State of the art and future prospect of maintenance and operation of road tunnel

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Abstract: In Japan, road tunnels have increased in both total length and number, and there are some tunnels still in service that were completed more than 50 years ago. In order to maintain such tunnels efficiently with decreasing public funds, deformation of tunnels should be detected at an early stage, and appropriate measures taken at the right time. This paper describes the present status, problems, and future prospects for road tunnel maintenance in Japan.

Keywords: maintenance, repair, inspection, deformation

1. Introduction

Road tunnels in Japan have increased every year in both total length and number. There are approximately 9,000 tunnels in Japan with a total length of about 3,100 km (as of April 2005, Figure 1), some of which were completed more than 50 years ago and are still in service. As the service life of tunnels has been extended, the number of old tunnels and those suffering deformation of the lining concrete due to deterioration of materials, etc. has increased. To efficiently maintain tunnels in spite of decreasing public funds, deformation of tunnels should be detected at an early stage, and appropriate measures taken when required. This paper describes the present status, problems, and future prospects for road tunnel maintenance in Japan.

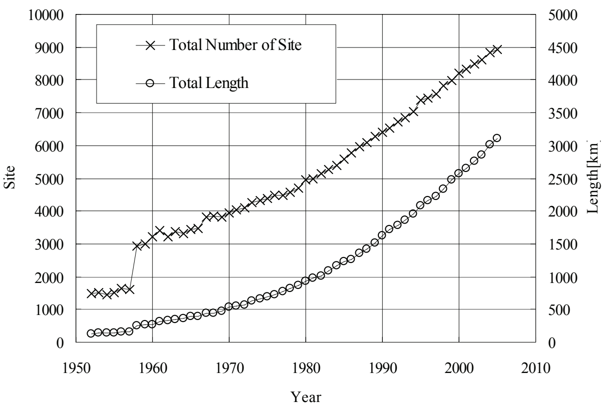


Figure 1 Changes in the number and total length of road tunnels

2. Present status and issues of maintaining road tunnels

Today, road tunnels in Japan are maintained based on the Manual for Maintaining Road Tunnels[1)] (Japan Road Association, December 1993), and the Guideline for Periodical Inspection of Road Tunnels (draft)[2)] (National Highway Division, Road Bureau, Ministry of Land, Infrastructure and Transport, April 2002), which stipulates methods for detecting exfoliation of lining concrete and other deformation that may cause a risk to users even without failure, such as executing periodical close visual inspection and hammering tests and standardizing inspection reports.

As shown in Figure 2, road tunnel maintenance involves three procedures: 1) inspecting and examining the tunnels to detect deformation, checking their soundness and collecting references on countermeasures, 2) evaluating soundness to understand the causes of detected deformation and judge whether countermeasures for the deformation are needed, and 3) repairing and reinforcing using suitable methods according to the deformation. The technologies used and issues of each procedure are described below.

2.1 Inspection and examination technologies

The majority of deformation in existing tunnels is accompanied by cracks, loosening and/or exfoliation of lining concrete. Thus, tunnels are inspected for such signs. Conventionally, tunnel linings were visually checked for cracks either by walking or using a boom lift, and any cracks found were sketched. However, this method requires a lane to be closed, is time-consuming, cannot easily detect cracks high up such as on arches, and suffers from subjectivity in recording the cracks. Especially, the expanded diagram of cracks, which records the states of cracks, loosening and exfoliation, must be as objective as possible since it provides information on which subsequent operations are based, such as understanding the causes and deciding methods for assessing soundness and repairing and reinforcing the lining, as well as important indices for subsequent management such as the progress of cracks.

Thus, advanced technologies have been developed to solve these problems and are recently used in the tunnels of expressways and some highways. For example, photographs of the surface of a tunnel lining are taken by driving a vehicle equipped with a laser beam device and CCD cameras inside the tunnel, and the captured images are processed by a system that automatically prepares expanded diagrams that record cracks (Photograph 1). Loosening and

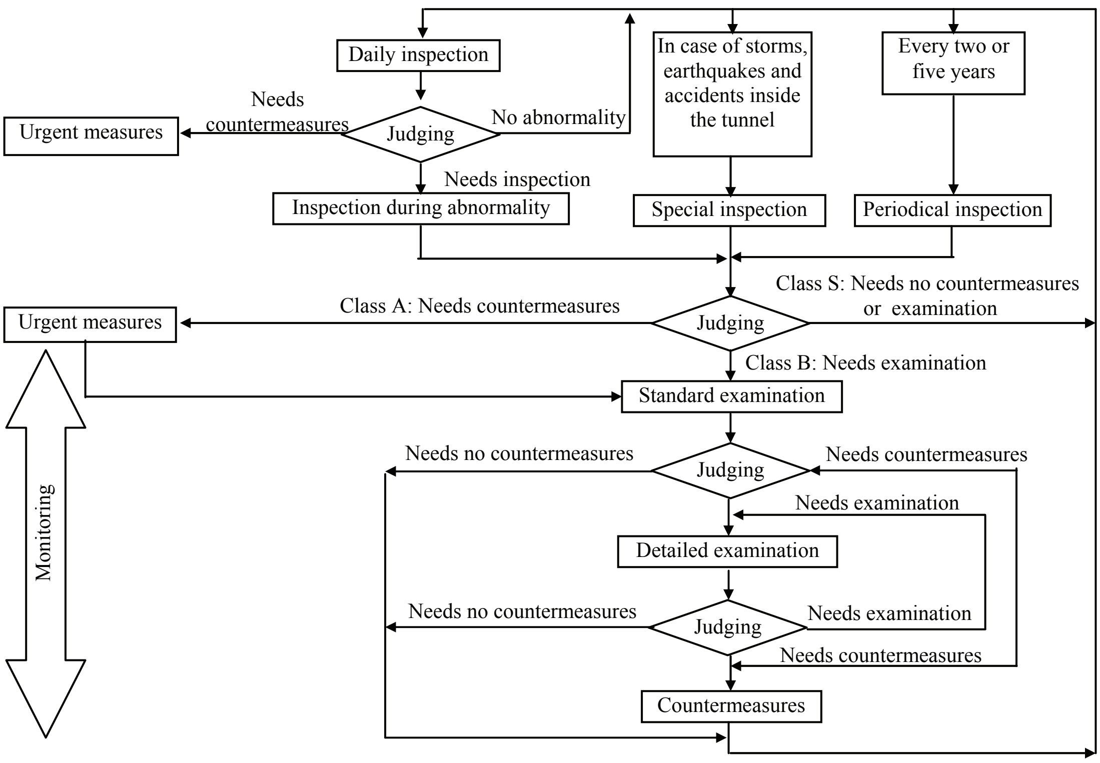
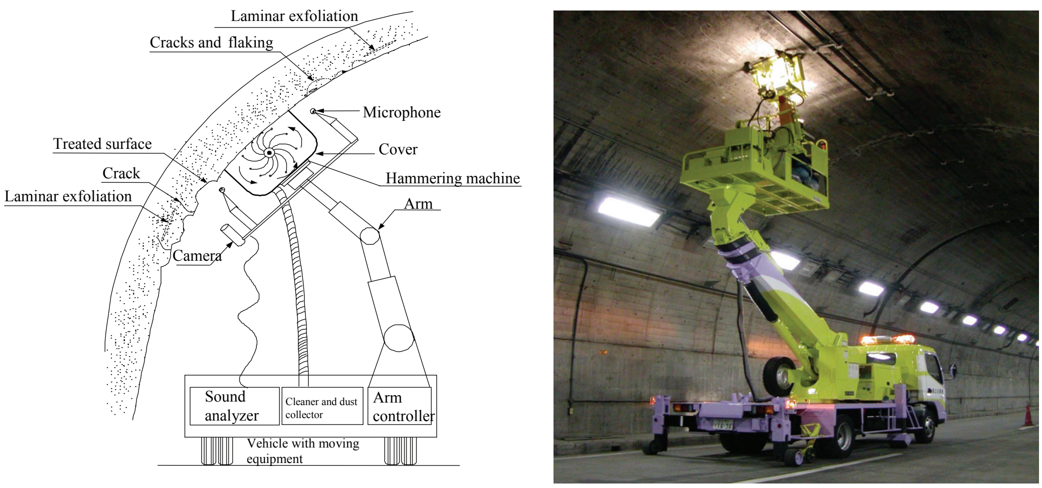


Figure 2 Flow of inspecting and investigating road tunnels

exfoliation of lining concrete have been detected mainly by hammering tests performed by workmen on boom lifts, but this method suffers the same problems as crack detection. Several feasible methods have been developed, including mechanically detecting loosening of lining concrete using thermal infrared rays, detecting loosening of the concrete inside linings and honeycombs using ultrasonic waves, which could be detected only by hammering tests, and mechanically detecting loosening using hammering sounds as shown in Photograph 2. The inspection results are used to examine concrete linings for voids behind the lining and the thickness of the concrete. Vehicles equipped with

Photograph 1 Checking for cracks using a laser beam[3)]



Machine outline Practical machine

Photograph 2 Mechanized hammering tester[4)] electromagnetic-wave probes have been driven to mechanically and linearly measure the sizes of voids and lining thickness. However, this method requires sophisticated and specialized knowledge to interpret the results, and measurement is difficult when there are steel bars and sections of high water content in the lining. Thus, a device is being developed for examining the states of linings, voids and the ground by drilling small holes into the lining concrete (Photograph 3).

Photograph 3 Checking for voids behind lining by drilling holes[5)]

2.2 Technologies for evaluating soundness

The soundness of road tunnels is evaluated in terms of deformation, urgency of taking countermeasures, safety of users and vehicles, structural safety, and effects of maintenance works, and is classified into the four classes shown in Table 1. The soundness is comprehensively evaluated based on deformation of concrete lining detected during inspection, such as cracks, loosening and exfoliation, available references such as construction records, and data from other surveys on the topography and geology near the tunnel, the strength of the lining, and deformation of the tunnel, which are performed when necessary. Technologies and automatic systems are needed to objectively identify the causes of deformation and judge whether measures need to be taken by comprehensively analyzing inspection and examination results, such as the deformation, movement, and settlement speed of lining concrete and the progress, width, length, and shapes of cracks.

Table 1 Classes of tunnel soundness[1)]

Class	Contents
3A	Seriously deformed. Urgent measures are needed since users and vehicles are at risk.
2A	Deformed. Urgent measures are needed since the deformation may progress and endanger users and vehicles.
A	Deformed. Close monitoring and systematic measures are needed since the deformation may endanger users and vehicles in future.
B	Not deformed or slightly deformed. The deformation has no effect on users and vehicles, but the tunnel needs to be monitored.

2.3 Technologies for taking measures

Measures for deformed tunnel linings are broadly classified into: 1) repairing the lining to prevent the deformation from affecting users and vehicles, which does not improve the bearing capacity of the lining, and 2) reinforcing the lining to improve the bearing capacity and stability of the tunnel structure (Table 2). When the deformation is caused by external forces such as earth pressure, reinforcement is needed to increase the strength. However, deformation in most tunnels is caused by internal factors such as deterioration due to aging and drying shrinkage. Thus, few tunnels need reinforcement, and most are treated by repairing.

Repair works typically involve preventing the lining concrete from flaking and leaking water from dropping onto pedestrian paths and the road surface. Diverse repair methods using various kinds of materials have been developed, but no specific methods for choosing appropriate methods and materials according to the condition of deformation have been established. In many tunnels, repaired sections need to be repaired again due to deterioration of the repair agents, and so more durable repair technologies need to be developed.

Typical reinforcement works include back filling, installing rock bolts, involutional reinforcement, inner lining reinforcement, and centering reinforcement. However, most road tunnels have little free space inside, thus limiting the types of works that can be used. Effective methods for improving bearing capacity in small spaces need to be developed, and so involutional reinforcement that uses fiber-reinforced strong mortar is being developed. Since reinforcement works aim to improve the bearing capacity of the lining, the present and target bearing capacities of the tunnel must be correctly evaluated to design the works. However, it is difficult to evaluate quantitatively the external force and distribution on the deformed tunnel, and most reinforcement works are designed based on the experience of experts and works in the past; design methods based on structural calculations need to be established.

3. Maintenance of tunnels in future

Tunnels have been usually maintained by inspecting and examining tunnels, evaluating the soundness of deformations detected, and treating the deformations when necessary. The number of old tunnels will increase and so will the costs for maintaining the tunnels.

To efficiently maintain tunnels with limited funds, long-term approaches should be used, such as leveling the period of renovation and minimizing the expenses for taking measures. The series of works consisting of designing, executing, inspecting, examining, evaluating, and treating, which were treated respectively, should be integrated based on the following points:

Table 2 Repair and reinforcement measures for tunnels
○: major effect, Δ: additional effect

Class	Work	Effects		
		External force	Prevent flaking	Cut off water
Removing loosened sections	Chipping		○	
Treating the chipped surface	Installation of surface repair material		○	
Restoring the unity of the lining	Grouting cracks		○	
Supporting using supports	Wire nets		○	
	Stiffening plates		○	
	Centering reinforcement	○	○	
Reinforcing the inner surface of the lining	Inner reinforcement	○	△	
	Inner concrete	○	△	
Preventing water leakage	Linear cut-off			○
	Planar cut-off			○
	Grouting	△Water pressure Frost pressure		○
	Lowering of water level			○
Filling voids behind the lining	Back filling	○		
Supporting the natural ground	Rock bolts	○	△	
Reconstructing the lining	Partial reconstruction	○	△	△
	Entire reconstruction	○	△	△

1) Tunnels should be designed so as to reduce the life cycle cost, such as by prolonging the service life of the tunnels.
2) Tunnels should be constructed by strictly controlling the quality in order to prevent deformation in future. The conditions at the time of completion should be recorded, and the records should be stored.
3) Tunnels should be inspected, examined and evaluated by establishing inspection items and intervals based on engineering and statistical foundations, taking objective records of quantitative data and using consistent evaluation criteria.
4) Tunnels should be treated by establishing methods for determining the optimum method by considering the effects on traffic during the construction in terms of various measures and construction time.

The entire history of tunnel designing, construction, inspection, examination, and treatment should be recorded and compiled in a database, which should be constantly renewed and utilized.

Measures against deformation should be executed by objectively understanding and evaluating the soundness of the tunnel, predicting the mid-term to long-term soundness, estimating the cost of maintaining the tunnel, which is the life-cycle cost, and deciding the optimum measures and optimum time in order to make best use the limited funds. In other words, the concept of asset management should be used to systematically and efficiently maintain tunnels.
Technologies need to be developed and experts should be trained in order to promote these approaches. Technologies that need to be developed include those for controlling the quality during construction, automated and efficient inspection, examination and recording methods, those involved in quantitative and time-sequential evaluation of data for predicting soundness, methods for predicting deterioration, measures for improving the durability of tunnels and prolonging their life, and technologies for mitigating the effects of repair and reinforcement works on traffic and society. Experts should be trained to a certain level of knowledge and experience on all stages of designing, construction, inspection, examination, soundness evaluation, and taking measures, and should also have a thorough knowledge of maintenance works conducted at the sites.

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