Trial of infrastructure asset management for subway tunnels

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Abstract

The social infrastructure that rapidly developed during the period of high economic growth in Japan is now aging, and improvements in maintenance and management efficiency have become an important issue. Related to the maintenance and management of railway structures, the "Maintenance Standards for Railway Structures and Commentary" was enacted in January 2007. Based on this, railway operators conduct regular inspections and document the deterioration status, deformation types, etc. Based on this inspection data, repair plans are formulated for the railway structure and then, the repairs are carried out. In previous research, prediction of future deterioration of the tunnel and development of repair plans based on the inspection data were conducted from the macro perspective (e.g., the entire line). In practice, repair plans are also being formulated in micro units (e.g., sections between adjacent stations). In this research, the conventional deterioration prediction method was implemented for every section between adjacent stations in a certain line. It was found that the current deterioration state and the predicted future deterioration rate differ depending on the section. The optimum distribution of annual repair amount for each section was then determined by considering two factors: (1) the predicted deterioration rate for the next ten years and (2) the number of spans judged as classification A at the inspection of 2016.

Keywords: subway tunnel, asset management, deterioration prediction

1. Introduction

The social infrastructure that rapidly developed during the period of high economic growth in Japan is now aging, and improvements in maintenance and management efficiency have become an important issue. Related to the maintenance and management of railway structures, the "Maintenance Standards for Railway Structures and Commentary" was enacted in January 2007, and a partial revision of "Notification on periodic inspection of facilities and vehicles" was implemented in February 2007. Based on these, railway operators conduct inspections regularly and document the deterioration status, deformation types, etc. Based on this inspection data, repair plans are formulated for the railway structures and the repairs are carried out [1].

In recent years, budgets have become tighter as the society ages, and construction-related investment capacity has tended to decrease. Efficient management strategies for social infrastructure are therefore required even more than previously. Under such circumstances, the necessity of asset management is increasing, especially in the field of maintenance of existing social infrastructure. Asset management refers to activities for maximizing the value of assets by appropriately managing financial assets such as stocks and bonds in consideration of risks and profitability. When this concept is applied to the maintenance and management of social infrastructure, the social infrastructure is regarded as assets of society, and companies are required to manage the assets for the benefit of society, while fulfilling their accountability to society.

In previous research, prediction of future deterioration and development of repair plans based on the tunnel inspection data are conducted from the macro perspective (e.g., the entire line). In practice, repair plans are also being formulated in micro units (e.g., sections between adjacent stations). In this research, the existing examination method is applied and the optimal amount of annual repair for every section between adjacent stations on a certain line is calculated under various constraint conditions.

2. Deterioration prediction

2.1 Inspection data and targeting sections

In this study, inspection data for a subway tunnel provided by Tokyo Metro Company is studied, and the future deterioration condition of the tunnel is predicted. The inspection is conducted every two years, and the data used in this research was collected in 2014 and 2016. In the inspection records of the subway tunnels, the kilometers of the points where defects were found, concrete deformation areas (e.g. upper floor), types of defects (e.g. water leakage), and judgement classifications (in order of the degree of damage, A1, A2, B, C, S) are recorded. The outline of the deterioration judgement classification defined in the “Maintenance Standards for Railway Structures and Commentary” is summarized in Table 1.

Table 1: Outline of deterioration judgement classification

<table>
<tr><th colspan="2">Classification</th><th>Condition of the structure</th></tr>
<tr><td rowspan="4">A</td><td></td><td>Deterioration which threatens (or may threaten) safety operation, normal operation, safety of public and passengers</td></tr>
<tr><td>AA</td><td>Deterioration which threatens safety operation, normal operation, safety of public and passengers
Deterioration which needs urgent measure</td></tr>
<tr><td>A1</td><td>Deterioration which is reducing the performance of the structure
Deterioration which has a risk of losing performance by heavy rain, flood, earthquake, etc</td></tr>
<tr><td>A2</td><td>Deterioration which could lose the performance of the structure in the future</td></tr>
<tr><td colspan="2">B</td><td>Deterioration which has a risk of changing to classification A in the future</td></tr>
<tr><td colspan="2">C</td><td>Slight deterioration</td></tr>
<tr><td colspan="2">S</td><td>No deterioration</td></tr>
</table>

The prediction of deterioration in this research is conducted for 32 sections between the stations labelled from A to X, with excavation methods and ground conditions of the line as listed in Table 2. The inspection data are divided according to each section, and then processed by the method described in section 2.2.

Table 2: List of targeting sections

Section between adjacent stations	Open-cut		Shield	
	Stiff soil	Soft soil	Stiff soil	Soft soil
A - B	Sect. 1	-	-	-
B - C	Sect. 2	-	-	-
C - D	Sect. 3	-	-	-
D - E	Sect. 4	-	Sect. 5	-
E - F	Sect. 6	-	Sect. 7	-
F - G	Sect. 8	-	-	-
G - H	Sect. 9	-	-	-
H - I	Sect. 10	-	-	-
I - J	Sect. 11	-	-	-
J - K	Sect. 12	-	Sect. 13	-
K - L	Sect. 14	-	-	-
L - M	Sect. 15	Sect. 16	-	-
M - N	Sect. 17	-	-	-
N - O	Sect. 18	-	Sect. 19	-
O - P	-	-	Sect. 20	-
P - Q	-	-	Sect. 21	-
Q - R	-	-	-	Sect. 22
R - S	-	Sect. 23	-	-
S - T	-	Sect. 24	-	Sect. 25
T - U	-	-	-	Sect. 26
U - V	-	Sect. 27	-	Sect. 28
V - W	-	Sect. 29	-	Sect. 30
W - X	-	Sect. 31	-	Sect. 32

2.2 Processing of inspection data

For this study, the kilometers and the judgement classifications in the records are processed, and the aggregation method called "Worst Value Method (WVM)" is developed to compile the huge amount of inspection data. The outline of this method is illustrated in Fig. 1. The WVM is a method of selecting the most severe of all recorded classifications in each span, as a representative classification of the corresponding span. If there are no records of defects in a span, the classification of the span will be "S." Here, spans are defined by dividing a tunnel into 1 m lengths.

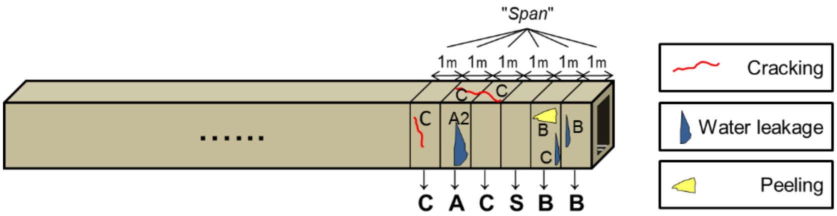


Fig. 1: Outline of the "worst value method (WVM)"

The continuous data of the percentage of each judgement classification is obtained by rearranging the processing results with respect to the age of each span. Fig. 2 shows an example of this data. Here, the following two preconditions are assumed, and linear interpolation and extrapolation are employed when there is no corresponding data.

1) The deterioration classification does not improve naturally without repair (e.g. from "A" to "B").
2) All the spans are in classification "S" at age 0.

This data processing is carried out for each section.

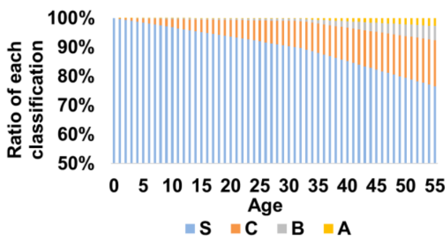


Fig. 2: Example of continuous data (Sect. 1)

2.3 Prediction of tunnel deterioration

In predicting the future deterioration state of the tunnel from the classification results as in Fig. 2, the Markov process is used to predict the classification transition due to aging. The Markov process explains a process in which the future behavior depends only on the current state, and not on the past. It is often used to predict the deterioration process of road pavement and bridge structures, but it is applied here to the tunnel structure and tunnel members [2].

When the theory is applied to the annual deterioration of the tunnel, a deterioration transition matrix (DTM) is obtained. The DTM describes the annual transition of each classification, as presented in Table 3. Here, it is assumed that there are only two patterns of transition: one is to maintain the same classification, and the other is to degrade by only one classification.

Table 3: Example of deterioration transition matrix (Sect. 1 / Age 33-34)

			Ratio of each classification at Age34			
			S	C	B	A
			0.8859	0.0979	0.0115	0.0048
Ratio of each classification at Age33	S	0.8916	0.9936	0.0064	0	0
	C	0.0950	0	0.9700	0.0300	0
	B	0.0097	0	0	0.8906	0.1094
	A	0.0037	0	0	0	1

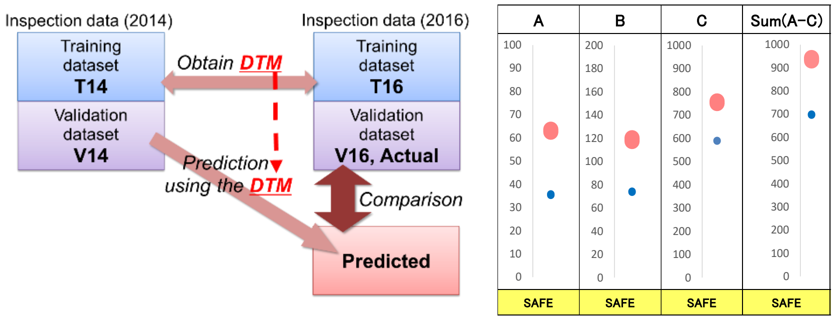
The transition due to aging can be expressed by the following equation (Eq. 1).

$$(P'_S \quad P'_C \quad P'_B \quad P'_A) = (P_S \quad P_C \quad P_B \quad P_A)\begin{bmatrix} K_{SS} & K_{SC} & 0 & 0 \\ 0 & K_{CC} & K_{CB} & 0 \\ 0 & 0 & K_{BB} & K_{BA} \\ 0 & 0 & 0 & K_{AA} \end{bmatrix} \qquad \textbf{Eq. 1}$$

Here, P'_X is the existence probability of classification X while P_X is that of the previous year, and the matrix $[K_{IJ}]$ is the DTM. In the DTM, K_{CB} represents the percentage of sections with classification C that degrade to classification B in the following year and K_{CC} represents the percentage of classification C section that remain at the same classification C in the following year. Using the DTM, the future deterioration state of each section is predicted, and in Section 2.4, the predicted values are validated.

2.4 Evaluation of the appropriateness of the prediction method

The validity of this prediction method is verified by applying the concept of 95% confidence intervals and the cross-validation method. In this method, the inspection data of 2014 and 2016 are respectively divided into two datasets: a training set and a validation set. These datasets are referred to as 14T, 16T, 14V, 16V, respectively. The dataset 14V is then processed by the DTM, which is obtained from the two training sets (14T and 16T), and the predicted values are calculated. By repeating this calculation 1000 times, 95% confidence intervals of the predicted values are obtained, and compared to that of 16V. An outline of the process is depicted in Fig. 3(a), and a result of the comparison is shown in Fig. 3(b). Here, the sections of open-cut structure and stiff soil were collectively evaluated. Cases where the predicted value is greater than the actual value are judged as “SAFE,” and the converse cases are judged as “DANGEROUS.”



	A	B	C	Sum(A−C)	S
Predicted	63 ～ 64	117 ～ 120	751 ～ 760	930 ～ 944	24657 ～ 24668
Actual	35 ～ 36	74 ～ 74	588 ～ 590	697 ～ 700	24901 ～ 24903
Relative error	43% ～ 45%	37% ～ 39%	21% ～ 23%	25% ～ 26%	1% ～ 1%

(a) Outline of the method (b) Comparison result (Open-cut / Stiff soil)

Fig. 3: Validation of prediction method

According to Fig. 3(b), there are no "DANGEROUS" cases. This may be due to the fact that the WVM focuses on the most severe defect and estimates the worst conditions [3].

3. Discussion of the repair plan

3.1 Method for evaluating tunnel integrity

In preparation for developing the repair plan, a quantitative evaluation of tunnel integrity is necessary. In this study, the integrity of the subway tunnel structure is evaluated by obtaining the scored level value from the deterioration classification. Each classification level k_i is scored as follows: S:10, C:8, B:6, A:1. The values used in this scoring are determined by interviews with the inspection staff members who are engaged in the maintenance of the subway tunnels of Tokyo Metro Company. The integrity value h (hereinafter, referred to as “health index”) of each section is evaluated by averaging the score of each span along that section, as given in Eq. 2.

$$h = \frac{\sum_{i=1}^{4} k_i n_i}{\sum_{i=1}^{4} n_i} \qquad (\text{i} = \text{S, C, B, A}) \qquad \textbf{Eq. 2}$$

where n is the number of spans assigned to each deterioration classification.

3.2 Ranking among sections

The optimum repair plan should be effective in both preventive maintenance and reactive maintenance. Both types of rankings are therefore calculated for all 32 sections. The results of these rankings are shown in Table 4. The preventive maintenance is calculated in (a), and the reactive maintenance is calculated in (b).

Table 4: Results of rankings among sections

(a) Deterioration rate for the next 10 years (***X***)

Rank	Section	Average decreasing amount of health index for the next 10 years (deterioration rate)	Rank	Section	Average decreasing amount of health index for the next 10 years (deterioration rate)
1	Sect. 16	0.144	17	Sect. 27	0.013
2	Sect. 4	0.110	18	Sect. 10	0.012
3	Sect. 15	0.074	19	Sect. 25	0.012
4	Sect. 18	0.051	20	Sect. 32	0.012
5	Sect. 29	0.043	21	Sect. 22	0.012
6	Sect. 24	0.041	22	Sect. 30	0.011
7	Sect. 23	0.035	23	Sect. 14	0.010
8	Sect. 9	0.035	24	Sect. 5	0.010
9	Sect. 12	0.023	25	Sect. 31	0.008
10	Sect. 28	0.021	26	Sect. 7	0.007
11	Sect. 21	0.019	27	Sect. 11	0.007
12	Sect. 1	0.019	28	Sect. 20	0.005
13	Sect. 19	0.018	29	Sect. 26	0.004
14	Sect. 6	0.017	30	Sect. 2	0.003
15	Sect. 13	0.014	31	Sect. 17	0.003
16	Sect. 3	0.013	32	Sect. 8	0.002

(b) Number of spans judged as classification A at the 2016 inspection (***Y***)

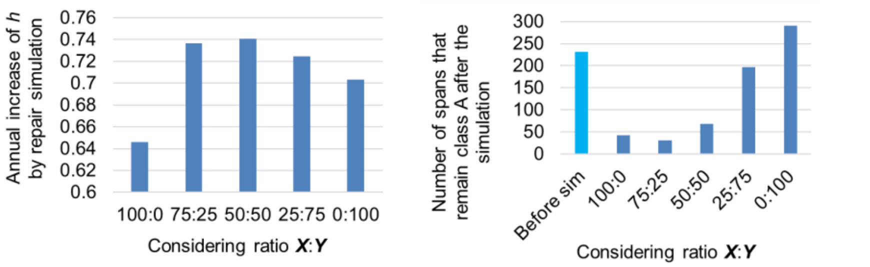
Rank	Section	Number of span judged as classification A	Rank	Section	Number of span judged as classification A
1	Sect. 22	29	14	Sect. 25	4
2	Sect. 16	24	14	Sect. 32	4
3	Sect. 13	22	19	Sect. 11	3
4	Sect. 5	20	19	Sect. 15	3
4	Sect. 19	20	19	Sect. 18	3
6	Sect. 28	15	19	Sect. 20	3
7	Sect. 3	13	19	Sect. 24	3
8	Sect. 30	12	24	Sect. 9	2
9	Sect. 14	8	25	Sect. 1	1
10	Sect. 7	7	25	Sect. 2	1
11	Sect. 29	6	25	Sect. 4	1
11	Sect. 31	6	25	Sect. 8	1
13	Sect. 26	5	25	Sect. 12	1
14	Sect. 6	4	25	Sect. 17	1
14	Sect. 10	4	25	Sect. 23	1
14	Sect. 21	4	25	Sect. 27	1

3.3 Repair simulation and the decision of optimum distribution

To optimize the repair plan, the above mentioned two rankings should be combined. In this study, the effective ratio for combining these two indexes (***X*** and ***Y***) is obtained by conducting repair simulation for 5 cases: (***X***:***Y***=100:0), (***X***:***Y***=75:25), (***X***:***Y***=50:50), (***X***:***Y***=25:75), (***X***:***Y***=0:100). It is assumed that the annual repair amount that can be allocated to the line concerned covers 100 spans. The method of determining the distribution of the 100 spans among each section is as follows.

1) The 100 spans are allocated to ***X*** and ***Y*** at each ratio.
2) The amount is further allocated to each section based on the rankings for each of ***X*** and ***Y***.
3) The repair amount of each section determined for each of ***X*** and ***Y*** is summed and the annual repair amount of each section is determined.

Results of the simulation for each ratio under consideration are compared from the viewpoints of repair efficiency and ensuring safety, shown in Fig. 4(a), and Fig. 4(b) respectively.



(a) Annual increase of health index by the simulation

(b) Number of spans that remain as class A after the simulation

Fig. 4: Results of repair simulation by considering ratio of two indexes

According to Fig. 4(a), the increase in the health index is relatively small when ***Y*** is not considered (***X***:***Y***=100:0). This is likely to be because a large amount of repair is carried out in sections where the classification A has not yet occurred. From Fig. 4(b), when ***X*** is not taken into consideration (***X***:***Y***=0:100), the number of the residual A-class spans is large because the determined repair amount is not enough to cope with newly generated A-class spans.

Judging from the combination of Fig. 4(a) and Fig. 4(b), it can be concluded that the ratio (***X***:***Y***=75:25) is best in terms of both repair efficiemcy and ensuring safety. The optimum distribution determined in this study is therefore as shown in Fig. 5.

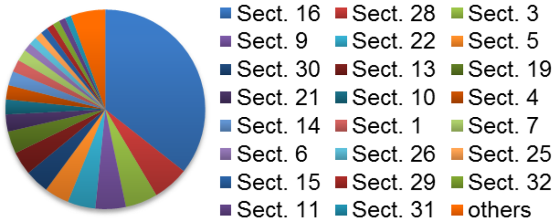


Fig. 5: Optimum distribution of repair amount among the concerned sections

4. Conclusions

In this research, the optimum distribution of annual repair amounts for each section between adjacent stations was determined by using the tunnel inspection data. The following results were obtained from the prediction of deterioration and the distribution of repair amounts:

1) Both the current deterioration state and the future deterioration rate differ depending on the section (Table 4).
2) An optimum distribution plan (***X***:***Y***=75:25) considering both repair efficiency and ensuring safety was determined by two factors: ***X*** indicating the future decrease in tunnel integrity and ***Y*** indicating the number of spans currently rated as classification A.

The following are currently under investigation for further improvement of the research.

1) The classification level k_i, which is scored only from the questionnaire survey given to inspection staff members of Tokyo Metro Company, is being reset to a factor that more closely matches the actual situation.
2) With the aim of improving the distribution of repair amounts among all the sections between adjacent stations owned by Tokyo Metro Company, the same analysis is being carried out on the other 8 lines.

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