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Control system modeling of stock management for civil infrastructure

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Abstract. Management of infrastructure stock is essential in sustainability of society, and its analysis and optimization are studied in the light of control system modeling in this paper. At the first part of the paper, cost of stock management is analyzed based on macroscopic statistics on infrastructure stock and economical growth. Stock management burden relative to economy is observed to become larger at low economic growth periods in developed economies. Then, control system modeling of stock management is introduced and by augmenting maintenance actions as control input, dynamic behavior of stock is simulated and compared with existing time history statistics. Assuming steady state conditions, applicability of the model to cross sectional data is also demonstrated. The proposed model is enhanced so that both preventive and corrective maintenance can be included as system inputs, i.e., feedforward and feedback control inputs. Optimal management strategy to achieve specified deteriorated stock level with minimal cost, expressed in terms of preventive and corrective maintenance actions, is derived based on estimated parameter values for corrosion of steel bridges. Relative cost effectiveness of preventive maintenance is shown when target deteriorated stock level is lower.

Keywords: stock management; control theory; system dynamics; preventive maintenance; optimization

1. Introduction

Management of infrastructure is essential for sustainability of society (Yanev 2007). Relationship between economic growth and public investment has been discussed from the view point of theory of economic growth (Aschauer 1990, Barro 1990, Gramlich 1994), and the effect of maintenance is also studied (Kalaitzidakis and Kalyvitis, 2004). Fig. 1 shows development of infrastructure stock and gross domestic product (GDP) of Japan, normalized by GDP deflator with respect to 2000 (Abé *et al*. 2007). Because scales of infrastructure stock and GDP are comparable, maintenance and replacement of infrastructure would cause considerable burden to national economy, while integrity of the stock is critical for economic activity. To reduce maintenance cost, effectiveness of maintenance actions at earlier stage of deterioration, i.e., preventive maintenance, has been emphasized (Yanev 2007, Abé *et al*. 2007).

The authors consider infrastructure management activity from three aspects, as shown in Fig. 2: i.e., i) risk management; ii) stock management; and iii) asset management (Abé and Fujino 2009a,

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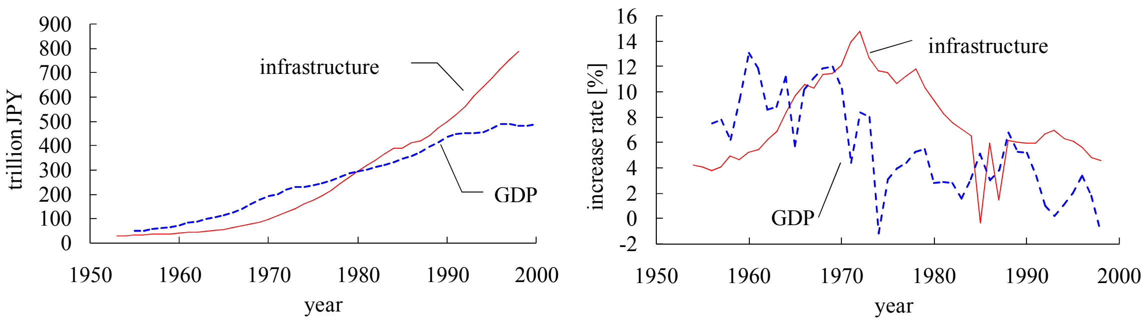
Fujino *et al*. 2009). Risk management focuses safety and vulnerability of infrastructure so that risk, particularly fatal risk, due to accidents or natural disasters, is minimized. Stock management is defined to improve durability and optimize environmental burden and life cycle cost. Asset management is to assure use and existence value, which reflects utility and functionality such as traffic volume in the case of highway bridges. In practice, these three aspects need to be integrated into a unified solution for each structure, with possibly different weights. For light use bridges, risk management would be the first and stock would be the second, but least attention would be required for asset consideration. In contrast, for heavy use structures, importance of risk management may be higher, but stock management consideration yield to asset management, since disruption to utility will not be tolerated.



(a) Infrastructure stock and GDP (b) Stock to GDP ratio

Fig. 1 Development of infrastructure stock and GDP in Japan.

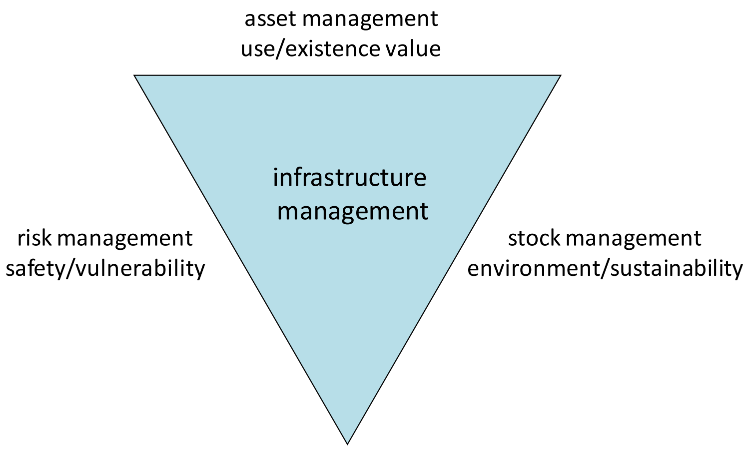
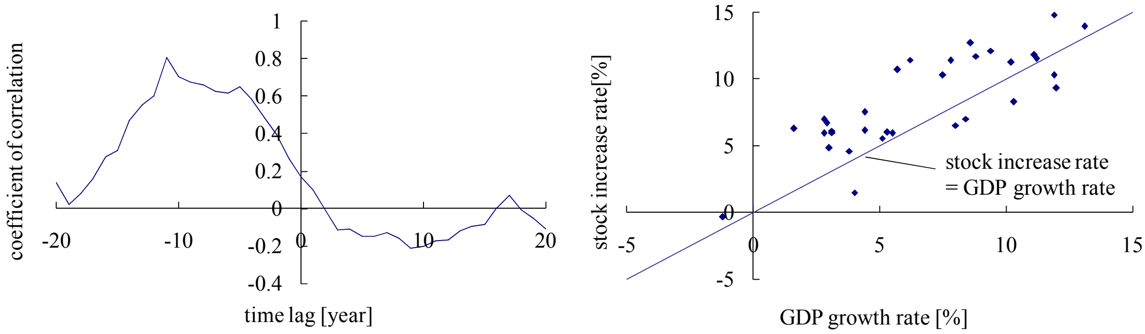


Fig. 2 Three aspects of infrastructure management



(a) Time lag between stock and GDP (b) Stock to GDP ratio with 11years of delay

Fig. 3 Effect of time delay between infrastructure stock and GDP growths

Among these three aspects, risk management of civil infrastructures for natural disasters and accidents has recently been reported by the authors in details (Fujino and Abé 2007, Abé and Shimamura 2014, Abé *et al*. 2014). In this paper, terms "asset" and "stock" are used to express different meanings as described above, although the term "asset" is commonly used to include both meanings in the existing literature (Uddin *et al*. 2013, Wenzel 2013, ISO 55000 2014). Here, the word "stock" is employed to emphasize that the formulation is focused on deterioration, and risk and functionality are not explicitly treated and considered secondary in the scope of the current paper.

In this study, a comprehensive framework for stock management is proposed based on control system theory, which generalizes statistical analyses of fragmented data sets on stock management collected in Japan and previously reported by the authors (Abé *et al*. 2007, Abé and Fujino 2007, Abé *et al*. 2008, Abé and Fujino 2009b, Abé *et al*. 2012), with further enhancement to national economic statistics.

First, national statistics are studied to provide macroscopic overview on dynamics of infrastructure stock and national economy. Then, control system theory is introduced to express system dynamics and maintenance action, and its optimization is investigated based on the proposed model. In the study of optimization, comparison of preventive and corrective maintenance is emphasized, because current practice is basically corrective, while advantages of preventive maintenance have long been discussed and stressed in engineering community (Yanev 2007, Abé *et al*. 2007).

2. Macroscopic analysis

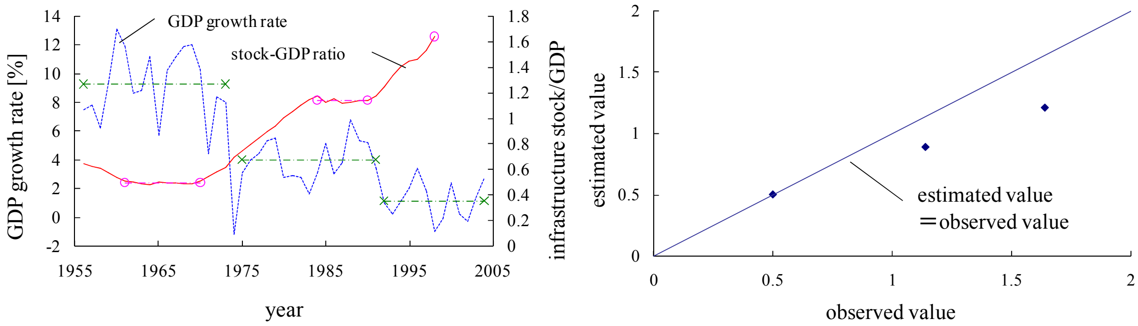
In this section, macroscopic statistical relationship between infrastructure stock accumulation and growth of GDP is discussed with consideration to time delay effect. Then, life cycle cost is estimated by statistical regression.

2.1 Stock and GDP

Macroscopically, difficulty of stock management, especially, sustainability is expected to arise when required cost for maintenance increases more than GDP, and takes larger portion of national economy. Because stock is essentially accumulation, while GDP is the annual flow, stock naturally tends to surpass GDP as economy grows. Time histories of corresponding growth rates of Japan are given in Fig. 1(b), which show that infrastructure growth follows economic growth.

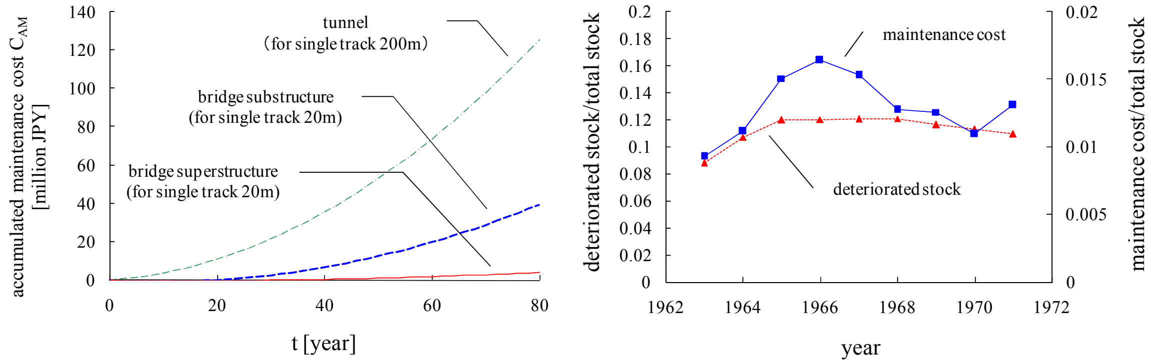
Cross correlation between growth rates of GDP and stock shown in Fig. 3(a) reveals maximum correlation of 0.8 at time lag of 11 years. Regression between stock and GDP growths with 11 years delay is provided in Fig. 3(b). This delay causes considerable increase of stock when economic growth descends as shown in Fig. 4(a). Stock to GDP ratio was around 0.5 at the high economic growth in 1960s, and increased up to 1.6 at 2000. Increase of stock to GDP ratio ρ by time lag of ΔT can be calculated as

$$\rho = \frac{S_0}{I_0} e^{(\alpha - \alpha_{GDP})\Delta T} \tag{1}$$



(a) GDP growth rate and stock-GDP ratio (b) Prediction of stock-GDP ratio

Fig. 4 Growth of infrastructure stock and GDP in Japan



(a) Accumulated maintenance cost (b) Deteriorated stock and maintenance cost

Fig. 5 JNR statistics on stock management where, s_0: initial stock; I_0: initial GDP; α: stock growth rate; and α_{GDP}: GDP growth rate. Fig. 3(b) indicates that values of α and α_{GDP} are almost equivalent with the time lag of 11 years. Fig. 4(b) shows comparison between the observed value of ρ and estimation by Eq. (1). Stock to GDP ratio is estimated by assuming ΔT =11 years lag, and piece-wise average values of GDP growth rate shown by chain line in Fig. 4(a) are substituted to both α and α_{GDP}. Delay in growth rates is observed to contribute rapid increase of stock, and subsequently relative increase of maintenance cost. This phenomenon would especially be observed at low economic growth conditions followed by high growth, which can be applied to many developed national economies. Delays between growth and socio-economic phenomena are commonly observed and have been pointed out to be one of the major causes of catastrophe in growth (Meadows *et al*. 1972).

2.2 Maintenance cost

Fig. 5(a) shows statistical regression of cumulative maintenance cost statistics collected from Japan National Railway (JNR) before privatization of 1986, normalized by passenger base fare to 1986 currency value. Details of the original data can be found in Abé *et al*. (2007), and Abé and Fujino(2009b). It can be observed that accumulated maintenance cost C_{AM} follows quadratic curve, i.e.

$$C_{AM} = c_m t^2 \tag{2}$$

Average annual life cycle cost which is summation of initial or replacement cost C_I and maintenance cost is given by

$$c = \frac{C_I + C_{AM}}{t} \tag{3}$$

Optimal life to minimize this average cost yields

$$t_{opt} = \sqrt{\frac{C_I}{c_m}} \tag{4}$$

by relationship between arithmetic and geometric means. Corresponding accumulated maintenance cost is calculated as

$$C_{AM} = c_m t_{opt}^2 = C_I \tag{5}$$

which equals replacement cost. Then, optimal annual average of maintenance and replacement cost becomes

$$c_{opt} = \frac{2C_I}{t_{opt}} \tag{6}$$

Therefore, annual maintenance and replacement cost to replacement cost would be $2/t_{opt}$. If structural lifetime is 100 years, annual maintenance and replacement cost would be 2% of the total stock. Because maintenance and replacement cost is expressed by constant ratio to stock, increase of stock to GDP ratio observed in the previous section would directly lead increase of maintenance and replacement cost.

JNR statistics on history of deteriorated stock and maintenance cost from 1963 to 1971 are shown in Fig. 5(b) (Abé and Fujino 2007). Approximately 10% of the stock is deteriorated and this state is maintained by annual spending of about 1 to 1.5% of total stock. Assuming this state is optimal, the expected life would be 130 to 200 years according to Eq. (6).

3. Fundamental feedback control system model

In this section, linear feedback control model of stock management is constructed and verified by the data of Fig. 5(b) as well as cross sectional data collected from local governments in Japan (Abé and Fujino 2009b).

3.1 Feedback control model

Linear feedback control system in matrix form can be expressed as

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{7a}$$

$$\mathbf{u} = \mathbf{C}\mathbf{x} \tag{7b}$$

To match the existing statistics in Fig. 5(b), a single output two state model is employed, where entire stock s and deteriorated stock d are taken as state variables and maintenance cost u is selected as a control input, i.e.

$$\mathbf{x} = \begin{bmatrix} s \\ d \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} \alpha & \varepsilon_1 \\ \beta & -\beta \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \varepsilon_2 \\ \delta \end{bmatrix}, \quad \mathbf{C} = \begin{bmatrix} c_s & c_d \end{bmatrix} \tag{7c,d,e,f}$$

Here, structures which need repair are categorized to be deteriorated, and others are defined to be sound. Although ratings of the structures are usually multiple and more than two, judgment for requirement for repair is paid higher attention and inspection specifications are well defined in details for this category in JNR. Therefore, these two states are employed owing to availability and reliability of data. This formulation can be extended to multiple condition ratings by expanding the number of states.

In infrastructure stock management, deteriorated stock would not be abandoned immediately, rather used continuously. Therefore entire stock, which includes deteriorated stock, is chosen as a state variable. Sound stock can be calculated simply by (s-d). Parameter α denotes infrastructure growth rate, β is annual deterioration rate representing ratio of generated deteriorated stock from sound stock for each year, δ stands for maintenance effectiveness to reduce deteriorated stock by $|\delta|$ with unit input of u. To be consistent with physical tendency, the following sign conventions are assumed: i.e., $\alpha > 0$; $\beta > 0$; and $\delta < 0$. Parameters ε_1 represents deteriorated stock influence on stock growth, and ε_2 is the interaction of maintenance cost and infrastructure stock growth. Both effects become prominent when restriction of public investment becomes stringent, and substitution between investment and maintenance is not negligible. In this paper, this interaction is neglected since the tendency is not clearly observed in existing statistics. However, in near future, this substitution could become substantial and would require attention. Feedback gain c_d expresses maintenance following detection of deteriorated stock which corresponds to corrective maintenance, while c_s is planned maintenance regardless of the results of inspection, i.e., preventive maintenance.

In this formulation, deterioration rate β does not change before and after the feedback maintenance action, and extension of life by repair is not explicitly modeled. Because maintenance actions cannot be separated in existing inspection records, this treatment of β is consistent with the available data. Change of deterioration rate can be implicitly included at the feedforward term or maintenance effectiveness terms, which will be explained in the next section.

Closed loop solution for the system with initial value of $\mathbf{x}_0=[s_0,d_0]^T$ is

$$s = s_0 e^{\alpha t} \tag{8a}$$

$$d = \frac{s_0(\beta+\delta c_s)}{\alpha+\beta-\delta c_d} e^{\alpha t} + \left[d_0 - \frac{s_0(\beta+\delta c_s)}{\alpha+\beta-\delta c_d} \right] e^{(-\beta+\delta c_d)t} \tag{8b}$$

Sign relationship of parameters yields $\alpha>0$, and $-\beta+\delta c_d<0$, and

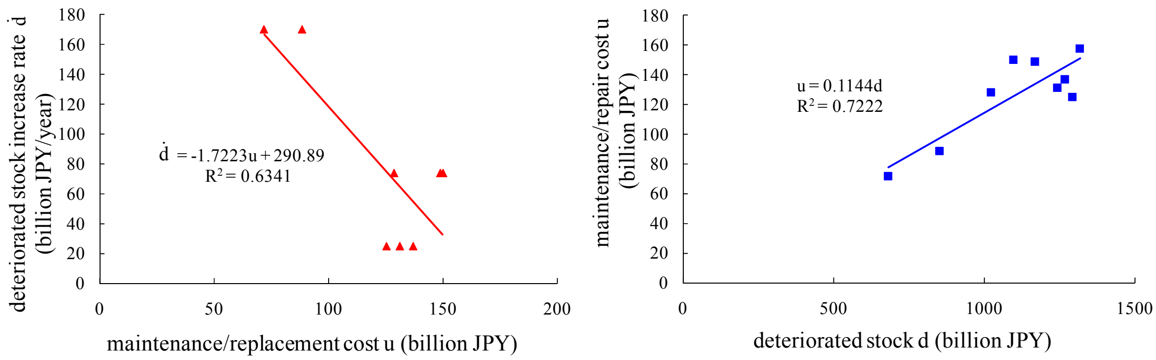
$$d \to \frac{s_0(\beta+\delta c_s)}{\alpha+\beta-\delta c_d} e^{\alpha t} \tag{9}$$

as t goes to infinity. Representing steady state by subscript ∞, ratio of deteriorated stock to total stock at steady state can be expressed by

$$r_\infty = \frac{d_\infty}{s_\infty} \to \frac{\beta+\delta c_s}{\alpha+\beta-\delta c_d} \tag{10}$$

Deteriorated stock ratio r_∞ decreases with increase of absolute values of α and δ. When $\alpha = \delta = 0$, no new construction and maintenance exist, and r_∞ becomes 1 as expected. Note that even with no maintenance r_∞ does not become 1 when new construction exists as

$$r_\infty = \frac{\beta}{\alpha+\beta} \tag{11}$$



(a) Maintenance cost and deteriorated stock rate (b) Deteriorated stock and maintenance cost

Fig. 6 Regression relationship for parameter estimation

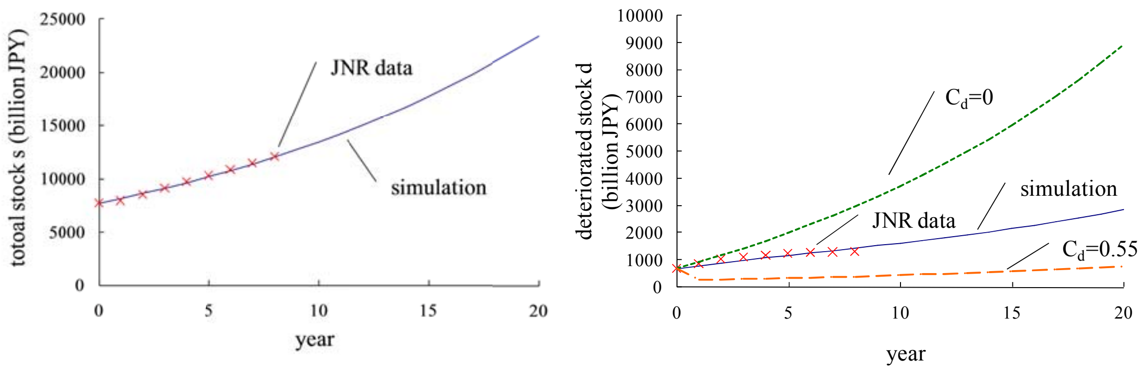
By Eq. (10), steady state value of deteriorated stock can easily be estimated for general conditions.

3.2 Time history analysis

JNR data, given in Fig. 5(b), are employed for time history analysis and verification.

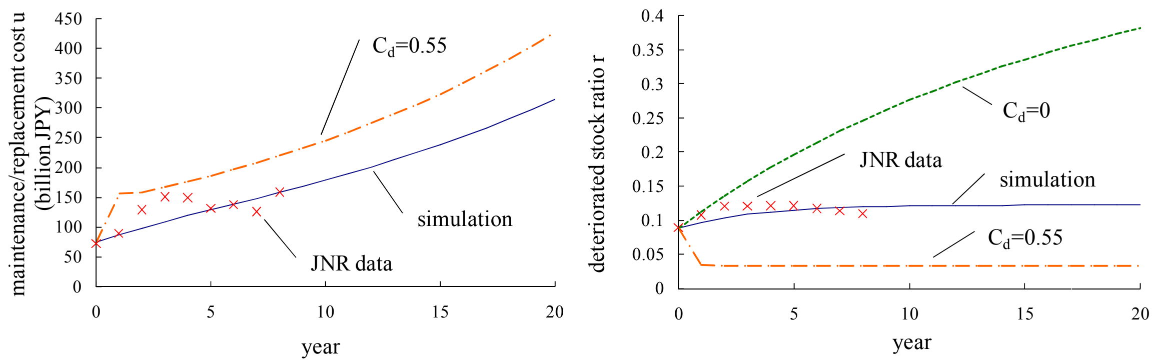
3.2.1 Parameter estimation

Parameter values in the system model are estimated as follows. First, the value of α is estimated to be 0.057 (standard deviation of 0.014) using stock data of the entire period. Then, value of δ is estimated to -1.7 by regression of d by u as shown in Fig. 6(a). Because intercept of regression corresponds to the increase rate of deteriorated stock without maintenance input u, the value β is estimated to 0.034 by dividing intercept value by average sound stock of 8755 billion JPY (standard deviation 1323 billion JPY).



(a) Total stock (b) Deteriorated stock

Fig. 7 Simulation results on stock



(a) Maintenance cost (b) Deteriorated stock ratio

Fig. 8 Simulation results on maintenance cost and deteriorated stock ratio

Because maintenance budget was calculated based on inspection results of deteriorated stock in management practice of the day, c_s is assumed to be 0, and c_d is estimated by regression of Fig. 6 (b) as 0.11 (coefficient of determination 0.72).

These parameter values are obtained through linear regression because of limitation of number of data points and may be affected by autocorrelation of error. Statistical reliability and accuracy of the parameter values needs to be investigated as larger sets of data become available.

3.2.2 Simulation

Employing above parameter values and applying 1963 values as the initial condition, JNR time history data is simulated. The results are shown in Figs. 7 and 8. Because of data restriction, same data set is used for both parameter estimation and simulation. Hence these results do not verify the model strictly, but it can be seen that average tendencies are reproduced and the model structure is capable of simulating fundamental properties of the system. Oscillating contents in Fig. 8 are not observed in simulation, which could be modeled by extending dimension of the model. Further data collection and improvement are needed for the extension.

In the same figures, parametric study results, where zero and five times of the actual maintenance, i.e., c_d=0 and c_d=0.55, are also plotted. Policy change can easily be simulated by the proposed model.

3.3 Cross sectional analysis

Model parameters can also be identified from cross sectional data, assuming steady state condition. Fig. 9 shows statistics of highway bridges owned by five local governments in 2006 (Abé and Fujino 2009b) arranged by system variables and parameters proposed in this study.

Parameters in the system are identified as follows. First, α is directly calculated from the ratio of new construction to stock for each local government. Then β is derived from Fig. 9. Vertical intercept of Fig. 9(a) corresponds to deteriorated stock ratio for no maintenance. Also, relationship between stock increase rate and deteriorated stock ratio is obtained from Fig. 9(b), hence the value of β is derived from Eq. (10) as 0.022 (standard deviation 0.021).

Finally, δ is obtained by the observation that intercept of Fig. 9(b) gives deteriorated stock ratio without new construction and assuming c_s=0 in Eq. (10), as -1.17 (standard deviation 1.18).
Both β and δ have relatively large standard deviation, which reflect variability of conditions of local governments.

Fig. 10 shows comparison of deteriorated stock ratios calculated using identified parameter values under the assumption of steady state condition and actual values. Correlation coefficient of Fig. 10(b) is 0.69.

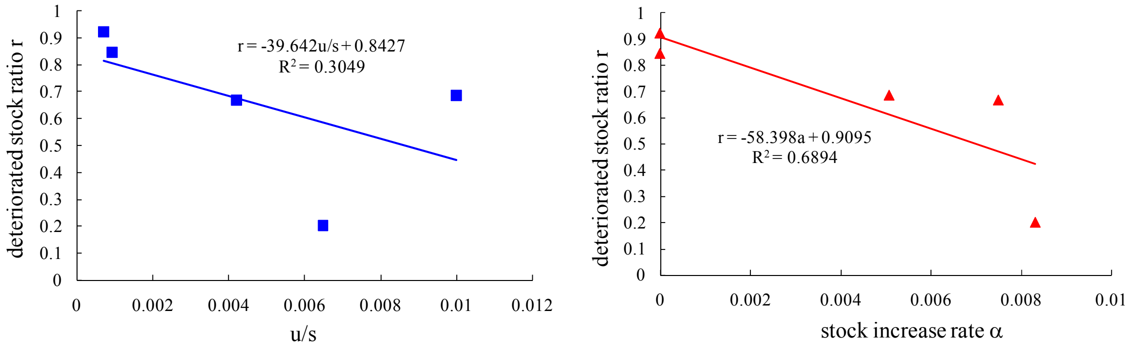
Absolute values of parameters β and δ are observed to be smaller than the value identified by JNR statistics in the previous section. Although direct comparison is difficult because of difference of statistical basis, it may be interpreted as the changes of technological and social conditions. Technological development lowered the value of β by improvement of durability, while change of social conditions reduces δ effect by more complicated field work environment and higher quality requirement.

4. Preventive maintenance model

In the previous section, the maintenance action is assumed as feedback of the deteriorated stock found in inspection, which reflects corrective maintenance. In this section, effect of preventive maintenance, which is maintenance action applied to sound stock is studied by enhancing the proposed control system model

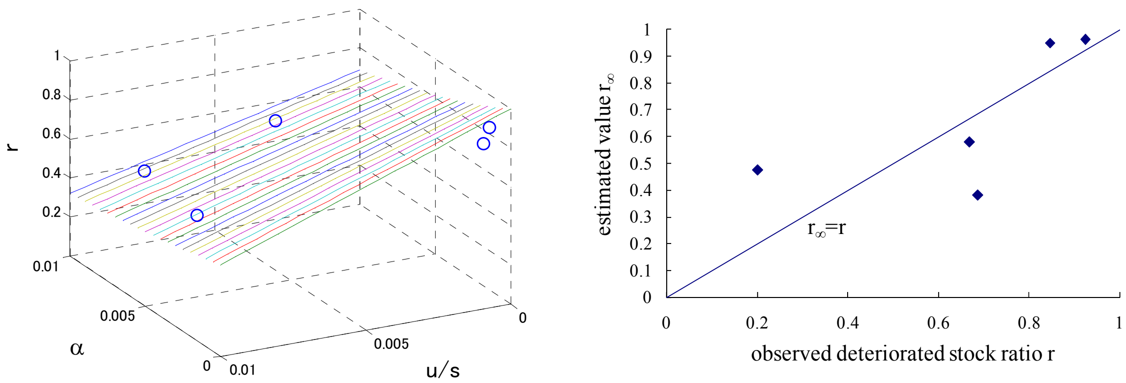
4.1 Enhancement of control system model

To model preventive maintenance, feedforward input is augmented and the system is extended to 2-input-2-state system



(a) Maintenance cost and deteriorated stock (b) Accuracy of estimation

Fig. 9 Statistics of local governments



(a) Observation and estimation (b) Accuracy of estimation

Fig. 10 Estimation in cross section data

$$\mathbf{x}=\begin{bmatrix} s \\ d \end{bmatrix},\quad \mathbf{u}=\begin{bmatrix} u_s \\ u_d \end{bmatrix} \tag{12a,b}$$

$$\mathbf{A}=\begin{bmatrix} \alpha & 0 \\ \beta & -\beta \end{bmatrix},\mathbf{B}=\begin{bmatrix} 0 & 0 \\ \delta_s & \delta_d \end{bmatrix},\mathbf{C}=\begin{bmatrix} c_s & -c_s \\ 0 & c_d \end{bmatrix} \tag{12c,d,e}$$

Here, u_s and u_d are inputs to express preventive and corrective maintenance actions. Parameters δ_s and δ_d stand for maintenance effectiveness for preventive and corrective maintenance respectively, and c_s and c_d are corresponding feedforward and feedback gains. Closed loop solution for d is

$$d=\frac{s_0(\beta+\delta_s c_s)}{\alpha+\beta+\delta_s c_s-\delta_d c_d}e^{\alpha t}+\left[d_0-\frac{s_0(\beta+\delta_s c_s)}{\alpha+\beta+\delta_s c_s-\delta_d c_d}\right]e^{(-\beta+\delta_s c_s-\delta_d c_d)t} \tag{13}$$

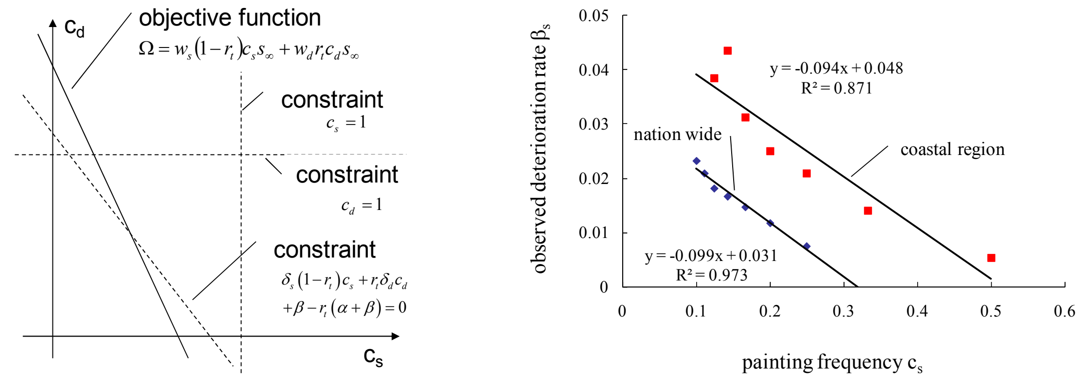
Steady state solutions are

$$d_\infty=\frac{s_0(\beta+\delta_s c_s)}{\alpha+\beta+\delta_s c_s-\delta_d c_d}e^{\alpha t} \tag{14a}$$

$$r_\infty=\frac{d_\infty}{s_\infty}=\frac{\beta+\delta_s c_s}{\alpha+\beta+\delta_s c_s-\delta_d c_d} \tag{14b}$$

Maintenance inputs at steady state can be expressed by

$$\frac{u_{s\infty}}{s_\infty}=c_s(1-r_\infty),\quad \frac{u_{d\infty}}{s_\infty}=c_d r_\infty \tag{15a,b}$$



(a) Optimization by linear programming (b) Parameter estimation

Fig. 11 Optimization method and parameters

4.2 Optimization

Optimization of control law, i.e., optimization of preventive and corrective maintenance gains c_s and c_d, is investigated. The optimization problem for stock management can be described as; i) target deteriorated stock ratio by minimum cost; or 2) minimization of deteriorated stock ratio by given budget. Because, mathematically, both optimization objectives can be transformed to fundamentally the same linear programming problem, the first optimization problem is solved in this paper.

Objective function is expressed by weighted sum of preventive and corrective maintenance at steady state

$$\Omega = w_s u_{s\infty} + w_d u_{d\infty} \tag{16}$$

If w_s and w_d are selected as preventive and corrective maintenance costs for unit stock, the sum Ω becomes total maintenance cost. Corresponding constraint is to keep target deteriorated stock ratio as specified value r_t

$$r_t = r_\infty = \frac{\beta + \delta_s c_s}{\alpha + \beta + \delta_s c_s - \delta_d c_d} \tag{17}$$

This optimization problem can be rewritten in terms of management variables, c_s and c_d. The objective function is now

$$\Omega = w_s (1 - r_t) c_s s_\infty + w_d r_t c_d s_\infty \tag{18a}$$

with constraints,

$$\delta_s (1 - r_t) c_s + r_t \delta_d c_d + \beta - r_t (\alpha + \beta) = 0\,,\;\; 0 \le c_s \le 1\,,\;\; 0 \le c_d \le 1 \tag{18b,c,d}$$

This optimization problem is a typical linear programming problem, which is shown Fig. 11(a). The condition for existence of solution is that the constraint has domain within the first quadrant.

$$\beta - r_t (\alpha + \beta) \ge 0 \;\text{ or }\; r_t \le \frac{\beta}{\alpha + \beta} \tag{19a,b}$$

If this condition is not satisfied, required r_t is achieved without any maintenance input.

In Fig. 11(a), inclination of the objective function is given by

$$\frac{w_s}{w_d}\left(1 - \frac{1}{r_t}\right) \tag{20a}$$

and inclination of constraint is

$$\frac{\delta_s}{\delta_d}\left(1 - \frac{1}{r_t}\right) \tag{20b}$$

If $w_s/w_d < \delta_s/\delta_d$, inclination of constraint is steeper than the objective function. Hence, optimal solution is to minimize the corrective maintenance, or equivalently, to maximize preventive maintenance, as for $\dfrac{r_t(\alpha+\beta)-\beta}{\delta_s(1-r_t)}<1$

$$c_s=\frac{r_t(\alpha+\beta)-\beta}{\delta_s(1-r_t)},\quad c_d=0,\quad \Omega=\frac{w_s(r_t(\alpha+\beta)-\beta)}{\delta_s} \tag{21a,b,c}$$

for $\dfrac{r_t(\alpha+\beta)-\beta}{\delta_s(1-r_t)}\geq 1$

$$c_s=1,\quad c_d=\frac{r_t(\alpha+\beta)-\beta-\delta_s(1-r_t)}{r_t\delta_d} \tag{22a,b}$$

$$\Omega=w_s(1-r_t)+\frac{w_d(r_t(\alpha+\beta)-\beta-\delta_s(1-r_t))}{\delta_d} \tag{22c}$$

On the other hand, if $w_s/w_d>\delta_s/\delta_d$,

for $\dfrac{r_t(\alpha+\beta)-\beta}{r_t\delta_d}<1$

$$c_s=0,\quad c_d=\frac{r_t(\alpha+\beta)-\beta}{r_t\delta_d},\quad \Omega=\frac{w_d(r_t(\alpha+\beta)-\beta)}{\delta_d} \tag{23a,b,c}$$

for $\dfrac{r_t(\alpha+\beta)-\beta}{r_t\delta_d}\geq 1$

$$c_s=\frac{r_t(\alpha+\beta)-\beta-r_t\delta_d}{\delta_s(1-r_t)},\quad c_d=1,\quad \Omega=\frac{w_s(r_t(\alpha+\beta)-\beta-r_t\delta_d)}{\delta_s}+w_d r_t \tag{24a,b,c}$$

The expression $w_s/w_d<\delta_s/\delta_d$ can be transformed to $|\delta_d/w_d|<|\delta_s/w_s|$, which indicates that the cost effectiveness of preventive maintenance is higher. Similarly, $w_s/w_d>\delta_s/\delta_d$ yields $|\delta_d/w_d|>|\delta_s/w_s|$, and shows relative advantage of corrective maintenance. In this way, the optimization solutions can also be interpreted intuitively.

5. Application to stock management

In this section, management application of the optimal solution is discussed followed by parameter estimation described in the first half. Among the parameters in the system model, α corresponds to new construction, which is assumed to be not directly related to maintenance and given exogenously. Parameters which need to be identified are: β, δ_s and δ_d.

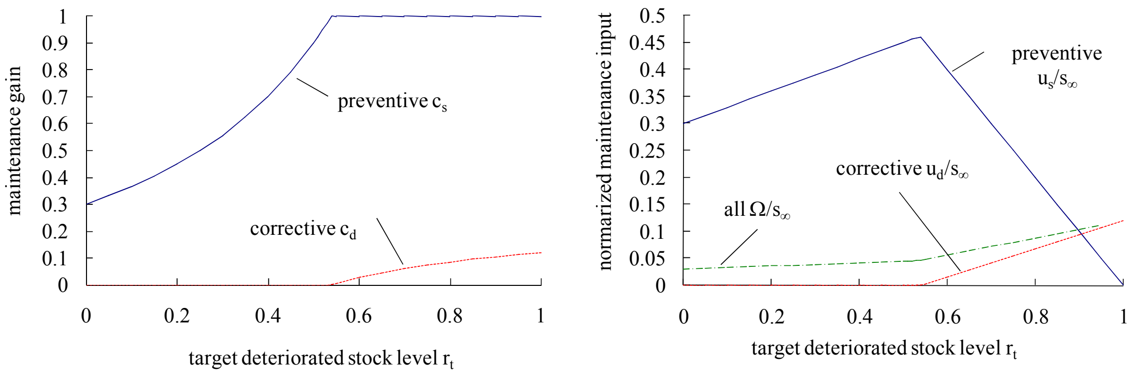
Here, corrosion of steel bridges is taken as an example. Major preventive maintenance for corrosion is painting. Fig. 11(b) shows comparison of corrosion life and painting frequency reported by JNR (Abé *et al*. 2007, Abé *et al*. 2008). Note that expected life is the inverse of deterioration rate β, and c_s corresponds to frequency of maintenance per year. Apparent deterioration rate β_s with preventive maintenance can be written as

$$\beta_s = \beta + \delta_s c_s \tag{25}$$

Hence, inclination of regression yields to preventive maintenance effect δ_s and vertical intercept equals to deterioration rate β. Deterioration rate at the coastal area is identified as 0.0487 and national average 0.0317. Preventive maintenance effect δ_s is -0.0946 for coastal area and -0.0995 for national average. Although deterioration rates are different, preventive maintenance effects are almost similar. In the following analysis, β =0.03, and δ_s =-0.1 are selected for simplicity.

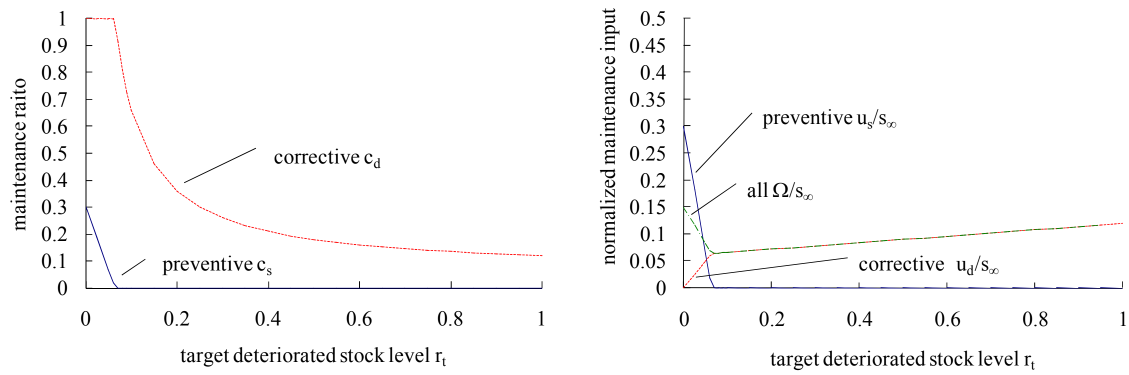
One of the popular corrective maintenance measures for cross-section loss due to corrosion is cover plate attachment. Expected lives before and after corrective maintenance are considered to be different, and the ratio gives the corrective maintenance effect as

$$\delta_d = -\frac{\beta}{\beta_d} \tag{26}$$



(a) Maintenance ratio (b) Normalized maintenance input

Fig. 12 Target deteriorated stock level and maintenance strategy (w_s=0.1, w_d=1)



(a) Maintenance ratio (b) Normalized maintenance inpu

Fig. 13 Target deteriorated stock level and maintenance strategy (w_s=0.5, w_d=1)

In other words, repaired stock and sound stock are not distinguished in the proposed model, corrective maintenance effect is modified to keep the deteriorated stock equivalent. Because in plate welding repair, expected life was assumed to be an half of the original life in JNR practice (Abé *et al*. 2007), δ_d =-0.5 is selected in the following analysis.

Applying these parameters to the results in the previous section, preventive maintenance becomes superior in this example of corrosion when $w_s/w_d<\delta_s/\delta_d$ = (-0.1)/(-0.5) = 0.2, which means preventive maintenance cost represented by w_s is cheaper than one fifth of the corrective maintenance cost w_d.

Fig. 12 shows target deteriorated stock level r_t and corresponding optimal c_s and c_d as well as maintenance quantity u_s, u_d, and Ω. In the analysis, growth rate α is taken 0 for simplicity. Similar tendency is observed for α around several percent. In this analysis, w_s is taken to be one-tenth of w_d, i.e., w_s =0.1 and w_d =1, which implies preventive maintenance is advantageous. When target deteriorated stock level r_t is small, only preventive maintenance is selected as seen Fig. 12(a). As target level increases, corrective maintenance are also included, because substantial deteriorated stock is allowed. To reduce maintenance quantity Ω, as shown in Fig. 12(b), lowering target level and increasing preventive maintenance is advantageous. Target level r_t zero is observed to give minimal maintenance theoretically. Note that, in reality, unexpected or unknown defects can appear, so corrective maintenance cannot be eliminated entirely.

Fig. 13 shows an example with w_s =0.5 and w_d =1, where corrective maintenance becomes relatively advantageous. Although corrective maintenance is superior in wider range, preventive maintenance should also be included to reduce deteriorated stock level r_t at lower values as shown in Fig. 13(a). Fig. 13(b) shows that total amount of maintenance is lowest at r_t =0.07. In order to reduce r_t below this value, increase of preventive maintenance is required, while preventive maintenance is relatively expensive in this case.

6. Conclusions

In this paper, dynamic modeling of infrastructure stock and its management are studied using statistics mainly collected by JNR before privatization of 1986. Major conclusions are as follows:

- Stock management cost is discussed based on macroscopic statistical analysis. Time history analysis of national economic statistics indicates stock management burden relative to economy tends to become larger at low economic growth followed by high growth, which is commonly observed in developed economies.
- Control system model for stock management is constructed and its validity is discussed based on estimated parameters from JNR statistics. By modeling maintenance actions as control input, dynamic behavior of stock is simulated and verified. Assuming steady state conditions, the model is also shown to be applicable to cross sectional data.
- The proposed model is enhanced so that both preventive and corrective maintenance can be included as system inputs. Optimal management strategy, which is combination of preventive and corrective maintenance, is derived based on estimated parameter values for corrosion of steel bridges. Relative advantage of preventive maintenance is shown when target deteriorated stock level is lower.

The proposed model is based on observed statistical dynamics of stock. For the project level or network level with small number of structures, where statistical treatment is not appropriate, further studies would be required to extend the concept to uncertainty of systems.

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