The influence that the Type of the Deterioration Prediction in Bridge Gives to a Maintenance Budget Plan

THE INFLUENCE THAT THE TYPE OF THE DETERIORATION PREDICTION IN BRIDGE GIVES TO A MAINTENANCE BUDGET PLAN

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***ABSTRACT*:** We usually decide maintenance scenario by minimized life cycle cost from deterioration prediction when we make the bridge maintenance budget plan. There are two types of deterioration prediction, which is graph type and condition transition type. Each type of prediction has a precondition and a characteristic, However, it is often that each prediction is not had a good command of well. In this study, we arrange characteristic of two deterioration predictions, and compare the way of calculation of LCC, and we make the phase of suitable scene and precondition clear. Next, we calculate the LCC of each deterioration predictions for the bridge, and we consider the influence that the difference of the deterioration prediction type gives to the maintenance management budget plan.

KEYWORDS: deterioration curve of graph type, deterioration curve of state transition type, maintenance plan

1. INTRODUCTION

Various movements have been reported regarding asset management. Asset Management Research Subcommittee (chairman: Kazumasa Ozawa, Professor of Tokyo University) was established in JSCE Construction Management Committee in August 2002, and presently more than half of the local prefectural governments are involved in activities related to revision of maintenance plan, starting with Tokyo, Aomori, Yokohama, Shizuoka and Osaka. In reality, however, due to perception gaps between local governments regarding maintenance and expensive inspection cost, the maintenance planning has not progressed favorably yet. The Ministry of Land, Infrastructure, Transport and Tourism launched the policy of longer life promotion project that would be effective as of 2007 FY, where the life of bridges is extended up to 100 years by changing the conventional repair method taken after problems actually occur to the frequent and preventive maintenance method taken before problems actually occur[1)]. Under the policy, local governments are encouraged to create maintenance plans and receive government subsidies covering half of the necessary cost if the following conditions are satisfied: civil engineering specialists must be involved in revising maintenance plan and the plan must be open to public. The effective period for subsidies is 5 years for national and main local roads controlled by prefectural governments and government ordinance cities, and 7 years for other local roads[1)]. According to this policy, it is expected that local governments start working on revising bridge longer life plans and maintenance plans energetically. Furthermore, according to the government's Proposal for Preventive Maintenance of Roads and Bridges[2)] issued on May 16, 2008, the following five concrete measures were proposed as preventive maintenance system focusing on early detection and countermeasures: institutionalized inspection, securing reliability of inspection and diagnosis, promotion of technological development, organization of technical bases, and establishment of database.

While revising maintenance plan for longer life, it is necessary to predict deterioration. However, in many cases, various prediction methods are mistakenly used. Specifically, there are two major prediction methods: graph type and state transition type having different preconditions and characteristics, but the both preconditions are sometimes confused under the asset management subsystem for LCC accumulation and budget levelization. For instance, in the graph type prediction method, it is impossible to represent state distribution at each fiscal year, whereas it is impossible to determine repair timing by the state transition type prediction method.

In this research, characteristics of the graph type and state transition type prediction methods are summarized and life cycle cost (LCC) calculation methods are compared to clarify the preconditions and suitable use situation of each type. Then, LCC for bridge is calculated for each type, and the impact of different prediction methods on maintenance budget plan is studied. Furthermore, studies are conducted regarding determination method of repair interval for members using the prediction methods, presupposed conditions of the prediction methods, and cautions required when determining repair interval using the graph type prediction method.

2. DETERIORATION PREDICTION UNDER MAINTENANCE BUDGET PLAN

2.1 Purpose of deterioration prediction

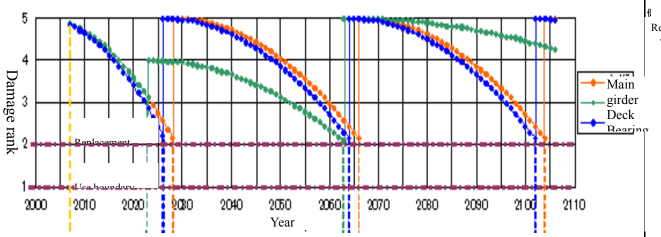
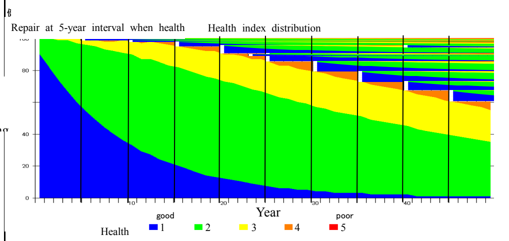
Deterioration prediction plays a substantially important role on asset management because prediction accuracy largely affects prior evaluation and project planning while taking total management into account.

In documents describing deterioration prediction, deterioration curves are often used where the vertical axis represents performance (health index) and lateral axis represents time. This curve is easy to see that health index becomes smaller as time passes and it recovers after repair. Factors that affect deterioration prediction are assumed to be structural or geometrical conditions, material types, environmental conditions, load fluctuation, etc. In reality, deterioration is difficult to predict because these factors relate with one another in a complicated manner. Therefore, the method commonly taken is to predict deterioration progress during a service period by deterioration factor and estimate performance degradation. **Table 1** shows the comparison of major prediction methods[3]. For instance, a formula is presented to predict quantitatively the progress of neutralization of RC member and permeation of chloride ions[4),5)]. Details on the method (A) are described on the document[6)] and other materials. On the other hand, the method (B), a typical deterioration prediction model, is the Markov Chain Model[7),8)]. However, the methods (A) and (B) sometimes are both used and there are deterioration progressing phenomena that cannot be explained by these prediction methods.

Table 1 Deterioration prediction method

⌋	(A) specify deterioration mechanism , And a method to predict a fall of a dynamic characteristic	(B) A method to predict a fall of a inspection rank statistically in testing
health index	Dynamic characteristics such as shearing force without push or fatigue strength of steel materials	The thing which evaluated inspection rank of Ⅰ, Ⅱ, Ⅲ, Ⅳ, OK shown in the inspection manual
merit	We can define demand performance as a health index definitely. For example, relations of a fall of a load-carrying capacity by fatigue and allowable stress	We can estimate a health index of the direct present from a inspection result We can express a complicated deterioration process in a simple model Revision by a inspection result is always necessary We contain many structure group and can evaluate it
de-merit	It is difficult to connect performance of load-carrying capacity with a inspection result For example, like bridge expansion and bearing, the damage and relations with a factor are complicated. It is difficult to specify mechanism of	As for the fatigue of steel materials, an omen is hard to appear from inspection result. Besides, a prediction from a inspection result is very difficult.

Table2 Comparison of LCC according to long-term budget plan depending on deterioration prediction methods

	Graph type deterioration prediction method	State transition type deterioration prediction method
Maintenance interval	Proportion of members that are below replacement boundary is not known because health index is average value. Thus, all members are repaired when the average health index reaches the replacement boundary. Repair interval is determined as a period from repair timing until the next replacement boundary.	Damage found at regular inspection carried out every five years as specified in the inspection guideline (draft) is repaired until the next regular inspection timing. Repair interval is basically five years.
Deterioration prediction model		
Inspection purpose	To check progress of damage due to deterioration	To detect damage
Risk when damage is found	Repair interval can be several decades depending on deterioration curve. Risk is relatively high because detection of new damage or damage due to quickly progressing deterioration may be overlooked.	Risk is relatively low because detection of new damage or damage due to quickly progressing deterioration may be detected by regular inspection.
Remarks	It is uncertain when replacement timing comes and thus it is hard to find link to short-term repair plan (judgment on repair necessity). When deterioration progresses slowly, however, cost reduction may be possible by omitting regular inspection conducted every five years.	It is easy to find link to short-term repair plan because repair necessity is judged at regular inspection conducted every five years.

2.2 Characteristics of deterioration prediction methods

As mentioned earlier, the deterioration prediction method used in maintenance planning is classified as graph type and state transition type, and **Table 2** shows the comparison between the two. In the state transition type, state-owned facilities are inspected every five years and damages found during the inspection are repaired, and thus relationship between inspection and repair is easy to understand. Some organizations specify the inspection frequency as every 10 years or every 15 years instead of every five years for cases where deterioration progress is slow. For instance, when deterioration progress is slow, because most of members do not reach the predetermined repair level yet, they are not repaired.

Here, studies are conducted on calculation method for repair timing, which is an important factor of LCC accumulation.

Each deterioration prediction type has a different concept regarding determination of repair cycle. In the case of graph type, repair interval may be calculated based on the assumption that repair should be conducted when the marginal maintenance line is reached. However, in the case of state transition type, there are two alternatives: determination by proportion of health index and by fixed number of years.

The two methods to determine repair interval in the state transition model are as follows: (1) assumption by proportion of health index (rank 3 or higher): 10 % or more (preventive maintenance) and 20 % or more, 30 % or more (corrective maintenance); and (2) assumption by number of years: preventive maintenance (2 years, 5 years), conventional maintenance (10 years) and corrective maintenance (15 years, 20 years). Results indicate that the longer the repair interval is, the smaller the health index is, although average health index varies. It is said that, although it depends on deterioration rate, for preventive maintenance, construction cost (LCC) is lower when maintenance interval is short. However, for corrective maintenance, LCC is lower when repair interval is longer. **Figs. 1 to 2** show repair examples as classified in (2) above. In **Fig. 1**, members ranked 4 or lower in health index are repaired every 5 years whereas in **Fig. 2** those ranked 4 or lower in health index are repaired every 10 years. As expected, the proportion of the members ranked 4 or lower is smaller when repaired every 5 years.

The characteristics of (1) are variable repair interval and unclear basis of proportion setting whereas the characteristic of (2) is constant repair interval. It is difficult to present the basis of percentage from experiences while trying to establish the scenario where repair is conducted when percentage of health index (rank 3 or higher) is a specified value or more.

On the other hand, deterioration curve may change after member is repaired depending on repair methods. However, within present knowledge, it is difficult to assume deterioration curve after repair because there is no inspection data (progress of damage) of repaired portions, and thus original deterioration curve should be used.

Further, when considering the present inspection works, maintenance design works and construction, whether repair is necessary is judged and detailed investigation, repair design works and construction are conducted only after problems are found at inspections carried out every several years. Therefore, nothing is done against damages found by inspections until the next inspection timing if repair is judged unnecessary. In the end, this customary method is based on the "inspection cycle equals repair cycle" principle and necessary portions are repaired on a budget acquired by the next inspection timing.

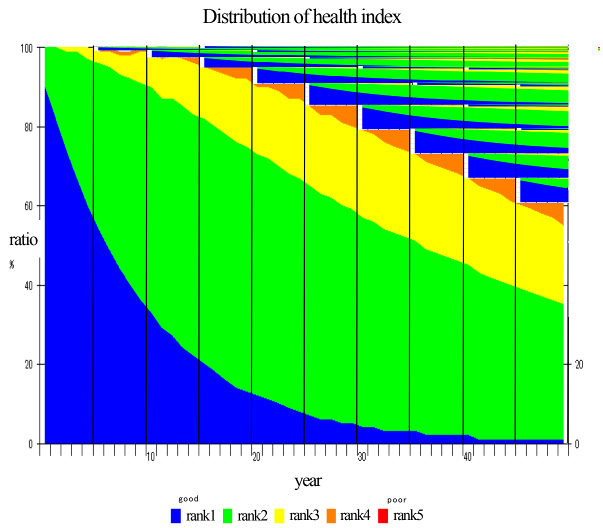


Fig.1 Distribution of health index (repair lower than rank 4 every five years)

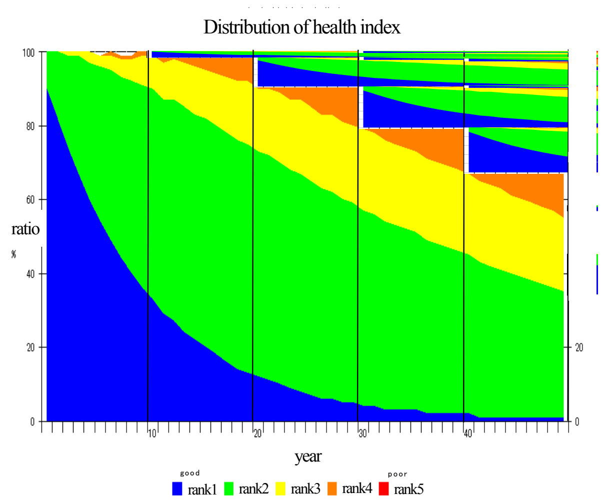


Fig.2 Distribution of health index (repair lower than rank 4 every ten years)

The difference of the calculation methods for deterioration prediction is studied as follows.

In the graph type, quadratic deterioration curves are prepared by the Ministry of Land, Infrastructure, Transport and Tourism according to member and material (see left in **Table 2**)[8]. On the contrary, in the state transition type, deterioration is predicted statistically using the past inspection results as mentioned in the document[7]. Therefore, deterioration prediction accuracy depends on the quality and amount of data used.

Next, the preconditions of the deterioration prediction methods are considered as follows. What does the graph type deterioration prediction curve represent?

When **Fig. 3** represents average health index, and if it shows that all members ranked 3 or lower (3, 2, 1) are repaired when the average health index reaches 3, not all the indices become 5 even after members ranked 3, 2, and 1 are repaired up to 5 because there are members ranked 4. The resulting curve will be a in **Fig. 3** if all members ranked 4, 3, 2, and 1 are repaired up to 5 when the average health index reaches 3, but in reality the members ranked 4 will be left because repair will be judged unnecessary. As a result, members ranked 4 remain and the resulting average health index will be b. Therefore, **Fig. 3** only shows the conceptual drawing of deterioration but does not show the entire deterioration condition. The deterioration curve will be a in **Fig. 3** when the entire area is repainted altogether as in bridge repainting process.

This deterioration curve is used to determine repair interval for calculating LCC, such as repair every X years for preventive maintenance (rank 4, 3) and repair every Y years for corrective maintenance (rank 2, 1).

To give a specific example, RC deck (5×4=20) for one span is considered. It will never happen that all the decks are ranked 3 after y3 years because they do not deteriorate uniformly. Instead, the correct understanding is that the average health index among these decks will be 3 after y3 years. In this case, there will be decks ranked 1, 2, 4, and 5 after y3 years, but their proportion is unknown. The condition represented by a is that all the decks (ranked 4, 3, 2, and 1) are repaired up to 5. But repair of decks ranked 4 is unnecessary and repair cost for decks ranked 2 and 1 will be high.

From this point, the graph type deterioration method

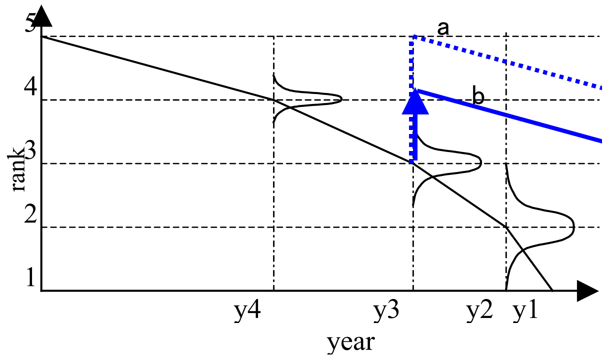


Fig.3 deterioration curve(graph type)

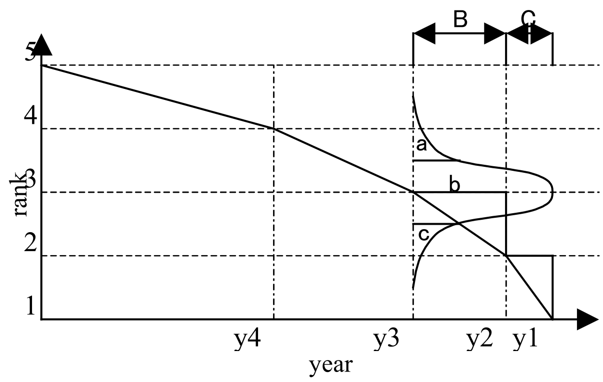


Fig.4 Image of state distribution on deterioration curve of graph type

is suitable for determining repair timing based on the average health index, but variations cannot be considered. In short, the graph type prediction method does not clarify whether variations are considered, and even if they are considered, it does not show how much.

Repair is represented in **Fig. 4** when variations are considered in the graph type deterioration method. When deterioration progresses more slowly than normal, repair is not required. When deterioration progresses more quickly than normal, repair is necessary and care must be taken to shorter period than normal during which the health index is maintained. Shorter period than normal where the health index is maintained may indicate changes of maintenance scenario. The concept of the period where the health index is maintained is shown in the drawing below, where conditions a, b, and c represent as follows.

a: Neglected

b: Occurrence probability of b × construction cost under rank 3 × quantity (B represents period during which health index is maintained)

c: Occurrence probability of c × construction cost under rank 2 × quantity (C represents period during which health index is maintained)

Which is suitable for budget levelization, the graph type or state transition type? Repair timing is necessary for budget levelization. The year can be read from the graph with regard to a selected health index in the graph type, but such information cannot be obtained in the state transition type unless the proportion of a selected health index or lower is specified. The same can be said to synchronized repair where the same type of members or adjacent members are repaired together at the repair timing for common use of temporal members because it also requires repair timing information.

3. LCC CALCULATION METHOD

3.1 LCC calculation method by graph type deterioration prediction

Fig. 5 shows the example scenario where each member (main girder, deck and bearing) is repaired every time when the damage level reaches the replacement boundary (damage rank=2). The generated repair cost is accumulated for the specified number of years

3.2 LCC calculation method by state transition type deterioration prediction using Markov Chain Model

As the example in **Fig. 6** shows, it is impossible to judge repair interval, or the number of years taken when a given health index is reached from the state transition graph. Therefore, LCC is accumulated by setting a certain inspection and repair interval. **Fig. 6** represents the scenario where repair interval is 10 years and inspection is carried out every 10 years, and damage found at the inspection is repaired. When members ranked 4 or lower are repaired every 10 years, then the scenario is represented as in **Fig.6**.

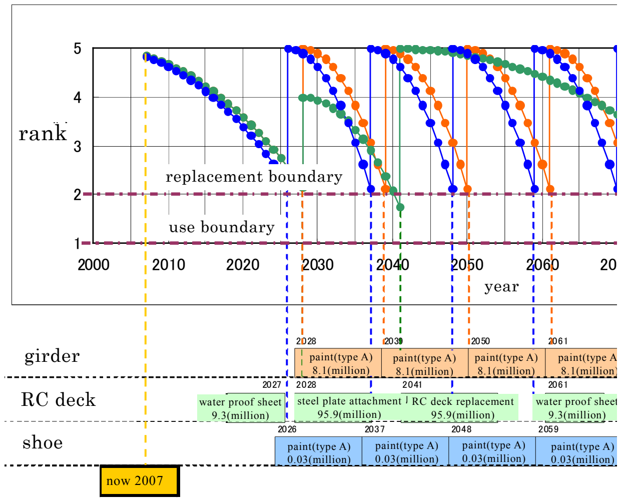


Fig.5 LCC (graph type)

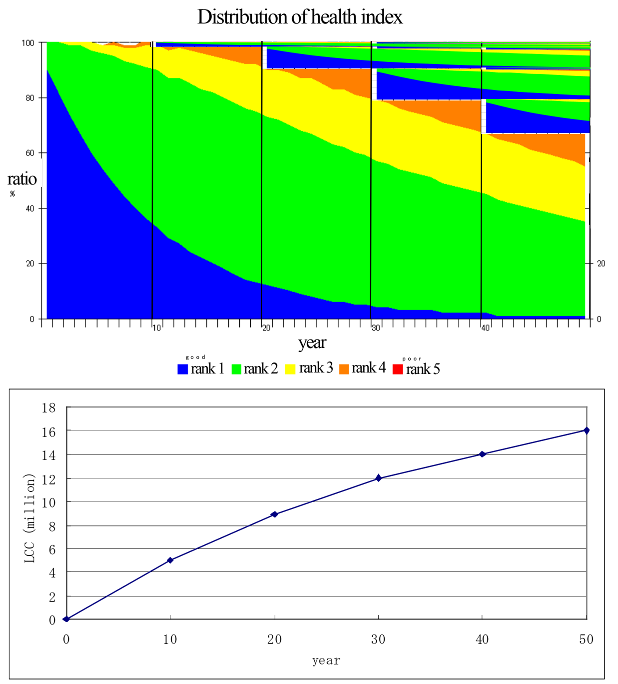


Fig.6 LCC (state transition type, repair lower than rank 4 every ten years)

4. ISSUES REGARDING LCC CALCULATION

Normally, when revising maintenance plan for longer life, scenario that minimizes LCC will be adopted. However, there are different issues depending on the deterioration prediction type used for assuming LCC. In the graph type deterioration prediction model, distribution of health index at a certain year is unknown although average health index is plotted. For this reason, proportions of conditions better or worse than expected are unclear, and thus risks when conditions become worse cannot be assumed.

On the other hand, in the state transition type deterioration prediction model, the timing (fiscal year) cannot be determined at which conditions reach the marginal maintenance line although conditions at each fiscal year can be determined. Therefore, there are two scenarios: one is preventive maintenance where inspection and repair interval is short; and the other is corrective maintenance where inspection and repair timing is long.

There is one more thing that should be noted here regarding revision of maintenance plan. When determining repair timing according to deterioration curve assumed by scenario, graph type deterioration curve is often used because, as mentioned earlier, repair timing can be determined. However, in reality, health index varies among members, and members under good conditions as well as bad conditions both exist. Such variations are represented just as average health index. It is simple if health index distribution is always like normal distribution. But if it is not the case, for instance, the case may exist where average health index is 2 but it is the result of many 1s and only the small number of 2s, 3s, 4s, and 5s. Then, repair timing obtained under such a condition is wrong. When multiple members are used in one facility, it seems most appropriate to think that, as typified by Markov's state transition graph, each member state transits from good condition to bad condition on a certain probability. Accordingly, it is assumed that there should be a link between state transition graph and average index graph. In other words, when using average health index graph for determining repair timing, state transition that is linked to the health index must also be considered because otherwise the resulting LCC will be determined on risky side. More specifically, (a) LCC when the timing at which average health index becomes 2 is considered and all members are repaired at such timing may be smaller than (b) LCC obtained under the scenario where members ranked 2 or lower (2, 1) are also repaired considering health index distribution when the average health index is 2. The LCC in (b) is linked to the state transition and thus assumed to be more realistic.

Studies have been conducted on issues of link between health index graph and state transition graph, and comparison between (a) LCC where members are repaired according to average health index and (b) LCC where state transition is considered have been made in the following sections.

5. APPLICATION EXAMPLES

5.1 Calculation conditions

Under the assumption that deterioration progress is more realistically represented by state transition graph, average health index is calculated from multiple state transition distributions under various deterioration rates. By doing this, link between state transition and average health index is ensured. Then, studies have been conducted regarding cautions when average health index graph is used for determining repair timing, issues related to average health index graph, and various LCCs depending on deterioration curve.

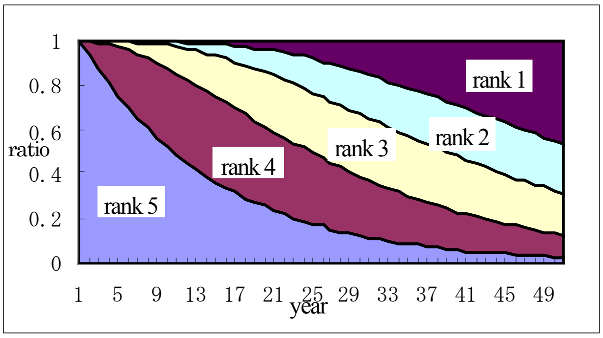
In the state transition graph used for study, four deterioration rates are used: p=0.96 constant (slow deterioration); p=0.93 constant (standard deterioration); p=0.90 constant (slightly quick deterioration), and p=0.85 constant (very quick deterioration). Probability of state transition to one more lower rank (5→4, 4→3, 3→2, 2→1) is set constant under each condition.

Average health index is calculated by formula (1):

$$hm=(r_5*5+r_4*4+r_3*3+r_2*2+r_1*1)/100; \qquad (1)$$

state transition probability

	5	4	3	2	1
5	0.93	0.07	0	0	0
4		0.93	0.07	0	0
3			0.93	0.07	0
2				0.93	0.07
1					1



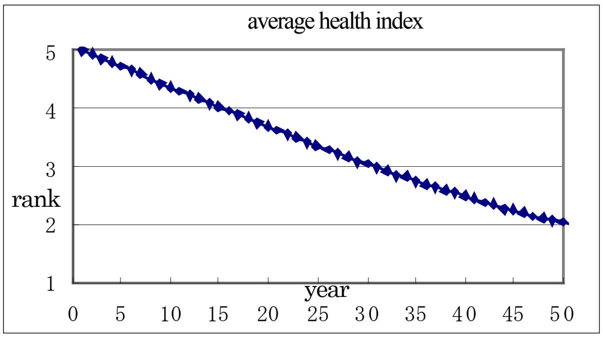


Fig.7 state transition probability, state transition and average health index (p=0.93, constant)

where,

r_5: proportion of rank 5 (%)

r_4: proportion of rank 4 (%)

r_3: proportion of rank 3 (%)

r_2: proportion of rank 2 (%)

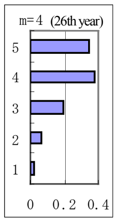
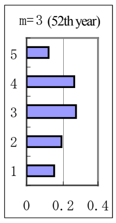
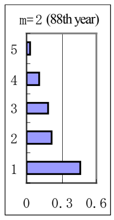
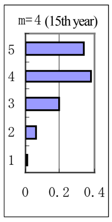
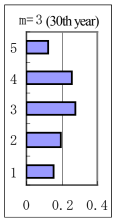
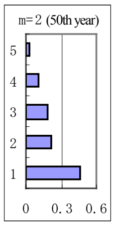
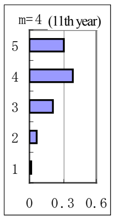
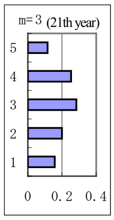
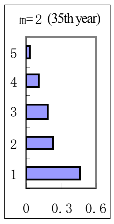
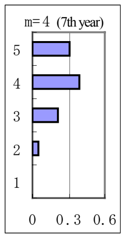
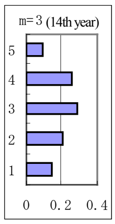
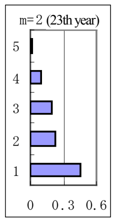
r_1: proportion of rank 1 (%).

Fig. 7 shows state transition probability, state transition graph, and average health index graph when p is 0.93 constant.

5.2 State distribution in average health index graph

The calculated average health index graph is linked to state transition graph. **Table 3** shows the distribution of health indices for respective year at which average health index reaches 4, 3, and 2. In **Fig. 7**, for instance, it takes 15 years, 30 years, and 50 years that average health index reaches 4, 3, and 2, respectively.

Table 3 Contribution of each rank when average health index become rank4,3,2

	average health index		
	4	3	2
p=0.96			
p=0.93			
p=0.90			
p=0.85			

From this result, the average health index graph does not show distribution as shown in **Fig. 4** when average health index is 2 or lower. While **Fig. 4** shows the image of uncertainty (probability distribution where value does not become as expected), if it shows state, the distribution should be wider over the range from 1 to 5. At the timing when average health index reaches 2, the largest proportion is rank 1, followed by rank 2, 3, 4, and 5. Caution must be taken here that the largest proportion is not rank 2. In other words, even when average health index reaches 2, most of members are ranked 1, which is worse than rank 2, according to the state distribution. This means that a proper repair timing is overlooked. However, the proportion of rank 2 increases if probability of state transition from 2 to 1 is very small because conditions of rank 2 become worse as time passes. According to Nishikawa, however, deterioration progress of structures is represented by an inversely-proportionate curve, meaning that the lower the performance becomes, the faster damage progresses[9)]. Therefore, it is unlikely that state transition from rank 2 to rank 1 rarely occurs, but rather, conditions become worse at an accelerated pace when the state reaches rank 2 and the resulting distribution is as shown in **Table 3**.

5.3 Comparison of LCCs

When members are repaired at the number of years when the health index reaches 4, 3, and 2 according to the average health index graph, LCCs have been compared using the following two scenarios. That is, when revising maintenance plans targeting lasting duration of 100 years, comparison has been made between the case (a) where repair interval is determined using the graph type prediction method to accumulate LCCs and the case (b) repair frequency is determined using the state transition distribution graph while also considering cases where member conditions become worse than the predetermined health index. In the case of (a), all members are assumed to have an equal target health index (no variations) because state distribution is unknown and thus repaired altogether. On the other hand, in the case of (b), when members are repaired when health index reaches 3, it is obvious that members ranked 3 are repaired according to the state distribution graph at this timing, but worse members ranked 2 and 1 must also be repaired while better members ranked 4 and 5 are excluded. Compared to the case (a), worse members must be repaired at higher unit price although better members are not repaired. Accordingly, it is possible to understand the influence on LCC because health index distribution is considered. The results are shown in **Figs. 8 to 11**.

For instance, **Fig. 12** shows the transition of state distribution and average health index when state distribution is considered, deterioration rate is p=0.85, and members are repaired when average health index reaches 2. In this case, members ranked 2 and 1 are repaired but those ranked 3, 4, and 5 are not, and therefore those ranked 3, 4, and 5 transit in the same way as before even after the repaired timing. On the other hand, it can be confirmed that members ranked 2 and 1 reach rank 5 after repair. It must be noted here that there are small number of rank 2 members at the repair timing because members ranked 3 transit to rank 2 at a rate of several % according to state transition probability each year.

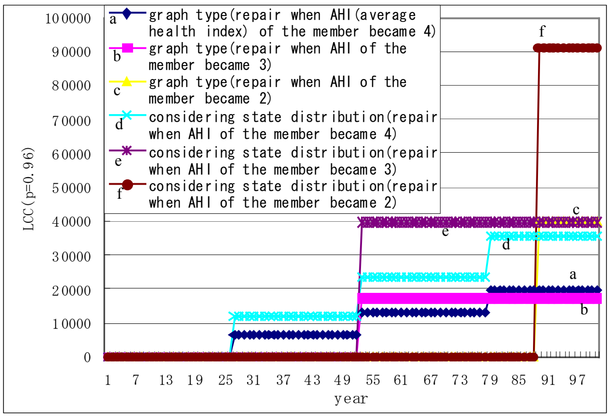


Fig.8 LCC (p=0.96)

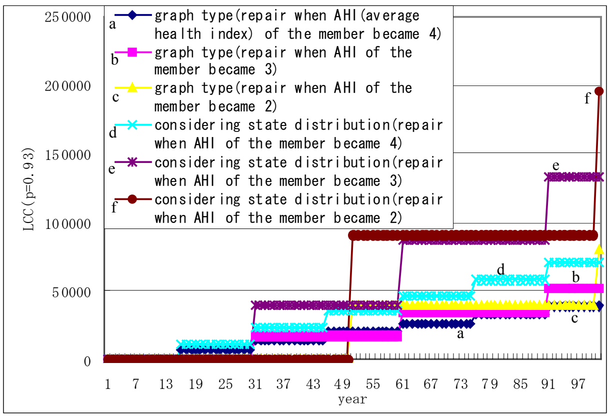


Fig. 9 LCC (p=0.93)

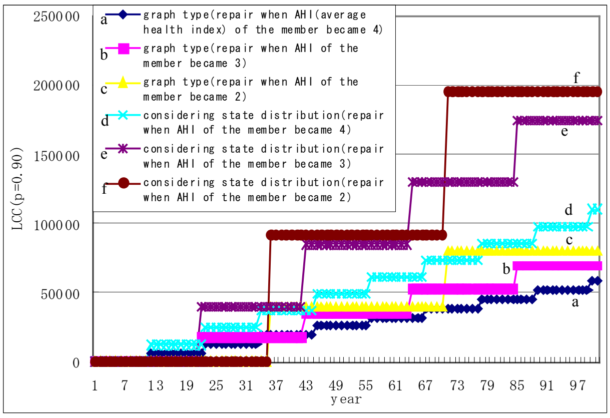


Fig.10 LCC (p=0.90)

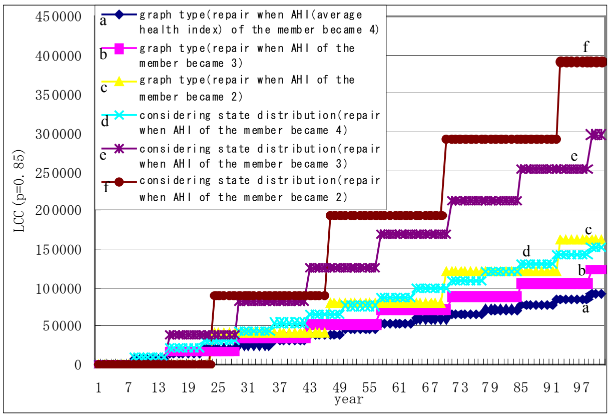


Fig.11 LCC (p=0.85)

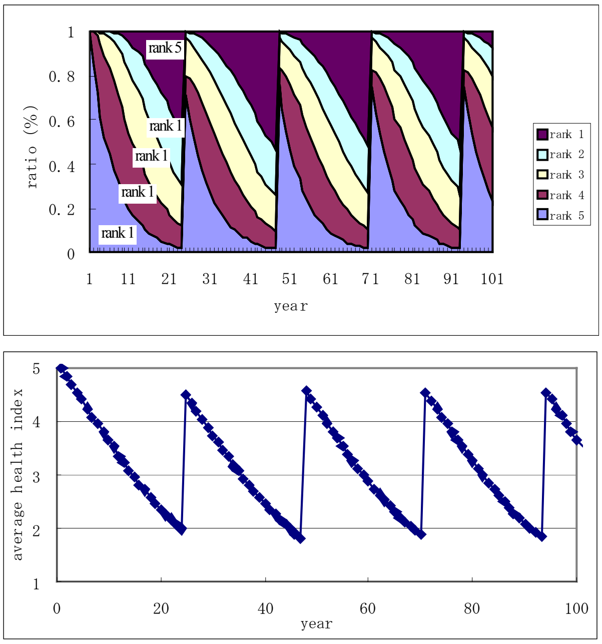


Fig.12 Transition of state distribution and average health index (p=0.85, considering state distribution, repair on average rank 2)

Table4 compairing of LCC

		using graph type deteriorasion curve	considering state distribution	rare
p=0.96	repair when average health index 4	19,500	35,299	1.81
	repair when average health index 3	17,500	39,429	2.253
	repair when average health index 2	40,000	90,985	2.275
p=0.93	repair when average health index 4	39,000	69,945	1.793
	repair when average health index 3	52,500	132,700	2.528
	repair when average health index 2	80,000	195,404	2.443
p=0.90	repair when average health index 4	58,500	110,760	1.893
	repair when average health index 3	70,000	174,724	2.496
	repair when average health index 2	80,000	195,342	2.442
p=0.85	repair when average health index 4	91,000	151,585	1.666
	repair when average health index 3	122,500	295,894	2.415
	repair when average health index 2	160,000	391,107	2.444

Table 4 summarizes the total LCCs. Regardless of deterioration rate, (1) LCC calculated using the graph type prediction method is smaller than (2) LCC when state distribution is considered. This tendency if represented by the ratio of (1) by (2), which is around 1.7 to 1.9 in the case of preventive maintenance (repaired when health index is 4) and 2.3 to 2.5 in the case of corrective maintenance (repaired when health index is 3 or 2). Furthermore, there is no big difference of LCCs when the repair timing is rank 3 and rank 2. LCC in (2) is larger than that in (1) because the case where members become worse than average health index, or repair that takes higher construction cost, is considered. The ratio of (1) by (2) in corrective maintenance is larger than that in preventive maintenance because the proportion of members increases where much construction cost is needed after being left for a while. LCC in corrective maintenance is larger than that in preventive maintenance in all the cases.

When calculating LCC for maintenance plan, LCC increases by 1.7 to 2.5 times depending on whether state distribution is considered at predetermined repair timing. The question is how people view the value from 1.7 to 2.5. There is no problem with LCC without considering this value when LCC is used only for materials describing which member is repaired when according to the maintenance plan currently prepared by local governments and the LCC amount does not count so much. However, when using LCC to calculate the budget for repair, as already mentioned above, it seems more realistic to use LCC where uncertainty of deterioration prediction and state distribution are considered.

6. CONCLUSION

In this research, under the assumption that deterioration progress of structures is represented by state transition graph more realistically, issues were pointed out when calculating LCC using the average health index graph linked to the state transition graph for maintenance plan. Then comparison was made between (a) LCC when members are repaired according to average health index and (b) LCC when state transition is considered to clarify the difference in value. When calculating LCC for revising maintenance plans, consideration is given to repair at the timing obtained from the average health index graph, but the result will represent deterioration progress more accurately when state distribution is also considered. Therefore, further discussions will be required regarding the necessity of considering state distribution for calculating LCC.

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