Life-Cycle Bridge Network Management under Uncertainty

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Abstract: Due to the increasing demand for maintaining deteriorating bridges efficiently, life-cycle bridge performance and cost analysis have been investigated extensively. A deteriorating bridge should be maintained to keep its performance above the predefined safety target. Maintaining a larger safety target requires a larger maintenance cost and results in a reduced probability of failure during the service life of a deteriorating bridge. This paper presents a probabilistic approach to determine the target performance level for life-cycle bridge management at the network-level. The target reliability indices of the individual bridges in a network are determined by simultaneously maximizing the reliability index of the bridge network and minimizing the expected maintenance cost over a predefined time period. An application of the proposed methodology is presented.

Keywords: bridge network, life-cycle analysis, optimization, performance, reliability, service life.

1. Introduction

Deteriorating bridges should be maintained to ensure the safety during their service life cost-effectively (AASHTO 2007; FHWA 2015; Frangopol & Liu 2007). Along with increasing demand for maintaining deteriorating bridges efficiently, life-cycle bridge performance and cost analysis have been investigated extensively during the last two decades (Frangopol & Soliman 2016). In general, the bridge owners and management agencies manage multiple bridges in a given region. In order to achieve the efficient service life management of multiple bridges in a network, life-cycle bridge performance and cost analysis at the network level are essential (Bocchini & Frangopol 2011; Hu et al. 2015; Yang & Frangopol 2018).

Maintenance types can be categorized into preventive and essential. As shown in Figure 1, preventive maintenance is performed at scheduled times, resulting in a reduction of the deterioration rate. The essential maintenance is performed when the bridge reliability reaches a target reliability index. The optimum life-cycle bridge management considering preventive and essential maintenances is generally affected by the target reliability. For example, if the target reliability index $\beta_{tg,2}$ is larger than $\beta_{tg,1}$, $\beta_{tg,2}$ leads to earlier essential maintenance, as shown in Figure 1. Finally, more frequent essential maintenance and larger maintenance cost can be induced by applying $\beta_{tg,2}$ instead of $\beta_{tg,1}$. However, a larger safety of a bridge with $\beta_{tg,2}$ is expected during its given service life than that associated with $\beta_{tg,1}$.

Several codes and standards including EN1990 (2002), ISO2394 (2015), ISO13822 (2010), and ASCE 7-10 (2013) prescribe the target reliability indices for a wide range of engineering structures. However, these target reliability indices are prescribed for the design of new structures and may not be appropriate for management of existing bridges. If the same target reliability index is applied for the design of a new bridge and bridge management, the bridge management may be uneconomical (Vrouwenvelder & Scholten 2010; Kim et al. 2020). Therefore, target reliability index for bridge management needs to be determined appropriately.
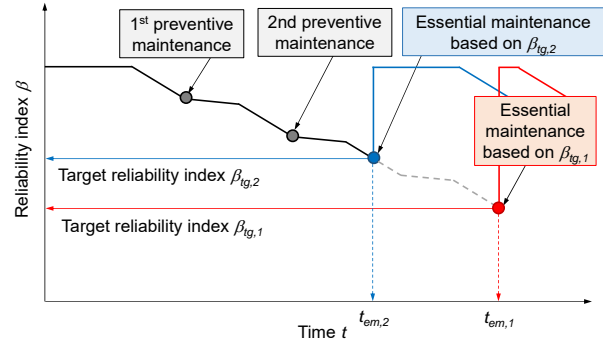

Figure 1. Reliability index profile with preventive and essential maintenances.

This paper presents a probabilistic approach to determine the target performance level for life-cycle bridge network management. The target reliability indices of the individual bridges in a network are determined using the multi-objective optimization associated with maximizing the reliability index of the bridge network and minimizing the expected maintenance cost over a predefined time period. When the same and different target reliability indices of the individual bridges are applied, the bridge network reliability indices and expected total maintenance costs of the Pareto solutions are compared. Furthermore, the relationship between the number of individual bridges in the network and the target reliability indices of the bridges are investigated. An application of the proposed methodology is presented.

2. Bridge Network Reliability

The bridge network reliability $P_{s,net}$ is expressed as (Liu & Frangopol 2005, 2006):

$$P_{s,net} = \sum_{i=1}^{N_{bn}} \left(P_{b,i} \right) \tag{1}$$

where N_{bn} is the number of branches for the connected bridge network; and $P_{b,i}$ is the occurrence probability associated with the ith branch. Assuming that the

individual bridges in the network are statistically independent, the occurrence probability $P_{b,i}$ is computed as:

$$P_{b,i} = \prod_{j \in \mathbf{S}}^{N_{s,i}} \left(P_{s,j} \right) \cdot \prod_{k \in \mathbf{F}}^{N_{f,i}} \left(1 - P_{s,k} \right) \qquad (2)$$

where $\mathbf{S}$ and $\mathbf{F}$ are the sets of bridges associated with safe and failure sates, respectively; $N_{s,i}$ and $N_{f,i}$ are the number of bridges in the sets $\mathbf{S}$ and $\mathbf{F}$, respectively; and $P_{s,j}$ is the reliability of the jth individual bridge.

When the bridge network consists of three individual bridges connected in series as shown in Figure 2(a), the number of branches for the connected bridge network N_{bn} is one. According to Eq. (1), the bridge network reliability $P_{s,net}$ becomes

$$P_{s,net} = P_{s,1} \cdot P_{s,2} \cdot P_{s,3} \qquad (3)$$

For the bridge network with three individual bridges shown in Figure 2(b), N_{bn} is three. Therefore, the bridge network reliability $P_{s,net}$ is equal to

$$P_{s,net} = P_{s,1} \cdot \left(1 - P_{s,2} \right) \cdot P_{s,3} + \left(1 - P_{s,1} \right) \cdot P_{s,2} \cdot P_{s,3} + P_{s,1} \cdot P_{s,2} \cdot P_{s,3} \qquad (4)$$

(a)

Number of branches for the connected bridge network $N_{bn} = 1$

(b)

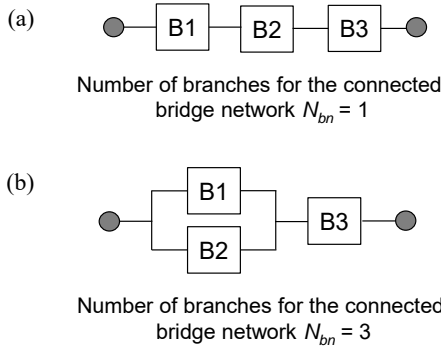Number of branches for the connected bridge network $N_{bn} = 3$

Figure 2. Bridge network connectivity: (a) series system; (b) series-parallel system.

The relation between the bridge network reliability $P_{s,net}$ and reliability index β_{net} is

$$\beta_{net} = \Phi^{-1} \left(P_{s,net} \right) \qquad (5)$$

3. Maintenance Cost

The maintenance cost of the bridge network is the total required cost for maintaining all the individual bridges in a network. For a predefined time period t_{pd}, the expected total maintenance cost $E(C_{ma})$ of a bridge network is computed as (Kong & Frangopol 2004a)

$$E\left(C_{ma} \right) = \sum_{i=1}^{N_b} \left[r_{ty,i} \cdot r_{sz,i} \cdot \int_0^{t_{pd}} C_i(t) f_i(t) dt \right] \qquad (6)$$

where N_b is the number of individual bridges in the bridge network; $r_{ty,i}$ and $r_{sz,i}$ are the parameters representing the type and size of the ith bridge, respectively; $f_i(t)$ is the probability density function (PDF) of the maintenance to be applied for the ith bridge; and $C_i(t)$ is the maintenance cost function. Considering that the essential maintenance is applied when the bridge reliability index reaches its

target value β_{tg}, the cumulative distribution function (CDF) associated with the PDF $f_i(t)$ in Eq. (6) is computed as (Kong & Frangopol 2005)

$$F_i(t) = P\left(\beta_i(t) < \beta_{tg,i} \right) \qquad (7)$$

where $\beta_i(t)$ is the reliability index of the ith individual bridge at time t. The maintenance cost function $C_i(t)$ in Eq. (6) is (Kong & Frangopol 2004b)

$$C_i(t) = f\left(\beta_i(t), \Delta\beta_i \right) \qquad (8)$$

where $\Delta\beta_i$ is the reliability improvement resulted from the application of the maintenance.

4. Target Reliability Index Considering Bi-Objectives

An increase in the target reliability of a bridge or a group of bridges in the network can lead to an increase in the bridge network reliability. However, additional maintenance cost is required. In order to address these conflicting objectives optimally, a bi-objective optimization problem needs to be solved. The associated bi-objective optimization is formulated as

- Find $\boldsymbol{\beta_{tg}} = \{\beta_{tg,1}, \beta_{tg,2}, \ldots. \beta_{tg,Nb}\}$
- For maximizing β_{net}, and minimizing $E(C_{ma})$
- Subject to $\beta_{lb} \leq \beta_{tg,i} \leq \beta_{ub}$

The design variables of this bi-objective optimization are the target reliability indices $\beta_{tg,i}$ of the individual bridges (or bridge groups) in the network. The objectives are maximizing the bridge network reliability index β_{net} and minimizing the expected total maintenance cost $E(C_{ma})$. The bridge network reliability index β_{net} is formulated with the target reliability indices of the bridge groups using Eqs. (1) and (5). The expected total maintenance cost $E(C_{ma})$ is computed using Eq. (6). $\beta_{tg,i}$ should range between the lower and upper bounds of the reliability index (denoted as β_{lb} and β_{ub}, respectively). In this study, β_{lb} and β_{ub} are assumed as 2 and 4, respectively.

The bi-objective optimization to determine the target reliability index is applied to an existing bridge network in South Korea. To reduce the number of design variables and computational cost of the bi-objective optimization problem, the individual bridges are grouped. Figure 3 shows the bridge network, in which three cities (i.e., Gwangju, Suncheon and Yeosu) are connected. This illustrative example is investigated to compare the Pareto solutions when the single and multiple design variables (i.e., same and different target reliability indices) are applied. For the formulation of the bi-objectives for the bridge network in Figure 3, information including the size, type, initial reliability index, maintenance cost function and reliability deterioration profile of each individual bridge is required. Most of the associated information can be found in Frangopol et al. (2001), Kong & Frangopol (2003, 2004a), MOLIT (2018), and Kim et al. (2020).

The Pareto solutions of the bi-objective optimization are solved using the multi-objective genetic algorithm in the MATLAB version R2016b. The computed Pareto solutions for the bridge network in Figure 3 are illustrated

in Figure 4. When the target reliability index is uniformly applied, the number of design variables is one (e.g., $\beta_{tg,g} = \beta_{tg,g1} = \beta_{tg,g2} \ldots = \beta_{tg,g14}$ for the bridge network in Figure 3). If each bridge group has its own target reliability index, the number of design variables is equal to the number of bridge groups in the network (e.g., $\beta_{tg,g1} \neq \beta_{tg,g2} \ldots \neq \beta_{tg,g14}$ for the bridge network in Figure 3). Table 1 provides the objective values of the representative solutions (i.e., $A_{S,1}$, $A_{D,1}$, $A_{D,2}$) in Figure 4.
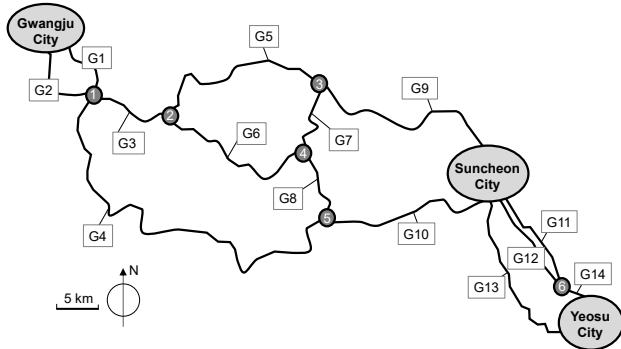

Figure 3. Schematic layout of the bridge network consisting of Gwangju, Suncheon and Yeosu cities in South Korea.
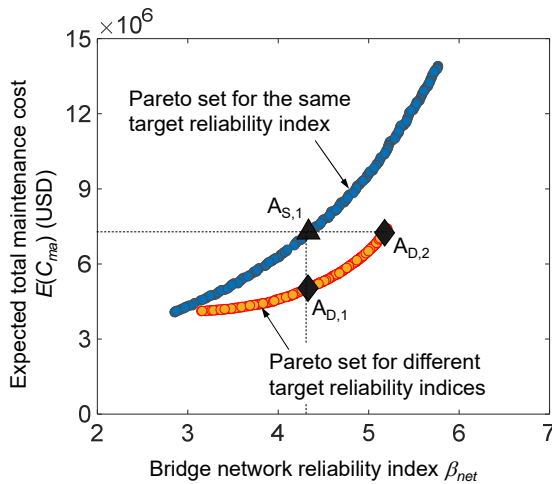

Figure 4. Pareto solutions of the bi-objective optimization for the bridge network in Figure 3.

Table 1. Objective values of solutions in Figure 4.

Solutions	Objective Values	
	β_{net}	$E(C_{ma})$ (USD)
$A_{S,1}$	4.33	7.25×10^6
$A_{D,1}$	4.33	5.03×10^6
$A_{D,2}$	5.18	7.25×10^6

As shown in Figure 4 and Table 1, solution $A_{S,1}$ associated with the same target reliability index requires the expected total maintenance cost $E(C_{ma})$ of 7.25×10^6, which is the same $E(C_{ma})$ of solution $A_{D,2}$ associated with different target reliability indices. However, solution $A_{S,1}$ results in less β_{net} than solution $A_{D,2}$ (i.e., $\beta_{net} = 4.33$ for solution $A_{S,1}$ and $\beta_{net} = 5.18$ for solution $A_{D,2}$). While solutions $A_{S,1}$ and $A_{D,1}$ have the same β_{net}, solution $A_{S,1}$ requires 44% additional maintenance cost $E(C_{ma})$ than $A_{D,1}$. From Figure 4 and Table 1, it can be found that the alternative with different target reliability indices leads to larger β_{net} for the same total maintenance cost if compared to the alternative based on the same target reliability index.

5. Conclusions

This paper presents an approach to determine the target reliability index for life-cycle bridge network management. From the bi-objective optimization based on maximizing the bridge network reliability index and minimizing the expected total maintenance cost of the bridge network, the Pareto set associated with the target reliability indices of the bridge groups in the network is obtained. The bridge network reliability indices and expected total maintenance costs of the Pareto solutions are compared when the same and different target reliability indices of the bridge groups are considered.

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