are parameter obtained from the past observation data of maximum hourly precipitation in a year.

The probability distribution function in which maximum hourly precipitation in a year is over than x (exceedence probability distribution function) *F(x)* is obtained in the following equation.

$$F(x) = 1 - f(x) \tag{4}$$

Using this exceedence probability distribution function *F(x),* the annual occurrence probability of maximum hourly precipitation *dF(x)/dx* is calculated.

d) Calculation of annual probability of failure
Using the conditional probability of failure *pf(x)* and the annual occurrence probability of maximum hourly precipitation *dF(x)/dx* which is calculated by the procedure mentioned above, the annual probability of failure *Pf* is calculated by the following equation.

$$Pf = \int pf(x) \cdot dF(x)/dx \cdot dx \tag{5}$$

This annual probability of failure *Pf* is taking into consideration even the heavy rainfalls that is not extremely generated from rainfalls with high generating frequency in the target area. When this value of a road slope is close to 1.00, it can be said that it is highly hazardous.

2.2 Evaluation of road damage

In order to evaluate the resulting anticipated damage on road when slope failure occurs, it is necessary to estimate whether collapsed soil reaches road or not. In addition, it is necessary to judge whether the road suffers damage by considering the effect of the present countermeasure. In this research, the road damage is evaluated according to the flowchart shown in **Fig. 6**.

a) Mathematical model of soil mass

Several models to estimate travel distance of collapsed soil and behavior of it are proposed. These models can be generally divided into 2 groups. The first group includes empirical model. The second group includes mathematical models, which describe the physical behavior of mass movement. Empirical formula, which is proposed by Scheidegger in 1973, is well used in experience model. This formula consists of the relationship between the travel distance, the slope height and the volume of collapsed soil. It is necessary to estimate not only the travel distance of collapsed soil but also behavior such as velocity in order to evaluate the effect of present countermeasure. Most of experience model can estimate approximate travel distance of collapsed soil, but it cannot evaluate the behavior. In order to evaluate the behavior of collapsed soil, it is necessary to use a mathematical model, which describes the physical behavior of mass movement. Therefore, in this research, we use the kinetic model of soil mass, which is proposed by Ashida et al. in 1984, as mathematical model. This model's momentum equation of a soil block moving on slope is formulated using rigid- and fluid-frictional laws.

b) Calculation of probability of damage

In this research, the following types of disaster are considered as damage that collapsed soil causes the road. 1) The collapsed soil reach the road, 2) the kinetic energy of the collapsed soil is over the absorbable energy of the present countermeasure and 3) the volume of the collapsed soil is over the pocket capacity of the present countermeasure. The probability of damage *Pd* is defined the probability that a road will suffer damage described above, when slope failure occurs. The probability of damage *Pd* is calculated by following procedures.

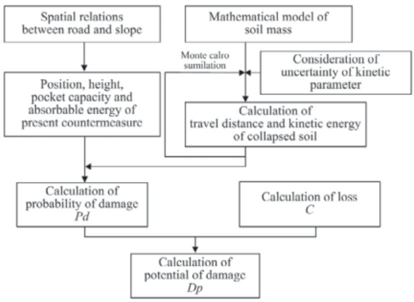

Fig. 6: The flowchart of evaluation of road damage.

Firstly, the travel distance and the velocity for calculating the kinetic energy are calculated by the kinetic model of soil mass. In the parameter used for this calculation, the volumetric concentration of soil mass vary widely and affects the result of this analysis. Therefore, in this research, in order to consider the uncertainty of the volumetric concentration of soil mass, it is dealt with as a random variable that varies in normal distribution and the normal random numbers of it are generated in each trial. This procedure repeats *N* times (the total number of trials) and the probability of damage *Pd* is calculated by following equations.

$$Pd = N' / N \quad (6)$$

where N' is the number of times that the collapsed soil reach the road and/or the kinetic energy of the collapsed soil is over the absorbable energy of the present countermeasure.

Moreover, when the volume of the collapsed soil is over the pocket capacity of the present countermeasure, the disaster probability is set to 1.00, because any damage is generated in the road.

c) Calculation of loss

As loss generated in road disaster, following things are mentioned. 1) The bulldoze cost of collapsed soil, 2) the restoration cost of collapsed road slope, 3) the time loss and travel cost with detour and 4) the damage of passing vehicles and passengers. In this research, the loss C is defined the volume of collapsed soil V, because the bulldoze cost, the restoration cost and injury/loss of life are proportional to V. Here, the volume of the collapsed soil V was calculated by multiplying the area of the most potentially dangerous sliding mass, which was predicted by the multi-planar sliding surface method, to the width of slope failure, which was estimated by field investigation.

d) Calculation of potential of damage

The potential of damage Dp is calculated by following equation.

$$Dp = Pd * C (= V) \quad (7)$$

2.3 Comprehensive evaluation

As the comprehensive evaluation, Risk R is calculated by the following formula, using the annual probability of failure Pf and the potential of damage Dp.

$$R = Pf * Dp \quad (8)$$

Risk R is the index, which combined both result of the evaluation of collapse risk, and the evaluation of road damage and it is possible to evaluate not only the danger for slope failure generating but also the damage scale with the generation of slope failure.

3. APPLICATION

We applied our risk evaluation method to 9 slopes along an actual national road in Japan. This national road passes through along steep slopes that are composed of the granite. The granite in this site has got very crumbly due to aeration and mountain slope are covered with as a surface soil layer that is composed of weathered granite. Therefore, in this site, slope failures are easy to be generated by heavy rainfalls.

3.1 Result of field investigation

We carried out field investigation for nine road slopes in order to obtain fallowing data.

- Longitudinal section … by surveying
- Distribution of potential failure layer … by portable penetration test (P.P.T.)
- Estimation of width of slope failure … by visual observation
- condition of the present countermeasure … by surveying and visual inspection

The example of longitudinal section and distribution of potential failure layer is shown in **Fig.7** and the results of field investigation are shown in **Tab.1**. In this research, the discriminative value of portable penetration resistance between a potential failure layer and the base rock is defined as 12 with reference to past research (Okimura, 1983).

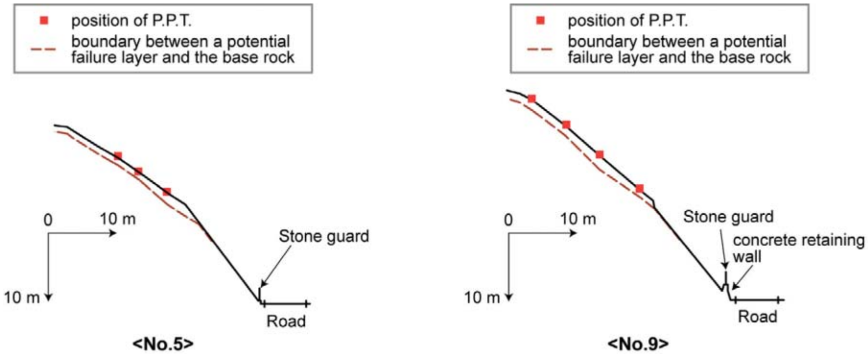

Fig. 7: Example of longitudinal section and distribution of potential failure layer.

Tab. 1: The result of field investigation.

Slope No.	Condition of the present countermeasure (height (m))	Absorbable energy of the stone guard (kJ)	Estimated width of slope failure (m)
1	concrete retaining wall (2.2) and stone guard (2.0)	56.0	17.0
2	concrete retaining wall (2.2) and stone guard (2.0)	56.0	5.0
3	concrete retaining wall (0.3) and stone guard (2.0)	104.0	10.0
4	stone guard (2.0)	100.0	5.0
5	stone guard (2.0)	100.0	5.0
6	stone guard (2.0)	175.0	10.0
7	concrete retaining wall (2.9) and stone guard (2.0)	53.0	5.0
8	stone guard (4.0)	95.0	7.0
9	concrete retaining wall (1.0) and stone guard (2.0)	90.0	4.0

3.2 Result of evaluation of collapse risk

The annual probability of failure *Pf* was calculated according to the flowchart shown in **Fig. 2**. The standard hyetograph, which was used to calculate the conditional probability of failure *pf(x)*, is shown in **Fig. 8**. Five slope failures induced by this rainfall on the slope along this national road in 1979. Using this standard hyetograph, assumed hyetographs according to various maximum hourly precipitations were made by the procedure shown in **Fig. 5**.
The input soil parameters for calculation of the conditional probability of failure *pf(x)* are listed in **Tab. 2**. These values were set with reference to past literatures (Matsuo, 1984, Okimura, 1983 and Nishi et al, 1989). First, using these data, we calculated the safety factor *F* by multi-planar sliding surface method and the conditional probability of failure at various

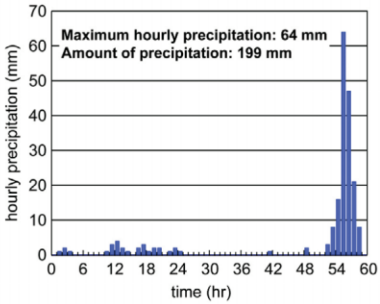

Fig. 8: The standard hyetograph in this site.

Tab. 2: Input soil parameter for calculation of *pf(x)*.

Parameters	Value (mean)	Standard deviation
Cohesion c' (kN/m^2)	3.92	1.56
Friction angle ϕ' (degree)	30.00	6.00
Unit weight γ_t (kN/m^3)	15.68	-
Saturated unit weight γ_{sat} (kN/m^3)	17.64	-
Coefficient of permeability k (m/hr)	0.20	-
Effective porosity λ	0.35	-

maximum hourly precipitations by the Eq. (1) on each slopes. In this research, the total number of trials was set at 1,000 times. **Fig. 9** shows the conditional probability of failure at various maximum hourly precipitations *pf(x)* on each slope. From **Fig. 9**, with the increase of *x*, *pf(x)* tends to also increase on each slope. At every *x, pf(x)* of slope No.9 is largest value in comparison to other slopes and this means that slope No.9 is most dangerous among slope along this national road. In comparison with slope No.2 and No.4, although No.4 is large value as compared with No.2 when *x* is smaller than 50mm/hr, opposite tendency is shown when *x* is larger than 60mm/hr. The similar tendency is observed between slope No.1 and No.8 and between No.5 and No.7. These mean that it is important to carry out the synthetic evaluation considering various amount of rainfall because the obtained result changes with input condition of rainfall. Next, using past 24 years rainfall record at the area for evaluation, we calculated the exceedence probability distribution function *F(x)* and the annual occurrence probability of maximum hourly precipitation *dF(x)/dx* shown in **Fig.10**. From **Fig.10**, in this site, the rainfall whose maximum hourly precipitation is 20mm/hr is most easy to generate, and next, 30mm/hr. On the other hand, the rainfall whose maximum hourly precipitation is 20mm/hr or 80mm/hr hardly occurs in the site. Next, using the results shown in **Figs. 8** and **10**, we calculated the annual probability of failure *Pf* by the Eq. (5) on each slope. **Fig. 11** shows the results of annual probability of failure *Pf* on each slope.

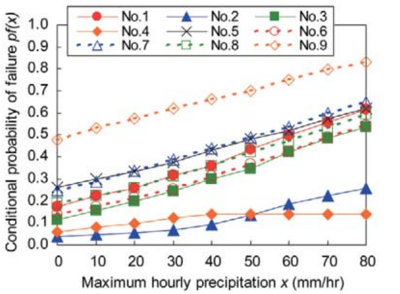

Fig. 9: The results of calculation of *pf(x)* on each slope.

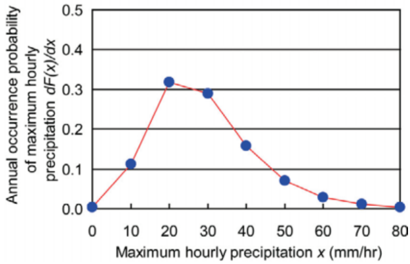

Fig. 10: The result of calculation of *dF(x)/dx*.

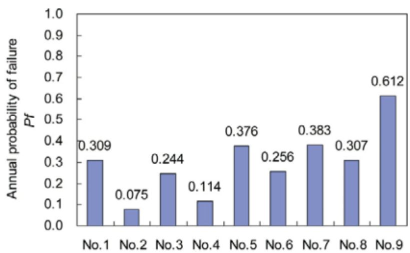

Fig. 11: The results of calculation of *Pf* on each slope.

In **Fig.9**, although the order relation of *pf(x)* between slope No.2 and No.4 (No.1 and No.8, No.5 and No.7) were inverted according to x, the evaluation of collapse risk could take into consideration the local characteristic of rainfall by taking into consideration the annual occurrence probability of maximum hourly precipitation. From **Fig. 11**, the value of *Pf* of slope No.9 is largest value in comparison to other slopes, followed by No.7, No.5, and No.1 in order. This means that slope No.9 is most dangerous slope.

3.3 Result of evaluation of road damage

The potential of damage *Dp* was calculated according to the flowchart shown in **Fig. 6**. The input parameters for calculation of the probability of damage *Pd* are listed in **Tab. 3**. These values were set with reference to past literature (Egashira et al, 1996). First, we calculated the travel distance and the velocity by the kinetic model of soil mass using these parameters. On each trial time, we checked whether the collapsed soil reached the road or not and whether the kinetic energy of the collapsed soil was over the absorbable energy of the present countermeasure. In addition, we checked whether the volume of the collapsed soil was over the pocket capacity of the present countermeasure. **Tab. 4** shows the probability of damage *Pd* on each slope, which were calculated by the Eq. (6). Since slopes were close to along this national road and the kinetic energies of the collapsed soil were large, Pd was calculated as 1.00 on all slopes except No.1. **Fig. 12** shows results of potential of damage *Dp* on each slope, which were calculated by the Eq. (7). From **Fig. 12**, the value of *Dp* of slope No.6 is largest value in comparison to other slopes, followed by No.5, No. 8, and No.9 in order. This means that slope No.6 gives most large damage to the road.

Tab. 3: Input soil parameter for calculation of *Pd.*

Parameters	Value (mean)	Standard deviation
Density of water ρ (t/m^3)	1.00	-
Density of soil particle σ (t/m^3)	2.65	-
Friction angle ϕ (degree)	30.00	-
Representative grain size d (m)	0.30	-
Volumetric concentration c_d(mm/hr)	0.50	0.10
Coefficient of restitution *ke*	0.85	-

Tab. 4: Results of calculation of *Pd* on each slope.

Slope No.	Probability of damage *Pd*	Slope No.	Probability of damage *Pd*
1	0.00	6	1.00
2	1.00	7	1.00
3	1.00	8	1.00
4	1.00	9	1.00
5	1.00		

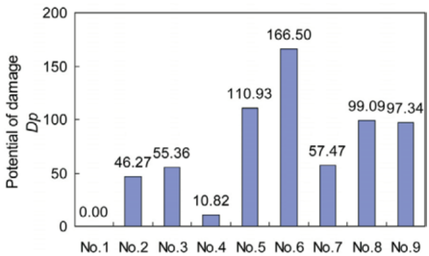

Fig. 12 Results of calculation of *Dp* on each slope.

3.4 Result of comprehensive evaluation

Fig. 13 shows results of Risk *R* on each slope, which were calculated by the Eq. (8).
As mentioned above, the order of result of the evaluation of collapse risk differed from that of result of evaluation of road damage. However, result of the comprehensive evaluation, which considered both result by Eq. (8), can calculate as the index of Risk *R*.
It can be said that this means that Risk *R* is useful an index for quantitative risk evaluation for the road slope. Moreover, the

results of priority decision for disaster prevention works by using the values of Risk *R* on each slope are shown in **Fig. 13**. From these results, in order to prevent or mitigate road disasters caused by rain-induced slope failures in this national road, it can be said that countermeasure for them should be taken for slope No.9, No.6, and No.5 in that order.

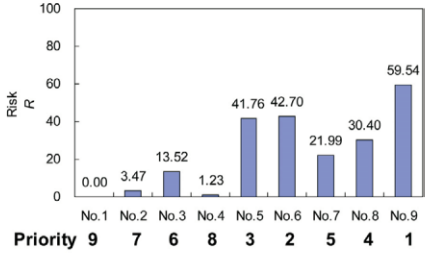

Fig. 13 The results of calculation of *R* on each slope and priority decision of disaster prevention works.

4. CONCLUTIONS

A risk evaluation method for slope failure caused by rainfall on road slope was proposed; the main features of this method can be summarized as follows: 1) The evaluation of collapse risk in consideration of the mechanical model of slope failure with the uncertainty of soil parameter and the local characteristic of rainfall in the site is performed. 2) The evaluation of road damage in consideration of the effect by the sliding block on the road such as the probability in which it reaches the road is performed. 3) By carrying out comprehensive evaluation of both evaluations, the risk level of road slope can be evaluated quantitatively.
Our method was useful for a quantitative risk evaluation method for the road slope, from the result of applying this method to an actual national road in Japan.

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