A Method to Determine the Priority of Investment in Disaster Prevention for Rainfall-related Slope Failure

Osamu NUNOKAWA
Senior Researcher,

Tomoyasu SUGIYAMA, Dr. Eng.
Senior Researcher,
Laboratory Head,

Naoyuki OTA, Dr. Eng.
Senior Researcher,

Geo-hazard & Risk Mitigation Laboratory, Disaster Prevention Technology Division

Slope failure resulting from heavy rainfall on railway lines is a common occurrence, making it essential to minimize the phenomenon in the interests of maintaining safe, punctual train operation. It is also necessary to evaluate the disaster risk of individual slopes by considering the probability and potential cost of rainfall-related slope failure. We developed a method to evaluate the potential for slope collapse using a risk assessment technique. This paper describes the method of priority determination for investment to prevent slope failure caused by intense rainfall through application of the technique developed.

Keywords: rainfall, slope failure, disaster risk, risk assessment method

1. Introduction

Disasters that obstruct safe and punctual train operation occur frequently as a result of rainfall-related slope failure on railway lines. Railway operators therefore secure safe and punctual train operation through investment to prevent slope failure and by restricting train operation when rainfall exceeding a certain threshold is observed. It is necessary to evaluate the disaster risk of individual slopes considering the probability and potential costs of rainfall-related slope failure in order to effectively invest in failure prevention measures. We developed a method to evaluate the potential for slope failure using a risk assessment technique. This paper describes the method of priority determination for investment to prevent slope failure caused by rainfall through application of the technique developed.

2. Definition of risk

Districts containing lines A, B and C – which have differing numbers of passengers and levels of slope resistance to rain (Fig. 1) – are assumed. In this case, it is difficult to determine the priority for investment in slope collapse prevention because the number of passengers and the level of slope resistance to rain are separate indices. Accordingly, we examined a method of calculating the level of slope risk in conditions of rainfall using a risk assessment method that simultaneously considers the number of passengers and the level of slope resistance to rain.

Generally, risk is defined as the yearly cost incurred as a result of external factors (such as rainfall), and is calculated by the following expression:

$$R_{isk} = P * C \quad (1)$$

Where,

R_{isk} : value of risk (yen/year)

P : probability of damage (times/year)

C : cost of damage (yen/time)

Fig. 1 Example of different line districts where slopes exist

The probability of damage is related to the level of slope resistance to rain etc., and the cost of damage is related to the number of passengers, etc. Accordingly, the level of slope risk in rainfall conditions is calculated based on (1).

Rainfall-related damage differs according to whether train operation is restricted in the event of a slope collapse. It is therefore necessary to set the events assumed at rainfall in order to calculate the level of slope risk, as well as to ascertain the probability of occurrence and the cost of each event. In this study, we classified the events assumed at rainfall into eight types as shown in Fig. 2. The level of slope risk at rainfall is calculated by the following expression:

$$R_{isk} = \sum_{i=1}^8 (P_i * C_i) \quad (i=1-8) \quad (2)$$

Where,

R_{isk} : level of slope risk at rainfall (yen/year)

P_i : probability of event (times/year)

Fig. 2 Events assumed at rainfall

C_i : cost of event (yen/time)

Essentially, the level of slope risk at rainfall is calculated by adding all the risks of each event. P_i is calculated from Fig. 2 by the following expression:

$$P_i = N_i * P_{ai} * P_{bi} * P_{ci} * P_{di} \quad (i = 1 - 8) \quad (3)$$

Where,

N_i : expected rainfall frequency (times/year)

P_{ai} : probability of slope failure

P_{bi} : status of train operation restriction

P_{ci} : generation time zone of slope failure

P_{di} : probability of damage to vehicles, etc.

3. Method of calculating risk

3.1 Probability of slope failure

It is necessary to evaluate the level of slope resistance to rain in order to calculate the probability of slope failure. In this study, we evaluated the level of slope resistance to rain using the method developed by Okada et al. [1, 2] and Sugiyama et al. [3, 4]. The level of slope resistance to rain that this method calculates can be shown by using indexes of train operation restriction in rainfall conditions as shown in Fig. 3.

This method of evaluating levels of slope resistance to rain calculates the critical rainfall at which slope failure occurs using the results of statistical analysis on data relating to past slope failures. The critical rainfall graph shown in Fig. 3 therefore indicates a 50% probability of

Fig. 3 Example of critical rainfall curve and restriction rainfall values

Fig. 4 Example of slope failure probability distribution

slope failure in the event of rainfall exceeding the values shown by the curve. The distribution of slope failure probability is shown in Fig. 4 under the assumption that the error margin for critical rainfall follows the same normal distribution as the difference between the actual value and the predicted value when this method is applied. The probability of slope failure is calculated from the distribution shown in Fig. 4.

3.2 Expected value of rainfall frequency

It is necessary to show the expected value of rainfall frequency with the same rainfall indexes used to ascertain the probability of slope failure outlined in Section 3.1. We concretely calculated the expected value of rainfall frequency according to the following procedure:

- 1) We analyzed rainfall history using data from the Automated Meteorological Data Acquisition System in the relevant slope neighborhood covering a

Fig. 5 Example of expected rainfall frequency distribution

period of about 30 years, and clarified the distribution of rainfall frequency throughout the year.

- 2) This distribution of rainfall frequency was approximated using the function expression of the normal distribution logarithm. The distribution of the expected values of rainfall frequency was also ascertained.
- 3) The expected value of rainfall frequency can be computed from the distribution of the expected values of rainfall frequency.

Figure 5 shows an example of the distribution of expected values of rainfall frequency.

3.3 Other probabilities of occurrence

Restrictions on train operation can be estimated from the restriction rainfall value as shown in Fig. 3. The generation time zone of slope failure indicates the time zone of trains passing by the targeted slope, and can be computed from the daily ratio of this time. The probability of damage to vehicles etc. is decided depending on factors including the scale and shape of slope failure. The probability of damage to vehicles etc. is therefore calculated by predicting the shape and scale of slope failure using the method proposed by the authors [5, 6].

3.4 Setting of cost items

Cost items depend on the characteristics of the line

Event No.	Cost item (yen/time)				Cost (yen/time) (total)
	Cost of damage vehicles, etc.	Cost of temporary measures	Cost of restoration measures	Cost of train operation	
Event 1	—	—	—	—	C_1
Event 2	—	—	—	—	C_2
Event 3	—	—	—	○	C_3
Event 4	—	○	○	○	C_4
Event 5	—	○	○	○	C_5
Event 6	○	○	○	○	C_6
Event 7	—	○	○	○	C_7
Event 8	—	○	○	○	C_8

※ ○ marks represent cost items corresponding to each event.

Fig. 6 Examples of cost items

※ ○ marks represent cost items corresponding to each event.

Fig. 7 Calculation flow of slope risk at rainfall

district where the slope for evaluation is located. In this study, we set four items as shown in Fig. 6, and arranged the events to which these four items correspond.

The cost of train operation differs for incidents involving slope collapse and those involving the restriction of train movement without slope collapse. The actual cost can be computed from the results of predicting the scale of slope failure, the profits made from train operation, etc.

3.5 Method of calculating risk

Figure 7 shows the flow of calculation for the level of slope risk at rainfall. This figure represents the calculation flow outlined in Chapter 3.

4. Use of risk calculation results

4.1 Conditions of calculation cases

This chapter explains the method used to determine the priority of investment to prevent slope failure based on the calculation cases.

We assumed three individual embankments in three line districts as shown in Fig. 8, and calculated the related risks. These embankments have different levels of slope resistance to rain, and the train operation profits and embankment sizes also differ. It is difficult to determine the priority of disaster prevention investment from these conditions alone. The conditions of calculation are outlined below.

- (1) Calculation of probability for each event

Figure 9 shows the critical rainfall curves and the rainfall value at which train operation is restricted. We created distributions of embankment failure probability from the critical rainfall curves as shown in Fig. 9. The distribution of the expected values of rainfall frequency is taken from Fig. 5. Table 1 shows the conditions used to calculate the probability of each event.

- (2) Cost of each event

For Embankments M_a and M_b (size: large), we assumed that the cost of temporary measures in the event of slope collapse was 10 million yen, and that the cost of restoration measures was also 10 million yen. For Embankment M_c (size: small), we assumed that the cost of temporary measures and the cost of restoration were 5 million yen each.

Fig. 8 The three embankments assumed for calculation

Fig. 9 Critical rainfall curves and restriction rainfall values for the three assumed embankments

We assumed the cost of train operation from the profit of operation each day as shown in Fig. 8. Specifically, we assumed that the cost of train operation restriction was 10% of the profit each day without embankment collapse. And the cost of that with embankment collapse was twice the profit of operation each day. Moreover, the cost of embankment collapse in the train driving time zone was assumed to involve an additional 20%

Table 1 Conditions for calculating the probability of each event

Embankment name	Ma	Mb	Mc
Critical rainfall (L)	14	13	12
Restriction rainfall value	Cumulative rainfall: 150 mm; Hourly rainfall: 40 mm/h		
Distribution of expected values of rainfall frequency	Fig. 5		
Generation time zone of slope failure	Overtime: 0.3; in time: 0.7		
Damage to vehicles, etc.	None		

increase. Table 2 shows the cost of each event assumed in rainfall conditions.

4.2 Calculation of current risk

Tables 3, 4 and 5 show the results of calculating the probability of occurrence, the risk of each event assumed at rainfall, and the total value of the risk for each embankment.

Regarding the probability of slope failure (the total value of the probabilities of occurrence from Events 4 to 8), the value for M_a was 0.268 times/year, that for M_b was 0.405 times/year, and that for M_c was 0.605 times/year according to these tables. In other words, the probability of slope failure became small when the level of critical rainfall was large.

The risk totals are ranked Mb, Ma and Mc from large to small. If the priority for disaster prevention investment is determined using these results, this will be the order of implementation. Thus, even using the current

Table 3 Results of risk calculation for Embankment M_a

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	69.093	0	1,194
Event 2	0.202	0	
Event 3	0.472	47	
Event 4	0.005	21	
Event 5	0.013	55	
Event 6	0.000	0	
Event 7	0.075	300	
Event 8	0.175	770	

Table 2 Cost of each assumed event at rainfall

Slope failure	Restriction of train operation	Generation time zone of slope failure	Damage to vehicles, etc.	Event	Cost (10,000 yen/time)		
					Ma	Mb	Mc
Non-failure	Non-restriction			Event 1	0	0	0
Non-failure	Restriction	Overtime		Event 2	0	0	0
		In time		Event 3	100	70	10
Failure	Non-restriction	Overtime		Event 4	4,000	3,400	1,200
		In time	Non-damage	Event 5	4,400	3,680	1,240
			Damage	Event 6	4,400	3,680	1,240
Failure	Restriction	Overtime		Event 7	4,000	3,400	1,200
		In time		Event 8	4,400	3,680	1,240

Table 4 Results of risk calculation for Embankment M_b

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	69.057	0	1,485
Event 2	0.172	0	
Event 3	0.400	28	
Event 4	0.016	54	
Event 5	0.037	137	
Event 6	0.000	0	
Event 7	0.106	359	
Event 8	0.246	907	

Table 5 Results of risk calculation for Embankment M_c

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	68.973	0	746
Event 2	0.137	0	
Event 3	0.319	3	
Event 4	0.041	49	
Event 5	0.096	119	
Event 6	0.000	0	
Event 7	0.140	169	
Event 8	0.328	406	

risk calculation results alone, the priority for disaster prevention investment can be quantitatively decided.

4.3 Calculation of risk after measures

In this section, we outline the calculation of risk in cases where measures to protect the surface of the embankment are executed, and clarify the effects of disaster prevention investment quantitatively. Specifically, the effect points (4.26) of measures to protect the embankment surface for the critical rainfall at each embankment shown in Table 1 were added, and the probability of each event assumed at rainfall was calculated. Moreover, the cost of measures on Embankments M_a and M_b was assumed to be 15 million yen each, and that for Embankment M_c was taken as 7.5 million yen. In addition, the cost of restoration after the implementation of measures in the event of embankment collapse was assumed to be 1.5 times greater than the current values.

Tables 6, 7 and 8 show the results of post-measure risk calculation, which indicate that the levels of risk after the implementation of measures are clearly less than the current values. This reflects that the probability of slope failure (the total of the probabilities for Events 4 to 8) is obviously less than the current level.

Next, we assumed the risk to be added every year, and calculated the cumulative risk for Embankment M_a before and after the implementation of measures. The results are shown in Fig. 10. The cost of the measures was assumed to be the initial value of the cumulative risk at the post-measure stage. When the current cumulative risk was compared with that after the implementation of

Table 6 Results of risk calculation for Embankment M_a after measures

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	69.110	0	208
Event 2	0.268	0	
Event 3	0.625	63	
Event 4	0.000	0	
Event 5	0.000	0	
Event 6	0.000	0	
Event 7	0.009	41	
Event 8	0.021	105	

Table 7 Results of risk calculation for Embankment M_b after measures

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	69.110	0	271
Event 2	0.260	0	
Event 3	0.608	43	
Event 4	0.000	0	
Event 5	0.000	0	
Event 6	0.000	0	
Event 7	0.017	65	
Event 8	0.039	163	

Table 8 Results of risk calculation for Embankment M_c after measures

Event	Probability of occurrence (times/year)	Risk (10,000 yen/year)	Total risk (10,000 yen/year)
Event 1	69.110	0	146
Event 2	0.249	0	
Event 3	0.581	6	
Event 4	0.000	0	
Event 5	0.001	1	
Event 6	0.000	0	
Event 7	0.028	41	
Event 8	0.066	98

Fig. 10 Cumulative risk before and after measures

measures, the latter value was found to fall below the current value within approximately 1.5 years. Thus, examination that considers investment efficiency can be achieved by calculating the number of years after which the cumulative risk at the post-measure stage becomes less than the current level.

5. Conclusion

This paper describes a method of calculating slope risk at rainfall in consideration of levels of slope resistance to rain, rainfall frequency, the cost of slope failure, etc. It was also clarified that the priority for disaster prevention investment can be determined quantitatively using this method. In future studies, we plan to examine a method of calculating risk in specific line districts or regions based on this technique.

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