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Development of Performance-Based Tunnel Evaluation Methodology and Performance Evaluation of Existing Railway Tunnels

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ABSTRACT

The concept of performance-based design, which mainly focuses on mechanical performance, has become the international standard, as in the case for ISO. The standardization of tunnel design has not been achieved because it requires integration of separate specialized fields, such as geotechnical engineering, structural engineering and concrete engineering. It is also required to clarify performance-based criteria for tunnel structures to suit specific use purposes (objectives), establish the concept of survey, planning, design, construction and maintenance based on such criteria, and develop proper management systems for operation and maintenance to suit specific tunnel use purposes. To this end, it is vital to develop a methodology for evaluating and verifying the performance of existing tunnels. This paper presents a new concept of performance requirements for tunnel structures and describes the method of quantitatively evaluating the total performance of existing tunnels in relation to the required performance, assuming the total performance to be based on the Analysis Hierarchy Process.

Keywords: Tunnel; Performance Criterion; Life Cycle Design; Performance-Based Design; Asset Management; Maintenance; Analysis Hierarchy Process

1. Introduction

In Japan, the development of technological (design) criteria for individual built facilities, such as roads, rivers, ports and buildings have conventionally been based on the historical backgrounds (experience), culture and objectives of each facility. In some cases, this individual development approach created considerable discrepancies among technological criteria when compared to each other. In other countries on the other hand, while the individual design approach used to be the main practice as well, ISO2394 [1] and Eurocode 0 have been issued in recent years as comprehensive design codes that specify the basics and system of structure design. Following this trend, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan formulated the "Basis of Structural Design for Buildings and Public Works [2]" in 2002. The MLIT National Institute for Land and Infrastructure Management felt it was necessary to set out principles and define terminology for technological criteria development for code writers, and assigned Japan Society for Civil Engineering (JSCE) to carry out research. In March 2003, JSCE (Basic Research Committee for Formulation of Comprehensive Design Code) compiled "Code PLATFORM ver.1.0 [3]". Comprehensive design codes represent a new design concept called "performance-based design," which largely focuses on the discipline of structural design. Based on this new concept, existing design codes are now being revised in such areas as concrete, seismic engineering and geotechnical engineering. The Japanese Geotechnical Society has already issued a design code for foundation structures called "Comprehensive Foundation Design Code [4]". This way, the performance-requirements based design system is now being established in Japan as part of the efforts to standardize structural design.

However, the standardization of tunnel design has not been achieved because it requires integration of separate specialized fields, such as geotechnical engineering, structural engineering and concrete engineering.

Therefore, it is necessary to understand the trend of international standardization and formulate comprehendsive design codes or specific design codes for tunnel structures in consideration for the nation's expertise in underground structure design and valuable traditional technologies.

On the other hand, it should be noted that the existing structures have been undergoing deterioration almost at the same time, notably since the turning of the century. **Figure 1** shows a history of tunnel development in Japan denoted by tunnel length and construction year, featuring railway tunnels as an example. It has been pointed out that today's infrastructure development should place importance on technologies that provide better maintenance of existing structures to prolong their service life, in addition to new structure development technologies. In other words, there is a need to shift our behavior focus from new built environment development (monozukuri), *i.e.* building new structures as part of the infrastructure to "system development," *i.e.* using existing structures in a sensible way in consideration for the specific mode of service assigned to each structure. This is also the case for the field of underground structures; structure design professionals are now required to shift design concept for the better utilization of underground space in the future. The current focus on conventional design technologies, which aim to ensure structural safety based on the notion of new built environment development (monozukuri), should be shifted to the development of a new design approach called the "Life Cycle Design Method [6]", which involves close examination of functions of structures to better use the existing built environment and is employed throughout service life including the maintenance phase. Tunnels and other underground structures are different from ground structures in that they can not simply be abandoned once constructed; if an underground space becomes unused due to some defects and abandoned, certain disturbance in the surrounding ground may be caused in the long run, such as in the form of subsidence and deformation of foundations of adjacent structures.

To serve as the international standard for the maintenance of existing structures, ISO13822 [7] was issued. Based on the concept of structure reliability and risk management, it sets forth the basic concepts of evaluating existing structures (e.g. buildings and bridges) by classifying them into the following: 1) Expected modification of use purpose, expected repairs, and prolongation of design service life; 2) examination of reliability as required by the administrator and insurance company; 3) time-dependent deterioration caused by loading and actions; and 4) damages, etc. caused by accidental actions. The code, however, does not describe how to evaluate the functions and service performance of a structure to ensure its original objectives.

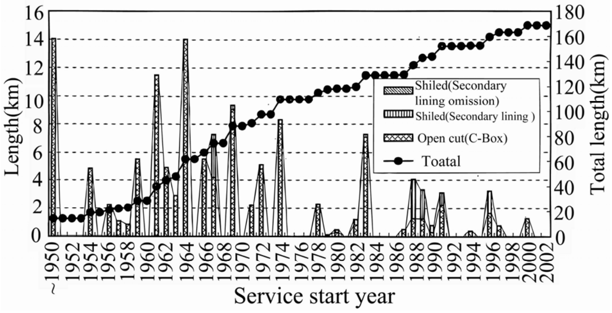


Figure 1. Change in the railway tunnel length in Tokyo Metro [5].

Considering the international trend of standardization of tunnel structures that focuses on performance criteria as described above, this paper first reestablishes the performance requirements for tunnel structures proposed by JSCE, and discusses the concepts of performance requirements for existing tunnels in their maintenance phase and management strategies based on them [8,9]. The paper goes on to taking existing road tunnels as the example to describe the method of calculating the Total Performance Index designed to comprehensively evaluate their actual performance at the maintenance phase.

2. Performance Requirements [10] for Tunnel Structures Based on Specific Objectives

2.1. Concept of Performance Requirements

The performance requirements for tunnels, which are used for various purposes such as roads, railways, water supply and sewage systems, power supply, and communication, are designated individually to suit their specific objectives within the basic performance requirements. It should be noted that the concept of structural design of tunnel structures is significantly varied among construction methods [11], and thus the specific performance requirements for a tunnel structure should be developed with careful consideration of its construction method. In the mountain tunnel construction method employed for considerably strong and highly self-supporting ground, the main structural system that provides a space to construct a tunnel is the natural ground itself, and thus the purpose of structural design is to maximize its natural capacity and provide manmade support. On the other hand, the shielding method, typically urban tunneling construction, is employed where hardly any self-support capacity is expected. The main structural system here should be manmade. This is one of the factors that make the structural design of tunnels difficult. It is thus necessary to identify major factors that differ between tunneling methods. **Table 1** shows an example of factors that differ between the mountain and shield tunneling methods (for railway tunnels). When closely examining the required performance, these differences among tunneling methods should be taken into account.

2.2. Development of Performance Requirement

Specific performance requirements are developed here based on the basic ones. **Table 2** shows an example of identification of performance requirements for road tunnels constructed in the mountain tunneling method. The primary categories for required performance consist of the basic performance requirements and their descriptions. Secondary categories and subcategories consist of phenomena used for evaluating the primary categories and for further evaluating the secondary categories, respectively. This means the performance given by the primary categories is satisfied if all the subcategory phenomena are satisfied. It should be noted here that the subcategory phenomena consist of those that can directly be evaluated and those that cannot, and that some of them allow quantitative evaluation while others only allow qualitative evaluation due to obscurity. To carry out the detailed evaluation of individual performance, specific verification indexes should be developed for all phases of planning, design, construction, and maintenance (service) to evaluate the actual performance. Focusing on the maintenance phase, the sections below describe the concept of evaluation of actual performance and management concept based on performance criteria.

Table 1. Differences in factors between tunneling methods (for railway tunnels).

	Mountain tunneling	Shield tunneling
Construction site	Mainly mountainous regions and suburbs (frost inside the tunnel considered)	Mainly urban areas (frost inside the tunnel Not considered)
Portal	Entrance exists in principle	No entrance in principle
Construction load	Not necessary to consider construction load in general	May be disturbed by construction load Require measures for stabilizing the cutting face during construction
Lining system	The lining concrete does not serve as a structural member in general (Plain concrete system in principle)	The lining (segment) serves as a structural member (Reinforced concrete, steel structure, and composite system)
Roadbed	Roadbed may be disturbed where there is no invert, affecting the running stability	The closure system consisting of segments creates no disturbance

Table 2. Performance requirements fragmented (shield tunneling method/railway).

	Primary categories	Secondary categories	Subcategories
To ensure required traffic volume safety and smoothly during the required service period	User safety	Ensure user safety	Ensure safe driving
			Not directly threatening to user safety
			Ensure safe evacuation of users in emergency
	User usability	Ensure user comfort	Ensure ride quality
			Not making users uncomfortable or feel insecure
	Structural stability	Ensure stability against assumed load	Ensure stability against continuous load
			Provide necessary seismic performance
			Ensure stability against assumed load change
			Ensure stability against assumed construction load
	Durability	Ensure durability against assumed deterioration factors	High corrosion resistance
			No deterioration in concrete
			Provide high water tightness
	Administrator usability	Ensure proper utilization by administrator	Satisfy required demands (traffic capacity)
			Ensure trains can be operated in a stable manner (at the fixed time)
			Ensure operation of auxiliary facilities for regular train operation
	Maintainability	Ensure provision of proper maintenance	Ensure safe & easy inspection
			Ensure safe & easy repair
	Impact on surroundings	Minimize impact on surroundings	Minor impacts on ground water
			Minor impacts on surrounding grounds
			Minor impacts on surrounding real estates

3. Performance Criteria Based Performance Criteria [12]

3.1. Concept of Management Based on Performance Criteria

"Performance criteria based management" means a strategic management in consideration of the lifecycle of the tunnel through determination of evaluation indexes based on performance requirements at all phases of planning, survey, design, construction, and maintenance and through execution of performance verification based on such evaluation indexes. **Figure 2** shows the management procedure based on performance criteria.

The basic concept of performance-criteria based management is to evaluate and verify the actual performance based on the same performance requirements for each phase of planning and design, construction, and maintenance (service) according to the use purpose (objectives) of a tunnel. To describe this concept, the maintenance phase of existing tunnel structures is highlighted here.

Conventionally, in the maintenance of existing tunnel structures, inspection, evaluation and remedial measures have been carried out or devised by setting individual criteria [13]. Such maintenance basically focuses on the development of remedies for individual troubles, and does not take the procedure of identifying the performance criteria, evaluating/verifying the actual performance, and devising necessary remedies. In practice, future measures are only considered on an as-needed basis within the limited budgetary restrictions.

On the other hand, performance-criteria based management is largely different in that it estimates future conditions based on the evaluation/verification of actual current performance, and makes decisions on the timing and method of remedies by employing the life cycle cost optimization approach based on the strategies of administrator. It should be noted, however, that the evaluation/verification items used in the evaluation/verification of actual performance are not very different from conventional inspection items; each inspection item serves as a performance verification index or alternative performance verification index used for evaluating or verifying the required performance.

Figure 3 shows only the basic principles of evaluating /verifying the actual performance, as compared to the basic performance requirements. The figure shows some examples of performance verification indexes that allow quantitative evaluation, corresponding to the basic performance requirements. Some performance verification indexes are designed to evaluate by employing an analysis or statistical approach based on the yield strength of members, cracking and other data obtained in tunnel inspection. As mentioned before, some indexes allow quantitative evaluation and some do not. It is thus practical to base comprehensive performance verification on a rating method using verification criteria consisting of five or so grades. In so doing, it becomes possible to weigh the priority of each performance requirement in terms of such conditions of target tunnel structure as use purpose, tunneling method, owner strategies and serviceability. For performance verification indexes that are difficult to evaluate quantitatively, the Analytic Hierarchy Process and other appropriate approaches, which will be mentioned in later sections, are employed to manage quantitative evaluation. The Total Performance Index is obtained by performing evaluation /verification of actual

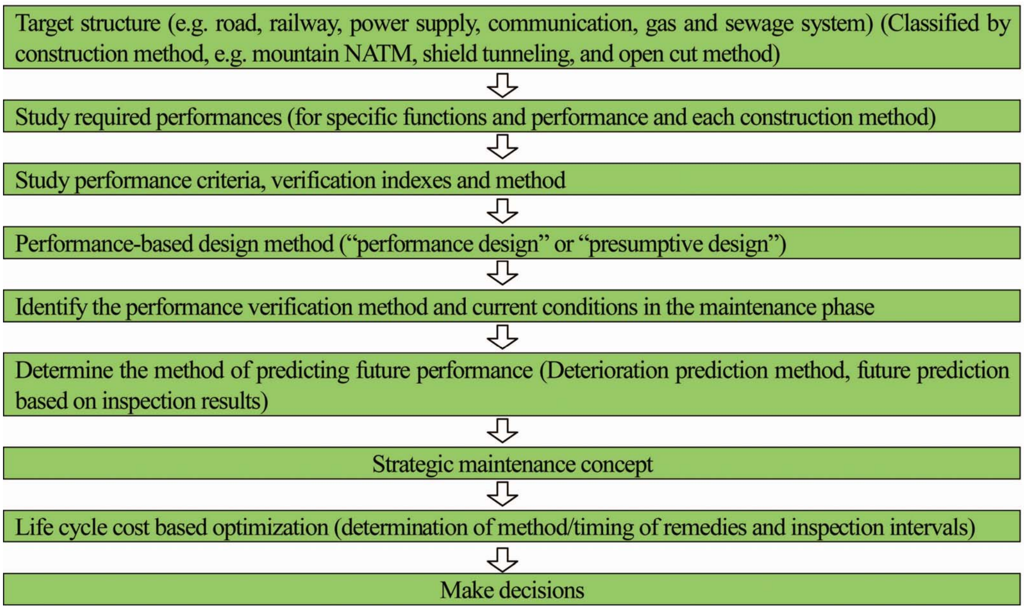
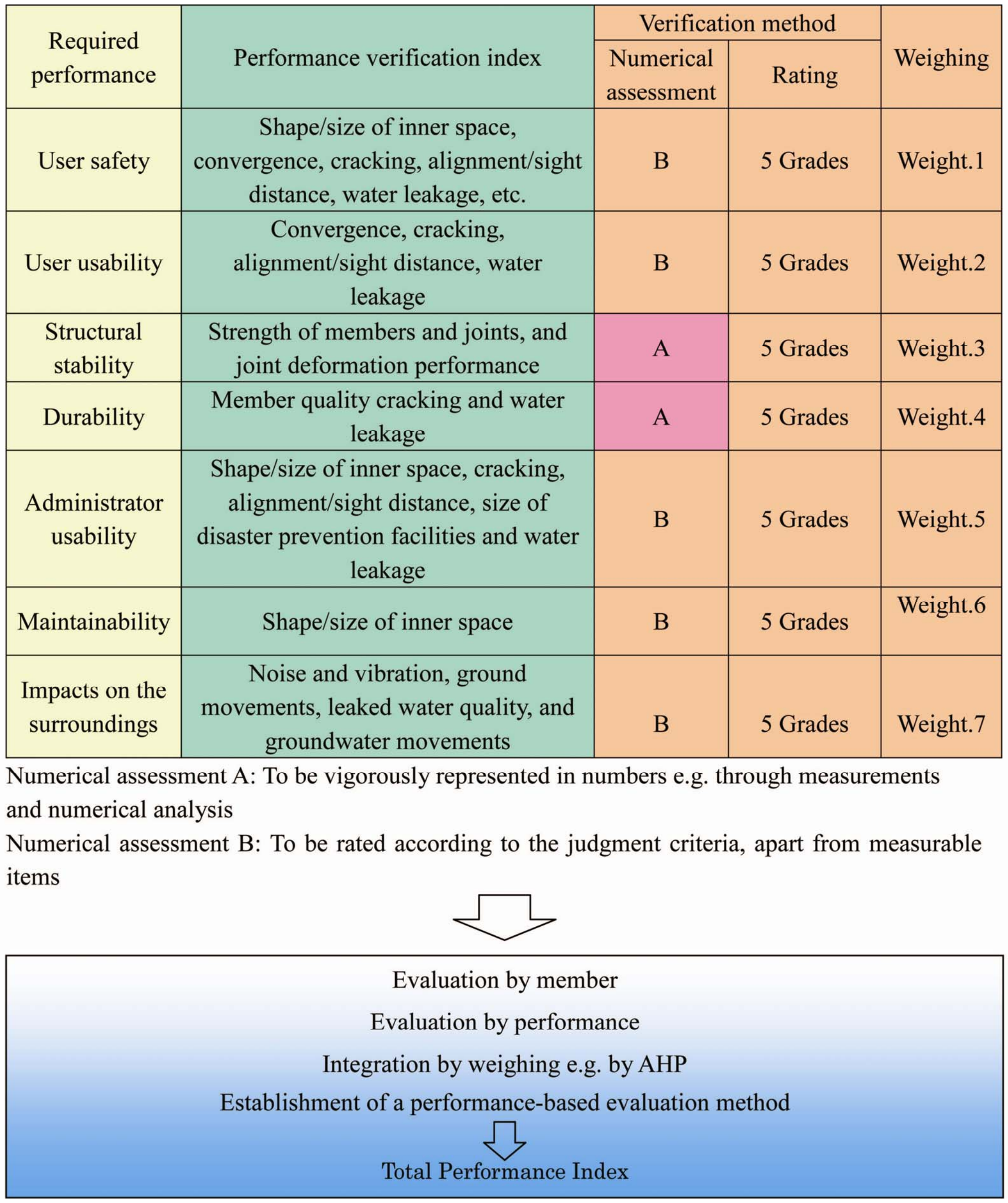


Figure 2. Procedure for performance-based management.



Required performance	Performance verification index	Verification method		Weighing
		Numerical assessment	Rating	
User safety	Shape/size of inner space, convergence, cracking, alignment/sight distance, water leakage, etc.	B	5 Grades	Weight.1
User usability	Convergence, cracking, alignment/sight distance, water leakage	B	5 Grades	Weight.2
Structural stability	Strength of members and joints, and joint deformation performance	A	5 Grades	Weight.3
Durability	Member quality cracking and water leakage	A	5 Grades	Weight.4
Administrator usability	Shape/size of inner space, cracking, alignment/sight distance, size of disaster prevention facilities and water leakage	B	5 Grades	Weight.5
Maintainability	Shape/size of inner space	B	5 Grades	Weight.6
Impacts on the surroundings	Noise and vibration, ground movements, leaked water quality, and groundwater movements	B	5 Grades	Weight.7

Numerical assessment A: To be vigorously represented in numbers e.g. through measurements and numerical analysis

Numerical assessment B: To be rated according to the judgment criteria, apart from measurable items

Evaluation by member

Evaluation by performance

Integration by weighing e.g. by AHP

Establishment of a performance-based evaluation method

Total Performance Index

Figure 3. Concept of evaluation/verification method for current performance corresponding to the required performance.

performance in the manner described above for each tunnel or span. This way, integrated management of the actual performance of tunnel structures becomes possible.

3.2. Prediction of Future Conditions

In performance-based management, it is required to ensure tunnel performance with minimum costs during the target service period or the actual service period that extends beyond the former. This concept is presented in **Figure 4**. To ensure the required performance in accordance with a reduction in the actual performance level, it is necessary to take measures for preventive maintenance or preventive management [14]. However, evaluation of the actual performance often involves considerable uncertainties because, as mentioned before, tunnel structures are constructed in highly uncertain ground.

That means even where the average actual performance meets performance requirements, the required performance may not be achieved when the damage probability shown in **Figure 5** is taken into account. In such cases, emergency remedies are required. Thus, the proper procedure for tunnel structures should be to frequently perform inspection to check the actual performance and ensure preventive management that provides repairs before the important actual performance, even if it is at the local level, becomes short of the required level [15]. It should also be noted that the inspection frequency con-

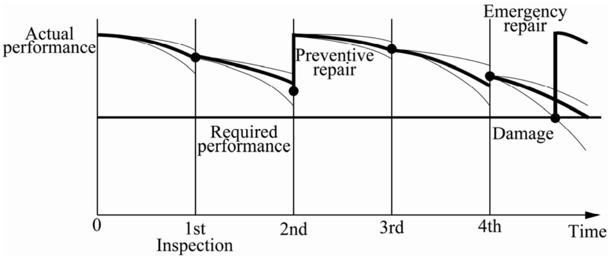


Figure 4. Concept of maintenance optimization strategy.

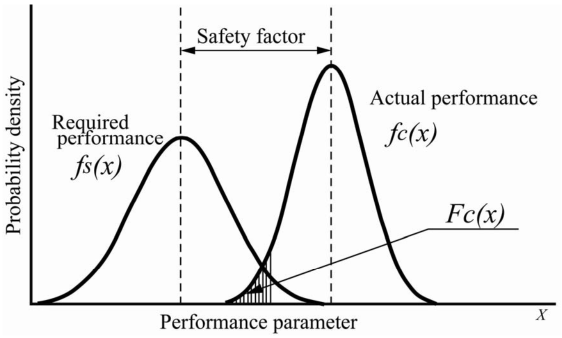


Figure 5. Concept of damage probability.

siderably affects the accuracy of prediction of future conditions based on the current conditions. **Figure 6** shows the concept of prediction accuracy in relation to inspection frequency. In the case of road tunnels for example, inspections are carried out almost every five years (every two years in more frequent cases) in general. An extremely low inspection frequency increases uncertainties. A reduction in the prediction accuracy is directly reflected in preventive management policies; it is thus necessary to properly determine the inspection frequency according to the serviceability of the tunnel.

3.3. Tunnel Serviceability

The serviceability of a tunnel structure depends on such factors as the use purpose, social functions, administrator's operation size, and financial resources, and is hence affected by the social roles and importance of the tunnel. It is thus necessary to determine the serviceability of each tunnel and consider a suitable management method. **Table 3** shows the service levels derived from serviceability and corresponding basic methods of management. The service levels are from "low" to "high". Tunnels categorized as "high" are defined as those such as expressways in urban areas having particularly significant social roles, which require detailed inspections and continuous monitoring at the maintenance phase and evaluation/verification of actual performance using indexes that allow numerical expression to a maximum extent. Tunnels categorized as "low", on the other hand, are necessary for the society but are not very busy or subject to particularly tight budgetary restrictions by the administrator. Such differences in serviceability should also be taken into consideration in the management method.

4. Evaluation/Verification of Actual Performance of Tunnels by Rating

4.1. Concept of Evaluation/Verification of Actual Performance of Tunnels by Rating [15]

The procedure for evaluating/verifying the actual performance by rating consists of identification of evaluation/verification indexes or alternative indexes for each item of performance requirements; determination of standard performance values in five grades for each index; calculation of actual performance values; integrate the values to obtain the Total Performance Index; and perform evaluation/verification using the Total Performance Index. **Tables 4(a)** and **4(b)** show an example of relationship between performance requirement items and performance verification/alternative indexes derived from past design documents and inspections (shield tunneling/railway tunnels).

This approach allows integrated quantitative evaluation of changes with time in the actual performance of individual tunnels and is effective in formulating mid- to long-term strategies. Tunnel structures required to provide a high level of serviceability need in-depth study of the probability of local damage and performance deterioration, and more detailed evaluation/verification through an increased frequency of inspection, continuous monitoring of locations having trouble risk, and calculations and statistical analysis using the inspection data obtained.

4.2. Evaluation of Actual Performance by the Analytic Hierarchy Process [16]

This section explains evaluation of the actual perform-

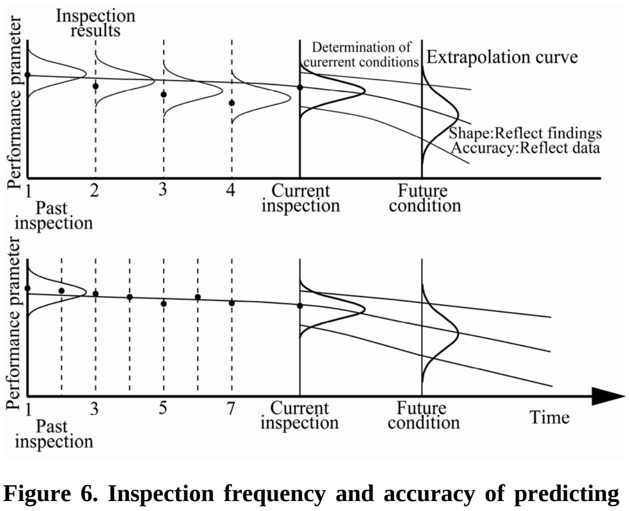


Figure 6. Inspection frequency and accuracy of predicting future conditions.

Table 3. Concept of serviceability-based management.

Service level	Low Low traffic volume/ Deterioration not progressed/Mountainous region	High High traffic volume/ Deterioration highly progressed/ Important route/ Emergency transportation route
Performance criteria	User safety/Usability/Structural stability/Durability/Administrator usability/ Maintainability/ Impacts on the surroundings	
Performance verification index	Select indexes that allow numerical expression to a maximum extent	
Design method	Presumptive design	Performance design
Monitoring	Inspection + Simple measurements as needed	Inspection + Measurements
Soundness evaluation method	Rating in principle	Performance-based evaluation method
Performance verification method at maintenance phase	Rating based on results of inspection (+ simple measurements)	Verification using numerical indexes, mainly derived from measurements
Prediction method for future conditions	Deterministic prediction (residual strength)	Prediction with uncertainties considered, e.g. through probabilistic approach
Decision making through LCC optimization	Life cycle costs assuming inspections and repairs	Perform optimization of life cycle costs

ance of a tunnel by the Analytic Hierarchy Process ("AHP") using lining data obtained from daily and regular inspections (observation/measurement data inside the tunnel). The Total Performance Index, TPI per tunnel span is given by

$$TPI = \sum_{i=1}^{N} P_i \cdot C_i \qquad (1)$$

where score given by the performance evaluation criteria, weighing factor derived from evaluation by advanced engineers, and the number of required performance evaluation item.

Table 5 shows an example of weighing by evaluation by advanced engineers engaging in the design, construction and management of tunnels, citing railway tunnels constructed in the shield tunneling method.

By going through the procedure described above, each evaluation value (TPI) for each construction span is rep-resented numerically for all performance requirements in an integrated way. The probability distributions that represent the route and a set of TPI per section give total generalized evaluation of actual performance of the target route and section. The performance evaluation criteria are defined in five grades for each required performance subcategory, *i.e.* 1) Undergoing no performance deterioration or assumed to be so; 2) Undergoing slight performance deterioration; 3) Undergoing performance deterioration; 4) Undergoing remarkable performance deterioration; and 5) In need of immediate remedy), which are scored 1, 3, 5, 7, and 15, respectively. **Tables 6(a)** and **6(b)** show examples of performance evaluation criteria for railway tunnels constructed in the shield tunneling method.

4.3. AHP-Based Evaluation of Actual Performance and Current Inspection Evaluation [16]

The actual performance is evaluated in AHP using the inspection results for railway tunnels constructed in the shield tunneling method. Two types of single track shield tunnels, *i.e.* a small-to-medium box segment section.

Rating tunnels using performance evaluation criteria based on the interior view of lining drawn from the results of inspection on 350 rings of box segment section, TPI is calculated using Equation (1). The results are compared against those of existing inspection evaluation implemented [17] (hereinafter, the "existing method"), the validity of AHP-based quantitative performance evaluation method is examined. According to the existing method, the soundness of tunnels is assessed in relation to: a) Users (safety and usability); b) Structural systems (load-bearing capacity and durability); c) Administrator (maintenance); and d) Progressiveness and (common) characteristics of disturbance. Judgment criteria are defined for each of the following cases: 1) Disturbance is caused by external force (cracking); 2) By material deterioration; and 3) By water leakage. The soundness of tunnels is evaluated by the judgment categories shown in **Table 7**, and then the timing of remedies is determined. The probability distributions of a set of TPI for each judgment result by the existing method are shown in **Figure 7**.

In the case of box segment, the average values of TPI are 1.006, 1.074, 1.335, and 2.446 for Judgment Category S, C, B and A, respectively.

It is thus indicated that TPI more or less represents the total results obtained in the existing method. These re-

Table 4(a). Performance requirements fragmented (shield tunneling method/railway).

Performance requirements				Performance evaluation items	
Primary categories		Secondary categories	Subcategories		
User safety	Ensure user safety	Ensure safe driving	Ensure good railway track alignment	1	Amount of track displacement (any impacts on driving safety)
			Ensure safe driving	2	Amount of displacement in tunnel alignment
				3	Conditions of any cracking or loosening of segments/secondary lining and of any corrosion, etc. in rebars in a region(s) that may threaten driving safety (e.g. directly above the tracks)
				4	Exposure of tracks to leaked water
			Ensure proper construction gauge	5	Leeway outside the construction gauge
		Not directly threatening to user safety	No flaking occurred	6	Conditions of any cracking or loosening of segments/secondary lining and of any corrosion, etc. in reinforcement\cement in a region(s) that may threaten driving safety (e.g. directly above the tracks)
			No water leakage occurred	7	Conditions of any water leakage in a region(s) that may threaten driving safety (e.g. platforms/concourse ceiling)
		Ensure safe evacuation of users in emergency	Allow proper layout/usage of disaster prevention equipment and provide evacuation routes for users	8	Leeway outside the construction gauge (clearance from disaster prevention equipment and room for evacuation)
User usability	Ensure user comfort	Ensure ride quality	Ensure good alignment and avoid any tunnel deformation that affects riding comfort	9	Amount of track displacement (any impacts on riding comfort)
		Not making users uncomfortable or feel insecure	No water leakage/cracking that makes users uncomfortable or feel insecure is observed	10	Development of water leakage/ cracking in a region(s) visible to users (e.g. platforms/concourse ceiling)
Ensure stability against assumed load	Ensure stability against assumed load	Ensure stability against continuous load	Provide necessary load-bearing performance against continuous load	11	Amount of tunnel convergence
				12	Development of cracking or damage in segments or secondary lining (structural deformation)
				13	Stress intensity or stress resultant of lining obtained in deformation analysis
		Provide necessary seismic performance	Lining provides necessary seismic performance against earthquake motions assumed during service life	14	Identification of seismic performance and damage level by analysis
		Ensure stability against assumed load change	Provide required load bearing capacity against impacts by neighboring construction work and load condition changes caused by change in surrounding environment assumed during service life	15	Amount of tunnel convergence and linear displacement
				16	Stress intensity or stress resultant of lining obtained in impact analysis
		High corrosion resistance	Lining provides necessary seismic performance against earthquake motions assumed during service life	17	Not evaluated in the maintenance phase
Durability	Ensure durability against assumed deterioration factors	High corrosion resistance	Rebars & steel segments with minimum speed of rust development in steels, e.g. bolts and splice plate	18	Presence of cracking/loosening, etc. in segments and secondary lining
				19	State of corrosion in rebars, bolts and splice plates
				20	Degradation indexes, e.g. cover concrete, remaining non-carbonated depth, chloride concentration, and water content
		No deterioration in concrete	No erosion or deterioration in liming concrete	21	State that cracking/erosion of segments and secondary lining
		Provide high water tightness	Minimize inducing any water leak that may cause deterioration of lining/equipment	22	Occurrence of water leakage

Table 4(b). Performance requirements fragmented (shield tunneling method/railway).

Performance requirements				Performance evaluation items	
Primary categories		Secondary categories	Subcategories		
Administrator usability	Ensure proper utilization by administrator	Satisfy required demands (traffic capacity)	Provide an inner space that accommodates the required number of railway tracks. En-sure the alignment is designed to allow the required train speed.	23	Not evaluated in the maintenance phase
		Ensure trains can be operated in a stable manner (at the fixed time)	Prevent the occurrence of water leakage or flaking that may obstruct the functions of auxiliary facilities involved in train operation	24	State of e.g. cracking and loosening in the regions of segments/secondary lining that affect auxiliary facilities involved in train operation.
				25	State of corrosion in steels in a region(s) that may affect auxiliary facilities involved in train operation
				26	State of water leakage in regions that affect auxiliary facilities involved in train operation
		Ensure operation of auxiliary facilities for regular train operation	Allow proper lay-out/usage of auxiliary facilities involved in train operation	27	Allowances outside the construction gauge, esp. in relation to auxiliary facilities
			Water inside the tunnel is properly drained to avoid any impacts on auxiliary facilities	28	Conditions of drainage facilities (e.g. blockage of drain ditches)
Maintainability	Ensure provision of proper maintenance	Ensure safe & easy inspection	Allow safe & easy daily patrolling, inspection and cleaning	29	Allowances outside the construction gauge (escape space used during patrolling/inspection)
		Ensure safe & easy repair	Allow installation of scaffoldings and stockyards for repair/reinforcement works Proper margin for repair /reinforcement provided in the inner section	30	Not evaluated in the maintenance phase
Impact on surroundings	Minimize impact on surroundings	Minor impacts on ground water	Minimize ground-water level changes Do not affect groundwater contamination on the surroundings	31	Changes in the groundwater level in surrounding areas
				32	Groundwater quality in nearby areas
				33	Water leakage survey inside the tunnel
		Minor impacts on surrounding grounds	Minimize ground surface settlement/upheaval	34	Amount of ground surface displacement in surrounding areas
				35	Occurrence of water leakage
		Minor impacts on surrounding real estates	Impacts on adjacent buildings/buried utilities are within the allowable range	36	Amount of displacement or development of cracks in neighboring properties
		Minor vibration and noise in the surroundings	Minimize impact of vibration /noise on the surrounding due to operation of train	37	Vibration/noise levels of ground surface and surrounding buildings

Table 5. Weighting factors given by evaluation by tunnel engineers.

Primary categories	weight factor (SD*)	Secondary categories	weight factor (SD*)	Sub categories	weight factor (SD*)	No
User safety	0.317 (0.125)	Ensure safe driving for users	0.152 (0.222)	Avoid any tunnel deformation that may obstruct the ensure safe driving	0.052 (0.128)	1
				Ensure good alignment and avoid any tunnel deformation that may obstruct the ensure safe driving	0.050 (0.148)	2,5
				Prevent the occurrence of water leakage or flaking that may obstruct the ensure safe driving	0.050 (0.210)	3,4
		Not directly threatening to user safety	0.092 (0.197)	-(nothing)	-	6,7
		Allow disaster prevention equipment to function in emergency	0.073 (0.191)	-(nothing)	-	8
User usability	0.124 (0.075)	Ensure ride quality	0.079 (0.235)	-(nothing)	-	9
		Not making users uncomfortable or feel insecure	0.045 (0.235)	- (nothing)	-	10
Structural stability	0.211 (0.093)	Ensure stability against continuous load	0.088 (0.146)	-(nothing)	-	11,12,13
		Provide necessary seismic performance	0.039 (0.099)	-(nothing)	-	14
		Ensure stability against assumed load change	0.047 (0.088)	-(nothing)	-	15,16
		Ensure stability against assumed construction load	0.037 (0.134)	-(nothing)	-	17
Durability	0.128 (0.085)	High corrosion resistance of steel	0.041 (0.162)	-(nothing)	-	18,19,20
		No deterioration in concrete	0.037 (0.160)	-(nothing)	-	21
		Provide high water tightness	0.049 (0.209)	-(nothing)	-	22
		Satisfy required demands	0.011 (0.188)	-(nothing)	-	23
Administrator usability	0.037 (0.017)	Ensure trains can be operated in a stable manner (at the fixed time)	0.015 (0.199)	-(nothing)	-	24,25,26
		Ensure operation of auxiliary facilities for regular train operation	0.010 (0.162)	Allow proper layout/usage of auxiliary facilities involved in train operation	0.005 (0.235)	27
				Water inside the tunnel is properly drained to avoid any impacts on auxiliary facilities	0.005 (0.235)	28
Maintainability	0.056 (0.037)	Ensure safe & easy inspection	0.031 (0.213)	-(nothing)	-	29
		Ensure safe & easy repair	0.025 (0.213)	-(nothing)	-	30
Impact on surroundings	0.127 (0.077)	Minor impacts on ground water	0.027 (0.152)	-(nothing)	-	31,32,33
		Minor impacts on ground surface	0.027 (0.120)	-(nothing)	-	34,35
		Minor impacts on surrounding real estates	0.036 (0.162)	-(nothing)	-	36
		Minor vibration and noise in the surroundings	0.037 (0.178)	-(nothing)	-	37
Total	(1.000)		(1.000)		(1.000)	

Table 6(a). Performance evaluation criteria used in AHP (shield tunneling method/ railway tunnels).

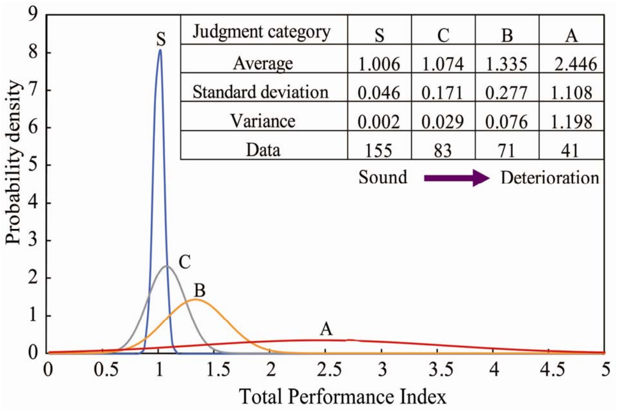
No	Performance evaluation items	Monitoring items The monitoring method is parenthesized
1	Amount of track displacement (any impacts on driving safety)	Amount of track displacement
2	Amount of displacement in tunnel alignment	Differential leveling and tunnel center line survey
3	Conditions of any cracking or loosening of segments/secondary lining and of any corrosion, etc. in rebars in a region(s) that may threaten driving safety (e.g. directly above the tracks)	• Location, length, width and range of cracking and corrosion: Visual observation and visible images • Loosening range: Hammering and infrared camera • Crack Pattern: Unfolded view of deformation • Progressiveness: Marking photographing, and cracking gauge • State of steel corrosion: Self potential, polarization resistance, and visual observation by chipping
4	Exposure of tracks to leaked water	• Location and amount of water leakage: Visual observation • Quality of leaked water: Water quality test
5	Leeway outside the construction gauge	• Measurement with a clearance car and electro-optical distance meter
6	Conditions of any cracking or loosening of segments/secondary lining and of any corrosion, etc. in reinforcement \cement in a region(s) that may threaten driving safety (e.g. directly above the tracks)	• Location, length, width and range of cracking/damage: Visual observation and visible images • Loosening range: Hammering and infrared camera • Crack Pattern: Unfolded view of deformation • Progressiveness: Marking, photographing, and cracking gauge • State of steel corrosion: Self potential, polarization resistance, and visual observation by chipping
7	Conditions of any water leakage in a region(s) that may threaten driving safety (e.g. platforms/concourse ceiling)	• Location and amount of water leakage and visual observation
8	Leeway outside the construction gauge (clearance from disaster prevention equipment and room for evacuation)	• Measurement with a clearance car and visual inspection
9	Amount of track displacement (any impacts on riding comfort)	• Measurement of amount of track displacement and train oscillation
10	Development of water leakage/ cracking in a region(s) visible to users (e.g. platforms/concourse ceiling)	• Visual observation
11	Amount of tunnel convergence	• Amount of convergence: Convergence gauge and electro-optical distance meter
12	Development of cracking or damage in segments or secondary lining (structural deformation)	• Location, length, width and range of cracking/damage: Visual observation and visible images • Loosening range: Hammering and infrared camera • Crack Pattern: Unfolded view of deformation • Progressiveness: Marking ， photographing, and cracking gauge • State of steel corrosion: Self potential, polarization resistance, and visual observation by chipping
13	Stress intensity or stress resultant of lining obtained in deformation analysis	• Displacement: Convergence measurement and measurement of openings and joint offsets between adjacent segments • Strain and stress of members: Strain measurement • Strength and deformation characteristics of lining concrete: Strength test (boring test, rebound hammer method, hammering & sounding, and anchor pullout method), and elastic modulus test
14	Identification of seismic performance and damage level by analysis	• Characteristic values of materials: Design characteristic values of materials, measurement of strain in the actual structure, and strength test and dynamic elastic modulus test on the actual structure
15	Amount of tunnel convergence and linear displacement	• Amount of crown settlement: Differential leveling and electro-optical distance meter • Amount of convergence: Convergence gauge and electro-optical distance meter • Amount of linear displacement: Differential leveling and electro-optical distance meter • Crack patterns: Visual observation
16	Stress intensity or stress resultant of lining obtained in impact analysis	• Displacement: Convergence measurement, measurement of openings and joint offsets between adjacent segments • Strain and stress of members: Strain measurement • Strength and deformation characteristics of lining concrete: Strength test (boring test, rebound hammer method, hammering & sounding, and anchor pullout method), and elastic modulus test
17	Not evaluated in the maintenance phase	-

Table 6(b). Performance evaluation criteria used in AHP (shield tunneling method/railway tunnels).

No	Performance evaluation items	Monitoring items the monitoring method is parenthesized
18	Presence of cracking/loosening, etc. in segments and secondary lining	• Location, length, width and range of cracking/flaking: Visual observation and visible images • Loosening range: Hammering and infrared camera • Crack patterns: Unfolded view of deformation • Progressiveness: Marking, photographing, and cracking gauge
19	State of corrosion in rebars, bolts and splice plates	• State of corrosion of exposed steels: Visual observation and measurement of thickness reduction due to corrosion • State of corrosion of steels in concrete: Self-potential polarization resistance electromagnetic wave radar and visual observation by chipping • Progressiveness: Photographing and rust fluid status
20	Degradation indexes, e.g. cover concrete, remaining non-carbonated depth, chloride concentration, and water content	• Cover depth: RC radar, chipping and scaling • Remaining non-carbonated depth: Measurement of carbonation depth chloride concentration: • Measurement of chloride concentration Water content: Water content test • Environmental conditions: Measurement of airborne saline matter, chloride concentration of leaked water, exposure to rainwater, exposure to sunlight, temperature and humidity
21	State that cracking/erosion of segments and secondary lining	• Cracking: Bleeding of gel, location/length/width/range/depth of corrosion and scaling, visual observation, hammering, measurement of thickness reduction due to corrosion • Crack patterns: Unfolded view of deformation • Progressiveness: Marking, photographing and cracking gauge • Physical property deterioration of lining concrete: Strength test, elastic modulus test, physical property test (e.g. alkali content, aggregate reaction, microstructure, and chemical composition) • Environmental conditions: Concentration of toxic substances in leaked water, water supply status, exposure to sunlight, temperature and humidity)
22	Occurrence of water leakage	• Location of water leakage: Visual inspection • Quality of leaked water: Water quality test • Changes in water leakage: Sensor measurement
23	Not evaluated in the maintenance phase	-
24	State of e.g. cracking and loosening in the regions of segments/secondary lining that affect auxiliary facilities involved in train operation.	• Location, length, width and range of cracking: Visual observation and visible images • Loosening range: Hammering and infrared camera • Cracking patterns: Unfolded view of disturbance • Progressiveness: Marking, photographing, and crack gauge
25	State of corrosion in steels in a region(s) that may affect auxiliary facilities involved in train operation	• State of corrosion of exposed steels: Visual observation, measurement of thickness reduction due to corrosion • State of corrosion of steels in concrete Self-potential polarization ,résistance electromagnetic wave radar and visual observation by chipping • Progressiveness: Photographing and rust fluid status
26	State of water leakage in regions that affect auxiliary facilities involved in train operation	• Location of water leakage: Visual inspection • Quality of leaked water: Water quality test
27	Allowances outside the construction gauge, esp. in relation to auxiliary facilities	• Measurement with a clearance car and electro-optical distance meter
28	Conditions of drainage facilities (e.g. blockage of drain ditches)	• Location and status: Visual observation and photographing
29	Allowances outside the construction gauge (escape space used during patrolling/inspection)	• Measurement with a clearance car, visual observation and electro-optical distance meter
30	Not evaluated in the maintenance phase	-
31	Changes in the groundwater level in surrounding areas	• Water level measurement
32	Groundwater quality in nearby areas	• Water quality test
33	Water leakage survey inside the tunnel	• Visual inspection and photographing
34	Amount of ground surface displacement in surrounding areas	• Ground surface displacement: Observation of ground fissure and subsidence and displacement measurement
35	Occurrence of water leakage	• Amount of leaked water: Visual observation, photographing and measurement of amount of leakage
36	Amount of displacement or development of cracks in neighboring properties	• Amount of displacement: Displacement measurement • Cracking: Cracking survey, e.g. crack width
37	Vibration/noise levels of ground surface and surrounding buildings	• Vibration/noise level: Measurement of vibration and noise

Table 7. Judgment categories according to the existing method (for railway tunnels).

	Structure State
A	State that threatens operational safety, safety of passengers, public safety, guarantee of regular train operation that might cause this state
	Deterioration that threatens operational safety, safety of passengers public safety, guarantee of regular train operation and which require emergency countermeasures
	Progressive deterioration that cause the performance of structures to drop, or heavy rain, floods, or earthquakes that might impair the performance of structures
	Deterioration that might cause a future performance drop of structures
B	Deterioration that might result in a future soundness rank of A
C	Slight deterioration
S	Sound



Judgment category	S	C	B	A
Average	1.006	1.074	1.335	2.446
Standard deviation	0.046	0.171	0.277	1.108
Variance	0.002	0.029	0.076	1.198
Data	155	83	71	41

Figure 7. TPI probability distributions by judgment category in the existing method (Box segment section).

sults indicate that the results of both methods may become consistent if the scores are determined more appropriately. Now, the performance requirements, which determined TPI, are categorized according to the primary, secondary and sub categories to examine which of these categories affect TPI and identify the influencing factors. The results are shown in **Figure 9** through **Figure 11**.

Figure 9, where the judgment result is "A" in the existing method, shows that the primary categories greatly affecting TPI are found to be "user safety" and "structural stability". **Figure 8** shows that in the existing method, "cracking and water leakage" is the most common major factor, which is almost the same as the major factor that determined TPI in the existing method. More detailed analysis of influencing factors using the sub categories are shown in **Figure 10**. It is shown in **Figure 10**, where the judgment result is that the most influenceing secondary categories are "stability against continuous load" and "not directly threatening to user safety". **Figure 11** judged as "A" also shows that the most influencing subcategory is "Prevent the occurrence of water leakage or flaking that may obstruct the ensure safe driving". **Figure 8** shows that in the existing method, "(1) Disturbance by external force" and "(3) Disturbance by water leakage" are the most common major factors, which are almost the same as those that determined TPI in the existing method.

These indicate that on the whole, the determining factors of judgment results in the existing method and TPI are more or less consistent. In the case of box segment section, those judged as "A" in the existing method are most affected by cracking and water leakage, while in TPI, the non-presence of flaking or water leakage that may threaten user safety under "User safety performance" is most influential.

These results show it is possible to comprehensively quantify the actual performance of tunnel structures by employing AHP using already available inspection results such as the interior views of lining obtained in the existing method.

5. Conclusions

This paper outlined the concept of performance criteria for tunnel structures and a management methodology based on that concept to be used in the maintenance phase for existing tunnels. Citing existing road tunnels, it went on to explaining how to perform calculations in one of the approaches to comprehensively evaluate actual performance in the maintenance phase, namely the Total Performance Index.

In evaluating/verifying the actual performance based on performance criteria, although it is possible to quantitatively evaluate the actual performance, there is a lack of empirical data to be used for determining the thresholds in verification. Future research should focus on the collection of actual data to carry out technological studies to enhance the accuracy of evaluating/verifying the actual performance.

Currently in Japan, each owner and administrator is studying management methodologies for tunnel structures on an individual basis [18]. Unfortunately, their

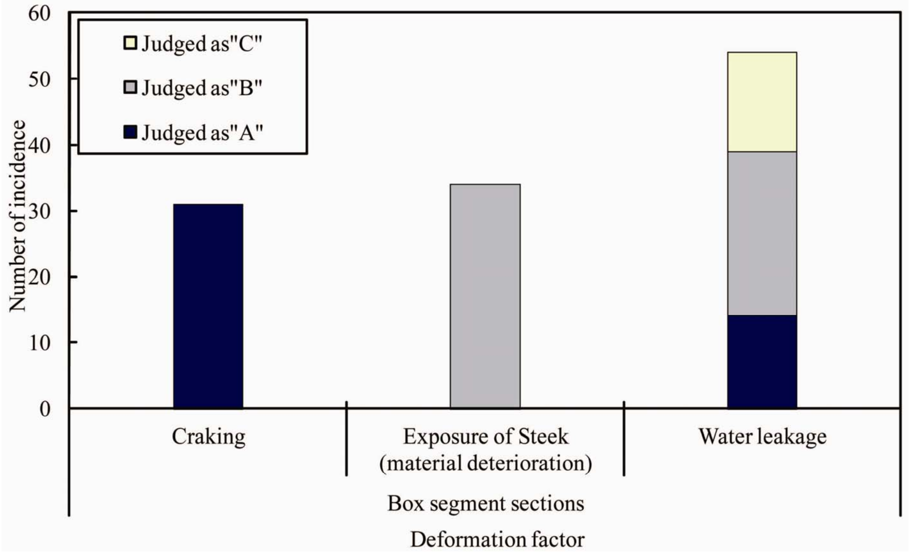
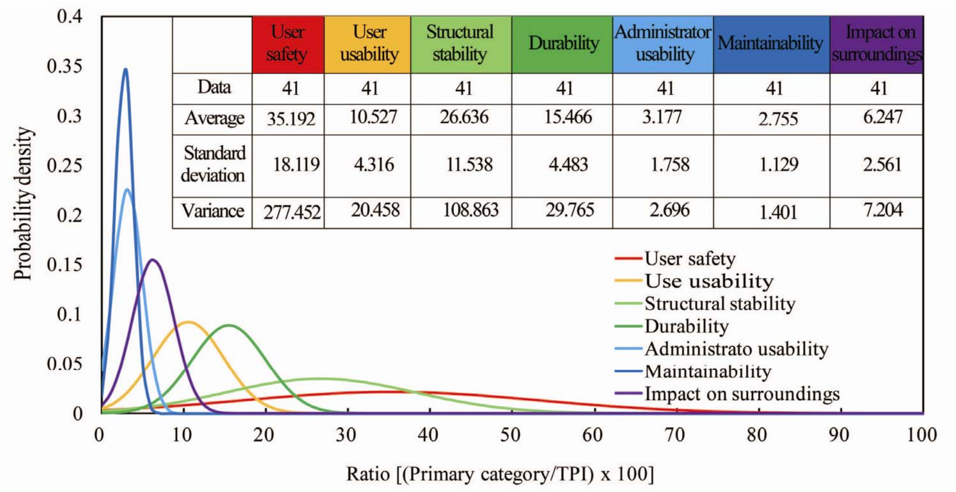
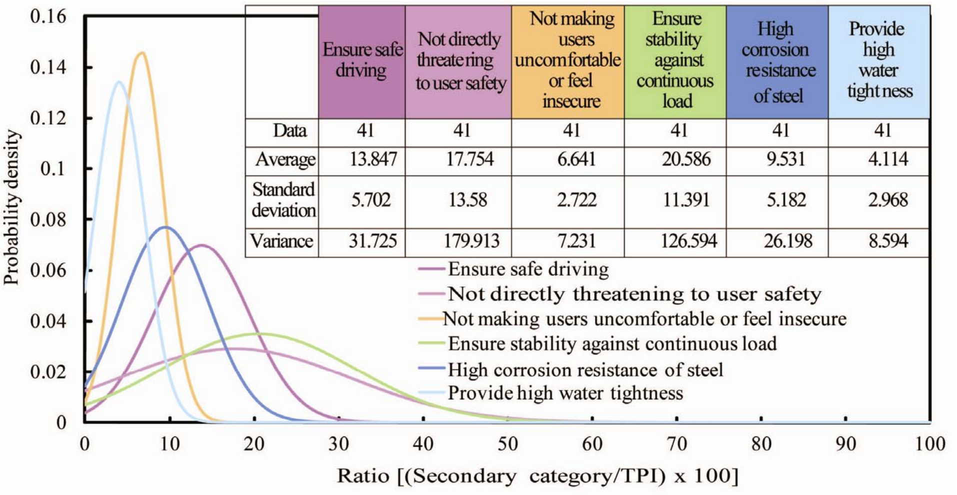


Figure 8. Judgment deformation according to the existing method.



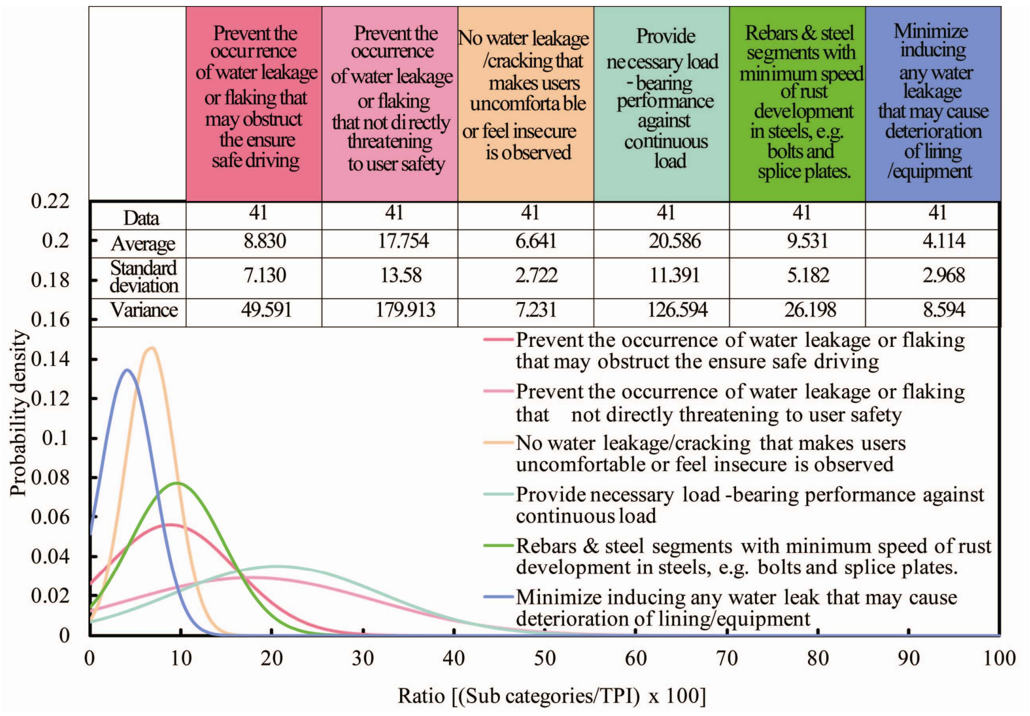
	User safety	User usability	Structural stability	Durability	Administrator usability	Maintainability	Impact on surroundings
Data	41	41	41	41	41	41	41
Average	35.192	10.527	26.636	15.466	3.177	2.755	6.247
Standard deviation	18.119	4.316	11.538	4.483	1.758	1.129	2.561
Variance	277.452	20.458	108.863	29.765	2.696	1.401	7.204

Figure 9. Major factors of primary category (Judged as "A" in the existing method) (Box segment section).



	Ensure safe driving	Not directly threatering to user safety	Not making users uncomfortable or feel insecure	Ensure stability against continuous load	High corrosion resistance of steel	Provide high water tightness
Data	41	41	41	41	41	41
Average	13.847	17.754	6.641	20.586	9.531	4.114
Standard deviation	5.702	13.58	2.722	11.391	5.182	2.968
Variance	31.725	179.913	7.231	126.594	26.198	8.594

Figure 10. Major factors of secondary category (Judged as "A" in the existing method) (Box segment section).



	Prevent the occurrence of water leakage or flaking that may obstruct the ensure safe driving	Prevent the occurrence of water leakage or flaking that not directly threatening to user safety	No water leakage /cracking that makes users uncomfortable or feel insecure is observed	Provide necessary load - bearing performance against continuous load	Rebars & steel segments with minimum speed of rust development in steels, e.g. bolts and splice plates.	Minimize inducing any water leakage that may cause deterioration of liring /equipment
Data	41	41	41	41	41	41
Average	8.830	17.754	6.641	20.586	9.531	4.114
Standard deviation	7.130	13.58	2.722	11.391	5.182	2.968
Variance	49.591	179.913	7.231	126.594	26.198	8.594

Figure 11. Major factors of sub category (Judged as "A" in the existing method) (Box segment section).

studies are not widely shared in practical terms; tunnel administrators and engineers should cooperate with each other to discuss further to develop performance criteria and management methodologies based on such criteria.

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