BRIDGE LIFE-EXTENDING REPAIR PLAN CONSIDERING CONNECTIVITY OF THE EMERGENCY ROAD NETWORK IN DISASTER

F. Ogawa [1], Y. Chikata[2], S. Nakayama[3]

[1] *Technical Staff, Kanazawa University, Engineering and Technology Department, ogawa@se.kanazawa-u.ac.jp*
[2] *Professor, Kanazawa University, Institute of Science and Engineering, Faculty of Geosciences and Civil Engineering, chikata@staff.kanazawa-u.ac.jp*
[3] *Professor, Kanazawa University, Institute of Science and Engineering, Faculty of Geosciences and Civil Engineering, nakayama@staff.kanazawa-u.ac.jp*

Abstract

Each municipality has developed the life-extending repair plan of the bridges to maintain properly the bridge stock which aging simultaneously in the near future. The repair priority of bridge is considered in the plan based on the importance of bridges, such as the volume of traffic, crossing other roads or not, etc. However the plan does not take into account whether bridge failures when disasters occur can maintain the connectivity of the road network in the region.

Japan is located in the earthquake-prone area and severely damaged by earthquakes, such as the 2016 Kumamoto Earthquakes and the Tohoku Region Pacific Coast Earthquake in 2011. Because bridges are series element structures configuring the road network, it is also important to consider not only the soundness of the bridges, but also the connectivity of the road network. In particular, the bridges intensely constructed in during the period of high economic growth are going to be repaired all at once, it is necessary to manage the bridges and the road networks in preparation for the risk of disaster occurrence.

This research focuses on the management of the bridges on the emergency road network, and verifies the effectiveness of considering the disruption risk of the emergency road network at the time of disaster occurrence through the simulation of the bridge life-extending repair planning. Especially, an objective function related to road network connectivity is introduced to the simulation of life-extending repair planning for bridges on emergency roads. The effect of the risk reduction of road network connectivity is analyzed.

The result with the proposed method and the original repair plan with the objective function of leveling the budget in the term of the simulation were compared. The comparison of the results shows the slight increment of repair cost by repair ahead of schedule and the significant improvement of connectivity of road network. It is implied that the connectivity of the road network is improved with minor changes in the life-extending repair plan to account for road connectivity.

Keywords: Bridge management, emergency road network, life-extending repair plan

1. Introduction

A great number of the bridges in service in Japan were constructed during the period of economic development from the 1960s. These bridges have been aging, more than 50 years have passed since their construction. The appropriate operation and management of bridges under the conditions of a restricted budget and staff must be determined. Because the most existing bridges were built in the period of high economic growth, they will most likely require repairs at the same time. Therefore, there are many studies of Bridge Management System (BMS) (e.g [1][2][3]), and implementations are also proposed. Some of these systems have actually been adopted by municipalities that introduced a customized BMS to continue appropriate operation and managment their bridges. The system has often implemented the function to level the annual budget based on evaluation of the priority of bridge repairmen, considering the degree of damage and economic social indices such as traffic volume.

In recent years, large scale disasters such as the 2016 Kumamoto Earthquakes and 2011 Tohoku Region Pacific Coast Earthquake have occurred, and risk management is also required for such disasters [4]. Deterioration of existing bridges is expected to increase the risk of failure from a disaster occurrence. The bridges are parts of the surface transportation infrastructure; therefore, the increasing risk of bridge failure is associated with a decrease in the connectivity of road networks. In other words, maintenance actions should be planned to consider these issues.

In this study, a novel method is proposed for the formulation of a life-extending repairment plan of bridges considering the increasing risk of failure because of a disaster and the subsecuent decreasing connectivity of the road network.

2. Literature review

2.1 Reliability and vulnerability of the road network

In the field of transportation research, numerous studies associated with the evaluation of the road network connectivity have been conducted. In many cases, the aim of study was to increase resilience or to decrease vulnerability by assessing the traffic volume changes or arrival time delay when a particular road was closed.

Nakayama [5] reviewed the studies on the connectivity reliability and vulnerability of the road network, and summarized their perspectives and future works. It has been pointed out there that it is important to develop the evaluation method for road link reliability at a catastrophic disaster, by cooperating with other field studies such as earthquake engineering, after the Great Hanshin Awaji Earthquake that occurred in 1995 caused large scale social and economic loss. Usami et al. [6] proposed an evaluation method of the road functional strength which is defined as the probability of road closure due to a natural disaster. The road functional strength is evaluated using the indexes of road preservation such as the information on past road closures caused by heavy rain and storms. The result can be used as an effective material for evaluating alternative and resilient decisions abkout the priorities of road improvement. Furuta et al. [7] proposed a method for ordering the seismic reinforcement of bridges using a resilience index that is composed of the resistance to disasters and the recovery speed from disasters. The result of a numerical simulation implied that the resilience of the road network is increased and the safety such as the reduction of the evacuation distance and the number of isolated nodes is also improved, as compared with the conventional method that is based on the importance of the roads.

2.2 Formulation of bridge management plan

Several studies have been conducted on the formulation of a life-extending repair plan of bridges. Chikata et al. [8] proposed a method of formulating a realistic long-term bridge management plan that minimizes total repair costs and levels the costs each year. The study showed that bridges cannot be well maintained within the level of restricted budget if the bridges are in a bad condition at the beginning of the simulation. Kita and Chikata [9] applied game theory in bridge management and regarded each bridge as a player. A life-extending repair plan could be optimized considering the importance of each bridge by predetermining the appropriate utility functions for the individual players. Shibuya and Sugimoto [10] simulated the formulation of a bridge management plan considering the realistic conditions. In particular, the classification of maintenance categories according to the importance of the bridge, and the changes of budget constraints during the passage of time is considered. From the simulation result, the proposed method can be applied to the actual role of bridge management by municipalities. Hattori et al. [11] proposed a method for setting the objective function and adjusting the coefficient to achieve both level annual cost and an increasing in the mean soundness of bridges.

Minimizing the life cycle cost, leveling annual costs, and improving bridge soundness are often set as the objective functions for optimizing bridge life-extending repair plans [1, 10]. However, aiming for the operation of bridges in good condition through the bridge life-extending repair plan is not sufficient; it is also important to manage bridges considering the disruption risk to the road network due to natural disasters. The progression of bridge deterioration increases the risk of damage from natural disasters in the future. Because bridges are series element structures configuring the road network, it is also important to consider not only the soundness of the bridges, but also the connectivity of the road network.

2.3 Purpose and significance

In previous studies, life-extending repair plans for bridges have often been optimized to manage the bridges under a normal situation without the occurrence of a natural disaster. However time-series risk management considering is also required because bridge failures and road network disruptions occur owing to external factors such as natural disasters. Although many studies assessing road network vulnerability have been conducted, it is unlikely that the results apply to the management of individual surface transportation infrastructure such as bridges and to the development of a life-extending repair plan.

In a bridge management case study that considers road network disruptions due to disasters, Ogawa and Chikata [12] showed that there is a risk of disruption due to deterioration of multiple bridges in an emergency transportation road network in Ishikawa Prefecture in addition to planning of maintenance actions which consider road networks. The study further indicated that comprehensive bridge management considering the road network connectivity is important.

In this study, taking the emergency transportation road in Ishikawa Prefecture as an example, a formulation method of considering the road network connectivity in the event of a disaster in a life-extending repair plan for bridges was compared with the current method which does not consider, and the necessity of considering the connectivity of road network in the plan is discussed.

3. Method

3.1 Using data

Emergency transportation roads as polyline data from the National Land Numerical Information download service (emergency transportation road (line)) provided by the National Land Information Division, National Spatial Planning and Regional Policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan [13] are used as a transportation network. The endpoints of the polyline and the intersections of each polyline are set as nodes. The road corresponding with the nodes is set as the link.

The bridge data in the analysis use the results of bridge inspections provided by Ishikawa Prefecture, Hokuriku Regional Development Bureau, Kanazawa Office of Rivers and National Highways, and Kanazawa city, Hakusan city, and Komatsu city. The bridge health index (BHI) is evaluated with Table 1 which has been used for bridge soundness evaluations in actual life-extending repair plans by Ishikawa Prefecture [14]. The initial BHI is randomly set based on the current soundness ratio of the bridge inspection results by Ishikawa Prefecture.

Table 1 – Bridge evaluation

Deficiency rating	Description
V	No damage.
IV	Slight damage. Inspection data are recorded.
III	Damage. Follow-up investigation is required.
II	Damage in a large area. Detailed investigation is required
I	Serious damage. There is a possibility of danger to traffic.

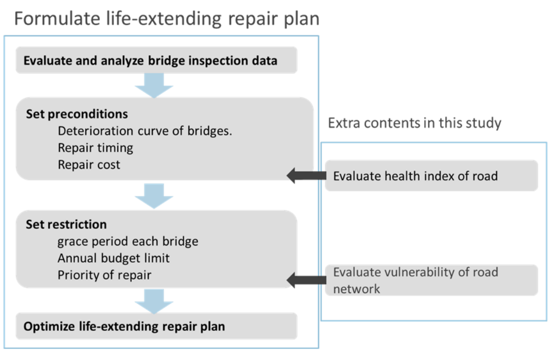

Fig.1 – Conceptual workflow of the proposed method

3.2 Plan optimization process

The simulation flow is shown in Fig 1 and the simulation preconditions are described as follows. The deterioration model is represented by Eq. (1) which has been adopted by many municipalities in the actual plan for repair of bridges for life-extension.

$$Y = 5 - ax^2, \quad (1)$$

where Y is the BHI, a is the coefficient of deterioration for each bridge, and x is the elapsed years from the time of construction or repair.

α is randomly set from a normal distribution ($\alpha \sim \mathrm{N}(a_{std}, a_{std} \times 0.1)$). α_{std} is set to 0.00164 with reference to the actual life-extending repair plan.

Refer to Table 1, the standard repair time of bridges assumes to be less than soundness less than 2. The soundness of the bridge is recovered completely (BHI returns to 5) when the repair work is performed. The repair cost of each bridge is generated according to a log-normal distribution (LN(0, 1)) because the bridge length distribution can be approximated by a log-normal distribution. The standard repair cost is represented as a unit. The time of repair is permitted to be from 9 years less than to 3 years more than the standard repair time. Repairs can be changed from three years before the standard repair period to nine years in advance. This indicates that the soundness of a bridge with standard deterioration stay between 1.5 and 3. Based on the conditions previously described, the optimization such as budget leveling will be implemented. The progression of the bridge deterioration increases the risk of damage by natural disasters, such as earthquakes and tsunamis. Traditionally, the risk is often represented by a calculation of the event probability and damage

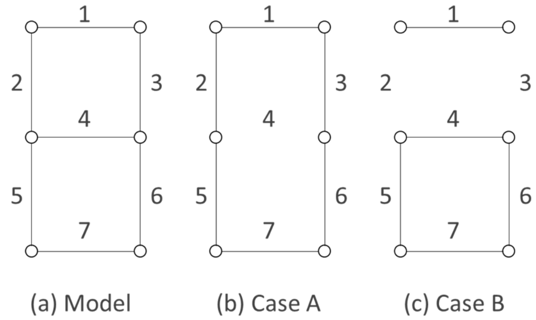

Fig.3 – Model of network vulnerability evaluation

amount. The risk factors that affect the bridge soundness are not identified in this study because they are associated with extreme events, such as the earthquakes and tsunamis that have a low probability and unpredictable occurrence.

The evaluation of the soundness and vulnerability of the road link is described as follows. The soundness of the road link was defined by the minimum soundness of the bridges (BHI) on the road link. If the BHI was less than 2.5, it was assumed that there was a risk to its usability if a natural disaster occurred. In addition, the road link where a bridge within a soundness less than 2.5 located was assumed impassable at the time of a disaster. The threshold value 2.5 was determined to refer to the description of the health index in Table 1. The bridge repair plan should be optimized to reduce the risk of the road link's disruption. The simulation period was set for 100 years. The genetic algorithm (GA) was used to obtain a semi-optimum solution because the combination of parameters was extremely large.

The disruption of the road network is described using simplified network model as shown in Fig.3. An initial road network is shown in Fig.3(a) as a simple example. In case A as shown (b) in Fig.3, the loss of link 4 will not affect the connectivity within the network as nodes can still be transported. However, in case B shown in Fig.3(c), the loss of the two links (links 2 and 3) will affect the connectivity within the network because the network has been divided into two network components. In this paper, the objective function is set to prevent the disruption shown in Fig.3(c).

In this study, three repair strategies are defined. In the first strategy named "Initial," the bridges are repaired without any optimization when the health index falls below 2. In the second strategy called "Strategy A," bridges with a health index below 2 are repaired during the allowable period and the plan is optimized by leveling the annual repair cost. In the third strategy "Strategy B," bridges with a health index below 2 are repaired as in Strategy A; additionally, the plan is optimized by minimizing the vulnerability of the road network. The semi-optimal solutions using the objective functions of Strategies A and B are compared.

$$obj = \min\left(\sum_{i=1}^{NB}\sum_{j=1}^{NY}\left(CO_{i,j}\right)^{p}\right) \tag{2}$$

$$obj = \min\left(\left(\sum_{i=1}^{NB}\sum_{j=1}^{NY}\left(CO_{i,j}\right)^{p}\right)\left(\sum_{i=1}^{NY} CL_i\right)\right) \tag{3}$$

where, $CO_{ij} = \frac{cost\ of\ i\text{-}th\ year}{annual\ cost}$ and $p = \begin{cases} 1(CO_{ij} \leq 1) \\ 2(otherwise) \end{cases}$.

NY denotes the simulation period, NB denotes the number of bridges, CL_i denotes the number of network clusters in the i-th year, and p denotes the coefficient that is the controlled penalty when the i-th year cost exceeds the annual cost. In the GA, solution candidates evolve through generations with the operations of selection, crossover, and mutation at each

Table 2 – Parameters of the simulation

Simulation period (year)	:	100	Max generations	:	3000
Number of bridges	:	1364	Population size	:	100
Number of road links	:	601	Crossover operation (probability)	:	uniform (0.6)
Number of nodes	:	413	Mutation probability	:	0.01
Budget restriction	:	Yes	Number of elite chromosomes	:	5

generation, and finally reach the optimal or semi-optimal solution. The parameters of the GA are shown in Table 2. Both the elitist and roulette-wheel selections are used as selection operators. The uniform cross-over is used as the cross-over operation. The grey code is used to encode to remain continuously with the stage of the mutation operator. From preliminary trial calculations, the maximum number of generations to ensure convergence is 3000. The results optimized by Strategies A and B are compared, and the influence of the road network connectivity is considered.

4. Results

The annual bridge repair costs for the simulation are shown in Fig.4. the accumulation of the annual repair costs is shown in Fig.5. The dashed lines in the figures indicate the completely leveled repair cost.

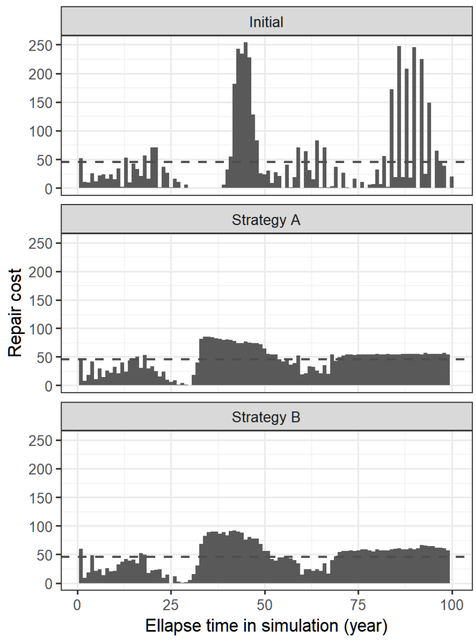

Fig. 4 – Annual repair cost

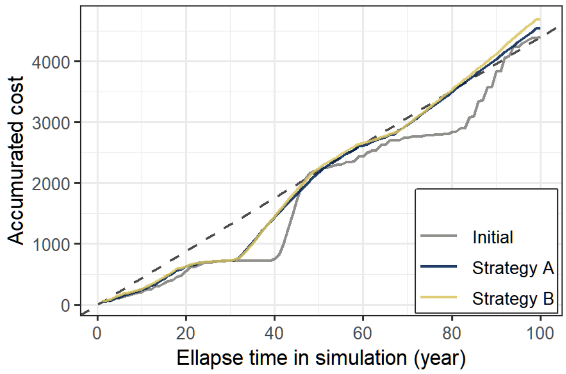

Fig.5 – Accumulation of annual repair costs

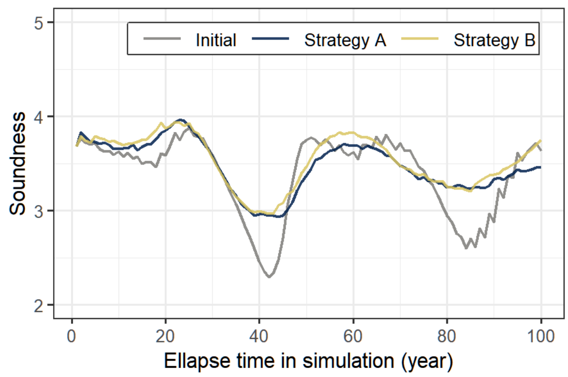

Fig.6 – Average health index of the road links

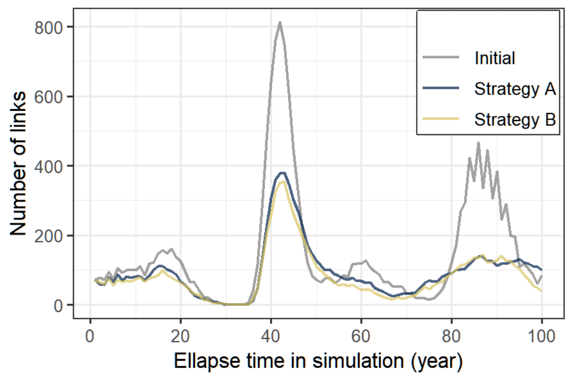

Fig.7 – Number of road links with health index below 2.5

Under the Initial Strategy, the annual repair cost varies widely because bridges constructed in the same period will need to be repaired simultaneously. In Strategies A and B, it can be confirmed that annual repair cost has been leveled, and the total repair costs are roughly the same. The number of repairs during the simulation in order from the largest to the smallest is Strategy B, Strategy A, and Initial (Initial Strategy: approximately 2900, Strategy A: approximately 3000, Strategy B: approximately 3100), and that affects the total cost. The result assumed no expectation of leveling the cost completely when the plan was optimized. A simple model is used here; therefore, the annual repair cost cannot be leveled completely. Shibuya and Sugimoto [10] showed that annual repair costs could be leveled by creating a complex model such as considering the unit smaller. In this study, verifying the effect of the road network connectivity on a life-extending repair plan is prioritized.

The transition of the soundness of the road link for each strategy is shown in Fig.6. The transition of the number of road links with a health index below 2.5 for each strategy is shown in Fig 7. Although there is no significant difference between the results of Strategies A and B, Strategy A shows better results. Both Strategies A and B have improved the health index of the road links and reduced the number of road links with a disruption risk compared to the initial strategy.

For Strategies A and B, the deviation from the standard repair time for repairs is shown in Fig 8. The number of repairs is larger in Strategy B than in Strategy A. The number of repairs ahead of the standard repair time is larger in Strategy B than in Strategy A and it is probable that this resulted in the differences between Strategies A and B as shown in Figs. 6 and 7. It is considered that Strategy B tended early repairs to reduce the risk of road network disruption. The number of network components which is represented the network has a disruption risk divided into multiple network due to link vulnerability is shown in Fig.9. Strategy A can reduce the components; However they remain approximately the same as in the initial strategy. On the other hand, Strategy B can reduce the components although the total repair cost increased slightly. This implies that considering the connectivity of the network in a life-extending repair plan is important.

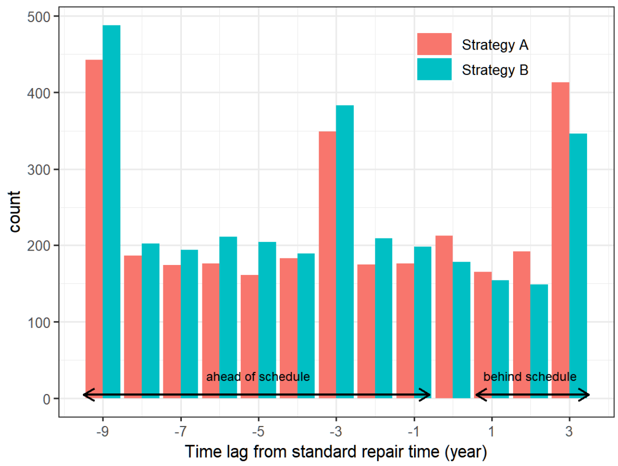

Fig.8 – The difference from standard repair time.

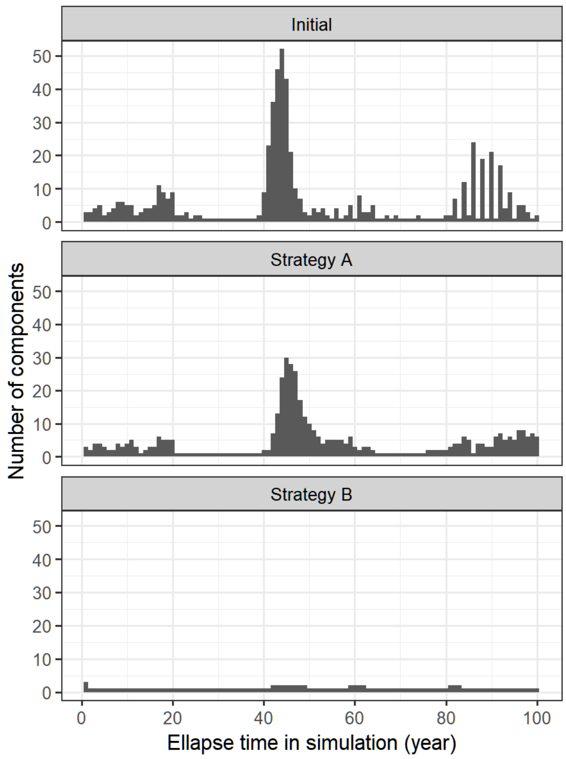

Fig.9 – Number of network components

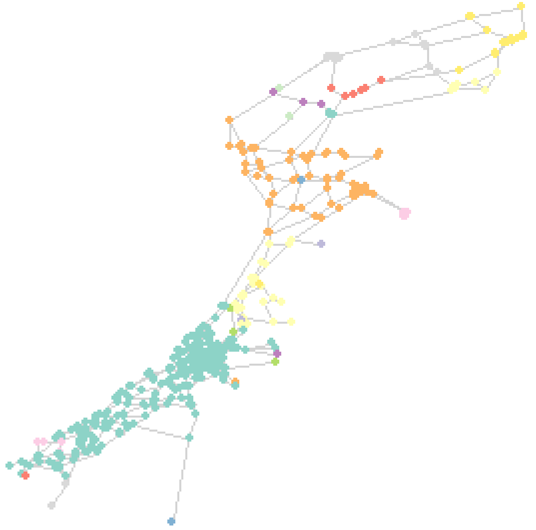

Fig.10 network evaluation in 44th year (Strategy A)

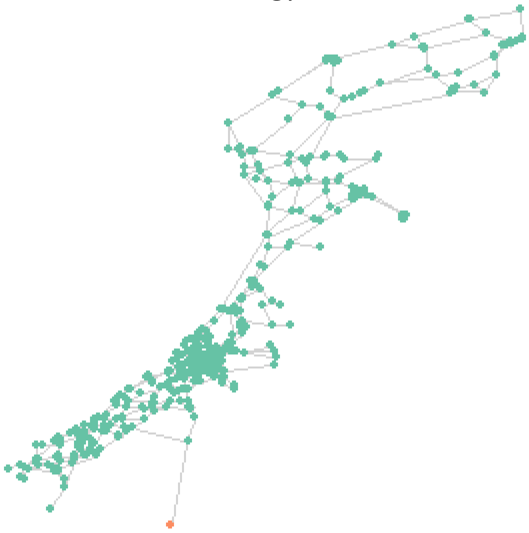

Fig. 11 network evaluation in 44th year (Strategy B)

Fig.10 and Fig.11 show the disruption risk of the network in 44th year when bridge deterioration progresses rapidly. Although in Strategy A, the risk of divisions into multiple networks increases as shown in Fig.10, only the nodes at the bottom of Fig.11show an increase the risk of isolation in Strategy B. The link divided from the other networks at the bottom of Fig.11 has a risk of disruption with the other links for a long time owing to its location in a mountainous area, its large number of bridges, and its longer length. Bridges on links with more significant disruption risks than the others require another countermeasure, such as more intensive repairs on that link, or a consideration to prepare other transport methods.

5. Conclusion

In this study, a novel method is proposed for the formulation of a long-term plan for maintenance of bridges considering the connectivity of the road network. The proposed method reduced the disruption risk of the road network by considering the maintenance of the road network connectivity with a slight increase in the total cost. However, considering the expectation of bridge deterioration and the frequency of disasters in recent years, it is important to formulate the life-extending repair plan of bridges and consider the risk of bridge failure and road network disruption in case of an emergency. The proposed method as shown in this study is suitable for effectively formulating a plan for repair with the goal of life-extension, considering the connectivity of the road network.

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