MAINTENANCE MANAGEMENT SYSTEM FOR RC SUBWAY TUNNELS BASED ON NUMERICAL PREDICTIVE MODELS COUPLED WITH ON-SITE MEASUREMENT INFORMATION

Tetsuya ISHIDA*, Yukihiro ISHIKAWA**, Mitsuhiro KAWABATA**,
Akira MARUYAMA***, Satoshi TSUCHIYA****

The University of Tokyo*
Tokyo Metro Company Limited**
ISS Incorporated***
COMS Engineering Corporation****

ABSTRACT**:** The authors propose a maintenance management system for RC subway tunnels suffering from chloride and carbonation induced corrosion. The proposed system consists of three subsystems. Firstly, by using numerical predictive models coupled with on-site measurement information, the engineering evaluation sub-system estimates or predicts the degree of deterioration of RC tunnel sections due to steel corrosion induced by carbonation and chloride ions. Then, in the maintenance prioritization subsystem, priorities are assigned to preventive maintenance and distressed concrete repair using preset thresholds. Finally, the project planning system is executed to allocate preventive maintenance and repairs on a year-by-year basis within imposed budget constraints. Through a couple of case studies, the proposed system is shown to be capable of managing structure data and on-site inspection results in an integrated manner and it is demonstrated to be helpful in drawing up maintenance management plans under various conditions.

KEYWORDS: maintenance management system, RC subway tunnels

1. INTRODUCTION

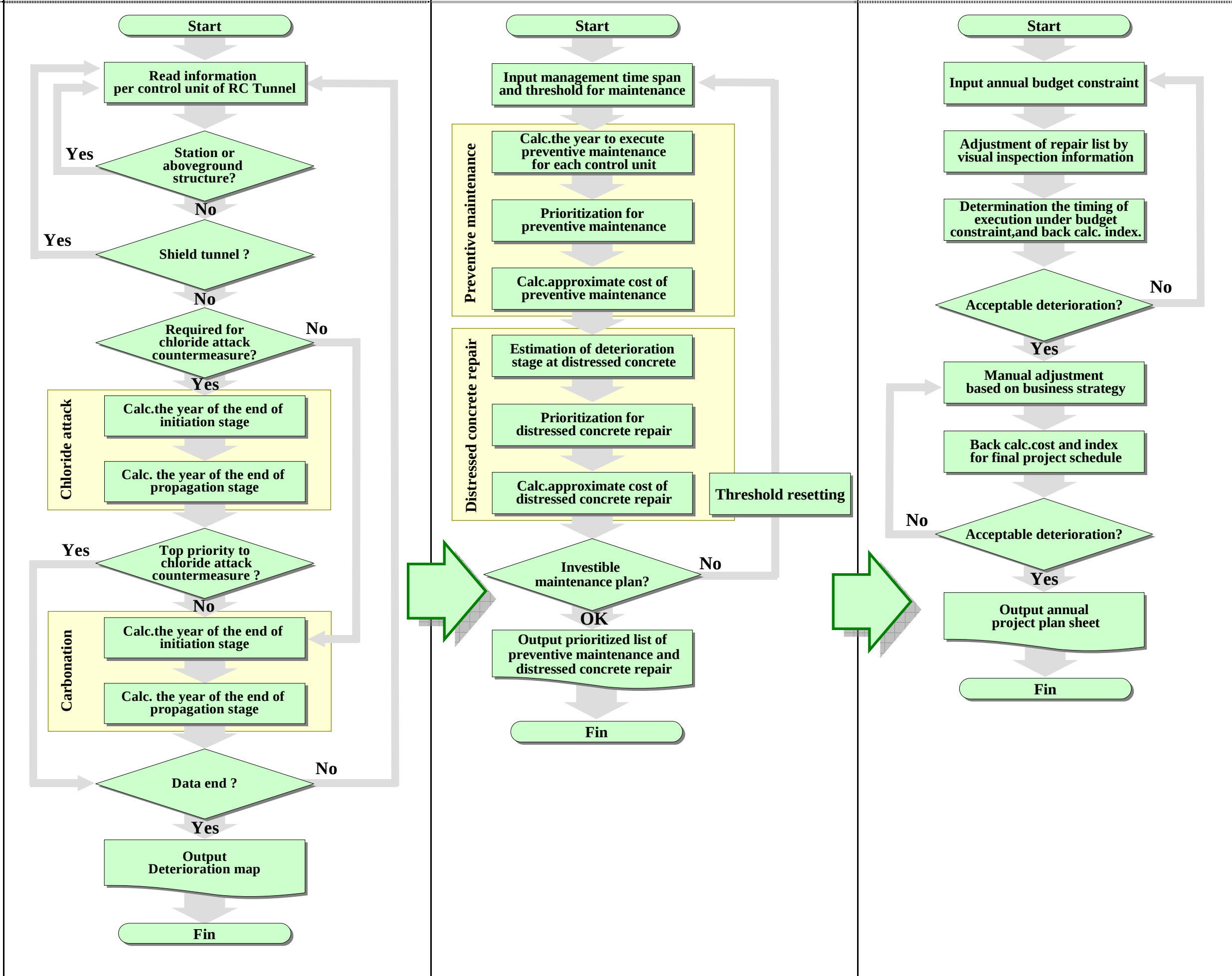
Tokyo Metro Co., Ltd. (abbreviated as Tokyo Metro) is responsible for maintaining the civil engineering structures related to nine subway lines with a total length of 195.1 km. These include the new Fukutoshin Line that opened on June 14, 2008. Of the structures maintained by Tokyo Metro, about 80 % consist of reinforced concrete (RC) tunnels and some of these have been in operation for more than 80 years. The significance of maintenance is expected to increase as the structures age.

Currently, maintenance is managed through general inspections that are conducted on a regular basis and individual inspections implemented when severe distress is identified by a general inspection. Maintenance work is carried out every time deterioration is found. However, there is a need to predict the condition of structures, assign a priority to individual maintenance measures, and implement the measures with preventive maintenance. In the current climate, where greater accountability is being demanded, it is essential to further improve the efficiency and transparency of structure maintenance.

One method of increasing the life of the social infrastructure stock that has recently been attracting attention is the concept of asset management.

Name	Subway Tunnel **Engineering Evaluation Subsystem**	Subway Tunnel **Maintenance Prioritization Subsystem**	Subway Tunnel **Project Planning Subsystem**
Purpose	To estimate or predict the degree of deterioration of unit RC tunnel sections due to steel reinforcement corrosion induced by carbonation and chloride ion attack, and to evaluate the soundness of the sections from an engineering standpoint	To set an engineering threshold for the repair of distresses in unit RC tunnel sections identified during preventive maintenance and on-site inspections, and to assign a priority to preventive maintenance and repairs based on the time taken to reach the threshold	To allocate preventive maintenance and repairs on a year-by-year basis within imposed budget constraints. The system is designed to allow visual inspection results to be incorporated and the priorities to be adjusted manually.
Input	1) Specifications of RC tunnels 2) Measured cover depths 3) Measured carbonation depths 4) Measured chloride ion concentrations	1) Evaluation of RC tunnels from an engineering standpoint 2) Distresses identified by inspection 3) Unit price of repair work 4) Management time span and the maintenance threshold	1) Priorities for preventive maintenance 2) Priorities for future repair 3) Results of visual inspection of distresses 4) Budget constraints

System Flow



Output	1) Evaluation of RC tunnels from an engineering standpoint 2) Corrosion index map	1) Priorities for preventive maintenance 2) Priorities for future repair 3) List of priorities for preventive maintenance and future repair (with their costs)	1) Maintenance management plan (draft)

Figure 2.1 Summary of maintenance management system

However, it has so far been applied to tunnel structures in very few cases. The primary reason for this is that the environmental conditions to which tunnels are exposed and the mechanisms of deterioration are complex and uncertain, while there are no established methods of evaluating the soundness of tunnels and predicting their condition.

Aiming to establish a more efficient system of maintenance management for tunnels, the authors have used measurement data to clarify the corrosion mechanisms affecting steel reinforcement under environmental conditions typical of tunnels, developed an engineering evaluation method for predicting the condition of a tunnel structure, and proposed a system for maintenance management. Further, through a case study of one subway line, the authors have verified the practicability of the system and clarified areas for future study.

2. OVERALL SCHEME OF THE SYSTEM

The proposed system of maintenance management consists of three subsystems, each with a specific purpose, as outlined in Figure 2.1. The program follows an orderly sequence from evaluation based on an engineering perspective to the formulation of a practical maintenance management plan. By interfacing the three subsystems, the program is able to output the work requirements.

The transfer of data among the subsystems is on a 'control unit' basis, where a control unit is a section of concrete in an RC tunnel with no specific points of variation with respect to concrete quality, construction year, structural type, construction work division, and environmental conditions. The average length of a control unit is 66 m (150 m at maximum and 2 m at minimum). The types of structure covered by this management system are RC tunnels constructed by the cut-and-cover method and by the caisson method. Other underground and aboveground structures are outside the scope of the system.

Considering the environmental conditions to which the underground structures are exposed, the system takes account of two main deteriorating factors: carbonation and chloride ion ingress (chloride ion attack). Factors of infrequent occurrence and that are hard to predict, such as great earthquakes and the effects of other construction work in close vicinity, are excluded from the study.

3. SYSTEM DETAILS

3.1 Engineering Evaluation Subsystem

In establishing the engineering evaluation subsystem, the degree of steel reinforcement corrosion in concrete is adopted as a control index for evaluating the soundness of an RC tunnel. A simplified method of predicting not only the time at which the steel reinforcement begins to corrode (i.e. the end of the initiation stage, JSCE 2007) but also the time at which a corrosion crack begins to progress in cover concrete (i.e. the end of the propagation stage, JSCE 2007) is investigated by applying a thermodynamic coupled analysis system DuCOM (Durability Models of Concrete, Maekawa et al. 2008) and simplified predictive methods, in addition to on-site measurements and nondestructive and core-sampling test results.

3.1.1 Chloride ion ingress

Steel reinforcement corrosion induced by the ingress of chloride ions is affected by the quality of the concrete, cover depth, water leakage history, the concentration of chloride ions in the penetrating water, and other factors. In this study, the point at which the concentration of chloride ions at the depth of the steel reinforcement reaches 1.2 kg/m^3 is defined as the end of the initiation stage. The concentration of chloride ions at this depth is determined using Equation (3.1).

$$C_{Cl} = C_0 (1 - erf(\frac{c}{2\sqrt{D \cdot t}})) \qquad (3.1)$$

where C_{Cl} = concentration of chloride ions at the depth of the steel reinforcement, kg/m^3; C_0 = concentration of chloride ions on the surface of the concrete, kg/m^3; c = cover depth, cm; D = diffusion coefficient of chloride ions, cm^2/y; t = time, year. Here, D and C_0 are determined by taking three samples at minimum per sampling point in a tunnel section suffering from chloride ion attack, such as

	Calculated cracking time (year)		Actual deterioration
Point A	-1.9～-0.3		Partial detachment from 2 years ago
Point B	+5.9～+23.8		No deterioration
Point C	+0.6		Some detachment
Point D	+6.2		No deterioration

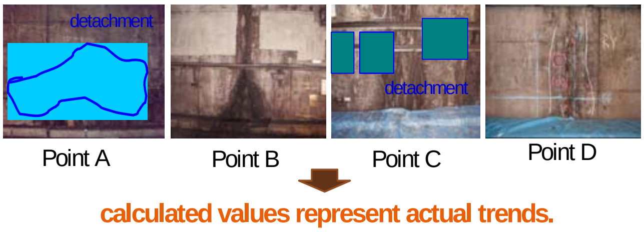


Figure 3.1 Comparison between estimated cracking time and actual observation

where a tunnel passes under a river, and applying the least square method based on this actually measured distribution of chloride ion concentration. Using this method, the time at which the concentration of chloride ions reaches the end of the initiation stage, t_1, can be determined from the time when C_{Cl} reaches 1.2 kg/m^3.

In addition, the time at which the concentration of chloride ions reaches the end of propagation stage, t_2, is given simply by Equation (3.2) (MLIT 2003).

$$t_2 = 0.4 \cdot t_1 \qquad (3.2)$$

It is also possible to estimate the history covering the period from the time of construction up to the present and make future predictions by carrying out inverse analysis using DuCOM based on the current profile of chloride ions in concrete (Figure 3.1, Takahashi et al. 2008). This is a method of predicting with accuracy the initiation and propagation stages by analyzing the migration of chloride ions into the concrete at each point and the consequent steel corrosion under the estimated environmental history. In this study, where the subject is an entire subway line, the simplified Equation (3.2) is used as a first approximation. The integration of an advanced simulation into the maintenance management system is a subject for future study.

3.1.2 Carbonation

Steel reinforcement corrosion induced by carbonation is affected by the quality of the concrete, the cover depth, presence of water, and other factors. In this study, the time at which the concrete at the depth of the steel reinforcement becomes carbonized is defined as the end of the initiation stage. Carbonation depth is given by Equation (3.3).

$$d_c = \alpha\sqrt{t} \qquad (3.3)$$

where d_c = depth of carbonation, mm; α = coefficient of carbonation rate, mm/year. The coefficient of carbonation rate is obtained from actual core sample measurements. Cores were taken at about 75 points along the target subway line and used to make predictions. At points where actual measurements were not taken, an average of the measurements at two nearby points was used.

The end of the propagation stage is calculated using a model based on DuCOM. The carbonation induced corrosion rate was calculated under various conditions. The resulting concrete corrosion rate in a tunnel without water leaks (with an average ground temperature of 15.6°C and average relative humidity of 62%) was determined to be 0.7-0.9 mg/cm^2. To be on the safe side in this study, the corrosion rate in the propagation stage is taken to be the higher value, 0.9 mg/cm^2. The initiation of cracking in the cover concrete is calculated by the equation proposed by Yokozeki et al. in 1997.

3.1.3 Control index for reinforcement corrosion

In order to estimate the degree of concrete deterioration, the cover depth was measured over the entire length of the target subway line at a constant elevation along inbound and outbound lines by the radar method. The resulting data for intervals of 1 m were stored in a database. The soundness of an RC tunnel is evaluated on a control unit basis from Equations (3.1) to (3.3) using these data.

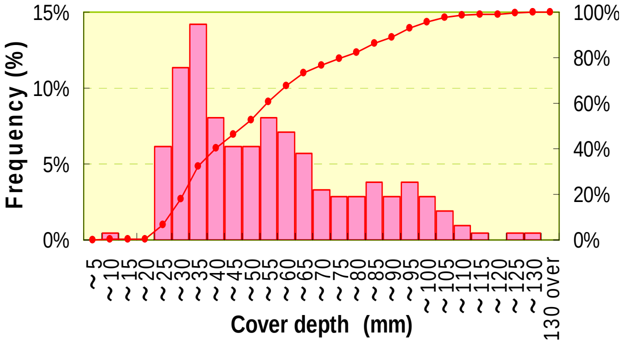


Figure 3.2 Measured cover depth in a control unit

Table 3.1 Calculation by representative cover depth (ex. Carbonation)

Cover depth (mm)	Mediam (mm)	End of initiation stage (year)	End of propagation stage (year)
0 – 5	2.5	1961	1961
5 – 10	7.5	1965	1967
10 – 15	12.5	1973	1978
15 – 20	17.5	1984	1993
20 – 25	22.5	2000	2011
25 - 30	27.5	2019	2034
…	…	…	…

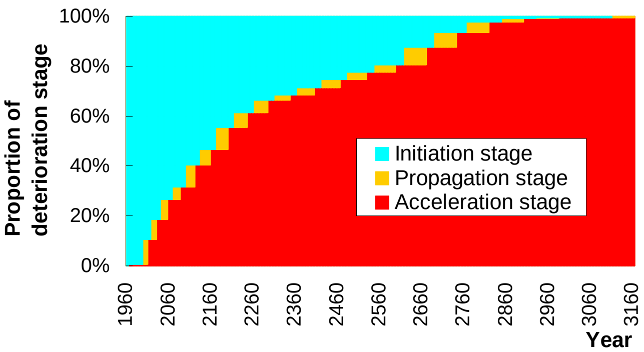


Figure 3.3 Time variation for proportion of deterioration stage

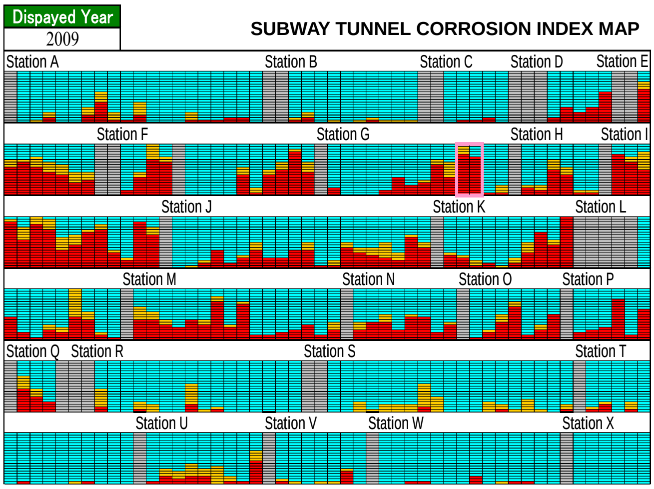


Figure 3.4 Corrosion index map at present

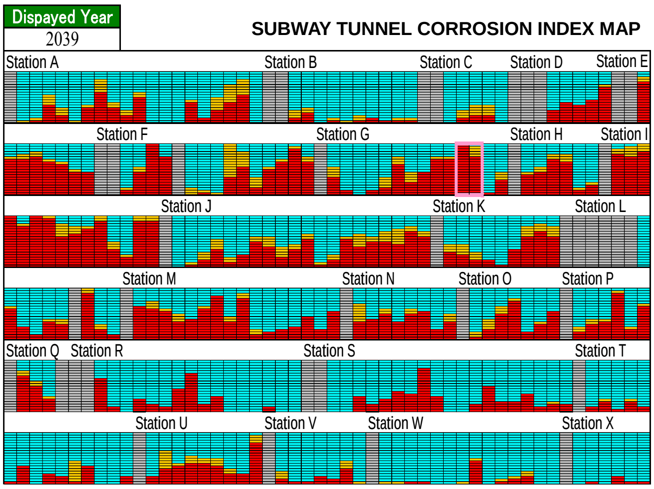


Figure 3.5 Corrosion index map 30 years later

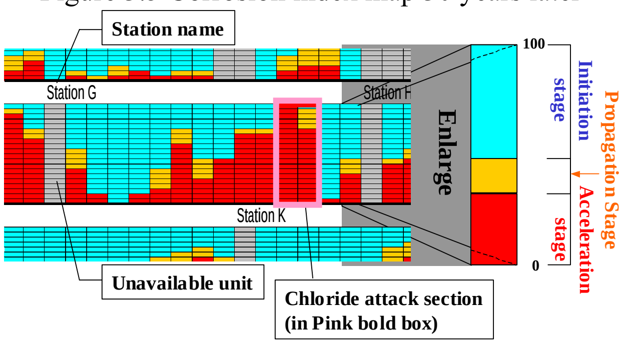


Figure 3.6 Description of corrosion index map

The actual procedural steps used in calculating a control index are as follows. First, the subject tunnel section is classified as either a section subject to chloride ion attack (such as under a river or near a canal or moat) or an ordinary section free of chloride ion attack based on the position of the control unit. Next, a histogram of cover depths is prepared in increments of 5 mm in each control unit, as shown in Figure 3.2.

Next, the year in which corrosion of the steel reinforcement reaches the end of the initiation stage and the end of propagation stage is calculated at the median of each cover depth range (Table 3.1).

The proportion of the control unit length in which steel reinforcement corrosion will reach the propagation and acceleration stages within T years ($T \geq 0$) is then calculated.

The change with time in the proportion of steel reinforcement corrosion reaching the initiation, propagation, and acceleration stages in each control unit can be obtained, as shown in Figure 3.3. These ratios are used as control indexes for evaluating the soundness of the RC tunnel on a control unit basis in the following maintenance prioritizing subsystem.

3.1.4 Corrosion Index Map

A corrosion index map of the entire subway line can be prepared by integrating the control indexes on a control unit basis. Figures 3.4 and 3.5 are typical results that visually show the deterioration of the subject subway line at present and 30 years from now. A key to the corrosion index map is given in Figure 3.6.

This corrosion index map is expected to make a significant contribution not only to the maintenance management strategies described later but also to the formulation of an on-site inspection plan.

3.2 Maintenance Prioritization Subsystem

The engineering evaluation of an RC tunnel accomplished by the above subsystem forms the basis for assigning priority to maintenance countermeasures in this subsystem. Priorities are assigned to both preventive maintenance measures used to control the occurrence and development of steel reinforcement corrosion as induced by chloride ion ingress and carbonation and to the future repair of distressed concrete as identified during on-site surveys. Of the on-site survey results, this system receives as inputs information about the location and type of distressed concrete.

In scheduling the work of preventive maintenance and repair, the first step is to set the time span of the maintenance plan for the entire subway line. A threshold is also set for each control index. Priorities are assigned in the order that the control index reaches the threshold within the preset maintenance time span.

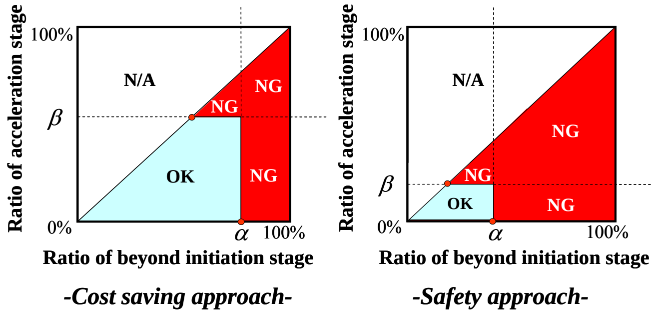


Figure 3.7 Definition of threshold α and β

3.2.1 Prioritization for preventive maintenance

For each control unit, preventive maintenance is scheduled for a time as calculated from the preset thresholds of the control indexes for the propagation and acceleration stages (that is, the proportion of the control unit length reaching these stages). The two thresholds used to determine whether to carry out preventive maintenance are the proportion (α) of the control unit where the steel reinforcement corrosion reaches the propagation stage and the proportion (β) of the control unit where steel reinforcement corrosion reaches the acceleration stage.

In Figure 3.7, where α is plotted against β preventive maintenance should be carried out when the proportions move into the red zone ($\beta \leq \alpha \leq 100\%$). Two example settings are shown in this figure. A cost-saving maintenance strategy can be achieved by setting the thresholds at high values, while a higher safety strategy would set them at low values.

3.2.2 Prioritization for distressed concrete repair

Tokyo Metro keeps a record of distresses such as water leaks, cracks, and floating, scaling, and exfoliated concrete found during general inspections. The steel reinforcement corrosion in these distressed parts can be predicted in the same manner as described in **3.1**.

Unlike preventive maintenance, which depends on treating the RC tunnel as a continuous inner surface with a series of cover depths, repairs to distressed concrete can be addressed in terms of

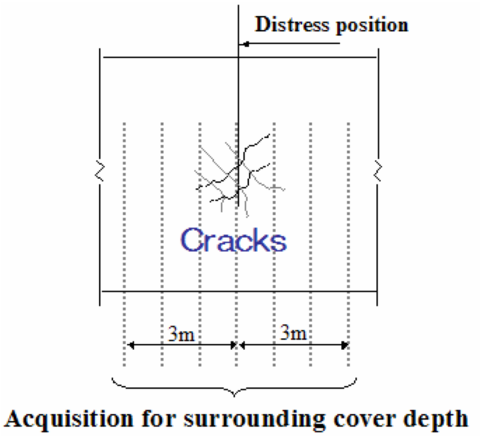


Figure 3.8 Cover depth range of distress point

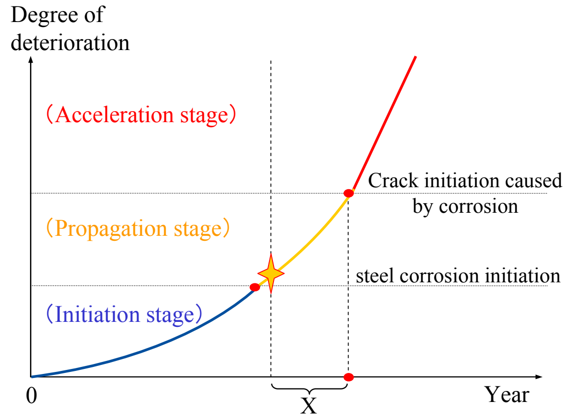


Figure 3.9 Estimation of deterioration stage to assign the priority for distressed concrete repair

Table 3.2 Example outputs of priority list

Prioritized list of preventive maintenance

Cntl. Unit	Chloride attack	Between stations	Beginning of Kilometer	End of Kilometer	Length	the year exceed "α"	the year exceed "β"	Req'd maintenance execution year	Unit price (per meter)	Cost of preventive maintenance
50	Yes	Sta.G–Sta.H	5732	5834	102	2009	2009	2009	80	8,160
51	Yes	Sta.G–Sta.H	5834	5924	90	2009	2009	2009	80	[illegible]
8	Yes	Sta.A–Sta.B	390	420	30	2009	2009	2009	80	
47		[illegible]Sta.K	5520	[illegible]			2009	2009	[illegible]	
			5924							

Prioritized list of distressed concrete repair

Distress ID	Chloride attack	Location (kilometer)	Repair area (sq.meter)	Cover depth at distress	Year the end of propagation stage	Req'd repair execution year	Repair method	Unit price (per sq.meter)	Cost of repair
272	Yes	7911	1.53	25.0	1960	2009	Chipping type.1	44	67
257	Yes	12,714	3.60	6.0	1963	2009	L.W. treatment	85	306
113		7,940	3.00	28.0	1963	2009	L.W. [illegible]	[illegible]	[illegible]
	Yes	5556	0.85	8.0	1960	2009	[illegible]		
		14512			1961	[illegible]			

individual information at specific locations. Accordingly, the degree of steel reinforcement corrosion at each specific location is used for determining the timing of repairs. Distressed areas may develop horizontally from any point, so the degree of steel reinforcement corrosion is predicted from the minimum value of cover depth in the range 3 m on either side of the actual point of distress. (Figure 3.8)

The margin of years until the end of propagation stage, (X), as shown in Fig. 3.9 is calculated for all existing distresses and the priority for distressed concrete repair is assigned according to the (X).

In this study, a rule was made that any distresses within a control unit are repaired at the same time as preventive maintenance is carried out in that unit. Priorities can be assigned to repair measures in a realistic and rational manner by associating repairs with preventive maintenance work.

3.2.3 Maintenance priority lists with costs

The cost of the repair work to be carried out within the preset time span can be estimated from information about the volume and unit price of the repair work. Then, priority lists of preventive maintenance and repair work can be output with cost information. Table 3.2 shows some example outputs.

3.3 Project Planning Subsystem

As described in the section above, objective priorities are assigned to preventive maintenance and distressed concrete repair using preset thresholds as parameters. Taking these outputs, the project planning subsystem provides support in formulating

Table 3.3 Ratings of distressed concrete by visual inspection

Soundness rating		Degree of distress
A	AA	Severe
	A1	Distress in progress. Performance also deteriorating.
	A2	Distress that could deteriorate performance
B		Distress that could become soundness rating A if it develops
C		Minor
S		None

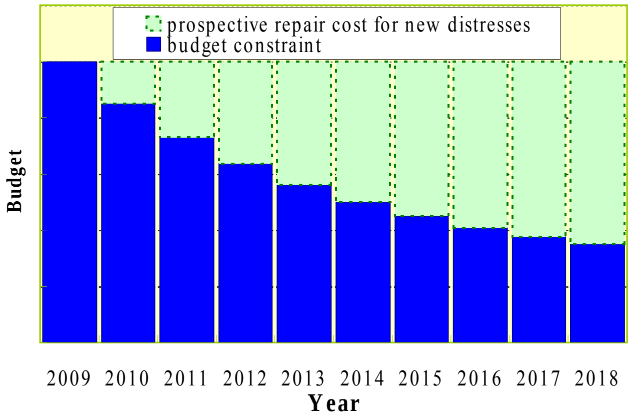


Figure 3.10 Image of budget constraint for distressed concrete repair

a practical maintenance plan on a yearly basis.

Taking budget constraints as input information, the subsystem selects maintenance projects that should be carried out each year and that it is feasible to implement. In addition, the system formulates a project plan for each selected maintenance project based on a rating (A, B, C, or S; see Table 3.3) determined from a visual inspection. The system allows the maintenance plan to be adjusted annually. Projects for preventive maintenance and distressed concrete repair that have been determined as described above based on the defined thresholds are selected as essential maintenance projects for the year. If any project cannot be carried out within the set budget, it is postponed until the following year. In addition, if visual inspection indicates that a repair project should be rated as urgent, it can be marked as an essential maintenance project.

In reality, there are many cases where the threshold has already been reached and many repair projects are rated as urgent based on visual inspection. As a result, many essential maintenance projects may need to be carried out in the first year of a plan.

If the budget does not fit into repair costs, the budget constraint or the threshold (which determines the year in which preventive maintenance or repair is to be carried out) is changed (see **3.2**), allowing for a project review and finalization of the project plan.

3.3.1 Budget constraint

An upper limit is placed on the budget for each year of the preset plan time span and this imposes limits on the selection of possible maintenance projects. Separate constraints are placed on the budgets for preventive maintenance and distressed concrete repair.

As regards the repair of distressed concrete, information about locations requiring repair work is obtained from the latest on-site inspections. However, the maintenance management plan does not cover other distresses that would newly appear within the preset time span, because it is very difficult to predict when, where, and what type of distress will occur. On the other hand, distresses such as water leaks are very likely to occur, so the upper budget limit is set taking into account the cost of repairing the distresses that are likely to occur. (Figure 3.10)

3.3.2 Adjustment of distressed concrete repair list using visual inspection information

Distressed concrete is rated as given in Table 3.3 by carrying out an on-site visual inspection.

Of the distresses rated A and B by visual inspection, those on the upper region (tunnel ceiling) might affect train services, so a plan is drawn up for immediate repair regardless of the priority determined by the system. It has been verified that repair measures for distresses with rating A tend to appear high on the list of priorities as determined in section **3.2**.

3.3.3 Manual adjustment

Maintenance project priority must necessarily be reviewed in some cases in view of the need to simultaneously work on sections in close proximity to each other or repair other facilities such as tracks and cables. For such special cases, the system provides a function for manually adjusting priorities.

3.3.4 Determination of work timing under budget constraint and back-calculation of index

In accordance with the revised priority for preventive maintenance and distressed concrete repair resulting from consideration of the visual inspection rating or manual adjustment, the maintenance projects that can be implemented each year under the budget constraint are determined. Where maintenance projects have to be postponed to the following year due to budget constraints, it is necessary to evaluate cases where the control index exceeds the threshold and judge whether the index remains in the allowable range.

The control index for determining preventive maintenance is affected directly by the distribution of cover depth in increments of 5 mm, but in fact the index does not change sharply every year. Further, chloride ion attack is, in some cases, confined to limited sections of a subway line. As a result, in many cases, it is thought that the index will fall within the allowable range even if a preventive maintenance project is postponed by a few years.

On the other hand, the postponement of distressed concrete repair must necessarily be reviewed with care according to actual conditions because it would reduce the margin of years until the end of the propagation stage.

3.3.5 Annual project plan sheet

Using the approach described, the list of maintenance projects that can be carried out within budget for each year of the preset time span of the plan is output from the system.

4. SYSTEM TRIAL STUDY

4.1 Estimation of overall cost

The three subsystems described in the earlier sections are here implemented for a single subway line and a sensitivity analysis is carried out. The time span of the maintenance plan for the line is set at 30 years. The analysis considers how much the required budget varies over the length of the plan as threshold values are changed.

First, the change in the cost of preventive maintenance is confirmed. The value of α, the proportion each control unit with steel reinforcement corrosion at the propagation stage, and of β, the proportion of each control unit with steel reinforcement corrosion at the acceleration stage, are varied in increments of 10%. Figure 4.1 shows the cost of preventive maintenance as a percentage of the cost (C_1) of repairing the entire length of tunnel. As can be seen from the figure, the cost varies greatly according to the value of the preset thresholds. In particular, the influence of β is large.

Similarly the cost of distressed concrete repair is calculated. (Figure 4.2) The cost of distressed concrete repair is represented as a percentage of the cost (C_2) of repairing all existing distressed concrete.

The cost of distressed concrete repair has a lower limit, although the tendency is the same as for preventive maintenance. The ratio of C_1 to C_2 varies from 82 to 18.

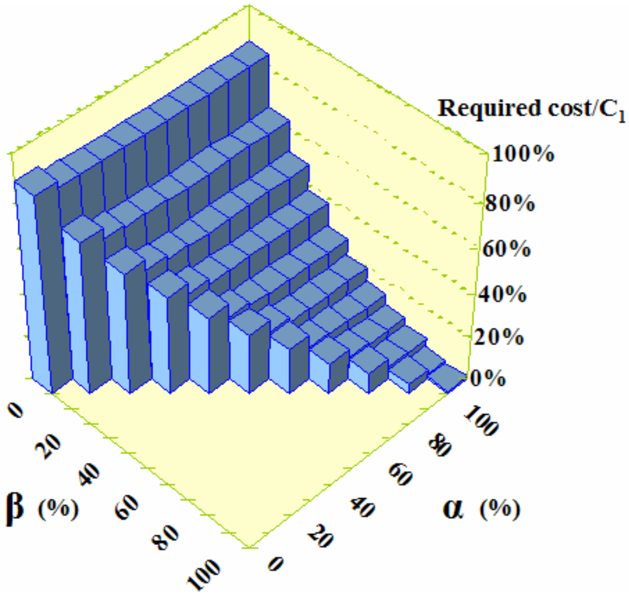


Figure 4.1 Preventive maintenance cost

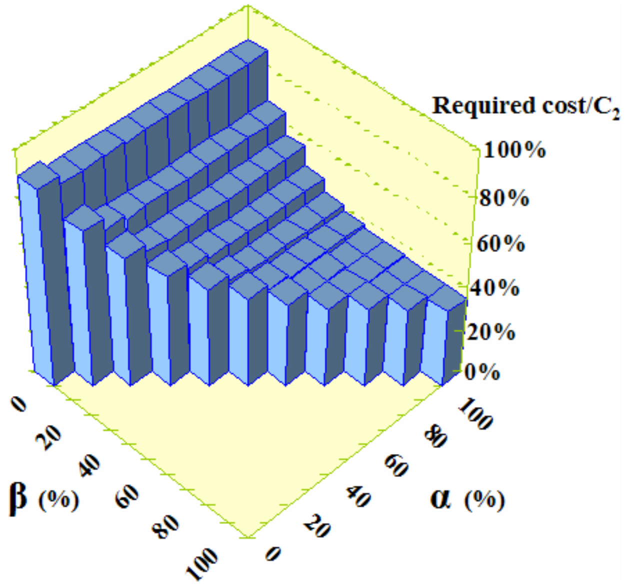


Figure 4.2 Distressed concrete repair cost

4.2 Case study

Based on the trends revealed by the sensitivity analysis, case studies based on two 30-year maintenance strategy scenarios are prepared as shown in Figure 4.3.

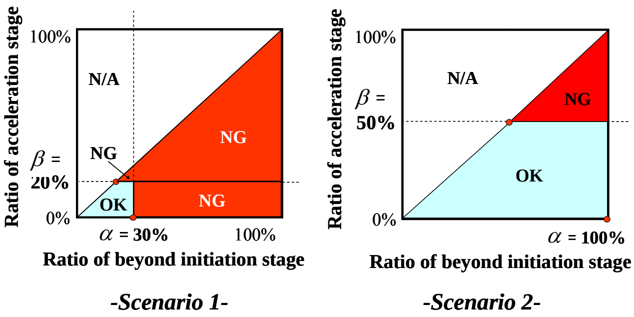


Figure 4.3 Threshold α and β for two scenarios

Scenario 1

Attaching importance to the structural safety of the RC tunnels, any distress that exists at an early stage before the development of steel reinforcement corrosion is repaired and then preventive maintenance is performed. In quantitative terms, the values of α and β are set at 30% and 20%, respectively.

Scenario 2

To limit the cost of repairs over 30 years, steel reinforcement corrosion is allowed to develop to some degree. In quantitative terms, the values of α and β are set at 100% and 50%, respectively.

With both scenarios, measures are implemented earlier for cases of distress with a rating of B or higher as determined in visual inspections.

Figure 4.4 shows the results of these case studies. The total cost of preventive maintenance and of distressed concrete repair in Scenario 1, where tunnel safety is a priority, is greater than in Scenario 2, with maintenance costs reduced by a factor of 2.30 and 1.14, respectively. The total tunnel length where steel reinforcement corrosion reaches the acceleration stage, at which cracking begins, in the year 2039 is 2.6% and 12.4% in scenarios 1 and 2, respectively. This indicates that the risk is higher in scenario 2.

It should be noted, however, that in this study the effect of repairs and differences in cost according to the timing of repair work are not taken into account. There may be a greater motivation to perform preventive maintenance if these effects were to be incorporated into the system.

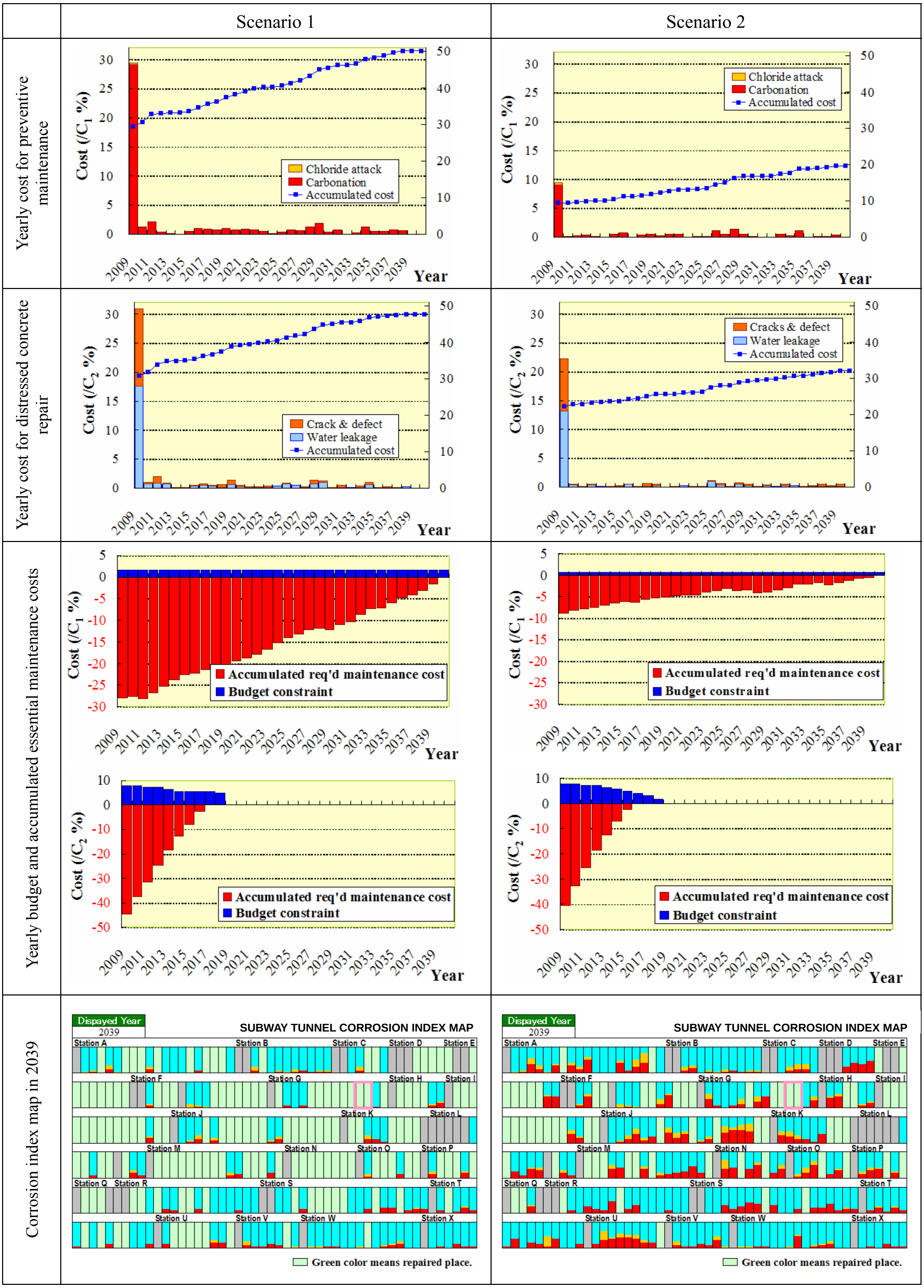


Figure 4.4 Case Study Results

5. CONCLUSION

The authors proposed a maintenance management system for RC tunnels based on the cover depth as measured by nondestructive testing. The system was run on a trial basis to generate a maintenance plan for an existing subway line. Implementation of the system entails on-site measurements, core sample test results, and a numerical analysis system.

The proposed system was shown to be capable of managing structure data and on-site inspection results in an integrated manner and it was demonstrated to be helpful in drawing up maintenance management plans under various conditions.

Further enhancements to the system will be possible by improving individual elements of the technology and accumulating more data.

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REFERENCES

JSCE, 2007. *Standard specification for design and construction of concrete structure*.

Maekawa, K., Ishida, T. and Kishi, T., 2008. *Multi - scale modeling of structural concrete*, Taylor and Francis.

MLIT, 2003. Recommendations from Committee on Management and Renewal of Road Structures in the Future (in Japanese) http://www.mlit.go.jp/road/current/kouzou/index.html

Takahashi, Y., Kagawa, S. and Ishida, T., Numerical simulation of chloride-induced steel corrosion in underground RC structures under various water leakage history, *Proceeding of Easec-11*, Taipei, Taiwan, 2008.

Yokozeki, K., Motohashi, K., Okada, K., and Tsutsumi, T., A rational model to predict the service life of RC structures in marine environment, *Forth CEMENT/ACI International Conference on Durability of Concrete*, SP170-40, pp.777-798, 1997.