	Capacity (Traffic condition)	0.228/0.243

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

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.

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

Table 4. Results of correlation analysis (continue)

Independent variable	Pearson coefficient of correlation (R)	Correlation analysis
Rebar Exposure	0.199	Weak
Drainage Condition	0.476	Distinct
Ground Condition	0.308	Distinct

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(Table 1).

Table 5. Performance factors excluded from assessment according to scenarios

Scenario #1	Scenario #2
Exfoliation, Spalling, Segregation, Pipe Utility Conduit Condition	Exfoliation, Spalling, Segregation

4.2 Cost-Effectiveness Analysis

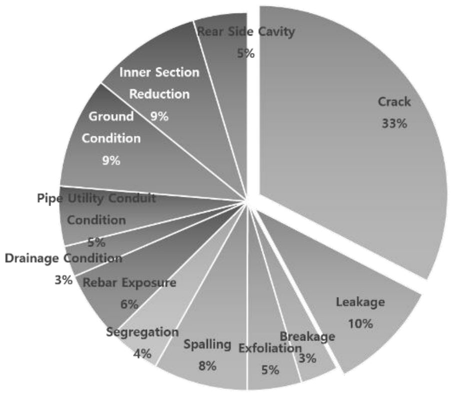
For the Cost-Effectiveness analysis of the performance evaluation system by the scenario, the cost-effectiveness ratio(C/E) shown in Eq. (9), which is generally used in the economic analysis of public projects, was applied(KISTEP, 2017; Commonwealth of Australia, 2006).

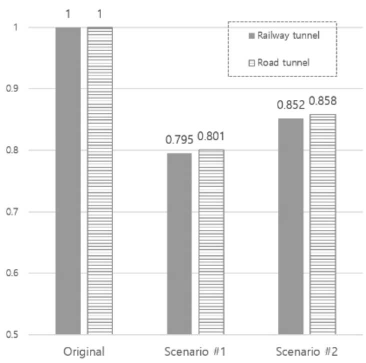
$$C/E = Total\ cost/Total\ benefit, \qquad (9)$$

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(performance factor).

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'.





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

Fig. 5. Cost effectiveness analysis for optimizing performance factors

5. CONCLUSIONS

In this study, in order to develop a performance-oriented evaluation system for roads and railroad tunnels constructed by the NATM method, 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 conducted to evaluate the importance of each performance evaluation index. A correlation analysis was conducted to evaluate the significance of the presented evaluation model. Finally, in order to derive a cost-effective evaluation system, the Cost-effectiveness analysis was conducted 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 derived.

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 evaluation 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’.

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

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