CURRENT SITUATION AND ISSUES CONCERNING THE MAIINTENANCE AND MANAGEMENT OF UNDERGROUND LIFELINE STRUCTURES IN JAPAN
- Evolving toward the Introduction of Information Technology, Automation and Robotization -

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Abstract: The enormous stock of underground lifeline structures constructed in Japan during the high economic growth period is aging with each passing year. In addition, the need for efficient execution of inspection, diagnosis and repair work is also increasing, as is the severity of the issues involved, including burgeoning repair and renewal costs; social impacts such as the traffic restrictions; and a shortage of specialized engineers, partly due to retirement of aging engineers. This paper introduces effective inspection and diagnosis technology and renewal technology used to maintain and manage domestic underground lifeline structures. In addition, inspection, diagnosis and repair technology for maintenance used to resolve the above-mentioned issues are addressed by classifying the element and systemization technologies. A broad survey is made of future directions are discussed for maintenance and management standards aimed at introducing common information technology, automation and robotization by operators possessing underground lifeline structures.

Keywords: diagnose and repair of underground structures, repair and renewal, railway tunnel inspection cars, pipe internal inspection

1. INTRODUCTION

Lifeline systems support modern lifestyles, and are indispensable to our daily lives. These lifelines include gas, electric, city water, sewerage, road, railway , telephone (telecommunications facilities) and other systems that have net-like structures and function as network systems.

In addition, vast quantities of underground lifeline structures were constructed in Japan mainly during the high growth period from the 1960s to the 1980s, and many of these structures are now more than 30 years old.

Current maintenance and management consists of primary inspections (essentially inspection and recording by visual observation) that are performed periodically on all structures, secondary inspections (mainly observation and photographic records) that are performed when necessary, and detailed inspections (surveys and records including core sampling and other surveys related to the reinforced-concrete) that are performed on portions found in the secondary inspection to have problems. However, inspection and repair work often require that tunnel functions be stopped or reduced, and there are also time limitations in many cases, especially for tunnels used by third parties. These lifelines also have net-like structures and function as network systems, so inspections and maintenance and management repairs must be performed without stopping the flow in a manner that would stall urban functions or hinder people's lifestyles. In addition, there is also the possibility of variance in human judgment when evaluating soundness by visual observation, as has been done so far.

In consideration of the above factors, issues concerning the maintenance and management of underground lifeline facilities include shortening inspection and survey times, introducing non-destructive inspection methods and other new technology that can eliminate variances in human judgment, technology for predicting degradation and damage, and technology that allows repair and reinforce work to be performed in a short time and in cramped locations, etc. In addition, management systems that take into account risk management and other factors for determining rational inspection periods, repair timings, repair methods and so on are also thought to be important.

2. CURRENT SITUATION AND ISSUES CONCERNING THE STOCK OF UNDERGROUND LIFELINE STRUCTURES IN JAPAN

Japan has an enormous stock of underground lifeline structures, as shown in Table 1.The current situation and trends concerning this stock are described below using expressways as an example, specifically the total service length and total tunnel length of expressways managed by the former Japan Highway Public Corporation (hereafter, "JH").

The network of national expressways and general toll roads managed by JH had reached a total length of approximately 7,000 km at the end of fiscal year 2001.The total tunnel length accounted for a total road length of approximately 650 km, and a total inbound and outbound lane length of approximately 1,200 km. Fig.1 shows that the ratio of expressways accounted for by tunnel structures was trending at 2% to 3% by around 1980, but has increased since to approximately 9% at present with the expansion of crosscut roads through mountainous regions.

The No. 2 Tomei Expressway and the Meishin Expressway, which are currently under construction, both have high tunnel ratios of 20%, and the overall tunnel length is expected to continue to increase in the future.

Table.1 Total Amount of Underground Lifeline Structures in Japan (Nationwide)

Public operator type	Unit	Total length	Remarks
Telecommunications	km	621,000	As of March 2003
Electric power	km	48,800	As of March 2003
Gas	km	224,000	As of March 2002
City water	km	681,000	As of March 2003
Sewerage	km	414,000	As of March 2003
Subways	km	687	As of July 2004

3. STANDARD VALUES FOR THE MAINTENANCE AND MANAGEMENT OF UNDERGROUND LIFELINE STRUCTURES

These structures are generally constructed underground where there are few changes in the environment, and can be used for long periods. However, a certain degree of degradation over time is unavoidable. Therefore, the safety of underground structures over time is becoming a prominent issue, particularly in recent years following the concrete peeling accident inside a tunnel that occurred in 1999.

Against this background, the task of setting standard values for satisfying structural performance requirements made of management data to perform proper maintenance and management. These standard values are used as standards for both human and roboticized work, but it should be noted that standard values for maintenance and management have not been standardized among lifeline operators. Table 2 shows the standard values for maintenance and management used by typical lifeline operators.

Table.2 Standard Values for Maintenance and Management by Typical Enterprises

Operator type	Judgment item	Priority management item	Value (Standard value)
Express ways	Risk of concrete peeling inside tunnels	Relationship between crack width and peeling	Crack width of approximately 0.5 mm or more (The risk increases at a crack width of 1 mm or more.)
Railways	Risk of concrete peeling inside tunnels	Relationship between crack width and peeling	Crack width of 0.5 mm or more
Subways	Effect on rebar corrosion in RC structures	Crack width	0.8 mm or more (These RC structures have rebars closely spaced within the lining materials, so cracks widths of less than 0.8 mm have little effect and are excluded.)
Sewerage	Reinforced concrete pipes	Damage	Width of 2 mm in the axial direction
		Cracks	Width of 2 mm in the circumferential direction

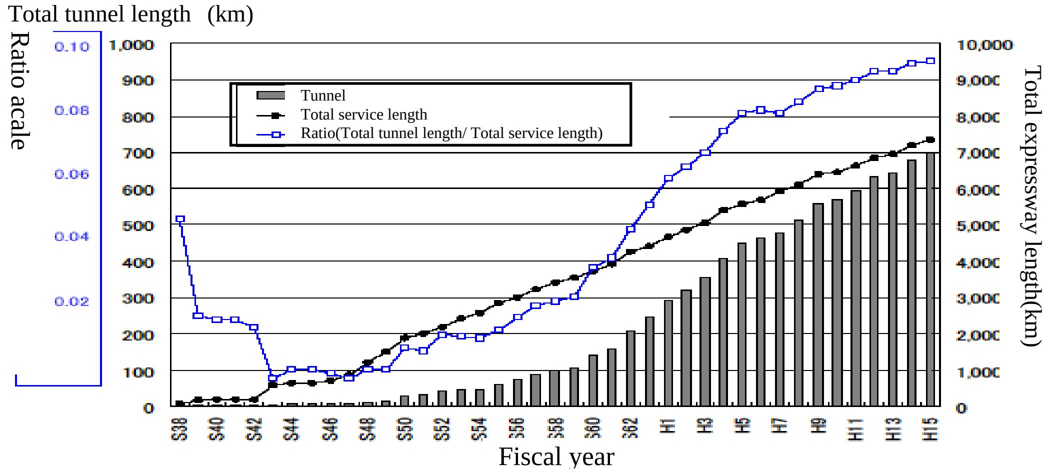

Fig. 1 Ratio of Expressways Accounted for by Tunnel Structures

Amidst these circumstances, each lifeline operator is pursuing efforts such as the automation of work using robots, with the aim of increasing work efficiency and swiftness to properly maintain these underground structures, and these technologies are being practically applied at a rapid pace.

4. INFORMATION, AUTOMATION AND ROBOTIZATION TECHNOLOGY USED IN UNDERGROUND LIFELINE STRUCTURES

Table.3 shows examples of inspection and survey technology using information technology and automation applied by lifeline operators, along with background and goals. Similarly, Table 4 shows examples of applying information processing and evaluation technology.

As described in Section 3 above, the main purposes and goals of inspection technology for concrete structures are detection of peeling to prevent concrete peeling accidents, cavity and crack surveys, and degradation surveys of reinforced concrete structures. However, the methods and element technologies used span a wide range, including visualization using argon lasers and line sensor cameras; the active infrared method which further increases the imaging accuracy of those cameras; and self-propelled high definition pipe cameras that are capable of direct or lateral vision.

In addition, the necessity of databases in lifeline facility maintenance and management hardly needs mentioning, and while there are some differences, each facility operator is compiling databases. Among these, the case of investigating a tunnel management system for expressways is a focus of particular attention.

This tunnel management system is a management system that aims to reliably understand changes and evaluate the soundness of expressway tunnels by continuously recording and accumulating inspection results. In addition, the accumulated inspection results are analyzed to estimate the causes of changes, predict future changes, select countermeasures, and perform effective medium- and long-term maintenance and management.
This is quite an important development for future investigations concerning the standardization of maintenance, management and renewal methods for underground lifeline facilities, and could also be considered a firm approach toward the introduction of comprehensive management and asset management methods. In addition, the comprehensive facility management systems of gas operators include mapped facility construction and maintenance and management data, and as such are the subject of attention as databases with both geographical data and facility data. These systems have been developed with the aim of mutual utilization between lifeline operators.

Some typical examples of these systems are introduced below.

Table. 3 Applied Examples of Inspection and Survey Technology Using Information Technology and Robotization

Operator type	Background for introducing information technology, etc.	Goals	Specific examples
Expressways	Crack surveys • Visual inspection in dark tunnel environments • Difficult work • Avoiding human error • Limitations on work time	• Highly accurate and efficient survey technology • Measurement accuracy: Crack width of approximately 0.5 mm or more	• Argon laser measurement system • CCD digital camera measurement system
Railways and subways	• Avoiding human error • Reduction in number of specialist technicians	• Improvement of visual inspections Measurement accuracy: Crack width of 1 mm Measurement depth using the far infrared method: 50 mm or more	• Filming wall surfaces with line sensor CCD cameras • Detection of peeling by active infrared image processing • Lining surface filming device using laser beams • Automatic generation of change development diagrams • Automation of soundness judgments
Sewerage	• Inability of people to enter pipes • Early detection of pipe damage and degraded locations	• Divided at an inner diameter of 800 mm • Highly accurate and efficient survey technology that does not depend on visual inspection	• Small diameter pipe inspection system using TV cameras • TV camera measurement system for large diameter sewer pipes

Table.4 Applied Examples of Information Processing and Evaluation Technology

Operator type	Background for introducing information technology, etc.	Goals	Specific examples
Expressways	• Increased amount of facilities requiring maintenance and management • Efficient inspection methods • Continuous recording and accumulation of inspection results	• Establishment of comprehensive management methods	• Tunnel management system ((1) Evaluation of soundness, (2) Estimation of change causes, (3) Prediction of degradation, (4) Selection of countermeasure methods, (5) Optimization of maintenance and management plans, etc.) • Crack Draw 21 Creation of change development diagrams and centralized management of various data
Sewerage	• Expanding installation of sewer systems • Full scale work to reconstruct superannuated pipes • Increased need to fully understand existing pipe conditions	• Determination of reconstruction policies and reflection to both basic plans and work plans	• SEMIS (Sewerage Mapping and Information System) • System for creating pipe internal development diagrams using mirror type TV cameras
Gas	• Increased conduit diagram density as populations increase • Rapid spread of conversion to underground sewer, electric, communications and other facilities	• Electronic referencing of work between enterprises • Mutual utilization between lifeline enterprises	TUMSY (Total Utility Mapping System)

4.1 Concrete Lining Surface Inspection Technology Using an Argon Laser

Crack measurement technology using an argon laser is technology that irradiates a laser beam onto the tunnel walls using a laser scanner, reads the subtle changes in the brightness of the laser beam reflected by the walls using a light sensor, and digitally converts and records this brightness in 256 levels. A clear image can be obtained by continuously reading this reflected laser beam light quantity data in the direction of vehicle travel. This measurement system continuously records and creates images from information on the tunnel lining concrete surface in the direction of vehicle travel, and can support a measurement cruising speed of up to 60 km/h. Fig.2 shows a general view of the inspection vehicle.

The soundness of the measured tunnel lining surface is evaluated by comprehensive judgment of the crack density, cracking format, water leakage and other lining surface information for each tunnel arc center.

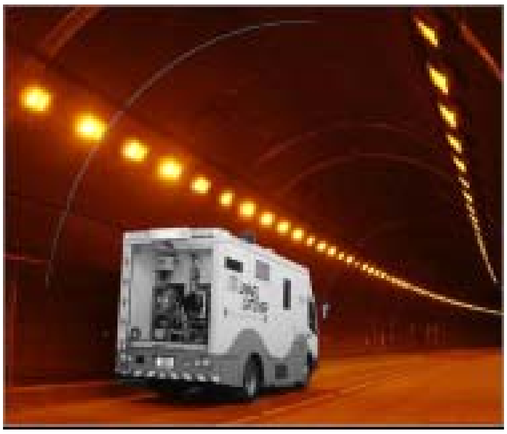

Fig. 2 Concrete Lining Surface Inspection Vehicle

4.2 System for Inspecting Peeling and Water Leakage Under the Lining Surface Using an Infrared Camera

This system detects changes in peeling and water leakage underneath the concrete lining surface. This technology performs infrared image processing using a thermograph with the aim of increasing subway tunnel inspection efficiency, acquiring objective and quantitative inspection data, increasing accuracy by automatically extracting degradation and other changes, and compiling a database to understand behavior over time.

This inspection system consists of a tunnel inspection train equipped with measurement units that acquire measurement data and an analysis unit that performs image and other processing on the data. These units have an off-line configuration. The tunnel inspection train has a three-car configuration consisting of a heater car, a motor car, and an imaging car in that order. Fig.3 shows a general view of the tunnel inspection train. Note that visible image data acquired with a CCD camera is also used to understand cracking, precipitants and other phenomena on the tunnel lining surface, and both the infrared images and visible images are used to complement each other in order to more accurately detect changes.

The specific inspection method is as follows. First, the tunnel lining is heated using an infrared activating irradiation unit (halogen lamp) mounted on the heater car. Next, the temperature distribution of the lining surface after irradiation heating is measured by an infrared area-type camera mounted on the imaging car that detects peeling locations. In addition, visible images of the lining surface are also obtained using a line sensor camera for crack observation that is equipped with a light source and also mounted on the imaging car. Peeling or other internal air layers are detected by changes in the concrete lining surface temperature distribution produced by the resulting differences in thermal conduction.

Fig. 3 Inspection System for Lining Sub-surface Peeling and Other Changes

4.3 Large Diameter Pipe Inspection System using TV Cameras

Large diameter sewer pipes contain large quantities of fast flowing water and are quite dangerous (including the possibility of hydrogen sulfide gas production), so the entry of inspection personnel has been restricted thus far. However, a large diameter pipe inspection and recording system has been developed and applied in recent years that allows detailed inspection in a safe working environment. This system is an image measurement system using four-point laser pointers, and makes it easy to gather and accumulate the information needed for maintenance and management, such as changes over time, through highly accurate measurement and conversion of conditions inside pipes into digital images and electronic data.

The inspection unit is a boat-type that consists of inspection cameras mounted on a float (Fig.4). Four-point laser pointers are installed at equal intervals, and crack widths and other information can be measured by calculating the on-screen scale from the laser pointer coordinate axes shown in the TV images. This system has an inspection performance capable of measuring cracks 1 mm wide on wall surfaces 3 m away.

4.4 Utilization of a Change Development Diagram Creation and Management System for Concrete and Other Structures

Fig. 4 Large Diameter Pipe Inspection System

This example describes a system that can greatly reduce the amount of work compared to conventional methods by efficiently converting change development diagrams for concrete and steel structures to electronic form and automatically calculating change amounts. This system makes it easy to manage past data over multiple years, such as periodic inspections, detailed inspection and other inspection results, repair histories, and on-site photo-graphs. It also increases the accuracy, efficiency and swiftness of long-term structural soundness evaluations, and allows centralized management of electronic data.

A specific example of utilizing this RC Structure Change Development Diagram Creation and Management System is given below. The procedures are as follows .

1) Sketched diagrams and filmed images taken during actual on-site tunnel inspection are loaded.
2) The sketched diagrams and filmed images loaded to the background are traced to create an electronic change development diagram (see Fig 6 and Fig. 7).
3) Crack start and end point coordinates, crack lengths, surface change areas and other items are auto-matically calculated.
4) Soundness evaluation is per- formed based on the evaluation score for each change.
5) Change causes (cracking, peeling and other surface degradation) are estimated.
6) Degradation (structural and functional degradation, etc.) is predicted.
7) The system is used as an overall management system for selecting countermeasures, etc.

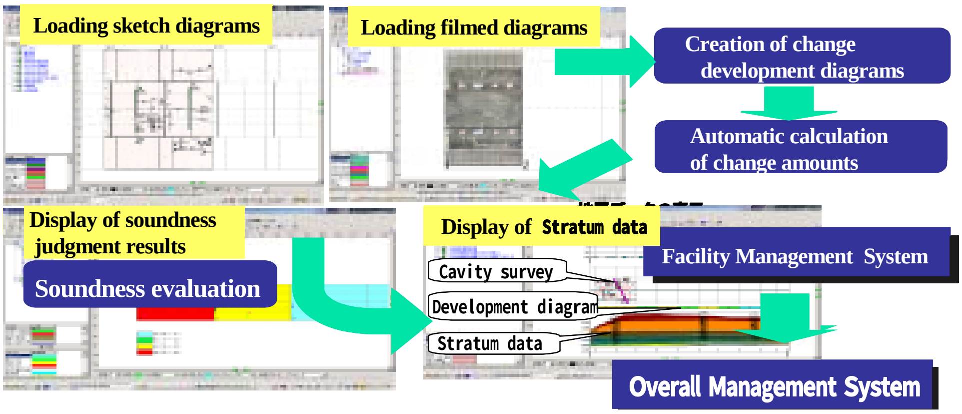

Fig. 5 Example System for Creating and Managing RC Structure Change Development Diagrams

Collaboration with various inspection and survey technologies (tapping inspection, etc.) allows adaptation to various systems.

Fig. 6 Tracing with a Tablet

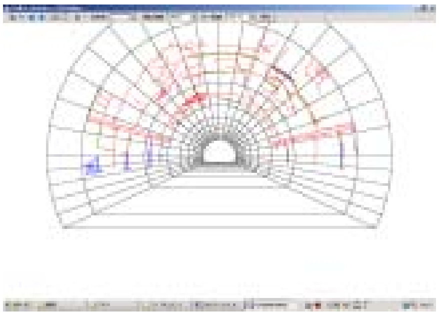

Fig. 7 3-D Display of Development Diagrams

5. SETTING AND STANDARDIZATION OF APPROPRIATE PERFORMANCE REQUIREMENTS FOR MAINTENANCE AND MANAGEMENT

Following establishment of the Standard Specifications for Concrete Structures Maintenance in 2001, various maintenance and management standards for roads, railways and other lifeline facilities are currently being established and revised. Among these efforts, the basic approach in the railway sector is being organized according to maintenance and management standards. This approach indicates required levels using expressions of performance based on a performance verification concept. In the visual inspection stage, performance is judged to be satisfied if there are no changes or only slight changes. When a problem is found, that is to say when performance is judged not to have been satisfied by visual inspection, a detailed inspection is performed and the yield strength etc. is calculated quantitatively. In this manner, appropriate management of performance requirements is realized by specific verification.

The issues when considering the future deployment of information technology, automation and robotization in the maintenance and management of underground lifeline structures are to determine how these systems should judge whether appropriately determined performance levels are satisfied, and what type of inspection system verification functions should be included. The setting of performance requirements is currently left to each lifeline operator.

Therefore, each lifeline operator should accumulate and utilize sufficient management data for maintenance and management in the same manner as for performance level settings during construction, verify differences from the values set during construction, and set appropriate performance requirements.

In addition, when the same degraded structures are evaluated by different robot systems or technicians using current information and automation technology, the evaluation results (output) sometimes differ greatly, so the evaluation accuracy must be increased. Sufficient calibration is needed to reduce the evaluation result variance and obtain proper evaluation results. This calibration should not focus on individual components such as robots, evaluation systems or personnel. Instead, a standardized system for verifying the overall system at the appropriate times is needed.

6. CONCLUSION

Robots generally perform only up to the primary judgment level at present, but the ideal case is ultimately for robots to also perform up to the secondary judgment level and even beyond, to the final judgment. In consideration of increased information sharing between lifeline operators in the future as well as differences in performance requirements and differing judgment thresholds by robots and humans, discussion is needed on the topic of the degree to which robotization should be used for judgments.

In addition, robots and other specifications that are the subject of technical development should be set using definite terms in accordance with the required measurement accuracy and resolution, etc. As mentioned above, although structural performance requirement settings differ for each lifeline operator, these setting values are extremely important, and efforts should be made to clarify development targets by setting limit values (thresholds) and other specific values using engineering expressions.

In the future, expansion to applied technologies and new joint development can be considered such as the nationwide deployment of railway inspection trains, or in case of pipeline facilities the sharing of technology and existing technical information by electric, communi-cations, city water, sewer and gas operators. It is greatly hoped that movements to standardize hardware aspects such as inspection tools and software aspects such as judgment criterion and management systems will appear from amongst these efforts.

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