A Multi-Level Asset Management Decision Method Considering the Risk and Value of Bridges

Jong-wan Sun¹, Kyung-hoon Park² and Min-Jae Lee*³

¹Researcher, Structural Engineering Research Division, Korea Institute of Civil Engineering and Building Technology, Korea
²Senior Researcher, Structural Engineering Research Division, Korea Institute of Civil Engineering and Building Technology, Korea
³Professor, Department of Civil Engineering, Chungnam National University, Korea

Abstract
For efficient and rational utilization of limited bridge maintenance budgets, a method which could be applied to project-level and network-level bridge maintenance decision making issues considering the performance and direct and indirect value of each bridge is proposed. A representative bridge performance is shown as a risk level which is a combination of risk degrees indicated by condition state and safety factor and the replacement value was calculated by considering the direct construction cost and implicit value of bridges in consideration of traffic environments according to the location. The risk matrix was composed using the risk level and the replacement value, and the risk grade which represented the overall risk of each bridge was defined. The model to convert the phased risk level of each bridge to the risk index which was the continuous and quantitative index by applying the utility theory was presented, and the formalized model for calculating network-level performance index considering the risk index and relative importance of each bridge was suggested. In order to consider actual applicability of the suggested method, an analysis on a large number of actual bridges was carried out. A prior preparation regarding the stable distribution of budget and structural and environmental risks is possible so that it would be possible to quantify objective decision making for bridge maintenance.

Keywords: bridge management system; asset management; risk, valuation; decision making

1. Introduction
It is difficult to secure the safety of all bridges evenly with reactive maintenance using post-maintenance management focused on severely deteriorated bridges at a project-level. Therefore, strong efforts for preventive maintenance are being made continuously, and for this purpose, it is necessary to identify the current bridge performance level and adopt a decision-making system considering the implicit values of a bridge.

The International Infrastructure Management Manual (IIMM) (INGENIUM and IPWEA 2006) published by the National Asset Management Steering Committee in Australia and New Zealand (NAMS) presents examples of basic risk calculation methods using the occurrence probability of risk cases and the resulting cost of cases. AASHTO bridge management analysis software (formerly Pontis) in U.S. which is evaluated to be the most advanced bridge management system uses the health index as the performance evaluation index of each bridge (Katou and Satou, 2008), and recently the utility value considering performance, risk, mobility and life-cycle cost is being applied (AASHTO 2011). The detailed guideline (MLTM 2010; NEMA 2014) is being prepared in Korea for managing public national infrastructure, and the performance evaluation method of each bridge and basic response directions are described in the detailed guideline.

Coe (2002) suggested a method to calculate the risk score considering various performance indexes of bridges, personnel and materiel loss, economic index, and occurrence scale, and establishment and use of the cost plan for bridges with high risk concerning decision making. Baker (2009) suggested a method to calculate the priority order considering cost changes according to the definition of risk cases from various viewpoints and risk reduction. Sathananthan et al. (2010) suggested a method to decide the risk for each bridge at the network-level and calculate the relative importance.

Various efforts to secure applicability in connection with the risk and value of each bridge for bridge maintenance systematically are being made. However, the previous bridge management system only presents
the performance of each bridge and the consequent response standards, and when there are a number of bridges requiring measures, no grounds for making a decision regarding the priority order of bridges to deliver measures is presented. Also, the implicit risk of each bridge and the network-level performance and value improvement effect due to maintenance measures are not considered quantitatively, and the potential value of bridges cannot be considered. Especially, the support of network-level decision making through a connection with the risk and value of bridges is not provided.

The purpose of this study is to suggest a project-level performance evaluation method by considering the internal and external performance as well as direct and indirect value of each bridge comprehensively and provide a systematic decision making support method for rational and safe bridge maintenance at the network-level. Also, the actual applicability was considered by applying the method suggested to a number of bridges.

2. Bridge Evaluation Method Considering Risk and Value

The bridge evaluation method in consideration of the risk and value of bridges can be classified into the project level and network level shown in Figs. 1. and 2.

The project level evaluation shown in Fig. 1. is divided into the risk evaluation and value evaluation of each bridge. The representative performance of each bridge according to the safety grade by bridge and the risk level which is a combination of condition and safety factor are drawn for each bridge. And, the replacement value which is expressed as the sum of the replacement cost and user cost is calculated. The risk matrix method for the occurrence result and probability is applied to draw the risk grade which is the final project-level evaluation grade. For a bridge which falls below the target management standard with determined risk grade, measures (construction method, etc.) are determined and estimated required costs and level of performance improvement after measures (risk level) are estimated. In Fig. 1., Ⓐ indicates all target bridges for management, Ⓟ indicates the selected bridges among all bridges, and Ⓡ indicates the bridges which are not selected.

The network-level bridge evaluation shown in Fig. 2. is carried out based on the project-level of each bridge evaluation result. The risk level, risk grade and replacement value calculated for each bridge are utilized. The risk index introduced for utilizing a number of each bridge evaluation results at the network level is applied to bridges before and after taking maintenance measures. The risk index is calculated by using the post-measure risk level and risk grade of selected bridges considering the budget limitation, budget allocation for each subordinate management authority and risk grade level among the target bridges for measures selected due to shortfall of the target management standard in project-level evaluation. Also, the risk index of bridges before measures which satisfy the target management standard is calculated and the replacement value based importance of all bridges is evaluated. It is possible to predict the maintenance budget, target for measures, post-measure network-level performance index with the method to find a countermeasure which satisfies the required conditions (budget or performance management target) by repeating the process to evaluate the improvement level of cost for measures on selected target bridges and the improvement level of network-level performance (risk index) after measures have been taken. Ⓡ in Fig. 2. indicates the target bridges newly adjusted in case the required conditions are not satisfied. The specific method and analysis cases for each process will be explained later.
3. Project-level Bridge Evaluation and Management

3.1 Definition of Risk Level According to the Bridge Performance Indicator

The main decision making issue in bridge management is to decide which bridge among damaged or deteriorated bridges is to be handled preferentially under the limited budget. A system to evaluate all bridges consistently is necessary for deciding the rational priority order in such decision making issue, and the performance index to judge the characteristics of each bridge quantitatively is also necessary.

Keeney and Gregory (2005) asserted that the performance index used for decision making should be understandable, utilizable, clear, inclusive and direct. The condition state and safety factor presented in the detailed guideline (MLTM 2010) are used to evaluate the performance of bridges in Korea as shown in Tables 1. and 2. The condition state represents the soundness according to visual judgment on the exterior of bridges, and the safety factor represents the implicit structural safety of bridges. The minimum value of two indexes was applied for the final safety grade, but there are limitations in ambiguity, inclusion and directness for using such indexes as the performance index suggested by Keeney and Gregory (2005).

Table 1. Meaning of Performance Measures

| Safety grade | Condition state | Safety factor |
|--------------|----------------|--------------|
| A            | Best condition with no problems | SF>1.0       |
| B            | Condition that a slight defect in assistance members has occurred and partial measures are required to improve durability | 0.9≤SF<1.0, Load carrying capacity>Design load |
| C            | Condition that a slight defect in main members or extensive defect in assistance members has occurred and measures are required to improve durability | 0.9≤SF<1.0  |
| D            | Condition that measures are strongly required due to defects in main members | 0.75≤SF<0.9 |
| E            | Condition that prohibition on use and urgent measures are required due to significant defects in main members | SF<0.75     |

In order to overcome such limitations regarding the final evaluation standards of bridges, the risk level (RL) was defined as the new performance index which could be utilized as a direct decision making evaluation index using two indexes including condition state and safety factor at the same time, while not using the minimum values. Since the structural safety of bridges should be considered preferentially in comparison to the external condition, C–E grades in which the safety factor fell below the design standard as shown in Table 2. were classified into RL 6–8 based on the safety factor by excluding the effect of condition state. Also, in case the safety factor exceeded the design standard, RL 1–5 were defined based on the condition state. RL has an advantage that it can show the risk level of a bridge clearly while considering the condition state and safety factor at the same time and is easy to understand and utilize.

Table 2. Definition of Risk Level

| Risk level | Condition state | Safety factor | Degree of risk |
|------------|----------------|--------------|----------------|
| RL 1       | A              | A–B          | Best condition with no problems |
| RL 2       | B              | A–B          | Condition which has no problem from the safety aspect but there is a risk of lower durability due to a slight defect in assistance members |
| RL 3       | C              | A–B          | Condition which has no problem from the safety aspect but there is a possibility of risk in the functionality aspect due to a slight defect in main members |
| RL 4       | D              | A–B          | Condition which has no problem from the safety aspect but a dangerous condition in functionality due to a defect in main members |
| RL 5       | E              | A–B          | Condition which has no problem from the safety aspect but very dangerous condition in functionality due to a serious defect in main members |
| RL 6       | A–E            | C            | Dangerous condition from the safety aspect which requires passing restriction immediately |
| RL 7       | A–E            | D            | Very dangerous condition from the safety aspect which requires passing restriction immediately |
| RL 8       | A–E            | E            | Extremely dangerous condition from the safety aspect which requires no passing immediately |

According to the definition of degree of risk for each RL, both measures to reinforce and restore design performance and repair for recovering usability should be carried out due to the structural safety issue of RL 6–8, and only measures for recovering usability are required for RL 1–5 which have no problem concerning structural safety. RL is inclusive and direct from the aspect that the clearer and detailed contents of the measure can be defined as one index. Also, it is not ambiguous in that it can be judged that it has the same risk in the case it is evaluated that RL is the same. Therefore, it is judged that RL is rational from the decision making aspect in comparison to the condition state, safety factor and safety grade used in the current guideline.

3.2 Bridge Replacement Cost and Valuation

If all bridges have the same value when their quantitative risk is judged, it is appropriate to invest the budget on a bridge with a high-risk level (RL) preferentially. However, each bridge has a different tangible and intangible value according to internal and external environments, so it is necessary to consider RL as well as the value of each bridge for rational decision making.
Infrastructure is considered as an asset and its accounting value is measured according to the introduction of a principle of accrual accounting in many countries. However, the tangible and intangible value standard of a bridge from the engineering usability aspect should be considered. For example, if there is a significant difference in annual average daily traffic (AADT) of the same type bridge, the bridge has the same accounting value but it cannot be considered that the bridge has the same value from the usability aspect, and also there is a difference in the deterioration, so the remaining life should be evaluated differently. Also, a bridge which has the same traffic volume but a different size has the same value from the usability aspect, but it cannot be considered that it has the same accounting value.

The sum of direct and indirect costs that occurred on the assumption of reconstructing the current bridge at the current location in the same form was defined as the replacement value (RV) and was utilized for drawing the rational value of the bridge. RV was defined as the sum of bridge replacement cost which was direct cost and user cost which was the indirect cost caused by the reconstruction of the bridge. The replacement cost consists of the construction cost, temporary structure cost and demolition cost, and the user cost is the implicit value considering the traffic environment according to the location of a bridge, and consists of the vehicles operating cost and time delay cost. The construction cost includes costs for design, construction and inspection, and the user cost is calculated by considering the main road where the bridge is included, the number and width of traffic lanes in detours and traffic volume per time and vehicle type. The detailed cost data for calculating the replacement cost and user cost was drawn from the cost model (MLTM 2012) developed for managing the lifestyle of bridges on general national roads.

Unlike the construction of new bridges, various reconstruction methods (installation of temporary structure, control of traffic lanes, etc.) may exist according to the existing traffic condition and environmental and technical conditions and a difference in the direct and indirect cost required occurs according to each method. Therefore, the minimum RV was defined as the best bridge value. Since RV is calculated by considering the direct cost required for reconstructing the current bridge and indirect cost occurred accordingly, it can be regarded that all explicit and implicit costs of bridges are included. It is RV at the moment when the reconstruction has been decided, it is assumed that there is no difference in the engineering deterioration level.

In order to judge the appropriateness of RV and applying it to a replacement cost model, RV and replacement cost on sample bridges were obtained and the frequency analysis was carried out. RV and replacement cost indicate the log normal distribution as shown in Fig.3. It was confirmed that RV considering the user cost which was the implicit value was higher on average in comparison to the replacement cost and the standard deviation increased by the variability such as traffic volume for each bridge and environmental condition.

![Fig.3. Probability Distribution of Replacement Cost and Value](image)

The range of RV was decided according to the range of cumulative probability distribution, and it was defined that as RV became higher, the importance (influence level) of the relevant bridge became higher.

### 3.3 Bridge Risk Evaluation and Management

The level of influence from the risk level (RL) and replacement value bridge defined earlier were considered for deciding the priority order of maintenance based on the risk of a bridge. The qualitative risk matrix method (Choi et al., 2013, INGENIUM & IPWEA 2006) was used for a method to consider two influence factors at the same time by considering the possibility of practical application. The risk matrix method was evaluated by the occurrence and consequence, and the risk considering RL according to the performance index and the level of influence according to replacement value (RV) was defined as the risk grade (RG) in this study. RG was divided into 5 sections from "V(5)" grade of 'very high' to "I(1)" grade of 'very low' for application.

| Cumulative Probability Range | Replacement Value Range | Impact |
|------------------------------|-------------------------|--------|
| F(RV)<0.2                    | RV≤7.46                 | Very Low |
| 0.2≤F(RV)<0.4                | 7.46<RV≤12.10           | Low    |
| 0.4≤F(RV)<0.6                | 12.10<RV≤18.32          | Medium |
| 0.6≤F(RV)<0.8                | 18.32<RV≤29.69          | High   |
| F(RV)≥0.8                    | RV>29.69                | Very High |

The level of influence from the risk level (RL) and replacement value bridge defined earlier were considered for deciding the priority order of maintenance based on the risk of a bridge. The qualitative risk matrix method (Choi et al., 2013, INGENIUM & IPWEA 2006) was used for a method to consider two influence factors at the same time by considering the possibility of practical application. The risk matrix method was evaluated by the occurrence and consequence, and the risk considering RL according to the performance index and the level of influence according to replacement value (RV) was defined as the risk grade (RG) in this study. RG was divided into 5 sections from "V(5)" grade of 'very high' to "I(1)" grade of 'very low' for application.
The response measures for each RG were classified according to the severity of damage that occurred and urgency of passing restrictions or repair measures as shown in Table 4, for the administrators' easy understanding.

| Risk grade | Response |
|------------|----------|
| I (Very low) | Condition that the damage is insignificant and does not require immediate repair but repair should be decided after a follow-up study |
| II (Low) | Condition that the damage is not serious but repair should be carried out after a detailed follow-up study |
| III (Intermediate) | Condition that the damage does not give serious trouble to the bridge but repair should be carried out soon |
| IV (High) | Condition that the damage is significant but no emergency measure is required and measures should be taken soon |
| V (Very high) | Condition that the safety level of the bridge falls below the design safety factor or the damage is very serious so that passing restrictions and emergency measures should be carried out first and measures should be taken immediately |

The risk grade is a performance index calculated by considering the condition state, safety factor, size, and importance of a bridge from the road traffic aspect comprehensively, and the same grade means a similar risk. Therefore, the risk grade can be used as a standard for the target management level of bridges, and it can be utilized directly for selecting the target for maintenance measures.

In the case of RL 6–8 where RL was evaluated higher from the bridge performance aspect since the present performance level fell below the design standard, RG was defined as V grade for all cases regardless of relative influence. In case it is safe from the performance aspect (Safety factor A or B) and the condition state is E grade (RL 5), V grade was assigned equally except for the case in which the relative influence was very low as extreme durability declined, and in the case of RL 4 (Safety factor A or B, condition state D), V grade in the case of Very High for the relative influence, III grade in the case of Very Low for the relative influence and IV grade for all other cases were assigned. In the same way, in the case of RL 2, 3, RG was assigned according to the relative influence, and in the case of RL 1, RG I grade which was the lowest grade was assigned regardless of relative influence. Such assignment of grade through risk matrix was drawn by considering the actual opinions of bridge management authorities and experts, and can be adjusted according to the status of the management authority.

The management authority decides the management level of the target bridge for management and takes measures through the defined RG. In order to manage a bridge over RG III grade (I–III grade), a bridge with very high relative influence can be managed with the maintenance measure over RL 2 (condition state B, safety factor B), a bridge with very low relative influence can be managed with the maintenance measure over RL 4 (condition state D, safety factor B) and other bridges can be managed with the maintenance measure over RL 3 (condition state C, safety factor B). Also, if the management authority intends to manage the bridges to RG II grade or higher (I, II grade), the management level can be secured in a method to take measures by selecting RL 1 (condition state A, safety factor B) in the case of very high relative influence, RL 3 (condition state C, safety factor B) in the case of very low relative influence and RL 2 (condition state B, safety factor B) for other cases.

4. Network-level Bridge Evaluation and Management

4.1 Calculation of Risk Index

The whole network-level performance evaluation is necessary for the decision making task of a bridge management authority such as budget investment to effect analysis, network-level performance management goal setting and determination of maintenance target for the year through the priority order, and it should be expressed as the average performance level of the management authority.

The performance index of each bridge expressed as the risk level or risk grade is defined in discrete form, so it is difficult to show the average network-level performance level or carry out the determinant evaluation within the same grade. Also, the evaluation standard for each risk grade is not a value expressed as quantitative value such as risk probability, and it cannot be assumed that the risk level or performance level changes linearly as the grade increases or decreases, so it is difficult to apply it as the whole network-level representative factor. In case it is difficult to quantify the evaluation index with a precise analytical method or probabilistic method, it is possible to define the utility function and use it as the evaluation index according to the qualitative preference evaluated by an expert group using the utility theory (Sun et al. 2011).

In this study, the preference (Proper level of bridge maintenance by a management authority from the bridge performance aspect) according to RL 1–8 was defined in the form of a utility function by applying the utility theory in order to define the continuous and quantitative risk index connected with risk level. The direct measurement to reflect the preference evaluation result according to the risk level carried out by 9 experts including the academic community, management authority, relevant industry and researchers was utilized for the evaluation of utility function. It can be confirmed that the difference in the preference value increases continuously from RL1 to RL6 as shown in Table 5., but it decreases in the following steps, and RL1–4 have a low average preference value while RL5–8 have a high average preference value.
In order to consider such characteristics, the polynomial regression analysis was carried out, and the quartic polynomial which has a high coefficient of determination was defined as the utility function model.

Table 5. Preference Assessment Results According to Direct Measurement

| Risk Level | RL1 | RL2 | RL3 | RL4 | RL5 | RL6 | RL7 | RL8 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Avg. of Preference | 0.00 | 0.05 | 0.11 | 0.24 | 0.42 | 0.66 | 0.87 | 1.00 |
| Standard Deviation | 0.00 | 0.01 | 0.01 | 0.04 | 0.06 | 0.05 | 0.02 | 0.00 |
| Gap of Avg. of Pref. | - | 0.05 | 0.06 | 0.12 | 0.19 | 0.24 | 0.21 | 0.13 |

4.2 Determination of Maintenance Priority for Bridges

The most general method for integrating the performance characteristics value defined for each bridge and using it at the network-level is the method to use the physical scale of each bridge such as the place, extension and top plate area as the weighted value (NASC 2012; Sun et al. 2011). However, the physical scale of a bridge cannot represent the tangible and intangible value of a bridge. Therefore, the ratio of the replacement value of each bridge accounting for the sum of replacement value of all target facilities for management was defined as the importance of a bridge based on the network-level replacement value. This can be formalized as equation (1).

\[ RV_i^N = \left( \frac{RV_i^P}{\sum_{i=1}^{n} RV_i^P} \right) \]  

(1)

Here, \( RV_i^N \) is the importance of each bridge \( i \) at the network-level, \( VR_i^P \) the replacement value of each bridge \( i \), \( N \) is the network-level which indicates bridge group, and \( P \) is the project-level which indicates each bridge.

4.3 Network-level Evaluation

The average performance index for all target bridges can be useful for the annual analysis performance trend of target bridges in a specific management zone or management authority, cost to effect estimation and comparison of maintenance level for each management authority. The average risk index \( (RI^N) \) of a specific target bridge group was defined as the sum of the product of project-level risk index \( (RI^P) \) of each bridge and replacement value-based network-level importance \( (RV_i^N) \) of each bridge as shown in Equation (2).

\[ RI^N = \sum_{i=1}^{n} RI^P_i \cdot RV_i^N \]  

(2)

Also, the main factor which is required for network-level decision making is to decide the scale of the target for maintenance measures. The scale of the target for maintenance measures can be defined by adding the characteristics values of bridges of which performance level (risk grade) falls below the target management standard. However, in case the management authority consists of various subordinate authorities and each subordinate authority has a different scale of secured bridges, it is difficult to compare the management level between subordinate authorities with the scale of target bridges only.

Therefore, the proportion of risky bridges (PRB) requiring maintenance interventions was considered for enabling intuitive relative comparison, and the proportion of risky bridges \( PRB^N \) requiring measures among all bridges can be formalized as Equation (3).

\[ PRB^N = \sum_{i=1}^{n} x_i (RG_i^P) \cdot RV_i^N \]  

(3)

Here, \( PRB^N \) is the ratio of bridges requiring measures among all bridges, and \( x_i \) is the control function which is 1 in case \( RG_i^P \) is unable to exceed the target management standard determined by the management authority or 0 in case it can exceed.

The network-level performance of target bridges for measures after final measures are carried out can be evaluated as shown in Equations (4) and (5).

\[ RI^N_a = \sum_{i \in X} (RI^P_i \cdot RV_i^N) + \sum_{i \in X} (RI^P_{ib} \cdot RV_i^N) \]  

(4)

\[ PRB^N_a = \sum_{i \in X} x_i (RG_i^P) \cdot RV_i^N \]  

(5)

Here, \( \alpha \) and \( \beta \) mean after and before measures respectively, and \( i \) means each bridge, \( X \) means the bridge group where measures are carried out among the bridges which fell below the target management standard and were selected as the target bridges for measures.

5. Case-study Analysis for Each Level

5.1 Target Bridge Information Analysis

The appropriateness of performance evaluation of each bridge considering the concept of risk and the validity of methodology suggested for supporting the network-level evaluation were reviewed using the above-mentioned risk level, replacement value, risk grade and risk index models. The analysis of basic information saved in the existing bridge management system (BMS) database regarding 3,582 actual bridges dispersed throughout the areas was carried out. The bridges managed by 10 local offices in 5 districts for each area were selected as target bridges for the whole network-level and small network analysis. The place, average service life of target bridges for each management authority and distribution of bridges for each safety grade are as shown in Table 6. Also, the risk level and replacement value evaluation on all bridges in each zone and office was carried out for the analysis at each level.
Table 6. Bridge Information

| Agency | No. of Bridges | Length (km) | Avg. Service Life | No. of Bridges by Safety Grade |
|--------|----------------|-------------|------------------|--------------------------------|
| Area Office |  |  |  | A | B | C | D |
| E 1 | 286 | 24.3 | 15.8 | 65 | 215 | 6 | - |
| E 2 | 402 | 45.2 | 16.6 | 128 | 269 | 5 | - |
| W 3 | 359 | 36.9 | 17.1 | 80 | 271 | 7 | 1 |
| W 4 | 285 | 24.2 | 15.2 | 104 | 177 | 4 | - |
| S 5 | 338 | 27.2 | 16.5 | 73 | 262 | 3 | - |
| S 6 | 379 | 33.2 | 16.1 | 150 | 221 | 8 | - |
| N 7 | 417 | 30.7 | 15.2 | 162 | 244 | 6 | 1 |
| N 8 | 364 | 33.5 | 14.5 | 60 | 301 | 3 | - |
| M 9 | 382 | 31.1 | 16.1 | 99 | 274 | 8 | 1 |
| M 10 | 374 | 28.8 | 16.3 | 44 | 317 | 13 | - |
| Sum. | 3,582 | 314.9 | 15.9 | 965 | 2,551 | 63 | 3 |

Table 7. shows the replacement cost and user cost of each management authority and total replacement value. Although there is a difference from region to region, the average value for each place is 2.36 billion KRW and 26.8 million KRW per m. The average user cost was 7.73% of the replacement cost.

Table 7. Value Assessment of Bridges

| Agency | Replacement Cost (10^8 Won) | User Cost (10^8 Won) | Total Value (10^8 Won) | Unit Value (10^8 Won) |
|--------|----------------------------|---------------------|-----------------------|----------------------|
| Area Office |  |  |  |  |  |
| E 1 | 6,725.6 | 666.4 | 7,391.5 | 25.84 |
| E 2 | 10,656.4 | 1,356.1 | 12,010.7 | 29.88 |
| W 3 | 8,708.5 | 594.5 | 9,302.6 | 25.91 |
| W 4 | 5,959.0 | 370.3 | 6,329.1 | 22.21 |
| S 5 | 7,341.8 | 672.4 | 8,013.7 | 23.71 |
| S 6 | 8,258.4 | 561.2 | 8,819.3 | 23.27 |
| N 7 | 7,630.1 | 391.5 | 8,021.4 | 19.42 |
| N 8 | 7,689.5 | 505.9 | 8,195.1 | 22.51 |
| M 9 | 7,887.0 | 456.8 | 8,343.6 | 21.84 |
| M 10 | 7,588.2 | 492.2 | 8,080.2 | 21.60 |
| Sum. | 78,450.58 | 78,444.5 | 6,067.3 | 84,507.2 |

The scale of bridges (places, extension, etc.) replacement cost, and user cost were linearly proportional, but the reconstruction condition of bridges such as installation of temporary structure changed according to the traffic environment and condition of each bridge (number of traffic lanes in the main road and detour, extension, traffic volume, etc.), so the correlation was not high. As shown in Fig.4.

5.2 Network-level Bridge Management Case Analysis

The average risk index of 10 local offices considered the utility function and importance of each bridge. The risk grade rate was evaluated using the risk grade calculated with the risk level and replacement value for each bridge and importance of each bridge.

The risk grade distribution and average risk index of each management authority are as shown in Fig.5.

These show that the average risk index of W4, S6 and N7 which had a high ratio of low risk grade (Risk grade V) is shown to be higher (lower risk). On the contrary however, the average risk index of M10 which had a high ratio of high-risk grade (Risk grade IV) is shown to be lower (high risk). If it is defined that the management goal is maintained at the risk grade III or higher, the budget should be invested on approximately 1.04% of bridges, and the budget should be allocated in the order of M10, S6, E2, N8, N7, S5, W4 and M9. Therefore, an evaluation method considering the risk and importance of bridges suggested in this study is a rational decision making method to allocate budget to necessary fields in comparison to the previous methods.

6. Conclusion

In order to manage a large number of bridges which were deteriorating continuously safely and economically, a rational and efficient method considering implicit risk and value was suggested. The representative performance of bridges was shown as the risk level with improved possibility of understanding, utilization, clarity, inclusion and immediacy in comparison to previous performance indexes such as condition state and safety factor which could be actually utilized as the factor for various decision making processes. Also, the replacement value of bridges was defined in consideration of explicit reconstruction cost and implicit indirect loss which
could be a burden to users, and it was considered as a relative influence which each bridge held in the existing network. The risk matrix considering the risk level and replacement value with the possibility of occurrence and risk level for the overall risk of each bridge was composed, and the risk grade which could be applicable flexibly according to the goal management level required by the management authority was defined. The risk grade could be utilized for selecting maintenance alternatives and setting the management goal directly.

The model which converted the risk level which was the leveled performance index of each bridge to the risk index which was the continuous and quantitative index by using the utility theory was presented and the formalization of network-level risk index was carried out though the combination of importance for each risk index and bridge. Also, the formalized model using the risk index and risk grade was suggested in order to calculate the size of dangerous bridges at the network-level by considering the importance of each bridge. And it can be used for deciding the grounds for budget allocation for each management authority, budget investment effect analysis, performance management level comparison and goal management level.

Since direct and indirect risk and value are considered in the suggested method in comparison to the allocation of budget based on quantity, it will enable rational decision making, stable accounting budget allocation and advanced preparation for structural and environmental risks, contributing to the securement of bridge safety.

If the suggested risk and value based performance evaluation method combines with the optimal decision making technique which could maximize the performance within the cost and investment effect information for actual measures and the restriction of budget, cost-efficient optimal decision making which could secure bridge safety while maximizing management efficiency within the range satisfying the restriction of budget could be drawn in the future.

Acknowledgements
This research was supported by grant (16RDRP-B066173-04) from the Regional Development Research Program funded by the Ministry of Land, Infrastructure and Transport of Korea, and National Research Foundation of Korea (NRF-2009-0090240).

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