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 and the maintenance and the effective operation for these infrastructures are now emerging the significant subjects. 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 public and private physical assets including subway tunnels during their use in the society, which enables us to manage physical assets effectively and efficiently. The goal aimed at this paper 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.

Keywords: asset management, underground railway tunnel, tunnel integrity, deterioration prediction

1 INTRODUCTION

In Japan, the construction of social infrastructure has been increasing since the high economic growth in the 1960s. The age of these infrastructures is more than 50s and their physical conditions are deteriorating. Further deterioration is expected to take place in the future and the maintenance and the effective operation for these infrastructures are significant subjects.

A managing method named as an infrastructure asset management is beginning to be employed recently. Asset management is the managing method, which has been invented to manage the financial assets owned by the bank customers. Infrastructure asset management is a strategic management of the public and private physical assets including subway tunnels during their use in the society, which enables us to manage physical assets effectively and efficiently. Consequently, it is possible to conduct a mid and long term efficient maintenance and create the operation method for the subway tunnel, in order to decide the proper budget plan for rehabilitation.

In this paper, social infrastructure is considered as the assets of the public and private sectors and the topics are focused on the deterioration and the rehabilitation. Infrastructure asset management methodology has been applied to subway tunnels by using the available tunnel inspection data. Tokyo Metro Company, which owns and operates the subway system in Tokyo, conducts two types of tunnel inspection procedures (a general inspection and a detailed inspection) according the railway structure maintenance and management standard codes specified by the Japan Ministry of Land, Infrastructure and Transportation.

By processing these tunnel inspection results, the integrity of the subway tunnel structure has been evaluated and a stochastic Markov process based matrix to estimate the degradation process of the subway tunnel has been obtained. The stochastic Markov process based matrix is named as the deterioration matrix and has been obtained according to the tunnel structure age. By using this matrix, the deterioration and the degradation of the subway tunnels have been predicted. The repair of the tunnel structure can be judged based on the tunnel integrity level predicted by using the deterioration matrix and the repairing cost can be calculated by the number of repairs and the integrity level based cost.

The cost effectiveness of the repair budget for the individual subway tunnel has been investigated numerically by cost-benefit analysis. By focusing on the repaired area and the frequency of the rehabilitation, the mid and long term maintenance numerical simulations have been conducted and the cost effectiveness has been evaluated.
2 ACCUMULATING AND PROCESSING THE TUNNEL INSPECTION RESULTS

2.1 Tunnel inspection results

In this study, the tunnel inspection data collected by the Tokyo Metro Company have been used to predict the deterioration of the subway tunnel. Tokyo Metro Company conducts two types of tunnel inspection procedures (a general inspection and a detailed inspection) by JRTRI (2007), The Japan Ministry of Land, Infrastructure and Transportation has recently specified the maintenance and the management standard for the railway structures.

A general inspection is conducted every two years. In this inspection, the inspection engineers are required to carry out the concrete hammering inspection and the visual inspection to the lower part of the tunnel cross-section. And for the upper part of the tunnel cross-section, they are required to carry out only the visual inspection. On the other hand, a detailed inspection is conducted every twenty years. And the inspection engineers are required to carry out the concrete hammering inspection and the visual inspection for the whole cross-section of the tunnel structure. The deterioration category used during the tunnel inspection by the Tokyo Metro Company is shown in Table 1 by Japan Ministry of Land, Infrastructure and Transportation (2010).

| Classification | Condition of the Structure |
|----------------|---------------------------|
| AA             | Deterioration which threatens safety operation, normal operation, safety of public and passengers |
| A1             | Deterioration which is reducing the performance of the structure |
| A2             | Deterioration which has a risk of losing performance by heavy rain, flood |
| B               | Deterioration which could lose the performance of the structure in the future |
| C               | Deterioration which has a risk of changing to rank A in the future |
| S               | Slight deterioration |
| G               | No deterioration |

Table 1. The deterioration category

2.2 Processing the tunnel inspection results

The tunnel inspection results provided by the general and detailed inspection procedures have been processed and classified as follows.

1) The whole length of subway tunnel section is divided into a sampling span of 5m. The deterioration category shown in Table 1 is assigned for each sampling span. If multiple deterioration categories are assigned in the same sampling span, the worst category is assigned to the sampling span.

2) The construction age of each sampling span and the soil characteristics around the tunnel section are recorded. The soil characteristics around the tunnel section are classified into 2 types. Soil A is relatively stiff stable ground and soil B is soft ground.

3) The frequency 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 level value from the deterioration category. Each deterioration category level $k_i$ is scored as follows, $S=10$, $C=8$, $B=6$, $A2=3$, $A1=1$, $AA=0$.

The value of this scoring has been provided by the experiences of the inspection engineers, who have engaged in the maintenance of the subway tunnels of Tokyo Metro Company in order to keep the running safety of the subway train.

The integrity value $h$ of each subway tunnel line is evaluated by averaging the score of each sampling span along the subway tunnel line, as given in Eq. (1).

$$ h = \frac{\sum_{i=1}^{n} k_i \cdot n_i}{\sum_{i=1}^{n} n_i} \quad (i = AA,A1,A2,B,C,S) \quad (1) $$

in which $n$: number of sampling span categorized to each deterioration category.

Fig.1 compares the tunnel integrity values of the upper part of the tunnel cross-section obtained from the general inspection and the integrity values from the detailed inspection, conducted for one of the oldest subway tunnel line in 2012. The subway tunnel was built from 1927 to 1939 and the integrity values are different dependent on the construction year. The integrity values from the detailed inspection procedure are smaller than those from the general inspection procedure, due to the difference in inspection procedures. For the upper part of the tunnel cross-section, the detailed inspection is conducted more carefully compared with the general inspection. The tunnel integrity of this old subway tunnel has been kept between category C and category B listed in Table 1. The tunnel section built in 1932 has been repaired in 2010 and the tunnel integrity has been significantly improved.
3.2 Relationship between the concrete carbonation and the tunnel integrity

The relationship of concrete carbonation and the tunnel integrity has been investigated by using the inspection results along the same subway line. This subway line was constructed around 80 years ago as mentioned in the previous section and the major cause of the degradation of this subway tunnel is considered to be the concrete carbonation. The concrete carbonation of the tunnel lining has been investigated on this old subway tunnel. The concrete carbonation progression rate is defined as (the carbonation depth (mm) / thickness of covering concrete of the tunnel lining (mm)). This carbonation rate has been obtained by the tunnel lining inspection and the relationship between the concrete carbonation progression rate and the tunnel integrity value has been investigated.

Fig.2 indicates the variation of the concrete carbonation progression rate at the tunnel lining sampling position along this subway line. It can be understood that the similar carbonation progression rate of the tunnel lining concrete core has been obtained at the close sampling positions.

The concrete carbonation inspection results can be divided into three groups as follows, according to the values of carbonation progression rate. Group.1 is allocated at the section between 0.1km~0.3km from the origin of the subway tunnel. Group.2 is allocated at the section between 0.5km~0.6km and Group.3 is allocated at the sections between 0.3km ~ 0.4km and 0.6km ~ 0.9km. The relation between the tunnel integrity value and the carbonation progression rate of each group is demonstrated in Fig.3.

Fig.3 indicates that the tunnel integrity value is small at the tunnel section, where the concrete carbonation progression rate is high. Consequently, the tunnel integrity evaluation from the tunnel inspection results used in this study is considered to be valid from the concrete carbonation progression rate of the tunnel lining.

4 TUNNEL DEGRADATION PREDICTION

4.1 Predicting tunnel degradation by deterioration matrix

Since the aim of this research is to predict the deterioration of the subway tunnel system as a group, the stochastic Markov process based method 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.

The deterioration transition matrix was produced and employed to predict the subway tunnel degradation. \( \{P_1\} \) is assumed to be the probability vector of each deterioration category at \( ln \) year after the construction and \( \{P'_1\} \) is assumed to be the probability vector of each deterioration category at \( ln+1 \) year after the construction. The relation between \( \{P_1\} \) and \( \{P'_1\} \) can be given as follows by using the Markov process method

\[
\begin{align*}
\{P_S P_C P_B P_A_1\} & = \{P_1 \ P_C \ P_B \ P_A_1\} \\
& = \begin{bmatrix}
K_{SS} & K_{SC} & K_{SB} & K_{SA1} \\
0 & K_{CC} & K_{CB} & K_{CA1} \\
0 & 0 & K_{BB} & K_{BA2} \\
0 & 0 & 0 & K_{AA1} \\
0 & 0 & 0 & 0 & K_{A1A1}
\end{bmatrix}
\end{align*}
\]

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 study, numerical simulations of the subway tunnel degradation have been performed by using the following assumptions.

a) The deterioration category does not be improved naturally without tunnel repair.

b) There are two patterns of deterioration for each tunnel sample span. The change of deterioration category is just by one category or it remains at the same category in the next year.
c) 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.

d) When the repair of the tunnel sample span is conducted, the deterioration category is brought back to category S.

Table 2. Example of deterioration transition matrix

| 74 years after construction | 75 years after construction |
|-----------------------------|-----------------------------|
| S  0.99701 0.00299 0 0 0 | 0.994314 0.005686 0 0 0 |
| C  0 0.994314 0.005686 0 0 | 0 0.926585 0.073415 0 |
| B  0 0 0.926585 0.073415 0 | 0 0.894061 0.005939 0 |
| A2 0 0 0 0.99701 0.00299 | 0 0 0 0.994314 0.005686 |
| A1 0 0 0 0 1 | 0 0 0 0 1 |

The example of the deterioration transition matrix produced is shown in Table 2 by using the assumptions above. Table 2 is the transition matrix which predicts the deterioration of the tunnel during the age of 74 years old to the age of 75 years old.

5 TRAIL TUNNEL REPAIR SIMULATION USING REPAIR SCENARIO AND REPAIR COST

5.1 Repair cost for deteriorated tunnel

The repair cost for each deterioration category has been decided from the actual amount of the repair costs. The repair costs used in the calculation are shown in Table 3. 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 as follows: A1 cost = 3.0 times A2 cost, B cost = 0.5 times A2 cost and C cost = 0.2 times A2 cost.

5.2 Numerical methods for repair simulation

Predicting the degradation of each subway tunnel was conducted by using the deterioration transition matrix. In order to reproduce the maintenance and the rehabilitation of the subway tunnels, the numerical repair simulation has been conducted under the following conditions.

1) The repair is conducted once a year.
2) Cost of repair is based on the value of Table 3.
3) The life expectancy of each repair is 10 years. After 11 years, that repaired sample tunnel span starts to deteriorate.
4) The prediction of the tunnel deterioration is conducted by using the deterioration transition matrix based on the inspection results at 2010

The variation of the tunnel integrity associated with the repair process considering the above conditions is shown in Table 4. The tunnel sample spans with deterioration categories A1 and A2 are assumed to be repaired every year. The repair process following the above scenario has been assumed to be repeated for 20 years.

5.3 Tunnel repair simulation results and evaluation

The factors of deciding the most suitable tunnel maintenance and management scenario can be selected from the following items; the repair method, the timing of the repair and the application range of the repair. In this paper, the repair frequency and the range of the repair application have been adopted and evaluated in terms of the repair budget investment.

The evaluation of the repair budget investment has been based on the cost-benefit analysis procedure. The ratio B (benefit) versus C (cost) has been assumed to be obtained as follows.

B (benefit) is assumed to be obtained as follows: \( \{ \Sigma \text{(increase of subway tunnel integrity by repair)} \times \text{(subway operating revenue)} \} \times \text{(tunnel repair budget)} / \text{(total budget of the entire business)} \).

C (cost) is assumed to be obtained as follows: \( \Sigma \text{(cost used for subway tunnel repair)} \).

The amounts of cost and benefit per year have been calculated for next 20 years separately and summed up to evaluate the effectiveness of the repair budget investment from 2011 to 2030. The tunnel repair scenarios have been assumed based on a) the repair application range and b) the frequency of repair.

a) Evaluation of the scenario in terms of the repair application range

The repair scenarios have been assumed by changing the repair application range. Three types of repair scenario have been assumed as follows: Scenario 1 is assumed to repair the deterioration range (A1, A2). Scenario 2 is assumed to repair the deterioration range (A1, A2, A1, A2), and Scenario 3 is assumed to repair the deterioration range (A1, A2, A1, A2, A1, A2, A1, A2, A1).
A2, B). Scenario 3 is assumed to repair the deterioration range (A1, A2, B, C).

Figure 4. The variation of the tunnel integrity

Table 5. Total expense and the value of B/C

| Total Expense (million JPY) | Scenario 1 | Scenario 2 | Scenario 3 |
|----------------------------|------------|------------|------------|
| B/C                        | 1.31       | 1.334      | 1.333      |

The numerical simulation results are summarized in Figure 4 and Table 5. The values of tunnel integrity have been kept over 9 for 20 years for all 3 types of scenario. Although Scenario 1 is currently adopted by the Tokyo Metro Company, Scenario 2 gives the highest B/C value and the lowest expense.

b) Evaluation of the scenarios in terms of the frequency of repair

Since the repairing of the tunnel sample span with category B is the key for the repair scenario as demonstrated in the previous section, five types of tunnel repair scenarios have been assumed by changing the frequency of the repairing of the tunnel sample span with deterioration category B as follows.

Scenario 4 repairs the category B every year. Scenario 5 repairs category B every two years, Scenario 6 repairs category B every three years. Scenario 7 repairs category B every five years and Scenario 8 doesn’t repair category B. Scenario 8 is the same as Scenario 1 in the previous section.

The numerical calculation results are summarized in Figure 5 and Table 6. Almost the same values of tunnel integrity have been obtained with all the scenarios and their values have been kept over 9 through 20 years. By raising the frequency of the repair of category B, the accumulation expense of 20 years has been reduced and the smaller B/C value has been obtained.

It is conclusively demonstrated that the tunnel repair should be conducted not only the current practice of the tunnel sample span with deterioration category A1 and A2 but also that with category B.

6 CONCLUSIONS

In this study, the cost effective repair and management policy on the individual subway tunnel has been investigated by using the numerical simulation based on the tunnel inspection results. The conclusions obtained from this study are summarized as follows.

1. The integrity values from the detailed inspection procedure are smaller than those from the general inspection procedure, due to the difference in the inspection procedures.
2. The tunnel integrity evaluation from the tunnel inspection results used in this study is considered to be valid from the concrete carbonation progression rate of the tunnel lining.
3. By obtaining the deterioration transition matrix according to the stochastic Markov process based method, the deterioration process of the subway tunnel has been predicted.
4. The tunnel repair should be conducted not only the current practice of the tunnel sample span with deterioration category A1 and A2 but also that with category B.

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