RESEARCH ON THE QUANTITATIVE RISK ESTIMATION METHOD OF ROAD SLOPE DISASTER

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ABSTRACT

This paper presents the framework of calculating the risk curve for road slope failures due to rainfall. First, the fragility curve is calculated based on the data such as past records of failures, precipitation records and results of slope stability inspection. Then the risk, defined as the socio-economical damages and losses, is estimated in the form of a risk curve based on the data such as the estimated scale of failures and the amount of traffic. This quantitative risk estimation method could help road administrators to undertake the effective and efficient risk management.

KEY WORDS

RISK CURVE/ SLOPE FAILURES/ RAINFALL/ FRAGILITY CURVE

1. INTRODUCTION

Because of topographical conditions, many roads in Japan are built in the proximity of slopes that are unstable and susceptible to collapses and failures. Although the progress in protection measures has significantly reduced the frequency of road slope disasters, an enormous number of road slopes still remain dangerous. Furthermore, disasters such as slope failures induced by torrential rains and large-scale rock mass collapses, which are difficult to protect, have been conspicuous in recent years. Under these circumstances, road administrators are required to implement effective risk management against slope failure disasters under limited financial resources and to explain to the public the actual slope disaster risk and the cost-effectiveness of mitigation measures.

The objective of this study is to develop a risk evaluation method to estimate the potential damage and loss due to road slope failures. The proposed method applies a concept of risk curve developed in the field of disaster insurance to quantifying the level of risk in road slope disasters. This method helps road administrators make a more rational decision for measures against slope disasters.The development of the risk curve consists mainly of the following two parts:

1) Hazard analysis: estimating the probabilities of slope failures and their magnitude based on information such as past records of failures, precipitation records, and data from slope stability inspection.
2) Risk analysis: calculating the total loss caused by slope failures, taking into account: a) property losses incurred by road administrators and users, b) human losses (death and injury) caused on road users, and c) economic losses (e.g. extra travel time for making a detour) incurred by road users and regional communities.

The proposed method was applied to an assessment of risk of a section of a national road to establish the procedure

2. RISK CURVE

A loss exceedance probability curve, which is called a risk curve in this paper, depicts the probability that a certain level of loss will be exceeded on an annual basis. The probabilistic risk analysis enables one to combine the set of events that could induce a given monetary loss and determine the resulting probability of this loss occurring. Figure 1 presents an example of a risk curve.

In this study, rainfall is considered as an event that causes slope failures. The y-axis represents the annual exceedance probability of the rainfall intensity, and the x-axis represents the expected loss. In Figure 1, point A means that a loss of 4 million yen or more occurs once in a 5-year period (probability of 0.2). An intercept on x-axis shows that the expected maximum loss is 5.3 million yen. The shaded area under the risk curve represents an approximation of the average annualized loss.

Furthermore, the shape of the risk curve also shows the magnitude and characteristics of slope failure risk of an entire road section or of its individual slope. For example, Figure 2 depicts the hypothetical risk curves of three different sections. In this case, section A has the largest risk at any occurrence probability level, and therefore requires the highest priority of implementing mitigation measures against disasters. While section B has a relatively high probability to have a moderate loss, it has very low probability to have a large loss. Therefore, daily road administration rather than costly protection construction works will be more desirable to minimize a potential loss by slope failures. Finally, disaster protection works for unstable slopes will be chosen as a desirable measure for section C that has some risk to have a large loss. As shown in Figure 2, the risk curve enables us to understand the current conditions of road slope disaster risk and to take the most appropriate measures to mitigate the risk.

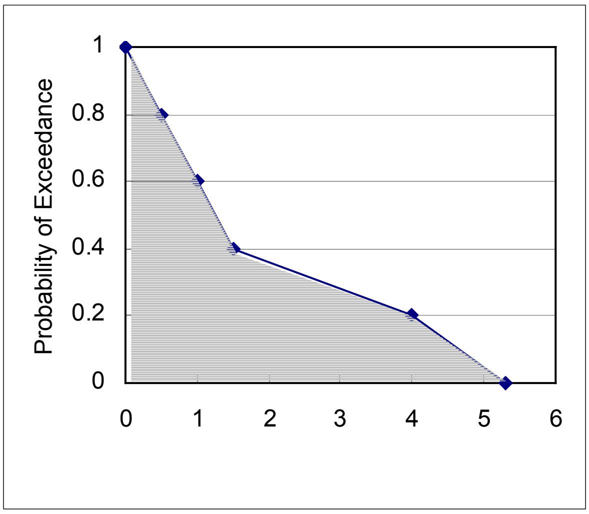
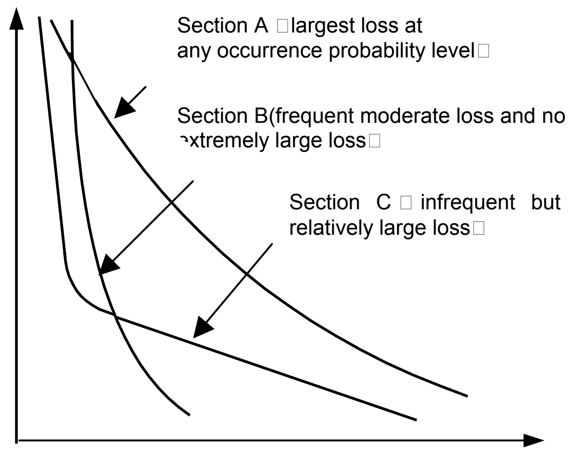


Figure 1. Example of Risk Curve
(Loss Exceedance Probability Curve)



3. PROCEDURE OF RISK CURVE DEVELOPMENT

The procedure for creating the risk curve for an individual slope along a roadway section is shown in Figure 3. The risk curve for a road section is developed by summing up the risk curves for all slopes within this section. This procedure is explained below using a case study.

3.1 SELECTION FOR THE CASE STUDY

The case study was conducted for a 32.5 km road section from Nichinan City to Miyazaki City of National Route 220 in Miyazaki Prefecture, Japan (Figure 4). Slopes along this section are extremely susceptible to failures since the slopes are dipped with weathered sandstone and mudstone, called “Miyazaki Group”. This section is designated as a special section subject to advance traffic regulation because of frequent sediment disasters caused by heavy rainfall. The number of natural and artificial slopes along this section and the number of slope failures in the past 20 years are shown in Table 1.

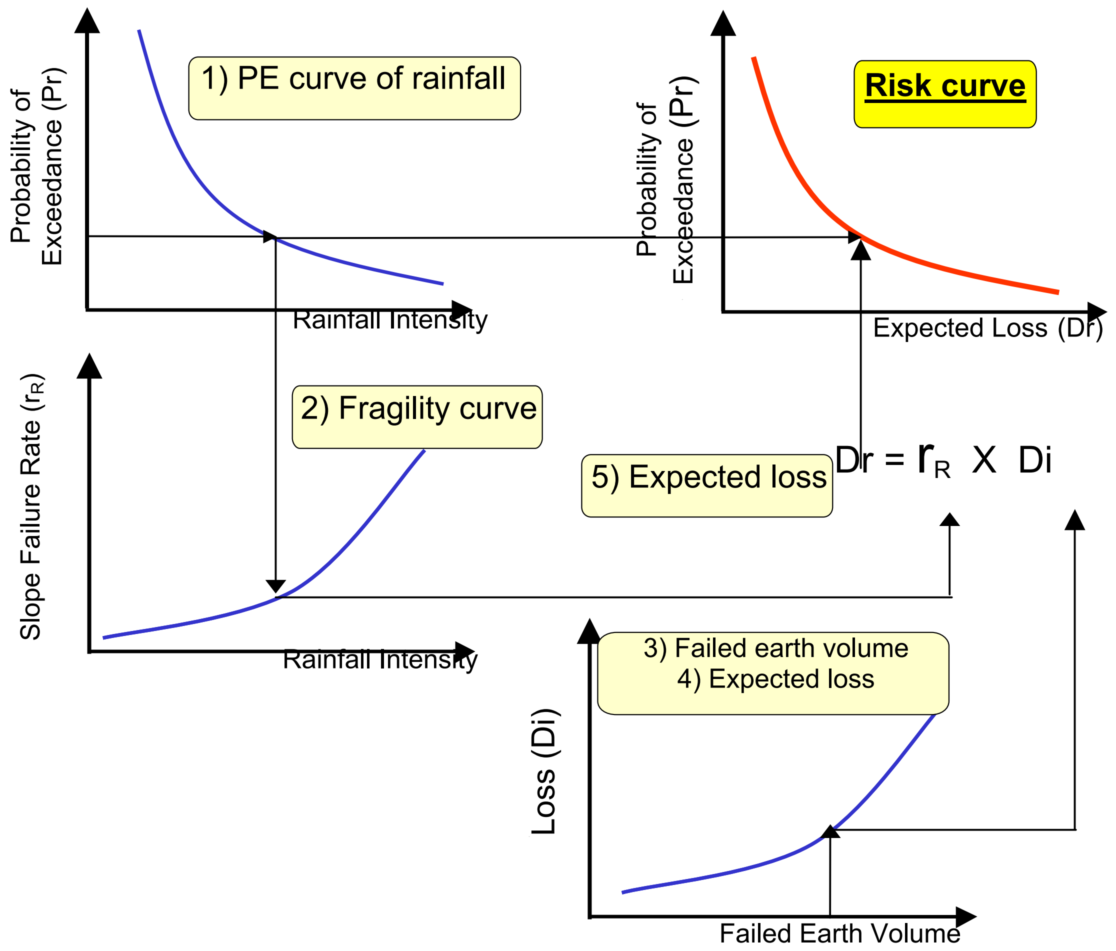


Figure 3. Procedure for developing a Risk Curve for an Individual Slope

Table 1. Number of Slopes and Number of Slope Failures in the past 20 Years

	Artificial Slope	Natural Slope
No. of slopes	79	103
No. of failures	13	36

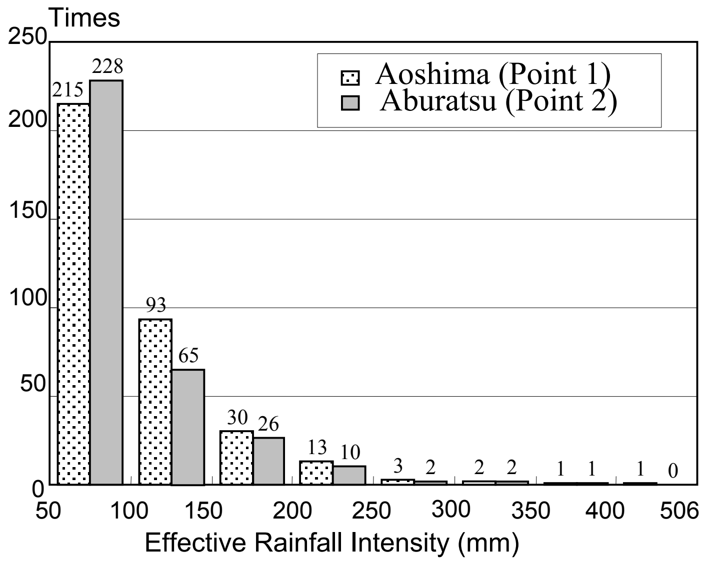


Figure 5 Histogram of Effective Rainfall Intensity

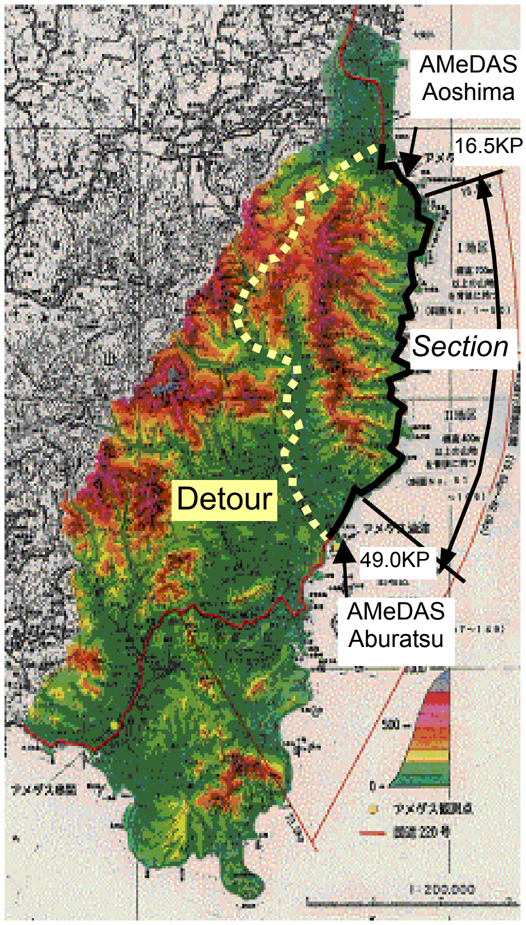


Figure 4. Section for Case Study

3.2 DEVELOPMENT OF THE ANNUAL EXCEEDANCE PROBABILITY OF RAINFALL INTENSITY

The effective rainfall was used as a rainfall intensity index in formula (1). The index is called equivalent continuous rainfall: the sum of the levels of rainfall in individual one-hour periods multiplied by reduction coefficients that are determined for individual time periods by the number of hours between each period and the time of observation. The effective rainfall reflects the influence of antecedent rainfalls that remain in the ground. The half-life period T in equation (1) is determined by the ground drain-ability. In this case study, 48-hour was found out to show the strongest correlation between slope failure probability and the effective rainfall for the studied section in the past.

$$Rw = \sum ai \times Ri \quad (1) \qquad ai = 0.5^{i/T}$$

Where Rw: effective rainfall, Ri: hourly rainfall i hours before observation, ai: reduction coefficient for rain i hours before observation and T: half-life period (hours).

Figure 5 presents the histogram of the number of times, when the effective rainfall level exceeded 50 mm in the past 20 years. The rainfall data were obtained form AMeDAS (Automated Meteorological Data Acquisition System owned by Japanese Meteorological

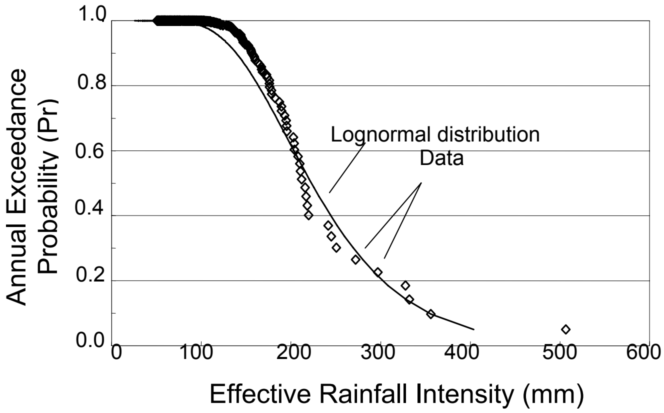


Figure 6 Annual Exceedance Probability of Rainfall Intensity

Agency). The annual exceedance probability is plotted against effective rainfall intensity using Iwai method (1), which is commonly used in the hydrology (Figure 6).

3.3 DEVELOPMENT OF FRAGILITY CURVE

A fragility curve represents the expected rate of failure (the number of slope failures divided by the total number of slopes) against rainfall intensity. The curve was developed through the process shown in Figure 7 (2), as explained below.

(a) Classification of Slopes by Failure Likelihood based on Slope Characteristics

First, individual slopes along the section are classified by failure likelihood level based on the slope characteristics, which are obtained from road slope inspections for anti-disaster by the regional office of MLIT. The inspection data include for both artificial and natural slopes:

1) presence of talus, landslide, overhangs, slide prone soils and rocks, dip slope, impermeable bedrock, soft overburden/ loose rock fragments/ debris, spring water, covering, condition of adjacent slopes
2)classification by angle and height of slopesThe discriminant function was developed by “Quantification Theory II”, a multivariate analysis method, using these slope characteristics as explanatory variables to judge the presence of failure in the last 20 years on each slope (3). Table 2 shows the score range of each slope characteristic obtained by the analysis.

The discriminant function value of each slope is the total scores corresponding to the slope characteristics (item) of each slope. The score ranges in Table 2 present the difference between the maximum scores and the minimum scores obtained from the variation in the slope characteristics. The slope characteristics resulting in the larger score range differentiate the value of discriminant function more significantly. In other words, such slope characteristics have a larger effect on the presence of slope failures in the past.

The discriminant function values of all slopes in the section were calculated based on Table 2. Then the slopes along the section were divided into three categories based on the magnitude of values as shown in Table 3.

Table 2 (1) Discriminant Function for Artificial Slope by Quantification

Order	Item (slope characteristics)	Score range size
1	Slope angle	0.89
2	Impermeable bed rock condition	0.85
3	Slope height	0.75
4	Failure prone geographical feature	0.56
5	Landslide scar, knick line	0.45
6	Overhang etc.	0.28
7	Failure prone rock property	0.20

Table 2 (2) Discriminant Function for Natural Slope by Quantification Theory

Order	Item (slope characteristics)	Score range size
1	Surface loose rocks, etc.	0.84
2	Impermeable bed rock condition	0.78
3	Slope deformation	0.69
4	Dip slope	0.62
5	Slope height and angle	0.41
6	Spring water	0.32

Table 3 Slope Failure Likelihood by Discriminant Function

Failure likelihood	Concept of Classification	Discriminant Function Value	
		Artificial Slope	Natural Slope
Large	Including equal number of failures in the past 20 years in each class	More than 0.7	More than 0.4
Moderate		-0.6 □0.7	-0.7 □0.4
Small	Slopes with no failure in the past 20 years	Less than -0.6	Less than -0.7

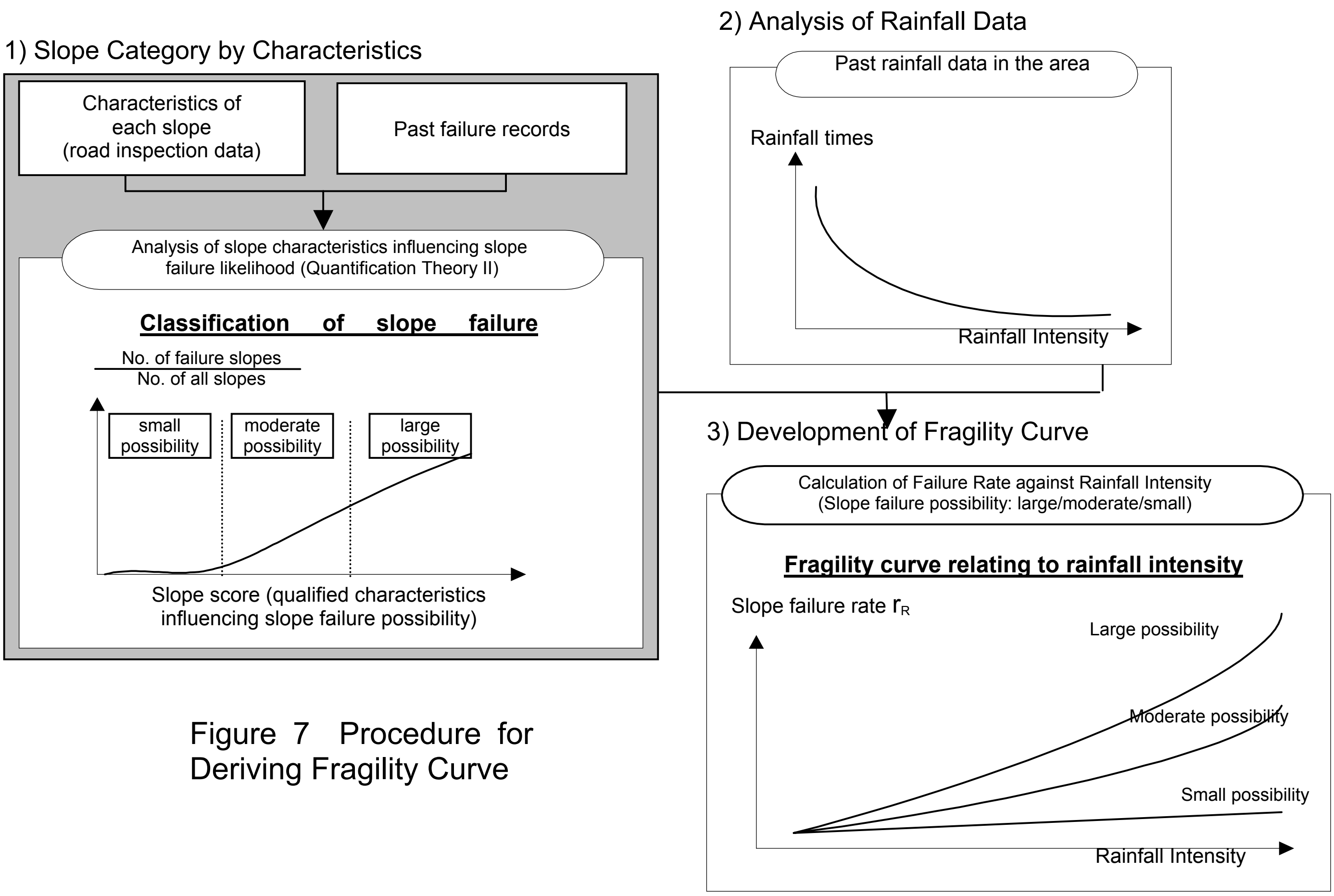


Figure 7 Procedure for Deriving Fragility Curve

(b) Classification of Slopes by Failure Likelihood based on Slope Characteristics
The slope failure rate for the level of rainfall intensity was computed for slope classes with large and moderate failure likelihood. The fragility curves were developed by maximum likelihood method assuming the effective rainfall intensity follows the lognormal distribution (Figure 8).

3.4 CALUCULATION OF THE FAILED EARTH VOLUME OF EACH SLOPE

In order to calculate the failed earth volumes, a regression equation corresponding to the slope characteristics was developed based on the slope failure data in the past. In this case study, because the slope height was found to be correlated most strongly with the failed earth volume, a regression curve for the volume was developed as an exponential function of slope height which is shown in Figure 9.

3.5 CALUCULATION OF LOSS BY SLOPE FAILURE

The expected direct and economic loss by slope failures is calculated by summing the following three loss items, which are all determined based on the failure earth volume and traffic volume on the road.

1) Cost of injuries and deaths (D1)
The loss of human beings was calculated by taking into account Automobiles hit by failed soil and rocks and Automobiles collided into failed soil and rocks. The value of human life was assumed to be 32,970,000 yen per person based on Manual for Road Investment Assessment Method (4).

2) Road restoration expenses (D2)
Using the past failure records, the road restoration expenses were computed by the regression analysis with earth volume, which was developed based on the past failure data.

D2 (Yen) = 9, 625 $\times$ failed earth volume (m^3) + 1, 361,600 (Yen)

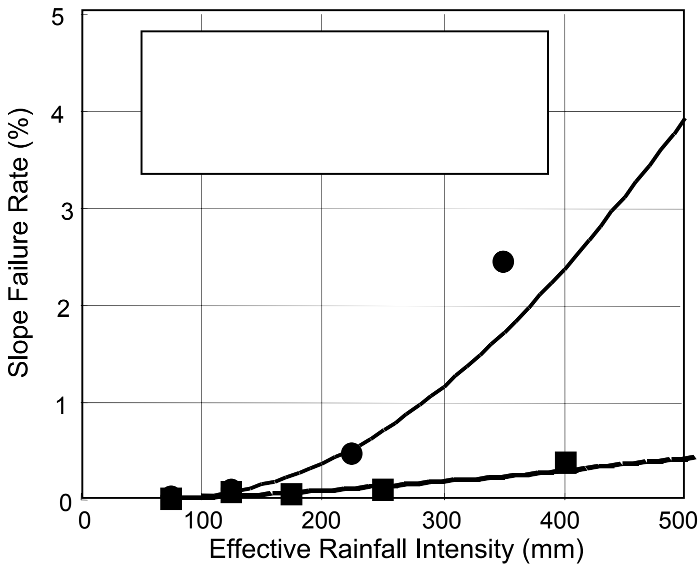


Figure 8.   Fragility Curve for Artificial Slope

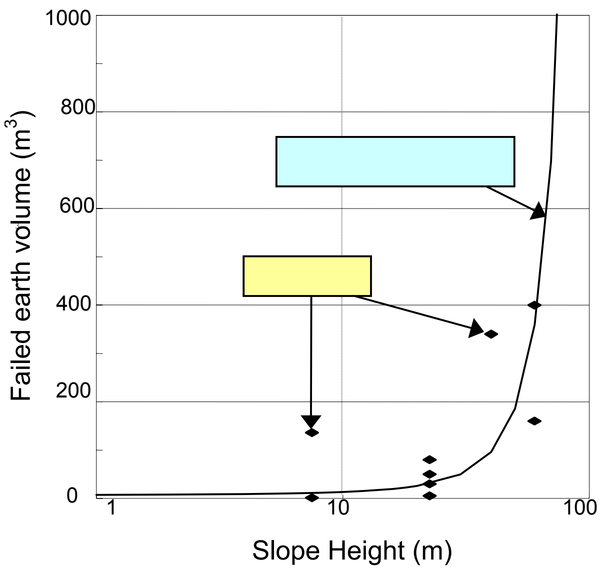


Figure 9   Regression Curve for Failed Earth Volume (Artificial Slope)

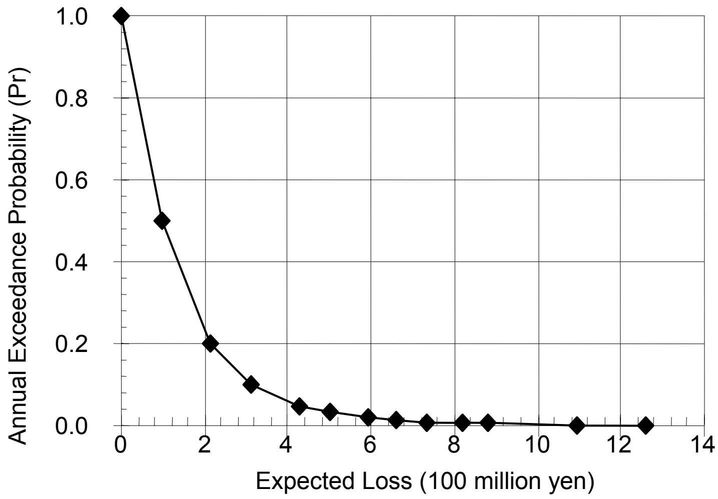


Figure 10 Example of Risk Curve for
Slope Failure due to Rainfall

3) Detour traffic loss (D3)

The required restoration period is computed by dividing the failed earth volume by the expected removable earth volume per day. Assuming that the road traffic makes a detour during the restoration period, the total loss caused by detours was calculated by summing the time loss and the depreciation of automobiles due to extra driving time. The unit prices of these expenses are given in reference (4).

3.6 DEVELOPMENT OF RISK CURVE

A risk curve for an individual slope can be calculated based on the procedure shown in Figure 3 by using the results of the analysis described in the previous sections:

1) the annual exceedance probability for each rainfall intensity
2) the slope failure rate for each rainfall intensity
3) the failed earth volume
4) the monetary loss corresponding to failed earth volume

Then, the risk curve of the section is developed by summing all risk curves of individual slopes along the road section (Figure 10)..An average annualized loss is determined by the area under the risk curve, resulting in about 150,000,000 yen in this case.

4. CONCLUSION

This paper presented a method for developing a risk curve to examine the probabilistic loss by slope failures corresponding to rainfall intensity, using past records of slope failures, precipitation records, and data from slope stability inspection.

A risk curve enables road administrators to perform efficient disaster protection measures. Road administrators can use the proposed risk curve to decide slopes or sections where protection measures must be undertaken with the highest priority, and select adequate risk management measures based on cost-benefit analysis.

In a future study, we will examine the uncertainty in the process to quantify the risks explained in this study and its effects on decision-making. In addition, we plan to conduct a rational risk management for road slope disasters by using the risk curve method for a modeled section.

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