Trial Asset Management System for Underground Infrastructure in Japan

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ABSTRACT

A reasonable maintenance management system for Japanese infrastructure is strongly required, since a significant number of infrastructures built around 40–50 years ago have rapidly deteriorated. A trial asset management system is introduced for the underground tunnels of the large tele-communication network system in Japan. A trial numerical simulation has been carried out to obtain and assess the asset management system for the underground structure of the Japanese tele-communication network. In this simulation, the deterioration prediction of the underground infrastructure employs the Markov stochastic process theory. Conclusively, the optimum maintenance scenario has been shown to be a pre-maintenance type countermeasure.

1. INTRODUCTION

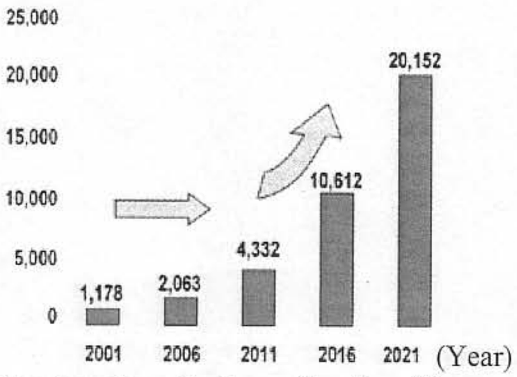


Fig.1 Number of road bridges older than 50 years

The background of this study is summarized as follows. At first, the rapid increase in the old existing infrastructures in Japan is observed. Figure 1 shows that the number of road bridges older than 50 years will begin to increase rapidly after 2011 and will increase by almost ten times by 2021. This implies that most of the road bridges have been constructed between the 1960s and the 1970s, i.e. the period of high economic growth in Japan.

The second is the projected decline in the Japanese population in the near future. Figure 2 exhibits the estimated future population trend of Japan. The population of Japan, which has continued to grow since the end of World War II, will enter a period of decline within a few years. The population peak of Japan, i.e. around 130 million, was

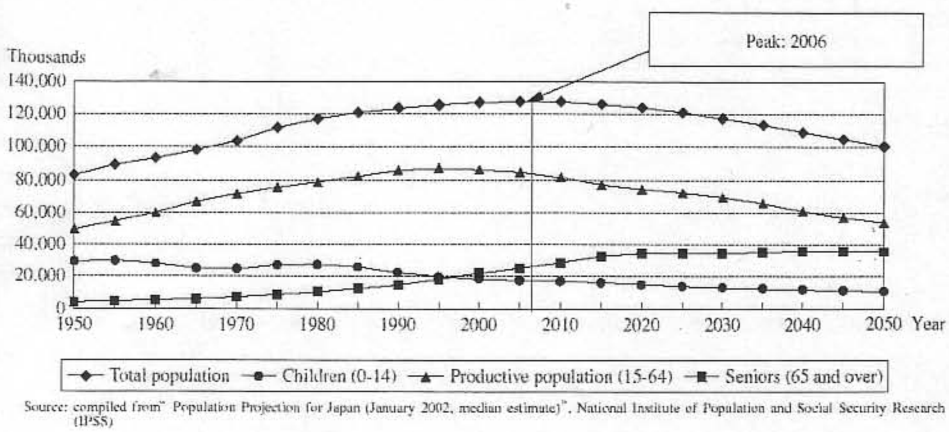
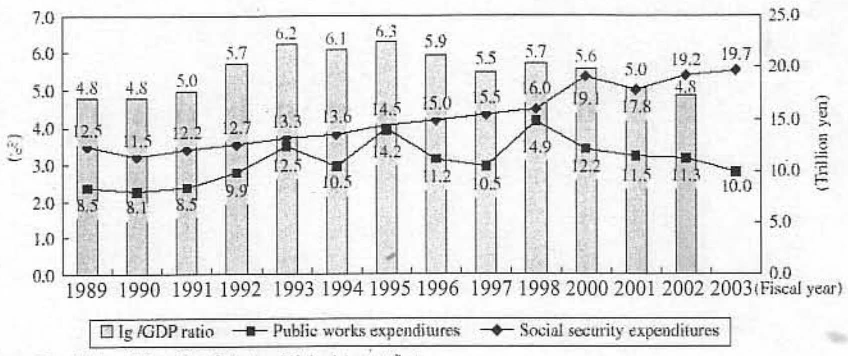


Fig.2 Estimated future population trend of Japan



Source: Compiled from Cabinet Office," System of National Accounts" etc.

Fig.3 Japanese financial restriction on public investment

reached in the previous year, 2006. It is expected that by the year 2050, the population will have decreased to 100 million. Moreover, the population of the aged generation—older than 65—increases, although the productive generation between 15 and 64 decreases.

The third is the financial restrictions on public investment. Figure 3 shows the changes in the ratio of ordinary government IG (i.e. Income Gross) to the GDP and changes in public works and social security costs. The ratio of the IG of the Japanese government to the GDP has been decreasing over these 10 years, which indicates the severe financial conditions of the Japanese government, as shown by the columns. Moreover, the government expenditures due to public works continue to decrease, in contrast to the monotonic increase in the expenditure on social security. It is expected that similar severe financial restrictions are in progress in Japan, from the abovementioned population trend.

The fourth is accountability and public approval. Based on the abovementioned current situations in Japan, it can be seen that the government or privatized companies, which own and operate the infrastructure, require policies for the smooth conduct of civil engineering projects, including reforming, repair and retrofit of the infrastructure. These policies should be based on accountability and public approval. Subsequently, the accountability and the public approvals should be achieved by disclosing the information and explanation obtained from asset management.

2. INFRASTRUCTURE ASSET MANAGEMENT SYSTEM

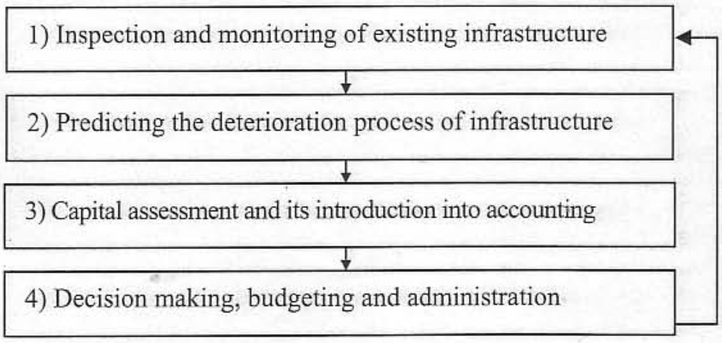


Fig.4 Infrastructure asset management system

The infrastructure asset management system consists of the rotation of four stages, as shown in Fig.4. The first is the inspection and monitoring of the existing infrastructure. Visual inspection of the damages to the infrastructure or automatic monitoring of the deflection of the underground structure detects deterioration, i.e. the ageing of the infrastructure. Inspected damages are categorized according to the degree of severity.

The second is the prediction of the deterioration process of the infrastructure. This prediction is required to produce the future maintenance scheme for the infrastructure. The method of prediction may be based on a theoretical mechanism, which controls the deterioration of the reinforced concrete by the chemical oxidization process. Another method employs the probabilistic procedure based on the statistical deterioration data, i.e.. the Markov stochastic process that was used in this numerical simulation. The third is the capital assessment of the infrastructure and its introduction into the accounting system. The fourth is the decision making, budgeting and execution by the organization. This process shall be rotated as shown in this figure.

3. TELE-COMMUNICATION NETWORK IN JAPAN

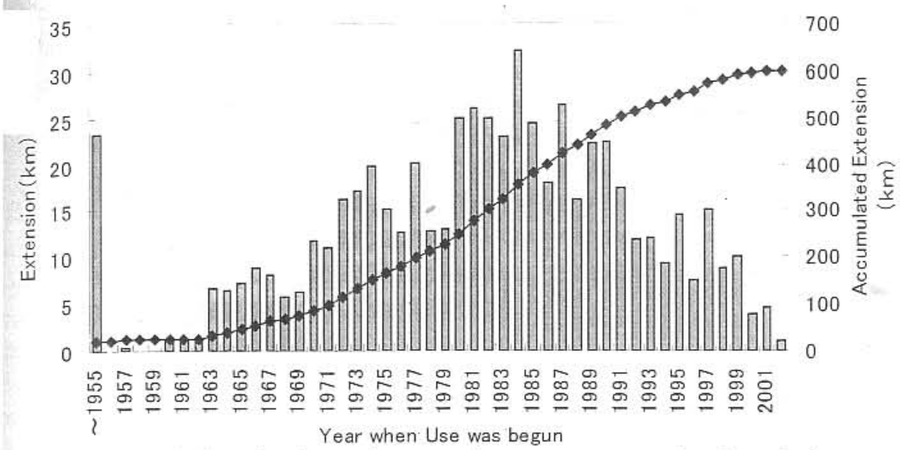


Fig.5 Variations in the underground structure extension length for tele-communication network

In this study, the tele-communication system, i.e. electric- and electronic-based telephone and communication network systems are adopted as an example of the infrastructure in Japan. Figure 5 shows the variations in the underground structure extension length during these five decades. For these 50 years, a considerable number of underground structures have been constructed for the communication cables by using a shield tunnelling method and an open-cut excavation. The vertical axis on the right-hand side indicates the total extension length of the underground structure for tele-communication. This length has reached almost 600 km throughout Japan.

4. TRIAL NUMERICAL SIMULATION

Trial numerical simulation has been carried out to obtain and assess the asset management system for the underground structure of the Japanese tele-communication network. In the simulation, the first step is to inspect and monitor the current status of the underground structure deterioration. Secondly, the deterioration transition matrix for the underground structure based on the Markov stochastic theory is derived by using the inspection results. Subsequently, the future deterioration of underground structure is predicted using the deterioration transition matrix. In order to maintain the required performance of the underground structure, countermeasures against deterioration and the repair costs are needed. Finally, the optimum maintenance scenario for the underground structure is discussed.

4.1 Inspection results of the underground structure deterioration

Table 1 Categorization of inspection results

Category	Crack density (m/m^2)*	Water leak
O	<0.5	No
A	>0.5	No
B	>0.5	Yes
C	>1.0	No
D	>1.0	Yes
E	>2.0	No
F	>2.0	Yes

*Crack density = Crack length with width >0.3 mm at every 1 m × 1 m section obtained by visual inspection.

Table 1 categorises the visual inspection results of the underground structure deterioration, according to the crack density and whether the water leak exists or not. Category O (Original) means that the crack density is less than 0.5 m/m^2 and without any water leak. From categories A to F, the severity of the deterioration becomes greater.

Table 2 shows the actual deterioration inspection results for the underground structure obtained from the Tokyo metropolitan area, as of 2005. The entire underground structure adopted in this simulation was constructed by the cut and cover method under nearly the same boundary condition. The number of inspected tunnels was 144 and the total length was 58.4 km. The inspection results for the underground tele-communication structure were classified into 4 groups according to the year of construction for each structure. The older the underground structure was, the greater the proportion of the severe deterioration became, as shown in the categories A and E.

Table 2 Actual inspection results for tele-communication underground structure

Age (Years)	Deterioration category							Total (cases)
	O	A	B	C	D	E	F	
16~25	8,267	233	119	172	31	546	22	9,390
26~35	29,856	1,339	614	566	73	2,585	56	35,089
36~45	22,231	1,215	307	378	145	1,997	44	26,317
46~55	1,216	67	12	25	5	87	6	1,418
Total	61,570	2,854	1,052	1,141	254	5,215	128	72,214

4.2 Markov stochastic process: Deterioration transition probability matrix

In this simulation, the deterioration prediction of the underground infrastructure has employed the Markov stochastic process theory. The basic assumptions and the procedure are as follows. The first assumption (a) is that a significant number of deterioration inspection results have some statistical characteristics. The second assumption (b) is that a deterioration process is determined by the current state of deterioration, i.e. the more severe the current state of deterioration, the greater the rate of deterioration.

At first, one of the deterioration categories, O, A, B, C, D, E and F, obtained from the inspection is assumed to correspond to the variable state X_n at time t = n. Subsequently, the conditional probability p_{ij} of transition of state variable X_{n-1} at t = n − 1 to X_n at t = n is defined as the following equations (1) and (2). The state variable vector $\{X_n\}$ at t = n is obtained by multiplying the state variable vector $\{X_{n-1}\}$ at t = n − 1 by the deterioration transition matrix $[P]$, as indicated in equation (3).

$$p_{ij} = P\{X_n = j \mid X_{n-1} = i\}, \qquad i, j \in s \qquad \textit{(s: set of state variables)} \tag{1}$$

$$\{X_{j1}, X_{j2}, \cdots, X_{jK}\} = \{X_{i1}, X_{i2}, \cdots, X_{iK}\} \cdot \begin{bmatrix} p_{11} & p_{12} & \cdot\cdot & p_{1K} \\ 0 & p_{22} & \cdot\cdot & p_{2K} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$\{X_n\} = \{X_{n-1}\} \cdot [P] \qquad [P] = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1K} \\ 0 & p_{22} & p_{23} & \cdots & p_{2K} \\ 0 & 0 & p_{33} & \cdots & p_{3K} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdots & \cdot\cdot \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{3}$$

If infrastructural repairs are carried out, the repair process can also be represented by the conditional probability q^d_{ij} , the same as in p_{ij}. Subsequently, the deterioration process including the repair can be represented by the conditional probability p^d_{ij}. The deterioration transition matrix including repair $[P^d]$ is obtained by multiplying $[P]$ by $[Q^d]$. Therefore, the state variable $\{X_n\}$ is obtained by multiplying the vector $\{X_{n-1}\}$ by the matrix $[P^d]$, as shown in equation (4).

$$\{X_n\} = \{X_{n-1}\} \cdot [P^d] \qquad ([P^d] = [Q^d] \cdot [P]) \tag{4}$$

Table 3 Variation in deterioration category percentage

Age (Years)	Deterioration category (%)							Total (%)
	O	A	B	C	D	E	F	
16~25	88.1	2.5	1.3	1.8	0.3	5.8	0.2	100
26~35	85.1	3.8	1.7	1.6	0.2	7.4	0.2	100
36~45	84.4	4.6	1.2	1.4	0.6	7.6	0.2	100
46~55	85.8	4.7	0.8	1.8	0.4	6.1	0.4	100
Total	85.3	4.0	1.5	1.6	0.4	7.2	0.2	100

The following procedure demonstrates the derivation of transition probability matrix $[P]$ for underground structure deterioration, using the actual inspection results of the underground structure as mentioned before.

1) The inspection results for the underground tele-communication structure as of 2005 were classified into 4 groups according to the year of construction for each structure, in order to average the randomness of the inspection results, as shown in Table 2. Table 3 summarises the percentage of the number of places for each deterioration category obtained against the total number of inspection.

Table 4 Derivation of transition probability matrix [P]

		Year 1975							
	Category	O	A	B	C	D	E	F	Age = 29
Year 1976	O	85.1	0.3	0.0	0.0	0.0	0.0	0.0	85.4
	A	0.0	3.5	0.2	0.0	0.0	0.0	0.0	3.7
	B	0.0	0.0	1.5	0.2	0.0	0.0	0.0	1.7
	C	0.0	0.0	0.0	1.4	0.2	0.0	0.0	1.6
	D	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2
	E	0.0	0.0	0.0	0.0	0.0	7.2	0.0	7.2
	F	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
	Age = 30	85.1	3.8	1.7	1.6	0.2	7.4	0.2	100.0

2) The yearly variation in deterioration was obtained by the interpolation of the data for 4 groups. For example, Table 4 shows the transition of deterioration for the underground structure from the age of 29 to 30. The right hand vertical column of this table exhibits the percentage of each category at the age of 29 and the bottom row indicates the percentage at the age of 30. Since the higher deterioration does not return to the lower category of deterioration without any repair, the left low triangular part of this matrix becomes zero. The rest of the matrix elements were determined as shown in this table.

3) Each element of the matrix was divided by the total percentage of each row at the age of 29. Consequently, the deterioration transition matrix [$P_{29,30}$] from the age of 29 to 30 is obtained. Therefore, the state variable vector $\{X_{age30}\}$ is obtained by multiplying the state variable vector $\{X_{age29}\}$ by the matrix [$P_{29,30}$], as indicated in equation (5). 30 deterioration transition matrices [P] were obtained from the ages 20 to 50, following the same procedure.

$$\underset{\{X_{age30}\}}{\{85.1,3.8,1.7,1.6,0.2,7.4,0.2\}} = \underset{\{X_{age29}\}}{\{85.4,3.7,1.6,0.2,7.2,0.2\}} \overset{[P_{29,30}]}{\begin{bmatrix} 0.996 & 0.004 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.946 & 0.054 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.082 & 0.118 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.875 & 0.125 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}} \quad (5)$$

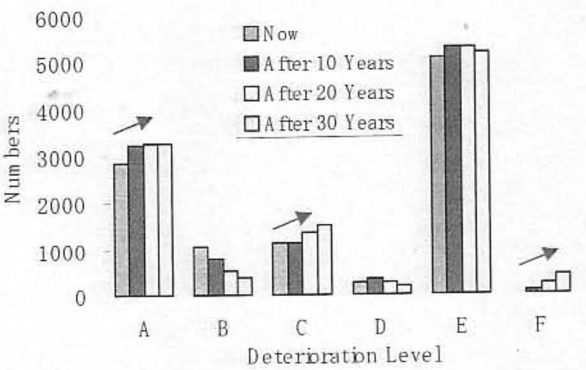


Fig.6 Future deterioration prediction of underground infrastructure

5. FUTURE DETERIORATION PREDICTION OF THE UNDERGROUND INFRASTRUCTURE

Figure 6 demonstrates the numerical simulation results of predicting the future deterioration of the underground infrastructure for the tele-communication network, using the deterioration transition matrix [P]. The prediction has been conducted for the age of 20- to 50-year-old structures. The number of deteriorated places for Categories A, C and F gradually

Table 5 Countermeasures against deterioration and their costs

Maintenance scenario	Targets of repair
Pre-maintenance scenario type (1)	A,B,C,D,E,F
Pre-type (2)	B,C,D,E,F
Pre-type (3)	C,D,E,F
Post-maintenance scenario type (4)	D,E,F
Post-type (5)	E,F
Post-type (6)	F

Cost of repair: JPYen 20,000 (US$170) / each place for category A,B,C. JPYen 46,000 (US$400) / each place for category D,E,F

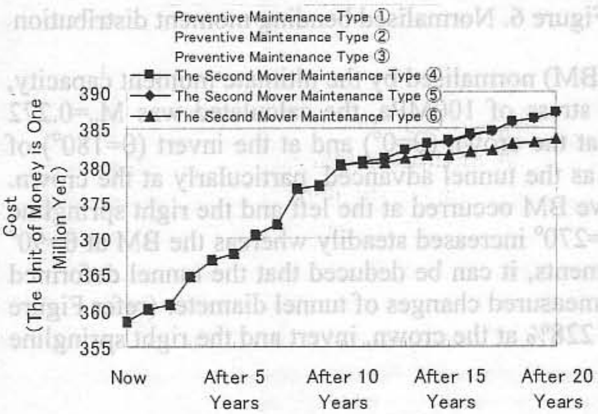


Fig.7 Comparison of the repair costs among pre- and post- scenarios

increases for the next 30 years, as indicated by red arrows.

Table 5 shows the countermeasures against the deterioration and the necessary costs. Six types of maintenance scenarios are prepared for the numerical simulation, as shown in this table. The first three types of scenarios are pre-maintenance ones, which repair the smaller damages prior to the occurrence of the severe damage and others are post-maintenance scenarios, which mainly repair the severe damages. The repair cost depends on the severity of deterioration. The repair cost for the severe damages D, E and F is almost double that for the small damages A, B and C. The pre-maintenance scenario costs are smaller than the post-maintenance scenarios by around 3% of the post-maintenance cost. If the decision making for the tele-communication underground structure asset management is based on the life cycle costs, the optimum maintenance scenario or policy is assumed to be a pre-maintenance scenario based policy.

6. CONCLUSIONS

In this study, a trial numerical simulation has been carried out to obtain and assess the asset management system for the underground structure of the Japanese tele-communication network. The conclusions obtained from this study are summarized as follows:

1) Infrastructure asset management system is required for accountability and a policy based on public approval.

2) The deterioration of underground infrastructure can be predicted using the Markov stochastic process.

3) Optimum maintenance scenario is a pre-maintenance type of countermeasure.

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