INVESTIGATION OF EVALUATION AND ESTIMATION OF TUNNEL LINING DETERIORATION BASED ON INSPECTION DATA

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ABSTRACT

This paper proposes deterioration methods based upon inspection data in order to carry out strategic maintenance and to rationalize life cycle cost for tunnel structures. The resistance of deteriorating tunnel structures is non-stationary stochastic processes, and reliability problems of such structures are essentially different of time-independent reliability problems. Hokkaido is compared with the area in other Japan, the tunnel lining damage of the present condition by frost damage and/or freezing crack are intense. While the forecasting of deterioration is one of the important issues in infrastructural management, it is often the cases where are few data stocks available for estimating the deterioration forecasting model. Firstly, the methodology of predicting of deterioration is discussed to model of tunnel lining. This paper presents the identification of the degrading process represented by the Ito stochastic differential equation. Secondly, for the prediction of the individual structure of tunnel lining, a probabilistic approach using the distribution of deterioration rates and its own historical inspection data is proposed. The validity of these methods is verified through the actual inspection data of tunnel lining. And, the applicability of the methodology presented in this paper is examined by the real data of the road tunnel lining in Hokkaido. In addition, the average deterioration curves, variance and distribution density of time history, are obtained by the inspection data of tunnel lining. And, a growth of the frost damage and/or freezing crack of tunnel lining can be predicted by this technique, it can repair before a tunnel lining breaks.

1. INTRODUCTION

Infrastructure maintenance is becoming increasingly important in Japan. Especially in Hokkaido, about 40% the conventional construction method road tunnels have been constructed over the past 40~50 years. Therefore, many conventional construction method road tunnels will come to its rehabilitation stage, and almost tunnel linings must be maintenance or repair (See Figure 1). Moreover, Hokkaido, northern part of Japan, is cold, showy region.

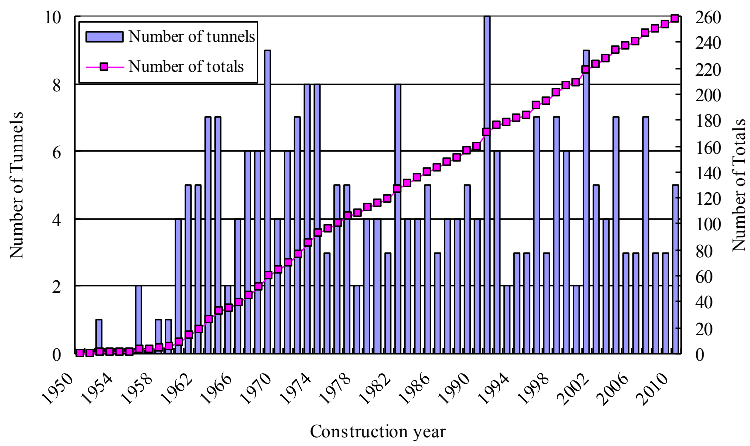
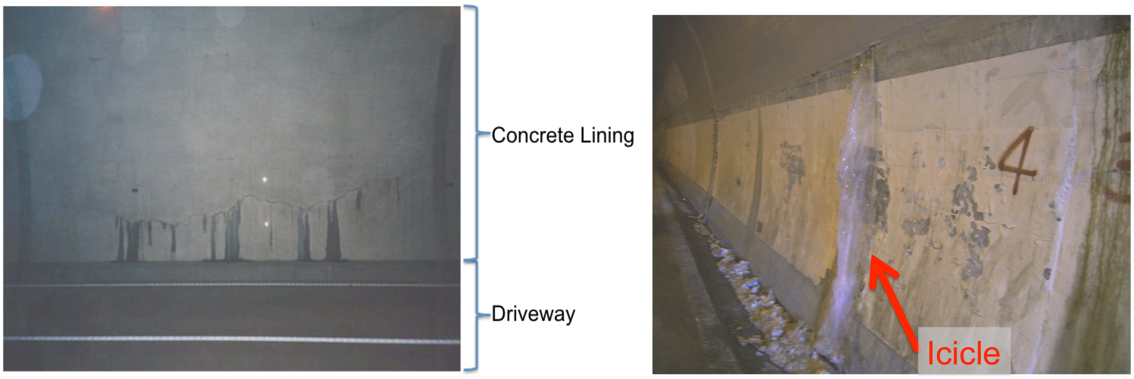


Figure 1 Number of the construction tunnel in Hokkaido



Picture 1 road lining concrete of frost damage

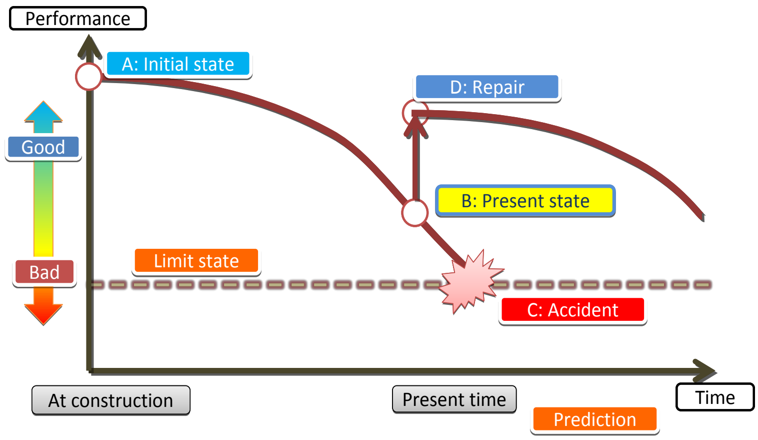


Figure 2 Life cycle cost for tunnel performance

The risk of frost damage is high. There have been cases in which the road tunnel lining has deformed as a result of freezing in winter. Hokkaido is compared with the area in other Japan, the tunnel lining damage of the present condition by frost damage and/or freezing crack are intense.
For example, as shown in Picture 1, a crack in a tunnel lining concrete caused by freezing of the surrounding ground due to cold air running through the tunnel in winter. Tunnel lining cracks like these grow every year. Damage distinguishing factor in the winter is a significant impact on the degradation process of the road tunnel lining. So, We focused on the inspection data of road tunnel in Hokkaido.
This paper proposes to select of the tunnel lining deterioration models based upon actual inspection data in order to carry out strategic maintenance and to rationalize life cycle cost analysis for tunnel structures [1]. The deterioration of the conventional construction method road tunnel lining is non-stationary stochastic processes, and reliability problems of such structures are essentially different of time-independent reliability problems. While the forecasting model of deterioration is one of the central takes in infrastructure asset management, it is often the cases where are few data stocks available for estimating the deterioration and/or degrading forecasting model (See Figure 2).
In this paper, it will be developed to the efficient tunnel lining maintenance based on the life cycle cost theory. Firstly, performance function of the deterioration evaluation value, the methodology of predicting of deterioration is discussed and described of the stochastic methods for tunnel lining. Secondly, a method is developed to identify degrading process of tunnel lining using inspected data of existing aged tunnels in cold, snowy Hokkaido. The stochastic model of deterioration and/or degrading process is described by the Ito stochastic differential equation. In addition, a growth of the frost damage and/or freezing crack of tunnel lining can be predicted by this technique, it can repair before a tunnel lining breaks.

2. CONSEPT OF TUNNEL MANAGEMENT SYSTEM

2.1. Model of Tunnel Management System

The model of tunnel management system presented in the paper is applied to the asset management of the road tunnels. Also, this research project will be developed to the

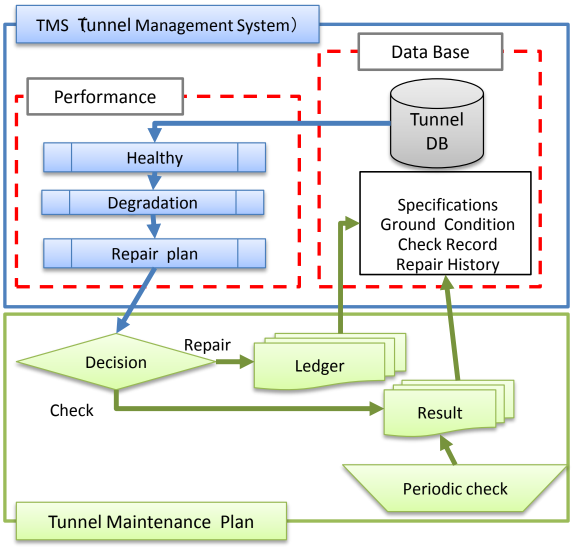


Figure 3 Tunnel management systems

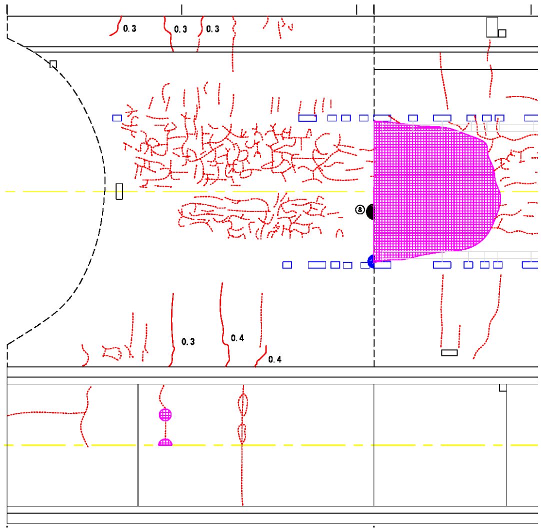


Figure 4 Inspection data of tunnel lining

efficient tunnel maintenance system and a quantitative criterion from pictures of tunnel lining using the life cycle cost theory (See Figure 2).

2.2. Present of Tunnel Management System

In this maintenance system is consist of the two following parts which shows in the Figure 3. Upper part is data store and estimated of the tunnel lining performance which based on inspection data.
Firstly, the database of the foundations of the basic specifications of the national highway tunnel in Hokkaido, a repair history, checks data, etc. is created.
Secondly, the degrading model based upon actual inspection data in order to carry out strategic maintenance and to rationalize life cycle cost analysis for tunnel structures. The resistance of deteriorating tunnel structures is non-stationary stochastic processes, and reliability problems of such structures are essentially different of time-independent reliability problems.
Lower part is the tunnel maintenance planning of the suitable repair time, and the optimal repair construction method for tunnel lining is constituted in the developing system.

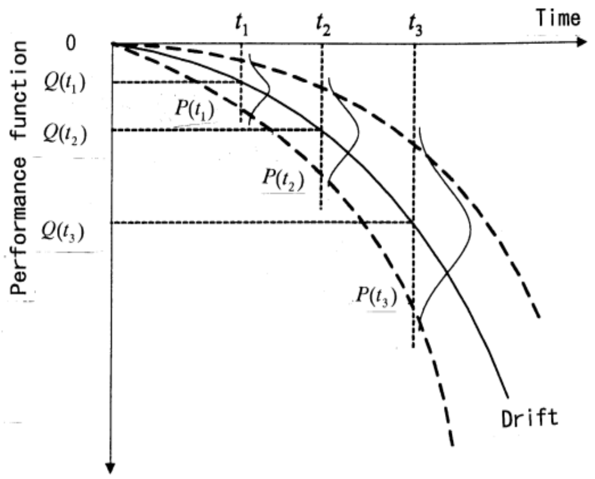
2.3. Quantification of Inspection Data

Inspected data from existing tunnels in Hokkaido are used for the quantification of tunnel lining. Here, six check damages or deteriorations of the tunnel lining shows as follow; 1) Crack, 2) Flaking off, 3) Water leak, 4) Joint and opening, 5) Faulty and Cave, 6) Efflorescence (See Figure 4) [2].

3. STOCHASTIC MODEL OF TUNNEL LINING DEGRADING PROCESS

3.1. Basic Model of Ito Stochastic Equation

The present problem is the estimation and/or identification of the deterioration process of the tunnel lining. The deterioration process of tunnel lining is represented by the Ito stochastic differential equation [3]. This Ito stochastic differential equation is well known model which generally called the Black-Scholes model in stock market.
Here, the deterioration rate or evaluation value $X(t)$ or the performance functions $Q(t_i)$ of the tunnel lining represented by the Ito stochastic differential equation as follows [4] , [5].



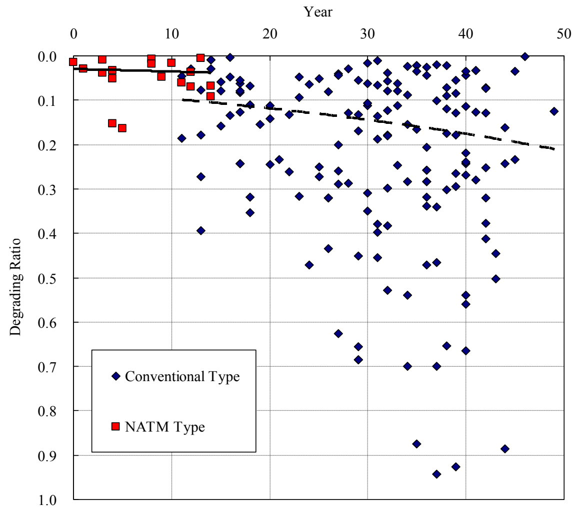


Figure 5 Performance (Degrading process) of tunnel lining

Figure 6 Degrading process of tunnel lining

$$dX(t) = \beta X(t)dt + \sigma X(t)dW_1(t) \qquad (1)$$

where, β :the constant drift parameter, σ :the constant volatility parameter or the volatility function $P(t_i)$, $W_1(t)$:the wiener process (see Figure 5).

For the prediction of the individual structure of tunnel lining, a probabilistic approach using the own historical repair data is proposed. And, assume that the performances of tunnel lining recovers immediately after each repair process, so that the deterioration rate or evaluation value $X(t_i) = Z(t_i)$ becomes discontinuous and returns to vertically at a repair time [6] , [7].

$$dZ(t) = \beta Z(t)dt + \sigma Z(t)dW_1(t) + \sum_{i>1} \{Z_1^* - Z_2^*\} \iota(t - t_1^*) \qquad (2)$$

where, ι :the Dirac measure.

The repair of deterioration is one of the central actions in infrastructural asset management, it is often the cases where are few existing records available for estimating the deterioration forecasting model.

3.2. Identification of Performance (Degrading process)

Inspected data from existing tunnels in Hokkaido are used for the identification of parameter of Ito stochastic differential equation. Inspection data of the conventional construction method road tunnel has been carried out last several decades, such as crack width, crack length and crack expanse of about 240 tunnels. The results summarized as degrading ratio from 0.0 (no damage) to 1.0 (critical damage).

It should be mentioned that most of the aged tunnels have repaired at certain period. It is quite difficult to identify based on the existing records, for example, when and how much repaired.

Figure 6 shows a degrading ratio of the conventional construction method type tunnels and NATM type of tunnels in terms of tunnel age and the reproduced degrading process identified by general solution of Ito stochastic differential equation using the tunnel inspection data.

Above mentioned reason, these results indicate degrading process of a group of tunnel. Therefore, it is served that these results are satisfactory for the degrading process of the tunnel lining described the Ito stochastic differential equation.

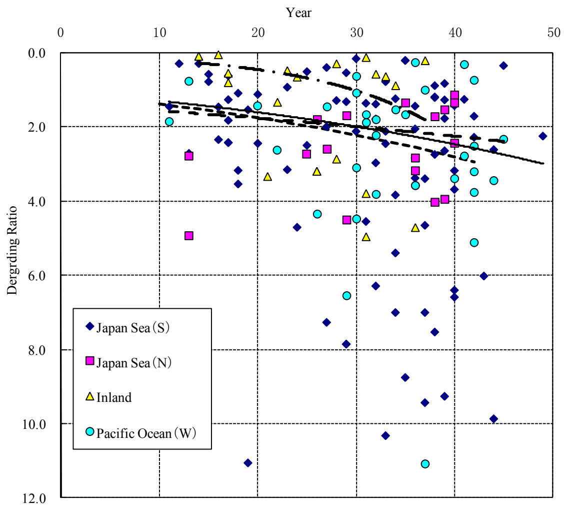


Figure 7 Degrading process of each area

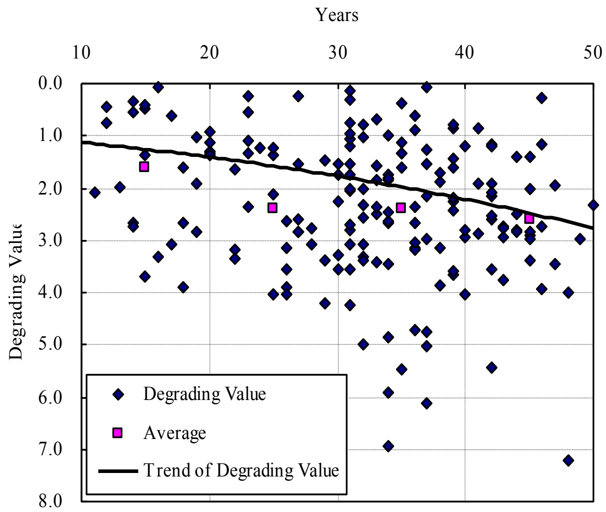


Figure 8 Degrading and average value of tunnel lining

But, the conventional construction method type tunnel inspection data are greatly spread and widely distributed. So the conventional construction method type tunnel inspection data are divided 6 areas, in which divided the Japan Sea south and north, Pacific Ocean east and west, inland and Sea of Okhotsk. Because of each area is different environment, especially during winter season.

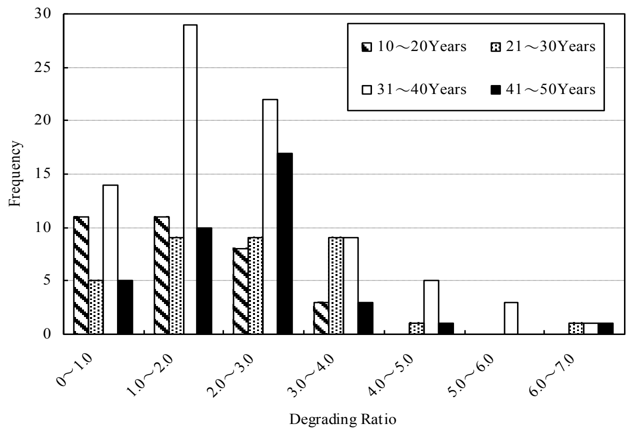


Figure 9 Distribution of degrading value

Figure 7 shows a degrading ratio of the the conventional construction method type tunnels in terms of tunnel area. In this figure, the reproduced degrading process of tunnel lining identified by general solution of Ito stochastic differential equation using the tunnel inspection data according to area.

And in figure 8, shows the distribution of the conventional construction method type inspection data are divided 4 periods. Here, the using the degrading ratio of the conventional construction method type inspection data are divided 4 periods, in which divided the 10-20 years, 21-30 years, 31-40 years, 41-50 years.

In the figure 8 shows an increase of the volatility or distribution average of the conventional construction method type in terms of tunnel age and the reproduced degrading process by using identified Ito stochastic differential equation.

And, these results indicate degrading process of a group of tunnel. Therefore, the tunnel lining evaluation results represented by the Ito stochastic differential equation were generally correct to results of detailed inspection at site.

Especially, in the Ito stochastic differential equation, the variance or distribution of considered repair effect is log normal distribution in Figure 9. The validity of these deterioration models of tunnel lining is verified through the actual inspection data in Hokkaido. And, the applicability of methodology presented is examined by the real data concerning the deterioration.

In addition, the average deterioration curves, variance and distribution of time history are obtained by the visual inspection data of tunnel lining, which was considered the repaired process of the each lining.

4. DEMAND PERFORMANCES OF TUNNEL LINING

In this section, a methodology to identify the Markovian transition probability matrix, which is presented to forecast the degradation process of cold region tunnel lining for performance based design.
Actually, the degradation states of the tunnel linings are categorized into several ranks, and their degradation processes are characterized by the tunnel management system.
Reliability, effect of rehabilitation, and steady state probability of tunnel linings, can be evaluated by this stochastic process.
The Markov Chain assumes that tranition matrix has a uniform timescale betweem the 'State of the Nature' θ^{n} in stage n and θ^{n+1} in stage n+1. This feature can be expressed in the folowing mathematical formula.

$$\mathrm{P_f}(\theta_{n+1} = y \mid \theta_n = z) \cdots = \mathrm{P_f}(\theta_n = y \mid \theta_{n+} = z) \quad (3)$$

$\mathrm{P_f}(\cdots)$ is the distribution of probability.

Generally, an optimized decision should be taken as a result of gradually developed action (stage θ^{n} and θ^{n+1}). The stage result from either one or several inspections, $i \in I = \{i_0, i_1, \cdots, i_p\}$ (e.g., $i_0 =$ no inspection, $i_1 =$ visual inspection) and sequentially executed measures $a \in A = \{a_0, a_1, \cdots, a_a\}$.
The appropriate adjustment of the Markov decision making process using the Bayesian approach enables information taken from periodical monitoring to be taken into consideration. Here, the Markovian transition probability matrix P of the tunnel lining as follows [8] , [9].

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \quad , \quad 0 \le p_{ij} \le 1 \quad (4)$$

$$\sum_{j=1}^{n} p_{ij} = 1 \quad (5)$$

where p_{ij} is transition probability of state i to j .

The Markovian transition probability matrix of the degradation states which are defined for fix intervals between the inspection points in time. And, the Markovian transition probability matrix carried out conversion to a discrete value from a continuation value of tunnel lining degradation. The applicability of the identification is investigated by the inspection data set of tunnel linings (see Table 1).

Table 1 Markovian transition probability matrix

Ranks	S	B	A	2A	3A
S	0.7	0.3	0	0	0
B	0	0.75	0.2	0.05	0
A	0	0	0.7	0.2	0.1
2A	0	0	0	0.65	0.35
3A	0	0	0	0	1.0

This Markovian transition matrix is identified by the inspection data set of tunnel linings. In this table, the Markovian transition matrix is defined for fix intervals between S to 3A. Here, S is excellent rank of tunnel lining. B is good. A is fair. 2A is poor. 3A is very poor. In this Markovian transition matrix, the state of lining moves S to B by the probability of 30% for next 5 years. And, state of lining stays S to S by the probability of 70% for next 5 years.
A future state of tunnel lining can be predicted by using this Markovian transition matrix. Using this Markovian transition matrix, a risk analysis and a life cycle cost of tunnel structure can predict in detail and correctly.

5. CONCLUSION

In this paper, an asset management methodology is presented to investigate the evaluation of tunnel lining degrading process. And, it also establishes the tunnel management system based on life cycle cost from inspection data in Hokkaido.
The proposed degrading process of tunnel lining is described by the Ito stochastic differential equation which was identifed by the inspected data of existing aged tunnels inspection data. Therefore, the basic examples of the degrading process are demonstrated based on the official records from existing aged tunnels.
The model of degrading process presented in the paper is applied to the asset management of the tunnel structures. And, we would like to continue to advance research of the deterioration process of the tunnel lining, and also the maintenance management of a tunnel lining at the cold region.

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