RISK MANAGEMENT OF INFRASTRUICTURES ON ROAD NETWORK IN HIDA AREA

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***ABSTRACT*:** A lot of infrastructures, such as roads and bridges, have been constructed to ensure our safety life and economic activities. Maintenance of the infrastructures costs huge sum of money and is getting to be serious financial problems. It is therefore quite important to develop a method which realizes a strategic decision-making of the maintenance and new constructions. This study presents a framework of risk management of infrastructures on road network. Real slopes, bridges and pavements existing in Hida area are selected as target infrastructures. Risks of each infrastructure are evaluated, and the optimum maintenance timing of each infrastructure is analyzed using a dynamic programming method. Finally, a trial calculation is conducted using evaluated risks. As a result, it is found the proposed framework is efficient for risk management of infrastructures.

KEYWORDS: risk management, infrastructure, road network

1. INTRODUCTION

There are many kinds of important infrastructures, such as roads and bridges. These infrastructures ensure our daily life and economic activities. It is however becoming difficult to construct new infrastructures because of budget cut of public works. Furthermore maintenance of existing infrastructures costs huge sum of money. It is therefore quite important to develop a method which realizes a strategic decision-making of the maintenance and new constructions.

A lot of research outcomes have been proposed for maintenance and risk management of infrastructures. This study presents a framework of risk management of infrastructures on road network. The key issue of the proposed framework is to evaluate the risk of various kinds of infrastructures all together, regardless of the type. Risks of real existing infrastructures are evaluated and the optimum maintenance timing of each infrastructure is analyzed using a dynamic programming method. Obtained results are used to conduct a trial calculation. Based on the obtained results of the trial calculation, advantages of proposed framework are discussed.

2. SETTING CONDITINOS

2.1 Target infrastructures and definition of risk

Slopes, bridges and pavements are selected as target infrastructures. These infrastructures are strongly related to road network. Road closure caused by rockfalls is defined as a risk event of slopes. State change of slopes is not considered in this study. On the other hand, deterioration of bridges and pavements are considered. Complete road closure and one lane road closure induced by deteriorations are defined as risk events of bridges and pavements, respectively.

Risk is defined as the product of the economic loss and the probability of the risk event as below,

$$R = P\sum D \quad (1)$$

where, R is the risk, D is the economic loss and P is the probability of the risk event.

2.2 Study area

Hida area, northern part of Gifu prefecture in Japan (Figure 1), is selected as a study area. Mountain areas are widely distributed, and there are a lot of target infrastructures in the area. Based on a survey data, 3023 slopes, 157 bridges and 997-meter pavements are employed in this study. The reason why the area is selected is because detailed survey data of infrastructures and accident data has been accumulated in the area.

Figure 1 Study area

2.3 Assumptions

Because objective of this study is to build a framework of risk management, following assumptions are used at present stage to simplify setting conditions. (a) Risk event of each infrastructure occur independently. Thus, Condimental occurrence of risk event is not considered. (b) Effects of earthquake and rainfall are not considered directly. This means these factors are not employed in calculations of the probability of the risk event.

3. PROBABILITY OF RISK EVENT

3.1 Probability of risk event of slopes

As mentioned in subsection 2.1, risk event of slopes is defined as road closure induced by rockfall. It is therefore necessary to evaluate rockfall probability at each slope. The probability is calculated based on a survey data. An intensive slope survey was carried out in 1996. A total of 3023 slopes were investigated by the experts in the study area, and separated into two types (rockfall and rock failure) and three levels (namely measures required (MR), observation (OB) and no measures (NM)). In addition, detailed information of each slope, such as geological characteristics and geometric configuration, were accumulated in the survey database. Based on the database, firstly, relative rockfall probability is calculated using a logistic regression analysis. Then the relative probability is calibrated to absolute rockfall probability using the rockfall accident data. Number of slopes and rockfall accidents are summarized in Table 1. As shown in the table, the study area includes three regions, Gero, Takayama and Furukawa. Different rockfall probability models are built in consideration of the rationality. Histograms of annual absolute rockfall probability are shown in Figures 2, 3 and 4. It is found the probability of Furukawa region is higher than other two regions. The reason is because number of rockfall accidents in Furukawa region is larger than that in other two regions.

Table 1 Number of slopes and rockfall accidents

Region	Evaluated Level	Number of slopes		Number of rockfall accidents	
		Rockfall	Rock failure	Investigated	Uninvestigated
Gero	MR	186	51	5	7
	OB	399	68	12	
	NM	204	10	0	
Takayama	MR	275	109	7	17
	OB	517	380	7	
	NM	133	36	0	
Furukawa	MR	277	35	11	16
	OB	126	20	5	
	NM	186	11	3	

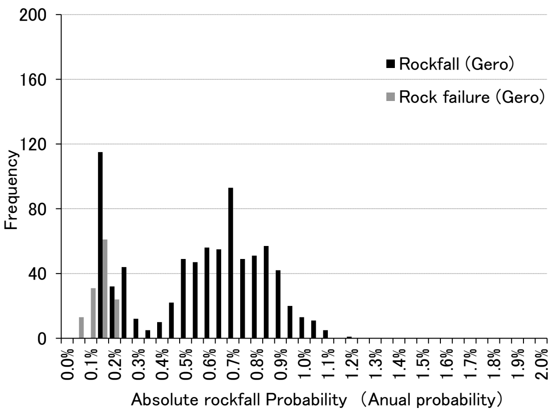

Figure 2 Rockfall probability (Gero)

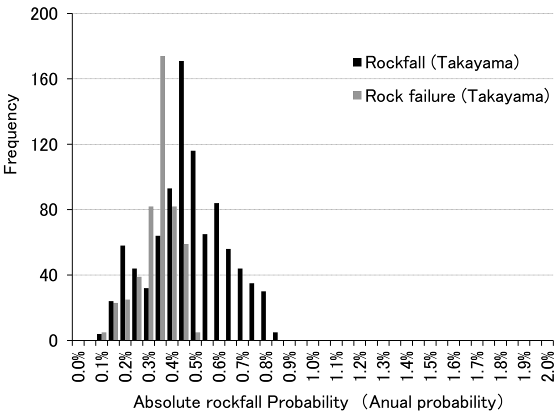

Figure 3 Rockfall probability (Takayama)

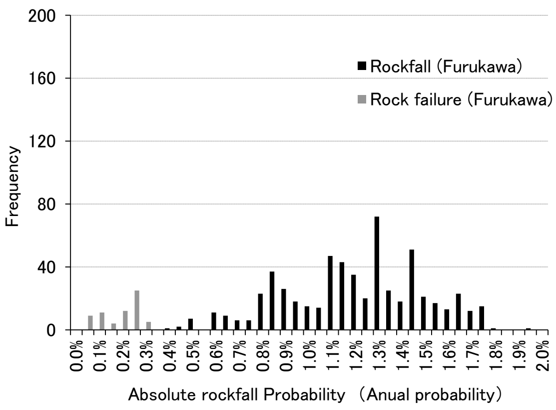

Figure 4 Rockfall probability (Furukawa)

3.2 Probability of risk event of bridges

Risk event of bridges is defined as road closure induced by deterioration of bridges. In other words, the risk event is a massive maintenance work associated with the road closure. We defined the risk event of bridges as shown in Table 2. The contents shown in the table are determined based on results of discussions with members of the managing unit of Gifu prefecture on bridge maintenance. As shown in the table, bridges are categorized into two types (steel and concrete), and deteriorations of principle components are considered.

Table 2 Risk event of bridges

Bridge Type	Component	Deterioration factors	Maintenance work
Steel	Edge of Girder	Corrosion	Replacement of Girder
	RC Deck	Fatigue damage of traffic loading	Replacement of deck
Concrete	Girder and Deck	Corrosion of reinforcing steel	Replacement of Girder and Deck

Deterioration models of bridges have been proposed in a previous study (Otake et al, 2011). In the study, detailed inspection data of 54 bridges existing in Gifu city were analyzed, and a health index of bridges were introduced. The health index takes from 1.0 to 5.0, and the smaller value indicate progression of the deterioration. A relation between degree of deterioration (health index) and the elapsed years was also proposed in the previous study. The proposed health index and Deterioration models are used in this study. According to the previous study, the deterioration rate is strongly depends on the age and design load capacity of bridges. Figure 5 and 6 shows the deterioration models.

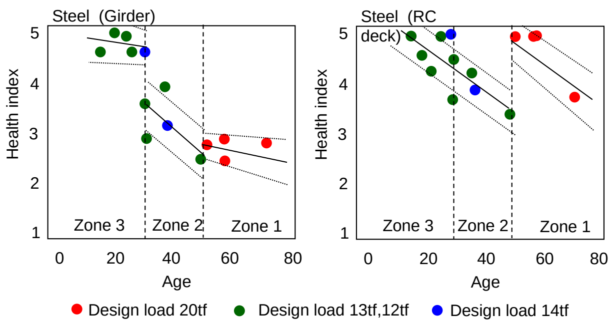

Figure 5 Deterioration models of steel bridges (Otake et al., 2011)

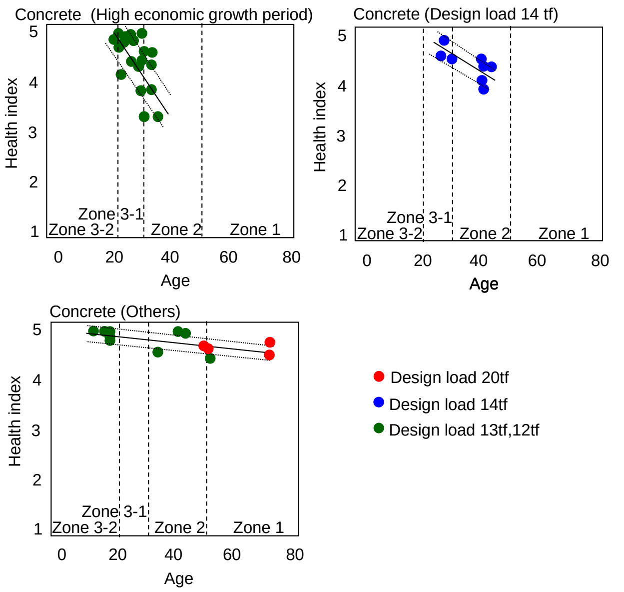

Figure 6 Deterioration models of concrete bridges (Otake et al., 2011)

It is assumed the risk event of bridges arise when the health index reach 1.5. Based on this assumption, the probability of the risk event is calculated. Figure 7 shows an image of the concept of the probability. The normal probability distribution is assumed around current health index, and the probability of the risk event is calculated as exceedance probability shown in Figure 7. When the health index becomes smaller value, large value of the probability arises. By using this concept, it is possible to calculate the probability at any value of the health index. Figures 8 and 9 show relation between the probability and the health index.

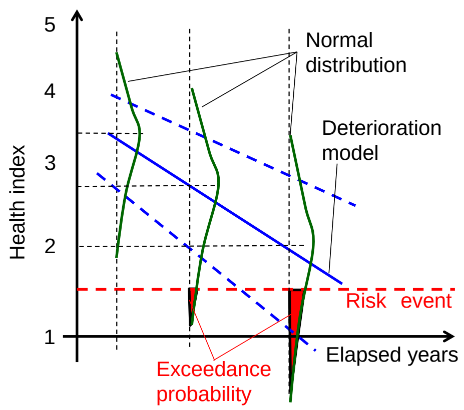

Figure 7 Image of exceedance probability of risk event

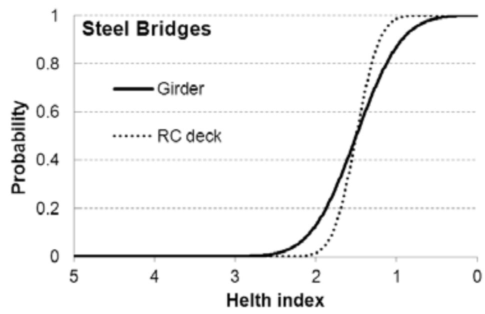

Figure 8 Probability-health index relations (Steel bridges)

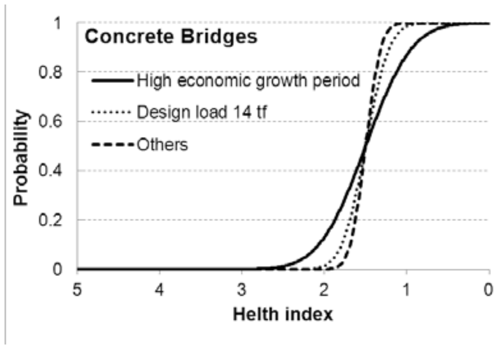

Figure 9 Probability-health index relations (Concrete bridges)

3.2 Probability of risk event of pavements

Risk event of pavements is the one lane road closure induced by deterioration of pavements. Evaluation procedure of the probability of pavements is almost same as that of bridges. Replacement of the pavement associated with the road closure is defined as the risk event. Although the health index is introduced in evaluation procedure of bridges, another index is used for pavements. MCI (Maintenance Control Index) is widely used in the management of pavements. The value of MCI is evaluated from some factors related to road conditions, such as crack, rut and flatness. The value takes from 0.0 to 10.0, and the smaller value indicate progression of the deterioration of pavements. The values had been investigated in about 50% of roads in study area. MCI is therefore used as deterioration index of pavement directly.

A deterioration model of pavements is obtained from MCI data and a maintenance history. Figure 10 shows a relation between age of pavements and MCI value. The age means elapsed years since the pavement had constructed. Because there is large variation in Figure 10, only one deterioration model is assumed shown in the figure. Then the probability of risk event of pavements is calculated using the concept shown in Figure 7. Figure 11 shows the obtained probability curve.

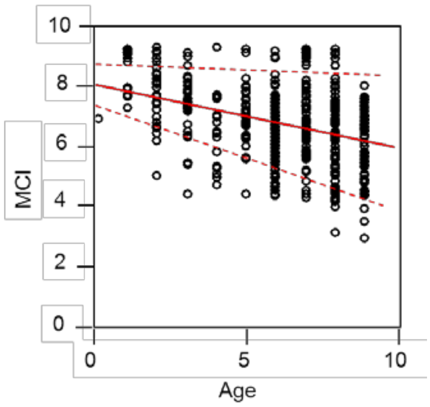

Figure 10 Age-MCI relations (pavements)

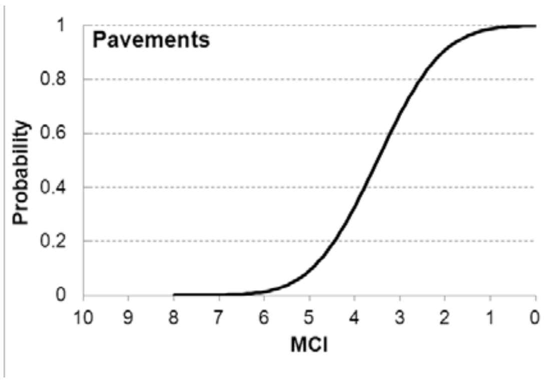

Figure 11 Probability-MCI relations (Pavements)

4. ECONOMIC LOSS

4.1 Evaluation items

As shown in Figure 12, the economic losses considered in this study are separated into two categories; direct loss and indirect loss. The direct loss includes the accident loss (D_1) and the restoration cost (D_2), and the indirect loss includes the circumvention loss (D_3) and the emergency medical service loss (D_4) . Thus, equation 1 can be described as below,

$$R = P(D_1 + D_2 + D_3 + D_4) \quad (2)$$

Calculation procedures of each evaluation items are explained briefly in following sections.

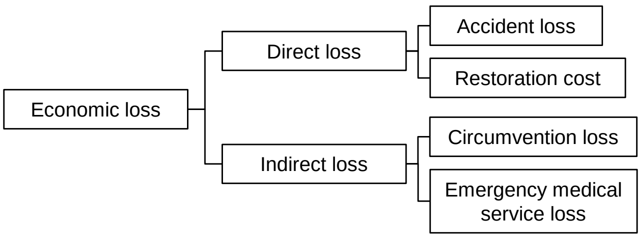

Figure 12 Economic loss

4.2 Accident loss

The accident loss of slope is calculated based on a supposition that drivers or passengers are injured or killed due to the rockfall. Public Works Research Institute (PWRI) (2004) proposed a concept of the accident loss. Figure 13 shows an image of the concept. Amount of the accident loss is evaluated based on trapezoid distribution shown in the figure. Height of the trapezoid means the value of human life. The value (242 million Japanese Yen (JPY)) is obtained from a report published by Japanese government (2007).

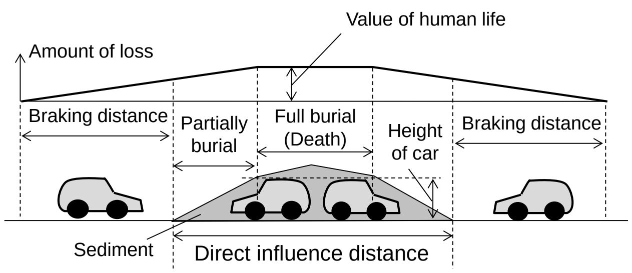

Figure 13 Image of accident loss of slope（PWRI, 2004）

The accident losses of bridges and pavements are calculated from compensation data of traffic accidents resulting from deterioration of road surface. 30 cases of the traffic accidents taken place during 2004 to 2009 in Gifu prefecture are used. As a result, 64000 JPY is defined as the accident losses for one accident.

4.3 Restoration cost

The restoration cost of slopes is evaluated from a history database of rockfall accidents. The data has been accumulated after 2008. Detailed information including restoration cost of each rockfall accidents are accumulated in the database. 115 cases of restoration cost data are used and the averaged cost (410,000 JPY) is employed as the restoration cost.

The restoration costs of bridges and pavements are defined as a cost which is required for massive maintenance work associated with road closure. Unite value of the restoration costs are summarized in table 3.

Table3 Restoration costs of bridges and pavements

Infrastructure (Type)			Maintenance work	Restoration cost
Bridge	Steel	Edge of Girder	Replacement of Girder	Jack-up 1,300,000 JPY/ Fulcrum Replacement of Girder 210,000 JPY/ Girder
		RC Deck	Replacement of deck	220,000 JPY/ m^2
	Concrete		Replacement of Girder and deck	330,000 JPY/ m^2
Pavement			Replacement	9,300 JPY/ m^2

4.4 Circumvention loss

The Circumvention loss is a loss induced by the road closure. The loss is calculated using following equation.

$$D_3 = CT \tag{3}$$

where C and T are amount of change of the consumer surplus and number of road closure days, respectively. C is calculated using increments of driving time and driving distance that are calculated from a traffic flow simulation based on the user equilibrium assignment theory. Unite amount of time value and driving cost are obtained from a manual published by The Ministry of Land, Infrastructure, Transport and Tourism (2008). Number of road closure days for each infrastructure is assumed as shown in Table 4.

Table4 Number of road closure days

Infrastructure (Type)			Number of road closure days
Slope			1 day
Bridge	Steel	Girder	2 days/ Fulcrum
		RC Deck	14 days
	Concrete		30 days + 0.19 days/ m^2
Pavement			0.01 days/ m^2

4.5 Emergency medical service loss

The Emergency medical service loss is related to death of emergency patients due to the road closure. Mortality rate of emergency patients is strongly depends on transportation time of ambulances. Hashimoto et al. (2002) studied about a relation between the mortality rate and the transportation time. In their study, brain hemorrhage, subarachnoid hemorrhage, acute myocardial infarction, pneumonia, cardiopulmonary arrest and brain infarction are employed as target diseases. These diseases and the model proposed by Hashimoto et al. (2002) are used in this study. Onset rate of each disease is analyzed using a medical data accumulated in the target area.

The one lane road closure is assumed to be risk event of pavements. It can be considered ambulances can run though even in the situation. Therefore, the emergency medical service loss is not included in the economic loss of pavements.

4.6 Results of evaluation of economic loss

Figures 14-18 show examples of evaluated economic loss of slopes, bridges and pavements. Results of the top 20 of each infrastructure are shown in the figures. Results of bridges are separated depending on the types and the components. The economic loss of pavements is evaluated with unit length of 100 m. Different colors are used to distinguish each economic loss. As shown in the figures, it is found the circumvention loss is a big part of economic loss in all infrastructures. There is big difference between the value of bridges and the values of other infrastructures. The difference is mainly comes from number of road closure days. As shown in Table 4, Number of road closure days is much longer than that of other infrastructures. The number of days strongly affects circumvention loss.

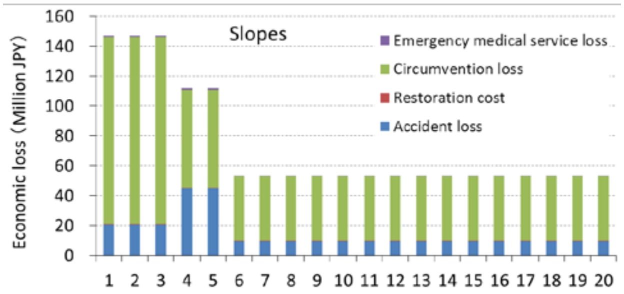

Figure 14 Economic losses of slopes

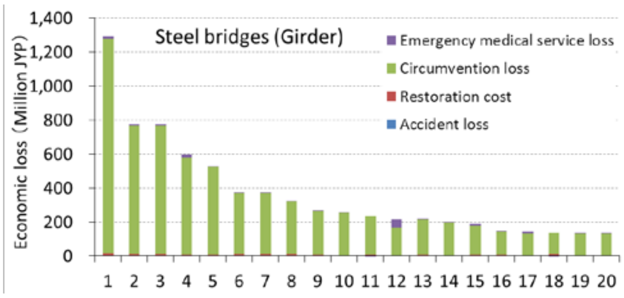

Figure 15 Economic losses of steel bridges (Girder)

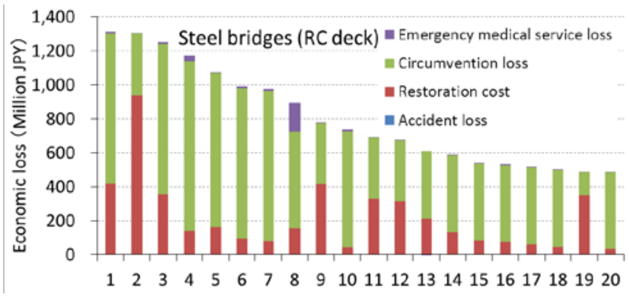

Figure 16 Economic losses of steel bridges (RC deck)

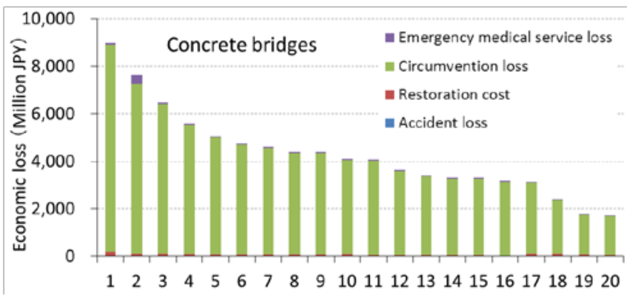

Figure 17 Economic losses of concrete bridges

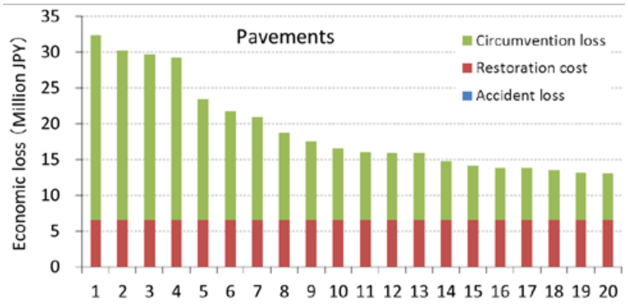

Figure 18 Economic losses of pavements

5. RISK MANAGEMENT

5.1 Current risks of target infrastructures

Values of current risk of slopes, bridges and pavements existing in study area are compared in this subsection. Figures 19-21 show calculated rick of each infrastructures. Results of the top 20 are shown in the figures. Because state change of slopes is not considered, the risks shown in Figure 19 don’t change temporally. On the other hand, the risks of bridges and pavements change due to the deterioration. It is therefore difficult to compare the risks using only the figures, but we can confirm a difference between infrastructures at current state. As we can see from the figures, risks of bridges are relatively larger than that of other infrastructures.

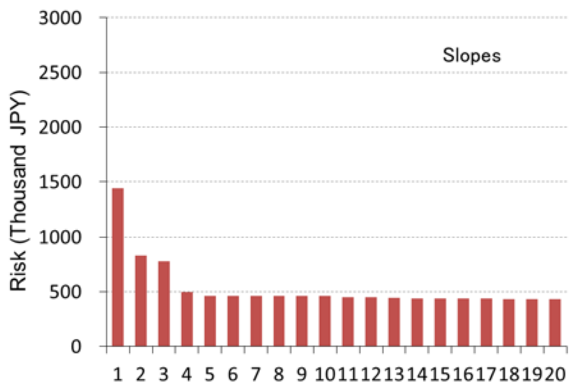

Figure 19 Risk of slopes

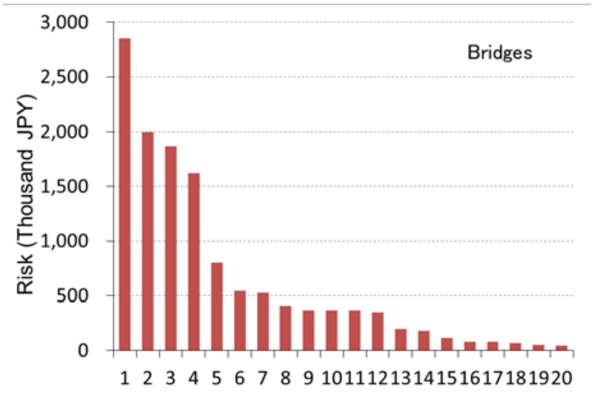

Figure 20 Risk of bridges

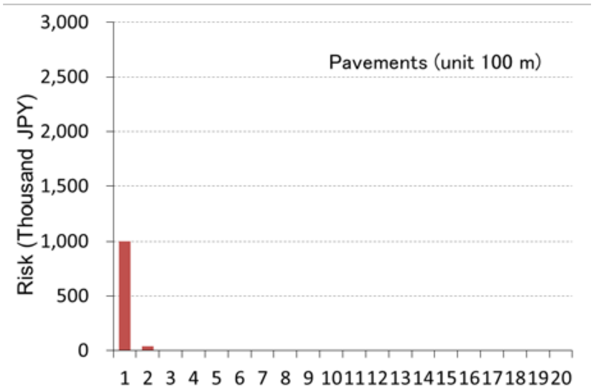

Figure 21 Risk of pavements

5.2 Optimization of maintenance plan

Here, an example of optimization of maintenance plan is discussed. As mentioned in previous subsection, risks of slopes are constant values. Therefore, measurement priority of each slope can be determined based on current cost-benefit ratio (B/C). On the other hand, there is optimum maintenance timing for each bridge and pavement because the deterioration is considered. In this study, the dynamic programing method (DP) is used to evaluate the optimum maintenance timing.

Because the costs of each infrastructure are required to consider maintenance plan, the calculation procedure of the costs are explained. The cost of slope had been evaluated by Gifu prefecture, and the information is directly used for slopes. The maintenance cost of bridges and pavements are calculated using in Tables 4-8. The maintenance costs depend on the health index or MCI. Effect of road closure induced by the maintenance works is considered in maintenance costs.

Table4 Maintenance cost of steel Bridge (Girder)

Health index	Maintenance work	Cost (JPY/m^2)	Number of Road closure days
4.5 – 5.0	Follow-up	50% of cost at health index 4.0	none
3.5 – 4.5	Partial recoating	40,000 (10% of area)	none
2.5 – 3.5	Full recoating	50,000	none
1.5 – 2.5	Reinforcement using backing plate	80,000	none
0.0 – 1.5	Replacement	1,300,000 / Fulcrum 210,000/ Girder	2 days/ Fulcrum

Table5 Maintenance cost of steel Bridge (RC deck)

Health index	Maintenance work	Cost (JPY/m^2)	Number of Road closure days
4.5 – 5.0	Follow-up	50% of cost at health index 4.0	none
3.5 – 4.5	Patching	40,000 (10% of area)	none
2.5 – 3.5	Reinforcement of bottom surface	50,000	none
1.5 – 2.5	Reinforcement of top surface	80,000	7 days
0.0 – 1.5	Replacement	220,000	14 days

Table6 Maintenance cost of concrete Bridge (PC)

Health index	Maintenance work	Cost (JPY/m^2)	Number of Road closure days
4.5 – 5.0	Follow-up	20% of cost at health index 3.0	none
3.5 – 4.5	Follow-up	50% of cost at health index 3.0	none
2.5 – 3.5	Grout reinjection	20,000	none
1.5 – 2.5	Reinforcement of outside cable	110,000	none
0.0 – 1.5	Replacement	330,000	19 days/m^2 + 30 days

Table7 Maintenance cost of concrete Bridge (RC)

Health index	Maintenance work	Cost (JPY/m^2)	Number of Road closure days
4.5 – 5.0	Follow-up	20% of cost at health index 3.0	none
3.5 – 4.5	Follow-up	50% of cost at health index 3.0	none
2.5 – 3.5	Patching (small scale)	40,000 (30% of area)	none
1.5 – 2.5	Patching (large scale)	100,000 (50% of area)	none
0.0 – 1.5	Replacement	330,000	none

Table8 Maintenance cost of pavements

MCI	Maintenance work	Cost (JPY/m^2)	Number of Road closure days
5.5 – 10.0	Overlay	1,800	none
3.5 – 5.5	Cutting overlay	3,100	none
0.0 – 3.5	Replacement	9,300	One line road closure

Life Cycle Cost (LCC) at time t which is total value from time t to the end of project life is defined as follows,

$$l(t,h(t)) = f(h(t)) + \min\left(\frac{l(t+1,h(t)-\Delta h_i)}{1+r}, m(h(t)) + \frac{l(t+1,h_0)}{1+r}\right) \quad (4)$$

$l(t,h)$: LCC at time t and state index h
$f(h)$: Risk at state index h
$m(h)$: Maintenance cost at state index h
Δh : Decrement of state index in one time step
h_0 : State index after maintenance work

Because LCC at next time step $t+1$ is used for calculation of LCC at time t, LCC values are calculated from the end of project life. The optimum maintenance timing of bridges and pavements are analyzed by minimizing LCC.

Two examples of maintenance plan under fixed project life (50 years) are considered to check effect of risk management. Concept of each plan is explained in what follows.

Plan A

Risks obtained in his study are not used, and current maintenance situation is assumed in this plan. Priority of measurement of slopes is determined based on amount of traffic and evaluation result of the slope survey data. Annual budget for slope measurement is assumed as 15 billion JPY. The amount of money is determined based on real budget in Gifu prefecture. As for bridges and pavements, fixed values of the health index and MCI are defined for maintenance timing. 2.5 and 3.5 are used as fixed values of the health index and MCI, respectively. Thus the maintenance timings of bridges and pavements are determined using only the values. Budget constraint of bridges and pavements are not considered.

Plan B

Results obtained in this study are efficiently used in this plan. Priority of measurement of slopes is determined based on B/C. The annual budget of slope is same as Plan A. The maintenance timings of bridges and pavements are determined based on the results obtained from the dynamic programing method. As same as plan A, budget constraint of bridges and pavements are not considered.

Results of above tow maintenance plans are shown in Figures 24-27. Figures 24 and 25 show histories of annual cost. Costs of each infrastructure are distinguished by different colors, and total amount of cost is also described in the figures. It is shown that maintenance timings of bridges and pavements change by using the dynamic programing method. The timings of Plan B are earlier than that of Plan A. Because of this earlier maintenance, the total cost can be reduced. According to the Figures 24 and 25, we can reduce about 10 % of the total cost. Although the difference of costs is not so big, there is big difference between risks of Plan A and Plan B. As we can see from the figures 24 and 25, total risk of Plan B are much less than that of Plan A. Risks of bridges and pavements are reduced especially. This tendency can be seen also in the LCC (Figures 25 and 26). This indicates the framework proposed in this study is quiet efficient for maintenance planning of infrastructures.

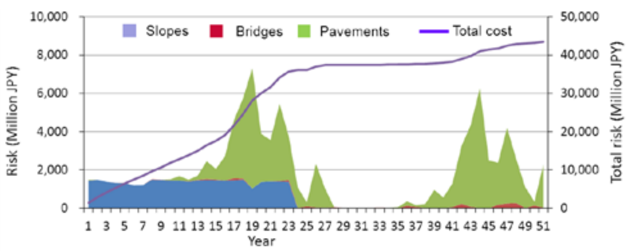

Figure 22 History of annual cost (Plan A)

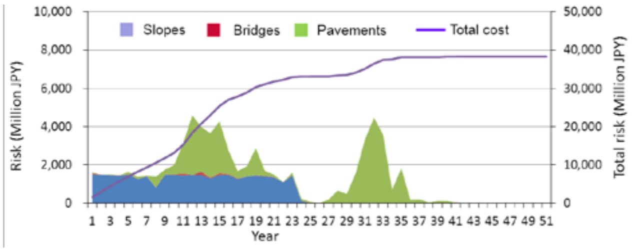

Figure 23 History of annual cost (Plan B)

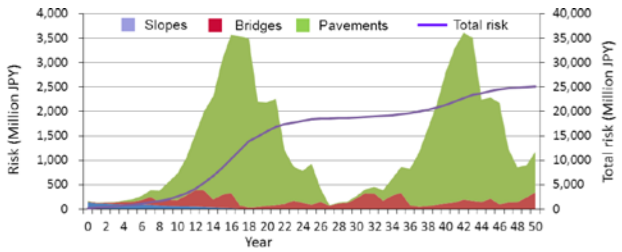

Figure 24 History of annual risk (Plan A)

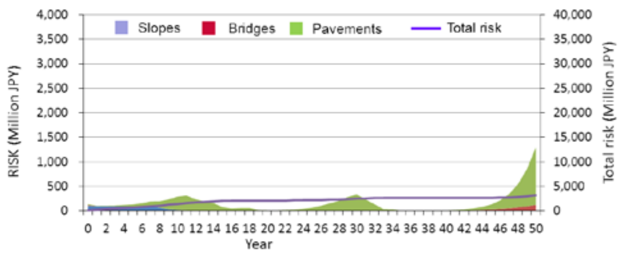

Figure 25 History of annual risk (Plan B)

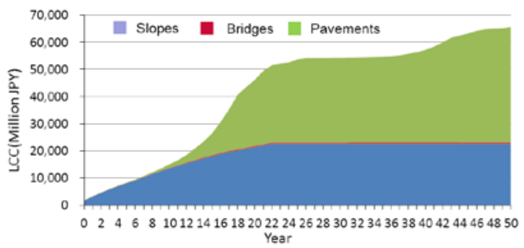

Figure 26 History of LCC (Plan A)

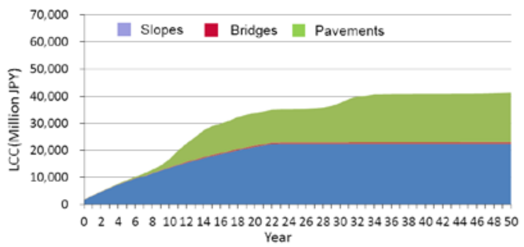

Figure 27 History of LCC (Plan B)

6. CONCLUTION

This study presents a framework of risk management of infrastructures on road network in Hida area. Risks of slopes, bridges and pavements existing in the area are evaluated under the unified framework. Two examples of maintenance plans are considered, and a trial calculation is conducted using the evaluated risks. As a result of the trial calculation, it is found the proposed framework is efficient for programing maintenance of infrastructures.

Optimum maintenance timings of bridges and pavements are considered in this study, however, Budget constraint is not considered. Optimization of maintenance plan under the budget constraint is remains as one of major problems to be solved.

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