

A trial infrastructure asset management for subway tunnels

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ABSTRACT: In Japan, the construction of social infrastructure has been increasing since the high economic growth in the 1960s. Right now it is a problem in Japan that these infrastructures are deteriorating. It is expected that further deterioration will occur in the future so the maintenance and operation for these infrastructures is now a significant subject.

Under these circumstances, a managing method named as an infrastructure asset management is beginning to be employed recently. Infrastructure asset management is a strategic management of physical assets during their life in the organization, which enables us to manage physical assets effectively and efficiently. The goal is to conduct a mid and long term efficient maintenance and operation plan for the subway tunnels and to decide the proper budget for rehabilitation.

1 INTRODUCTION

In Japan, the construction of social infrastructure has been increasing since the high economic growth in the 1960s. For this reason, there are considerable stocks of social infrastructure stored in our country. Right now it is a problem in Japan that these infrastructures are deteriorating. It is expected that further deterioration will occur in the future. However, new investment for social infrastructure has decreased due to the market recession and the political situation. The maintenance and operation for these infrastructures is now a significant subject.

Under these circumstances, a managing method named as an infrastructure asset management is beginning to be employed recently. Infrastructure asset management is a strategic management of physical assets during their life in the organization. It enables us to manage physical assets effectively and efficiently. Asset management was originally used for financial assets in investments, but in recent years it has been applied to social infrastructure too.

In this research, social infrastructure is considered as assets. Infrastructure asset management methodology has been applied to subway tunnels by using available tunnel inspection data. By processing the tunnel inspection data, a matrix to estimate the degradation of the subway tunnel has been obtained. By using this matrix, the deterioration and the degradation of the whole subway tunnels has been estimated and the degradation of the tunnel has been evaluated.

The goal is to conduct a mid and long term efficient maintenance and create the operation plan for the subway tunnel in order to decide the proper budget for rehabilitation.

2 ACCUMULATION OF THE TUNNEL INSPECTION DATA

2.1 Outline of the tunnel inspection data

In this research, the tunnel inspection data collected by the Tokyo Metro Co. was used to predict the deterioration of the tunnel. Inspection is conducted every two years. The inspection data used in this research was collected in 2010 and 2012. The outline of the deterioration category used in the Tokyo Metro Co. is shown in Table 1.

Table 1. The outline of deterioration category

Classification	condition of the structure
A	deterioration which threatens (or may threaten) safety operation, normal operation, safety of public and passengers
	AA deterioration which threatens safety operation, normal operation, safety of public and passengers deterioration which needs urgent measure
	A1 deterioration which is reducing the performance of the structure deterioration which has a risk of losing performance by heavy rain, flood, earthquake, etc
A2	deterioration which could lose the performance of the structure in the future
B	deterioration which has a risk of changing to rank A in the future
C	slight deterioration
S	no deterioration

2.2 Processing of the tunnel inspection data

The tunnel inspection data is processed as follows.

- 1) The whole length of subway tunnel is separated into a sample span of 5m. The deterioration category shown in Table1 is assigned for each sample span. If multiple deterioration categories are assigned in the same sample span, the worst category is assigned to the sample span.
- 2) The construction age of each sample span and the soil characteristic around the tunnel section are recorded. The soil characteristic around the tunnel section is classified into 2 types. Soil A is relatively stiff stable ground, and soil B is soft ground.
- 3) The distribution of each deterioration category is obtained for each construction age of the subway tunnel.

3 EVALUATION OF TUNNEL INTEGRITY

3.1 Method for evaluating tunnel integrity

The integrity of the subway tunnel structure is evaluated by obtaining the score value from the deterioration category. Each deterioration category is scored as follows, S:10, C:8, B:6, A2:3, A1:1.

The integrity of the whole tunnel section is evaluated by averaging the score of each sample span along that tunnel section. The value of this scoring is provided by the inspection staff members, who are engaged in the maintenance of the subway tunnels of Tokyo Metro Co. in order to keep the running safety of the subway train.

Figure 1 shows the tunnel integrity of the Ginza line, which is the oldest subway line in Tokyo. The integrity is evaluated by employing the inspection data, which was collected in the year 2010 and 2012. The tunnel integrity value evaluated from two series of tunnel inspection data at 2010 and 2012 has taken a close value. Also, the tunnel integrity value varied according to the construction age. This is perhaps because some repair work has been carried out at some sections along the tunnel.

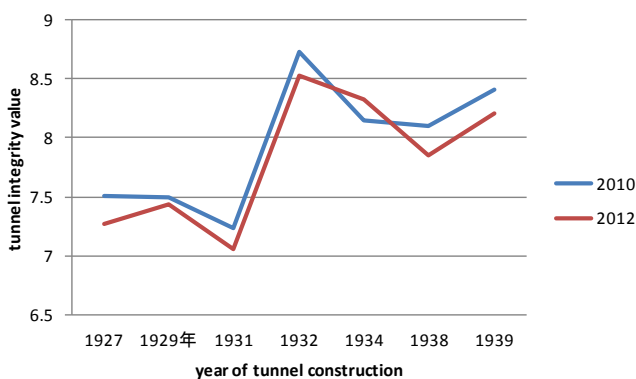


Figure 1. Tunnel integrity of the Ginza line

3.2 Relationship between the concrete carbonation and the tunnel integrity

The relationship of concrete carbonation and the tunnel integrity was investigated by using the inspection data along the Ginza line. The Ginza line has been constructed around 80 years ago and the major cause of the degradation of the Ginza line subway tunnel is considered to be the concrete carbonation. Therefore, the concrete carbonation progression rate (carbonation depth (mm) / thickness of covering concrete of the tunnel lining (mm)) has been obtained by the tunnel inspection along the Ginza line subway tunnel and the relationship between the concrete carbonation progression rate and the tunnel integrity has been investigated.

Figure 2 indicates the variation of the concrete carbonation progression rate at the sampling position along the Ginza line. From Figure2, it can be understood that the similar carbonation progression rate of the concrete core has been obtained at the close sampling positions.

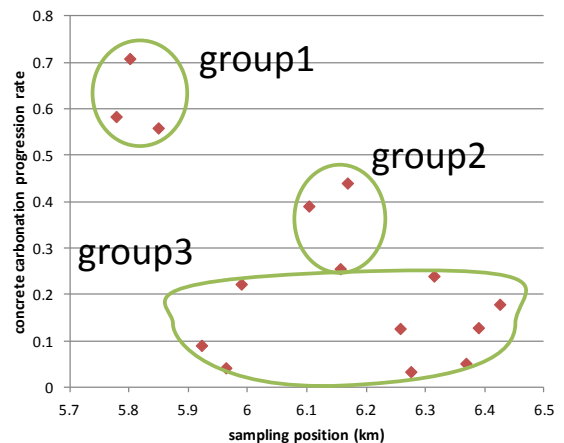


Figure 2. Variation of the carbonation rate along the Ginza line subway tunnel

The concrete carbonation inspection results can be divided into three groups, according to the values of carbonation progression rate: Group 1:5.7 km ~ 5.9km, Group 2:6.1 km ~ 6.2km, Group 3:5.9 km ~ 6.0km and 6.2km ~ 6.5km) The relation between the tunnel integrity value and the carbonation progression rate of each group is demonstrated in Figure3.

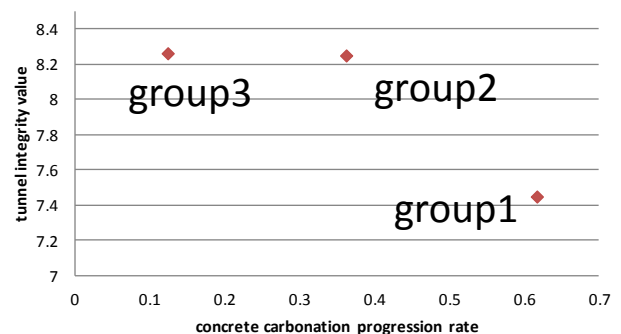


Figure 3. Relation between carbonation progression rate and tunnel integrity value

From Figure3, it can be understood that the tunnel integrity value is low, where the concrete carbonation progression rate is high. Consequently, the tunnel integrity evaluation from the tunnel inspection data used in this study is considered to be valid from the concrete carbonation progression rate of the tunnel lining.

4 PREDICTION OF TUNNEL DETERIORATION

4.1 Method for predicting tunnel deterioration

Predicting the deterioration of civil engineering structures can be classified into two types. One is to investigate the dynamic characteristics of the actual concrete structures by using the percussion method and another is to predict the deterioration statistically by using the inspection data. While the former method is used for a particular structures or a member of the structures, the latter can be covering the entire group of structures. Since the aim of this research is to predict the deterioration of the subway tunnel system as a group, the Markov method based on the statics is used to predict the tunnel deterioration. The Markov method is often used to predict the deterioration process of road pavement and bridge structures, but it is also applied to the tunnel structure and the tunnel members.

4.2 Creating a transition matrix for predicting tunnel deterioration

Using the following statistical concept, the deterioration transition matrix was created and employed to predict the subway tunnel deterioration. $\{P_x\}$ is assumed to be the probability vector of each deterioration category at t_n year after the construction and $\{P'_x\}$ is assumed to be the probability vector of each deterioration category at t_{n+1} year after the construction. The relation between $\{P_x\}$ and $\{P'_x\}$ can be given as follows by using the Markov method

$$\begin{matrix} \{P'_C & P'_B & P'_{A2} & P'_{A1}\} \\ t = t_{n+1} \end{matrix} = \begin{matrix} \{P_C & P_B & P_{A2} & P_{A1}\} \\ t = t_n \end{matrix} \begin{bmatrix} K_{CC} & K_{CB} & K_{CA2} & K_{CA1} \\ 0 & K_{BB} & K_{BA2} & K_{BA1} \\ 0 & 0 & K_{A2A2} & K_{A2A1} \\ 0 & 0 & 0 & K_{A1A1} \end{bmatrix} \quad (1)$$

in which K_{CB} represents the percentage of the category C tunnel sample span that degrades to category B in the next year and K_{CC} represents the percentage of category C tunnel sample span that does not degrade and remain at the same category C in the next year. In this research, numerical simulations of the subway tunnel deterioration are performed assuming the following assumptions.

- The deterioration does not be improved naturally without tunnel repair.
- There are two patterns of deterioration for each tunnel sample span. The change of deterioration cat-

egory is just by one category or it remains at the same category in the next year.

- Whole the subway tunnel deterioration category is assumed to belong to S category in year 2010, which means that the whole tunnel repaired in year 2010.

- When the repair of the tunnel sample span is conducted, the deterioration category is brought back to category S and kept at S category for 10 years.

The example of the deterioration transition matrix created using the assumptions above is shown in Table2. Table2 is the transition matrix which predicts the deterioration of the tunnel, where 50 years have passed after the construction.

Table 2. Example of deterioration transition matrix

	50years after construction	S	C	B	A2	A1
49years after construction		52.76%	33.31%	5.23%	8.20%	0.49%
S	53.78%	0.981	0.019	0	0	0
C	32.48%	0	0.994	0.006	0	0
B	5.26%	0	0	0.96	0.04	0
A2	7.99%	0	0	0	0.999	0.001
A1	0.49%	0	0	0	0	1

5 REPAIR BUDGET ALLOCATION TO THE INDIVIDUAL SUBWAY TUNNEL

5.1 Repair costs for deteriorated tunnel

The repair cost for each deterioration category was decided from the actual repair costs. The costs used in the calculation are shown in Table3. The actual cost required to repair the A2 category tunnel span is obtained from the actual repair work. The repair costs for other categories are obtained by multiplying the following factors to the repair cost of the A2 category (A1:3.0, B:0.5, C:0.2).

Table 3.The repair cost assumed for each deterioration category

deterioration category	repair cost (JPY)
A1	2313000
A2	771000
B	385000
C	154000

5.2 Prediction of tunnel deterioration considering repair of the tunnel

The prediction of subway tunnel deterioration considering the repair of the deterioration is carried out for 20 years from 2010 by using the procedure mentioned above.

Figure 4 is an example of the deterioration prediction results with repair. This example shows the distribution of the tunnel sample span numbers of each category according to the age of the subway tunnel section. In 2010, A1 and a part of A2, C category span have been repaired and the repair cost amounts to around JPY 110 million. Then, the next year tunnel deterioration distribution can be obtained by using the method mentioned in the previous section. The same procedure has been repeated for the next 20 years period.

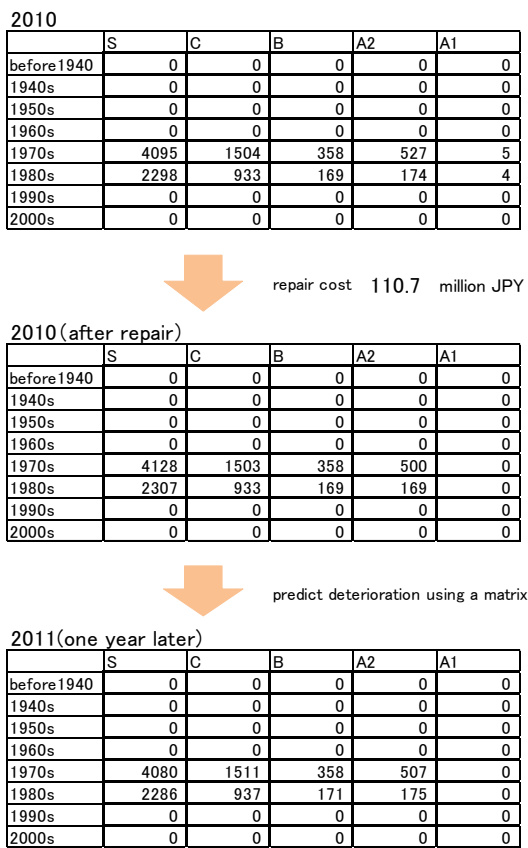


Figure 4. Example of deterioration prediction results considering repair

5.3 Evaluation of budget allocation strategy

Following the calculation procedure mentioned in the previous section, the trial budget allocation to 9 subway lines within the service area of Tokyo Metro Co. has been conducted by assuming that the annual total budget for the subway tunnel repair is JPY 1 billion. Cost effectiveness of this repair budget investment for 20 years is evaluated by changing the repair budget allocation to each subway line. The evaluation of the repair budget investment is based on the cost-benefit analysis. The ratio B(benefit) versus C(cost) is obtained as follows.

$$B(\text{benefit}) = \{ \Sigma(\text{increase of subway tunnel integrity by repair}) \times (\text{subway operating revenue}) \} \times (\text{tunnel repair budget}) / (\text{total budget of the entire business})$$

$$C(\text{cost}) = \Sigma(\text{cost used for subway tunnel repair})$$

The amounts of cost and benefit per year are calculated for the next 20 years separately and summed up to evaluate the effectiveness of the repair budget investment from 2011 to 2030.

The result is shown in Table 4. In this table, B/C value obtained from the calculation mentioned above is assumed to be 1, in the case of which the repair budget is allocated equally to each subway line. B/C value is higher than 1, when the repair budget is allocated considering the subway line length, the tunnel integrity before repair and the operating revenue of each subway line. It can be understood that it is possible to improve the cost-effectiveness of the investment by allocating the repair budget according to the physical characteristics and the transportation serviceability of the individual subway line.

Table 4. Cost-benefit analysis of repair budget allocation

allocation strategy	B/C
equal allocation	1
allocation considering line length	1.09
allocation considering tunnel soundness before repair, operating revenue	1.28

6 CONCLUSIONS

In this study, the cost effectiveness of the repair budget allocation to the individual subway line was investigated by using the tunnel inspection data. The following results were obtained from the numerical simulation of the subway tunnel deterioration and the repair budget allocation.

- 1) The tunnel integrity evaluation from the tunnel inspection data used in this study is considered to be valid from the concrete carbonation progression rate of the tunnel lining.
- 2) By obtaining the deterioration transition matrix according to the Markov method, the deterioration process of the subway tunnel has been predicted.
- 3) It is possible to improve the cost-effectiveness of the investment by allocating the repair budget according to the physical characteristics and the transportation serviceability of the individual subway line.

REFERENCES

- Akagi, H., M.Shiga, A.Hashimoto and A.Hayashi, 2007. A proposal of maintaining underground structure of telecommunication networks. Annual conference of Japan Society of Civil Engineers, 62, 385-386 (in Japanese).