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Development of performance evaluation model for road and railway tunnels in use

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Abstract. Accurately evaluating and predicting the performance of facilities is a key task in establishing a maintenance strategy for facilities. The importance of performance evaluation is becoming more pronounced, especially when the aging of facilities requires a huge budget. In this study, performance assessment models were developed for road and railway tunnels. Delphi analysis was performed to identify sub-elements necessary to evaluate the performance of a tunnel. The relative importance of the evaluation factors was derived from the AHP analysis. The correlation analysis was performed between each assessment factor and the final result to verify the significance of the model. For the correlation analysis, the survey data measured through precision safety diagnosis in tunnels in use was applied. The cost effectiveness analysis was also conducted according to the scenarios with different composition of performance factors in order to improve the practical applicability of the evaluation model developed in this study.

Keywords: AHP; evaluation; maintenance; performance; tunnel

1. Introduction

Infrastructures in Korea were intensively built in a short time during the period of rapid growth in the 1970s, and accordingly, their aging is rapidly progressing (MOLIT 2017). Deterioration of facilities can not only reduce user convenience, but also threaten safety. For this reason, the government has recently been making various efforts, such as enacting laws that regulate the management system of infrastructure in preparation for the deterioration of the infrastructure (MOLIT 2019). Developed countries such as the United States, the United Kingdom, and Japan are already preparing measures at the national level and investing necessary national finances (ICEE 2015).

In Korea, tunnels are positioned as a major component of infrastructure due to the geographical conditions of many mountains. Most of the tunnels in Korea have been constructed with NATM due to relatively good geological conditions, and the number of tunnels is constantly increasing year by year, so systematic maintenance is necessary in preparation for the aging of facilities (Moon *et al.* 2020).

In order to obtain the optimal effect with a limited budget in maintaining facilities, it is necessary to evaluate the current performance level of the facilities in consideration of various factors such as the purpose, capacity, and use environment of the facilities (Kang and Lee 2013, Lee *et al.* 2015).

In this study, in order to establish a performance-based evaluation system that can be applied in the maintenance of facilities and suitable for domestic conditions, based on the results of the existing research (An and Kim 2016, Choo *et al.* 2019, Gao and Chen 2019, Han *et al.* 2021, Kim *et al.* 2020, Moon et al. 2020), a performance-oriented evaluation model is derived for NATM tunnels with RC-lining (Fig. 1). Correlation analysis was conducted based on the precise safety diagnosis survey data of the actual tunnel in use to verify the adequacy of the derived evaluation model. In addition, in order to improve the effectiveness when the derived evaluation model is used in actual work, a cost-effectiveness analysis was conducted based on the maintenance scenario, and the evaluation items were optimized.

2. Theoretical background

2.1 Research procedure

In this study, in order to develop a performance evaluation model for tunnel in use, performance was classified into safety, durability, and usability. In addition, detailed evaluation items for each performance were identified through a literature survey on the evaluation system in use and a Delphi survey conducted with experts.

Performance evaluation items were quantified by analyzing the relative importance(weight) between performance and performance evaluation factors using AHP

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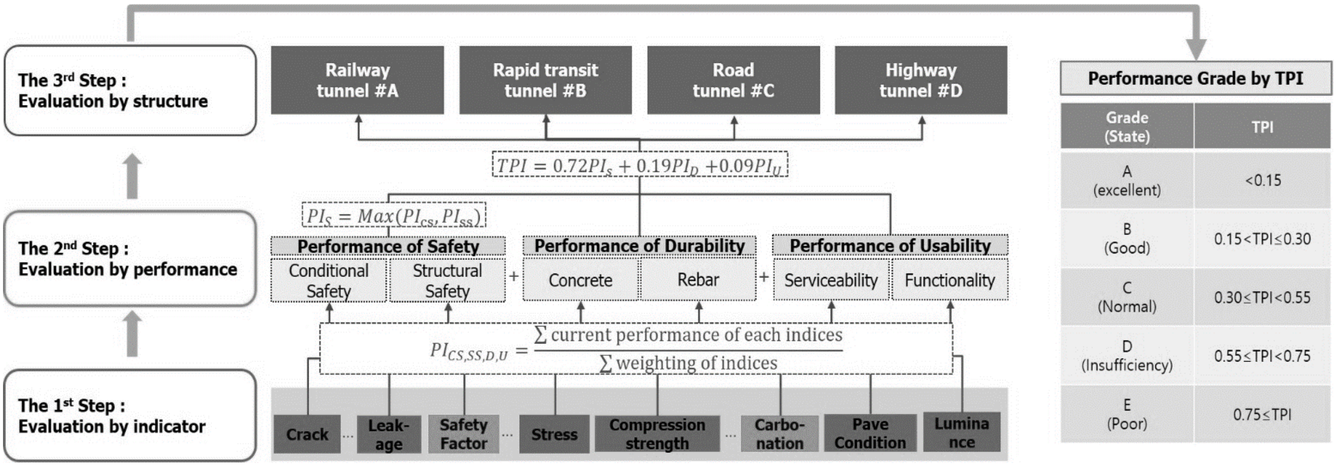


Fig. 1 Concept of performance assessment model for tunnels in use

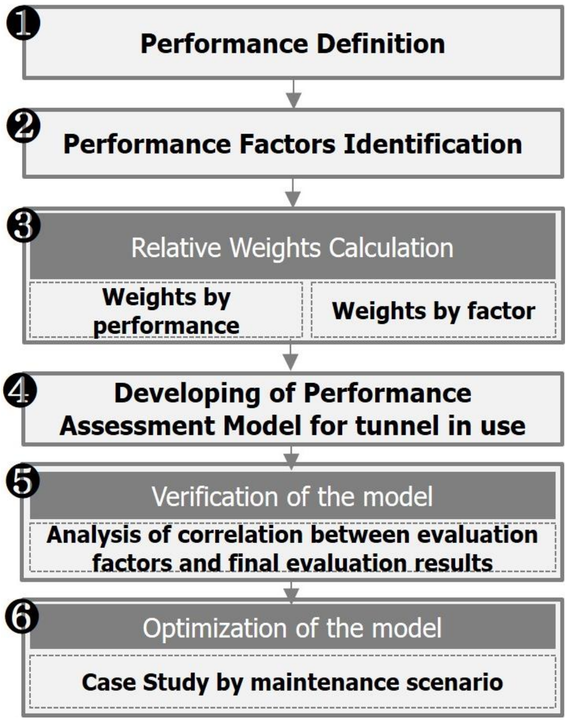


Fig. 2 Research procedure

analysis. An evaluation table for each tunnel type was presented by synthesizing performance indicators, evaluation criteria and weights. And finally, correlation analysis and cost-effectiveness analysis were performed to verify and supplement the evaluation model developed by the theoretical method (Fig. 2).

2.2 Delphi survey

The Delphi technique is a method of coordinating and integrating the opinions of distributed groups by repeatedly surveying the same panel. By sharing the results derived from each panel during the survey, consensus of distributed opinions is derived as the number of surveys is repeated.

In the Delphi technique, there is no clear regulation on the size of the panel, which is a group of experts, but there is a functional relationship between the reliability of the result and the panel size. When the number of panels is 13 or more, the reliability of the process between the questionnaires before and after is not a problem at all, and shows a high correlation of 0.80 on average.

The content validity of the Delphi survey result is verified using the content validity ratio(CVR). The minimum value for the CVR value is presented according to the number of panels, and when it is more than the minimum value, it is judged that there is content validity for the opinions of experts.

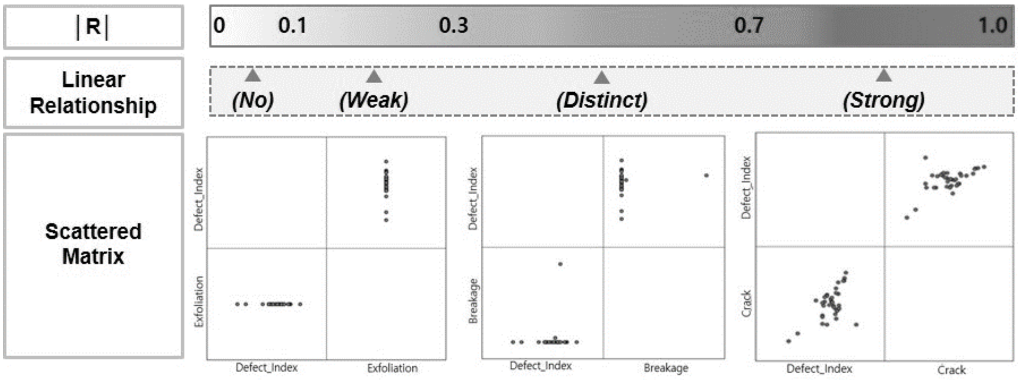
Content validity is calculated by the following Eq. (1), where, n_e is the number of panels that responded as valid, and N is the total number of Delphi panels that participated in the study. If all respondents say 'important', the CVR value is 1, and if less than 50% of respondents say 'important', the CVR value is 0. The criterion value for judging the content validity based on the CVR value depends on the total number of respondents, and since 14 experts participated in this study, the validity was evaluated based on the CVR value of 0.51 (Lawshe 1975). The minimum value for the CVR value is presented according to the number of panels, and when it is more than the minimum value, it is judged that there is content validity for the opinions of experts.

$$\mathrm{CVR} = (n_e - N/2)/(N/2) \tag{1}$$

The degree of consensus(agreement) which is a method of verifying whether the consensus between respondents calculated by the following Eq. (2), where, Q_3 is the third quarter, and Q_1 is the first quarter, and M_d is median (Kwon 2009).

$$Agreement \;=\; 1 - (Q_3 - Q_1)/M_d \tag{2}$$

It is possible to evaluate how well the expert panel's responses are consistent in the repeated survey process with stability. Stability can be measured by the coefficient of variation(COV) as shown in the following Eq. (3), which is the value obtained by dividing the standard deviation by the arithmetic mean. If the COV is less than 0.5, no additional questionnaire is needed. If the value is 0.5~0.8, it means that the response is relatively stable, and if the COV is more



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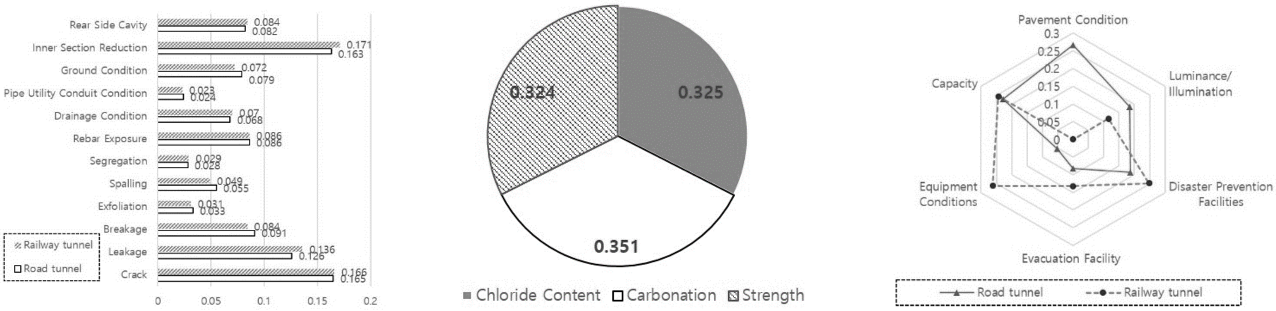


(a) Safety (b) Durability (c) Usability

Fig. 4 Linear relationship of the R value

than 0.8, the response is low, suggesting that an additional questionnaire is needed (Noh 2006). If the COV is less than .5, no additional questionnaire is needed. If the value is 0.5~0.8, it means that the response is relatively stable, and if the COV is more than 0.8, the response is low, suggesting that an additional questionnaire is needed.

$$\mathrm{COV} = \sigma/\mu \tag{3}$$

2.3 AHP (Analytic Hierarchy Process) method

The AHP is a method of setting weights of evaluation factors when making decisions in areas where quantitative approaches are difficult. As a technique designed to be suitable as a mathematical model in the decision-making stage, it derives relative importance by organizing, structuring, and systematizing experiences (Saaty and Vargas 2001). In other words, it can be said that it is a method of stratifying evaluation factors and determining relative importance through paired comparison (Park 2009, Xue *et al*. 2019).

The main preceding studies that derive weights for the evaluation of public facilities using this technique are as follows. KISTEC (2013) presented weights for each evaluation index of the shield TBM tunnel using AHP analysis to develop the performance evaluation criteria and maintenance manual for the shield TBM tunnel. Kimura *et al.* (2012) proposed a performance-oriented evaluation method for railroad tunnels, and the proposed evaluation method includes a total of 7 performances (user safety, usability, structural safety, durability, maintenance, etc.). The AHP analysis was used to determine the weight of the evaluation index of each performance.

2.4 Correlation analysis

Correlation analysis is a statistical technique that analyzes the linear relationship between two variables that are continuous (Kim *et al.* 2020). In this study, Pearson's increases, the value of the other variable also increases, and is calculated by the following Eq. (4).

$$\mathrm{Cov(x, y)} = E((x-\bar{x})(y-\bar{y})) \tag{4}$$

Pearson's correlation coefficient(R) is a standardized covariance value, which is the value obtained by dividing the covariance by the standard deviation of each variable. Like the covariance, if the value of R is positive(+), it means that the two variables are changing in the same direction (Fig. 3), and it is calculated as shown in the following Eqs. (5)-(8).

$$R = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}} \tag{5}$$

$$S_{xx} = \sum_{i=1}^{n} {x_i}^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n} \tag{6}$$

Table 1 Performance evaluation factors derived by Delphi-survey

Performance	Primary Category	Subcategory	CVR		Agreement		C.O.V	
			2nd	3rd	2nd	3rd	2nd	3rd
Safety	Tunnel Inside	Crack	1.00	1.00	0.86	0.86	0.27	0.27
		Deterioration of a Sealing	0.57	0.71	0.82	0.82	0.19	0.19
		Leakage	1.00	1.00	0.86	0.86	0.28	0.28
		Exfoliation	0.57	0.71	0.71	0.71	0.26	0.26
		Spalling	0.86	1.00	0.71	0.83	0.47	0.47
		Rebar Exposure	1.00	1.00	0.86	0.86	0.13	0.13
		Breakage	1.00	1.00	0.85	0.86	0.14	0.14
	Tunnel outside	Rear Side Cavity	1.00	1.00	0.73	0.85	0.10	0.10
		Inner Section Reduction	0.86	1.00	0.83	0.83	0.19	0.19
		Ground Condition	0.86	1.00	0.86	0.89	0.19	0.19
		Drainage Condition	1.00	1.00	0.71	0.71	0.17	0.17
		Pipe Utility Conduit Condition	0.57	0.57	0.86	0.86	0.09	0.09
	Structural Safety	Factor of Safety	0.86	1.00	0.86	0.86	0.08	0.08
		Displacement	0.86	1.00	0.85	0.85	0.09	0.09
		Stress	1.00	1.00	0.83	0.83	0.09	0.09
Durability	Concrete Lining	Strength	0.86	1.00	0.83	0.83	0.09	0.09
		Carbonation	0.57	1.00	0.83	0.83	0.27	0.27
		Chloride Content	0.29	0.43	0.60	0.65	0.00	0.00
Usability	Serviceability	Pavement Condition	0.57	0.57	0.80	0.80	0.14	0.14
		Illumination	0.71	0.71	0.83	0.83	0.08	0.08
		Luminance	0.71	0.86	0.83	0.83	0.09	0.09
		Disaster Prevention Facilities	0.71	1.00	0.83	0.83	0.09	0.09
	Functionality	Maintainability	0.43	0.71	0.65	0.82	0.09	0.09
		Traffic Conditions	0.57	0.57	0.80	0.82	0.13	0.13

$$S_{yy} = \sum_{i=1}^{n} y_i^2 - \frac{(\sum_{i=1}^{n} y_i)^2}{n} \tag{7}$$

$$S_{xy} = \sum_{i=1}^{n} x_i y_i - \frac{(\sum_{i=1}^{n} x_i)(\sum_{i=1}^{n} y_i)}{n} \tag{8}$$

3. Performance assessment model

3.1 Identification of evaluation factors

In this study, a total of 47 preliminary performance evaluation indicators were derived through literature research. Performance was classified into safety, durability, and usability. The evaluation index for safety was 25, and the durability and usability evaluation index were 11, respectively. Delphi analysis was conducted three times with a panel of 14 experts based on the preliminary performance evaluation indicators derived through literature research. In all evaluation items, the stability was found to be less than 0.5 and the agreement was analyzed to be close to 1, indicating that the agreement of panel responses was very high. In conclusion, it was judged that the opinions of the expert group had a very high degree of agreement, and items with a content validity of 0.51 or more were selected as a performance evaluation item.

Among the performance evaluation indicators derived through Delphi analysis, those that were redundant or that could not be investigated were removed through expert group discussions. Finally, a total of 24 performance evaluation indicators (15 safety, 3 durability, and 6 usability) were selected as shown in Table 1.

3.2 Relative weights of factor

In order to derive weights for each evaluation index, AHP analysis was conducted for tunnel experts with at least 15 years of experience in related fields. It was confirmed that the consistency ratio of the responses of each expert participating in the survey was 0.15 or less, and the relative importance analysis was conducted between the evaluation indicators using the corresponding responses (Fig. 4).

In the case of safety, indicators directly related to the safety of the tunnel, such as ‘inner section reduction’, ‘crack’, ‘leakage’, ‘rear side cavity’, and ‘ground condition’, were analyzed as relatively important. On the other hand, indices related to material deterioration such as ‘exfoliation’, ‘spalling’, and ‘segregation’, and ‘pipe utility conduit condition’, which has little effect on the structural safety of the tunnel, were analyzed to be of relatively low importance compared to other indicators. On the other hand, when comparing the importance of each safety evaluation index of roads and railroad tunnels, it was confirmed that the priorities were similar. This suggests that the impact of the use of the tunnel is insignificant in evaluating the safety. In terms of durability, the ‘carbonization’ item was found to have the highest relative importance. It was judged that this was due to the fact that alkaline concrete deteriorated to acidic components over time, and the passive film around the reinforced bar was destroyed, causing

Table 2 Performance evaluation table for a tunnel

Performance	Weight	Primary Category	Weight (road/railway)	Subcategory	Weight (road/railway)
Safety	0.72	Tunnel Inside	0.584/0.581	Crack	0.165/0.166
				Leakage	0.126/0.136
				Breakage	0.091/0.084
				Exfoliation	0.033/0.031
				Spalling	0.055/0.049
				Segregation	0.028/0.029
				Rebar Exposure	0.086/0.086
		Tunnel outside	0.416/0.42	Drainage Condition	0.068/0.07
				Pipe Utility Conduit Condition	0.024/0.023
				Ground Condition	0.079/0.072
				Inner Section Reduction	0.163/0.171
				Rear Side Cavity	0.082/0.084
Durability	0.19	Concrete Lining	1.0/1.0	Strength	0.324
				Carbonation	0.351
				Chloride Content	0.325
Usability	0.09	Serviceability	0.72/0.496	Pavement Condition	0.267/0
				Luminance/Illumination	0.184/0.116
				Disaster Prevention Facilities	0.187/0.248
				Evacuation Facilities	0.082/0.132
		Functionality	0.28/0.505	Equipment Conditions	0.052/0.262
				Capacity (Traffic condition)	0.228/0.243

corrosion of the reinforcing bar. Next, it was analyzed that 'chloride content' was the second most important. It was judged that this was because it promoted the corrosion of the reinforcing bar due to the salt penetrating into the concrete. When analyzing the importance according to the material, the items related to rebar corrosion accounted for 68% of the total, and the items related to concrete material deterioration accounted for 32% of the total. This suggests that the durability of reinforced concrete dominates in evaluating the durability of reinforced concrete lining.

In terms of usability, in road tunnels with visibility driving (it is important to secure the driver's visibility), 'luminance' linked to the brightness in the tunnel has a relatively high weight, and 'equipment condition' has a relatively low weight. On the other hand, in the case of railroad tunnels with instrument operation (system control is important), 'illuminance' was analyzed with low importance, and 'equipment condition' was analyzed with high relative importance.

For a comprehensive evaluation that considers safety, durability and usability, it is necessary to calculate the importance(weight) between each performance. The importance of each performance was analyzed by using the AHP method with the same panel of experts. As a result of the AHP analysis, it was found that the importance was high in the order of safety (0.72), durability(0.19), and usability(0.09).

3.3 Verification of the model

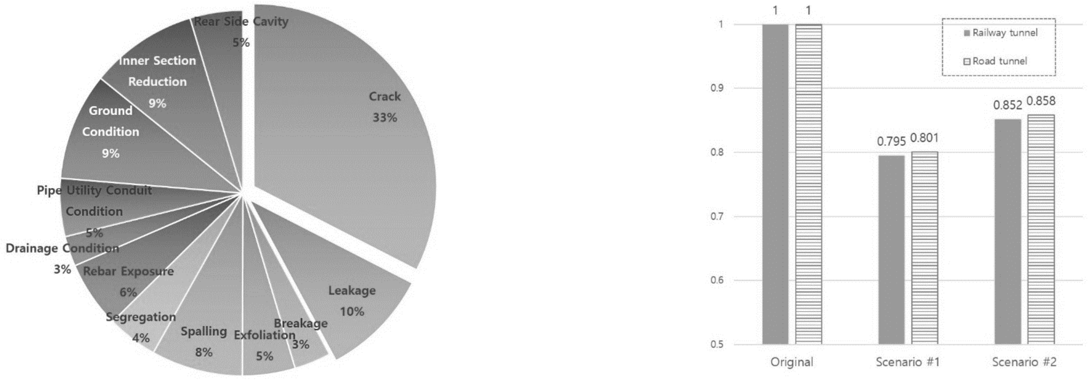
In order to verify the adequacy of the evaluation model for each tunnel type proposed in this study, a correlation analysis was performed between the performance evaluation items and the final evaluation results. The data used for the correlation analysis were the results of the precise safety diagnosis conducted by KISTEC for the last 10 years (Table 3), and statistical analysis was performed using the Pearson correlation coefficient (R) for the analysis method.

Table 3 General status of tunnels for correlation analysis

Type of Tunnel	Tunnel Method	Average Length(m)	Average Ages(years)	Defect Index(average)
Road Tunnel	NATM	2,730	16.3	0.247
Railway Tunnel	NATM	5,150	17.2	0.248

Table 4 Results of correlation analysis

Independent variable	Pearson coefficient of correlation (R)	Correlation analysis
Crack	0.570	Distinct
Leakage	0.410	Distinct
Breakage	0.112	Weak
Exfoliation	-	-
Spalling	0.121	Weak
Segregation	0.014	Weak
Rebar Exposure	0.199	Weak
Drainage Condition	0.476	Distinct
Ground Condition	0.308	Distinct



(a) Damage frequency of tunnel (b) Cost effectiveness analysis by scenario

Fig. 5 Cost effectiveness analysis for optimizing performance factors

In statistical analysis, the detailed evaluation index of each performance was set as an independent variable and the defect index was set as a defendant variable. However, newly proposed evaluation items such as ‘inner section reduction’, ‘durability’ and ‘usability’ were excluded from this analysis. As a result of the correlation analysis using the SPSS statistical package, the evaluation indicators for ‘crack’, ‘leakage’, ‘drainage condition’ and ‘ground condition’ were analyzed as 'clear correlation' with the final evaluation result. Therefore, the evaluation index, weight and evaluation method proposed through this study were judged to be statistically significant (Fig. 5).

On the other hand, ‘breakage’, ‘exfoliation’, ‘spalling’, ‘segregation’ and ‘rebar exposure’ indicators related to material deterioration of the lining were analyzed with relatively low correlation with the final result as a result of the correlation analysis (Table 4). These results indicate that the tunnel to be evaluated is a relatively recently constructed tunnel, and there is a limit to observing material deterioration over time, and thus it was judged to have a rather low correlation. It is considered that additional analysis is necessary using the data surveyed after the increase of the public use period in the future.

4. Optimization of the model

4.1 Simulation scenario

In facility maintenance, field investigation is an essential task in collecting basic data for performance evaluation. The more data collected, the more accurate evaluation of the facility can be made. However, excessively detailed investigations cause excessive costs, so the manager must set the appropriate level of investigation items for maintenance purposes.

In this study, in order to optimize the evaluation system developed by the theoretical method, the Cost-Effectiveness analysis was conducted by varying the investigation level (evaluation item) for each maintenance scenario.

The scenario for the Cost-Effectiveness analysis was divided into two cases as follows. The first scenario is a case where, as a result of performing a sensitivity analysis on the result of analysis of importance(AHP), the performance indicator, which is the lower 50% in all cases, is excluded from performance evaluation. The second scenario is to exclude evaluation items that have not been statistically verified and are of low importance from the performance evaluation. In other words, the items excluded in this case are indexes with a weight of the lower 50% of the five items (breakage, exfoliation, spalling, segregation and rebar exposure) analyzed as having a low correlation with the final evaluation result.

4.2 Cost-effectiveness analysis

For the Cost-Effectiveness analysis of the performance evaluation system by the scenario, the cost-effectiveness ratio(C/E) shown in Eq. (9), which is generally used in the economic analysis of public projects, was applied (Kim *et al.* 2017, Commonwealth of Australia 2006).

$$\mathrm{C/E} = Total\ cost/Total\ benefit \qquad (9)$$

In the cost of facility inspection and evaluation, the external labor cost accounts for the largest portion. Therefore, in Korea, the cost of inspection and evaluation is calculated based on the external labor cost (MOLIT 2018). In this study, the cost for the tunnel performance evaluation is assumed to be the external labor cost. Here, the external labor cost is proportional to the on-site survey time, and the survey time is proportional to the number of on-site surveys. Therefore, the proportion of each performance indicator to the external labor cost can be replaced by the frequency of occurrence of the inspection item.

KISTEC (2014) analyzed the occurrence frequency of each evaluation item by using the results of detailed safety diagnosis of 47 tunnels in operation (Fig. 5(a)). In this study, the frequency was assumed as cost. In addition, the effectiveness of tunnel performance evaluation varies according to the acquisition level of important information related to facility performance. Therefore, in this study, the effectiveness is assumed to be the value obtained by multiplying the weight of each performance indicator by the likelihood.

As a result of the cost-effectiveness analysis for each scenario, it was analyzed that C/E ratio of scenario #1 (when the lower 50% item as a result of sensitivity analysis was excluded from the evaluation) was the lowest (Fig.

5(b)). In other words, it was analyzed that it is advantageous in terms of economy(efficiency) to perform performance evaluation excluding ‘exfoliation’, ‘spalling’, ‘segregation’ and ‘pipe utility conduit condition’.

5. Conclusions

In this study, in order to develop a performance-oriented evaluation system for road tunnels and railroad tunnels constructed by NATM, preliminary evaluation indicators for each performance were derived by analyzing previous studies, and evaluation indicators for each performance were derived by conducting the Delphi survey. In addition, the AHP analysis was carried out to evaluate the importance of each performance evaluation indices. Correlation analysis was performed to evaluate the significance of the presented evaluation model. Finally, in order to derive a cost-effective evaluation system, the Cost-effectiveness analysis was carried out for each scenario in which performance evaluation indicators were different. The main conclusions of this study are summarized as follows.

1. The performance of tunnel in use can be divided into safety, durability, and usability. Through three times of the Delphi surveys and expert group discussions, 24 performance evaluation indicators (safety 15, durability 3, usability 6) were selected.

2. The weight of each performance evaluation index was analyzed using the AHP method. In the case of safety, indicators directly related to the safety of the tunnel, such as ‘inner section reduction’, ‘crack’, ‘leakage’, ‘rear side cavity’, and ‘ground condition’, were analyzed as ‘relatively important’. In the case of durability, it was analyzed that ‘carbonation’ and ‘chloride content’ related to the corrosion of the reinforcing bar were ‘highly important’. In the case of usability, it was analyzed that the importance of indicators (‘pavement condition’, ‘capacity’, and ‘disaster prevention facilities’) directly related to user satisfaction and safety were high in road tunnels, and in the case of railroad tunnels, the indicators (‘equipment conditions’ and ‘disaster prevention facilities’) related to system operation were analyzed to be relatively important.

3. Based on the weights of each evaluation index, a performance evaluation table for road and railroad tunnels constructed with NATM was proposed. A correlation analysis between each evaluation index and the final result was performed based on the survey data measured through precise safety diagnosis in tunnel in use, and as a result, there was a clear correlation in the evaluation index of ‘crack’, ‘leakage’, ‘drainage condition’ and ‘ground condition’. However, the evaluation indicators analyzed with relatively low correlation found in this study need further studies.

4. As a result of the Cost-effectiveness analysis for each scenario, it was analyzed that it is advantageous in terms of efficiency to carry out the performance evaluation excluding evaluation items with low importance and occurrence frequency.

5. The performance evaluation model of the tunnel reflecting the safety, durability and usability presented in this study may contribute to the establishment of various maintenance strategies for facility managers who need to systematically budget for maintenance due to facility aging issues.

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