13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure

DOI: 10.3217/978-3-99161-057-1-124

Graph network representation and intelligent evaluation for service performance of bridge clusters

Shunlong Li[1*], Jie Wang[2]

[1]School of Transportation Science and Engineering, Harbin Institute of Technology, 73 Huanghe Road, 150090 Harbin, China

[2]School of Transportation Engineering, East China Jiaotong University, 330013 Nanchang, China

email: lishunlong@hit.edu.cn, wangjhit@163.com

ABSTRACT: As the most vulnerable part of the infrastructure transportation network, bridges will inevitably encounter problems such as aging and degradation throughout their entire service life [1]. The maintenance costs for all bridges within the region are increasing year by year [2]. When the financial conditions are insufficient to fully cover the costs, many domestic provinces and cities adopt the maintenance and repair plans based on single bridges relying on experience and the "fire-fighting" post-event repair mode [3]. There are few scientific management models that focus on the overall service performance of the regional bridge clusters. This leads to either excessive or insufficient detection and maintenance. Therefore, there is an urgent need for a systematic intelligent assessment framework for existing bridge clusters. However, current research on service performance evaluation and prediction for large-scale bridge networks suffers from multiple limitations, such as limited research objects, simplified modeling forms, difficulty in quantitative assessment, generalized prediction outcomes, and insufficient consideration of maintenance decision-makings [4].

Therefore, this study focuses on graph network representation and intelligent evaluation for service performance of bridge clusters. Firstly, a systematic comparative analysis of two distinct graph network representation methodologies (undirected and directed network) is conducted based on actual bridge cluster cases of different scales. Secondly, Second, tailored intelligent assessment frameworks of vulnerability are developed for each representation. Finally, benchmarking against evaluation outcomes reveals critical performance differentials across methodologies. This work thus establishes a theoretical foundation for intelligent operation and maintenance strategies in bridge network management.

(1) For the undirected graph network representation methodology

As shown in Figure 1, the National highway (NH) network in the northeast of China connects 11 cities and 37 counties, and has 1772 bridges. It can be seen hat the bridge assessment states are unevenly distributed. Funds for maintaining expressway bridges are abundant, and thus such bridges are in relatively good condition. Meanwhile, ordinary highway bridges, especially in poverty-stricken counties near the border, are underfunded.

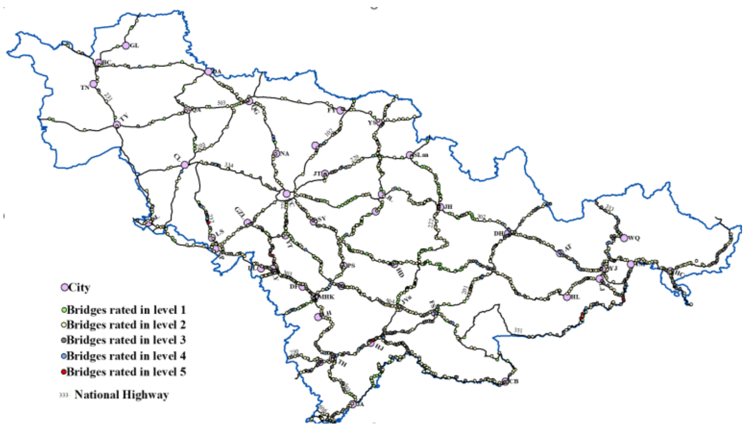

Figure 1. NH network with evaluated bridges.

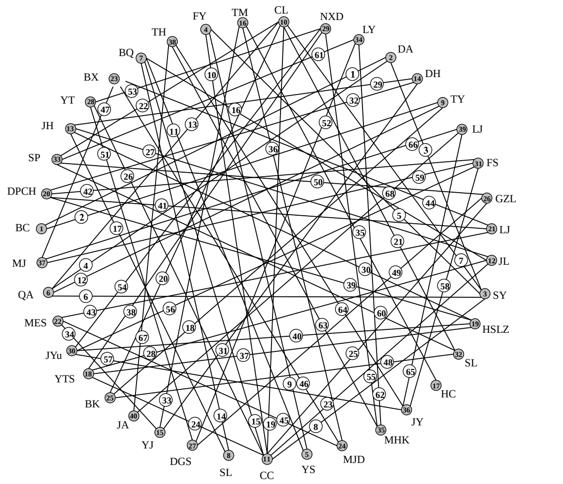

Figure 2. modelling result of the NH bridge network.

As a bridge network contains a significant amount of information, modelling a large-scale bridge network is complex. In this study, a undirected bridge network can be treated as an overlay of a topological graph and the corresponding information network. The nodes and edges in the topological graph of a bridge network represent intersections (or cities) and highways between nodes, respectively. Regarding the information group, a bridge network should contain the properties of nodes and edges, including the city (or node) name, the actual length of each edge (or NH) between nodes, and the assessment state of bridges on each edge. The NH bridge network is established as shown in Figure 2.

The intelligent assessment framework for the undirected bridge network adopts vulnerability as an indicator, utilizing backward thinking to evaluate network resilience. It methodology intentionally disrupts a portion of the network and quantifies

DOI: 10.3217/978-3-99161-057-1-124

component importance by comparing pre- and post-damage performance indices. In detail, the proposed vulnerability index accounts for both bridge failures and their impact on bridge network performance from a probabilistic perspective. Additionally, the probability of bridge network connectivity, denoted as $P(C)$, is used to evaluate the performance of bridge networks with unreliable components. Therefore, the vulnerability index of the ith bridge $V_{bridge}(i)$ and the bridge network $V_{network}(G)$ are defined as:

$$V_{bridge}(i) = \left[P(C) - P\left(C \mid \bar{B}_i\right)\right] P\left(\bar{B}_i\right) \tag{1}$$

$$V_{network}(G) = \sum_{B_i \in G} \left[P(C) - P\left(C \mid \bar{B}_i\right)\right] P\left(\bar{B}_i\right) \tag{2}$$

Herein, G represents the undirected bridge network, and C and $\bar{C}$ indicate the events of the bridge network being connected and disconnected, respectively. B_i and $\bar{B}_i$ indicate the event of the ith bridge safety and failure, respectively. $P\left(\bar{B}_i\right)$ and $P\left(C \mid \bar{B}_i\right)$ are the ith bridge failure probability and the network connectivity probability given the ith bridge failure, respectively. Evidently, $P\left(C \mid \bar{B}_i\right)$ demonstrates the effect of a bridge failure on network connectivity performance from a probabilistic view. The results indicate that vulnerability index of the NH bridge network is 4.80×10-3, and the vulnerability of each equivalent bridge in the NH bridge network is shown in Figure 3. This approach effectively identifies critical bridges that elude detection by conventional indicators, a finding that should be emphasized in the future maintenance strategies formulated by the provincial management department.

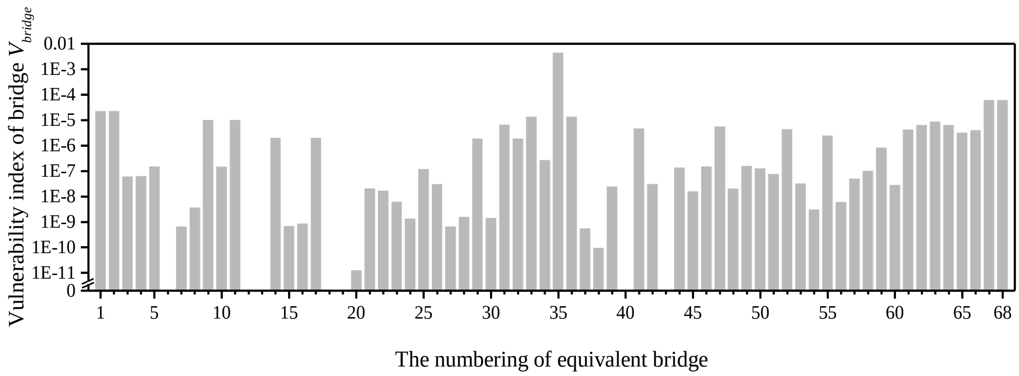

Figure 3. Vulnerability index of each equivalent bridge in the undirected NH bridge network.

(2) For the directed graph network representation methodology

As shown in Figure 4, it considered a city located in the southern part of the Yangtze River Delta, China. As an important economic centre, a well-functioning transportation network is the foundation of regional economic development. Therefore, based on the inspection information of 299 actual bridges in the city, the directed bridge network was established by fully considering the direction of the streets (one- or two- way street) and bridge types (single- or double- deck bridge) between all nodes in the urban city. As shown in Figure 5, the topological model contained 63 nodes and 216 directed edges, including 107 two-way edge pairs and two one-way edges are constructed.

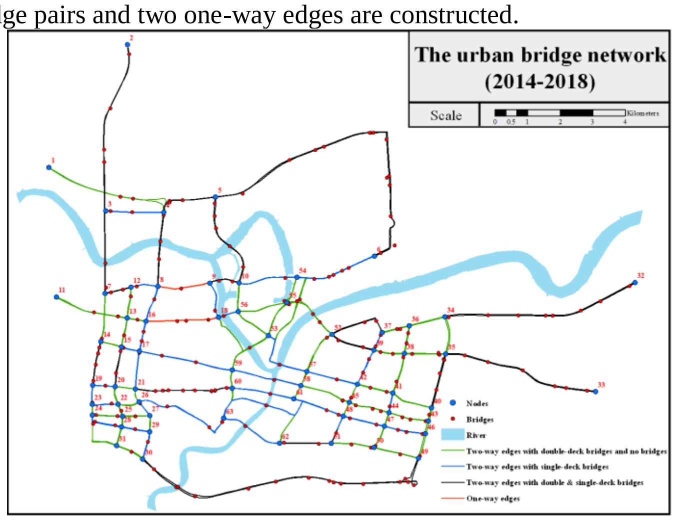

Figure 4. Physical location of the bridge network.

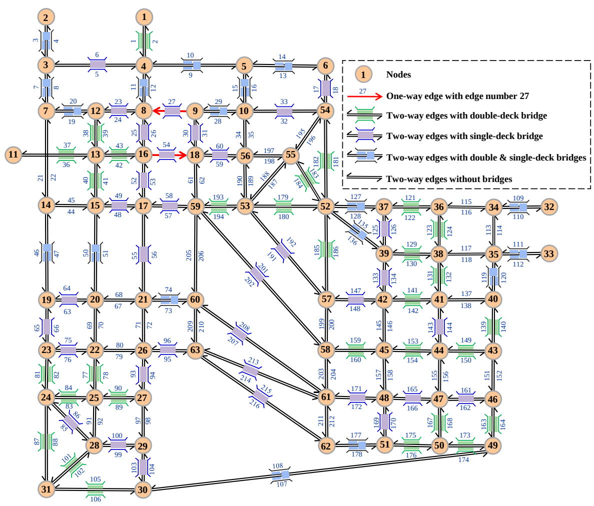

Figure 5. modelling result of the directed bridge network.

DOI: 10.3217/978-3-99161-057-1-124

To describe the different edge dependencies in the directed bridge network, an extended network model and importance index $\gamma(i, j)$ is proposed, and simulation methods are applied to calculate the results.

$$G_{\text{extended}} = (V, E_1, E_2, \cdots E_m) \tag{3}$$

$$\gamma(e_{i\to j}) = P(G, \bar{e}_{i\to j}) = P(G \mid \bar{e}_{i\to j}) P(\bar{e}_{i\to j}) = \frac{Num(G|\bar{e}_{i\to j})}{N} P(\bar{e}_{i\to j}), m = 1,2,3$$

$$\begin{aligned}\gamma(e_{i\to j}) &= P(G, \bar{e}_{i\to j}, e_{j\to i}) + P(G, \bar{e}_{i\to j}, \bar{e}_{j\to i}) \\ &= P(G \mid \bar{e}_{i\to j}, e_{j\to i}) P(\bar{e}_{i\to j}, e_{j\to i}) + P(G \mid \bar{e}_{i\to j}, \bar{e}_{j\to i}) P(\bar{e}_{i\to j}, \bar{e}_{j\to i}) \\ &= \frac{Num(G|\bar{e}_{i\to j}, e_{j\to i})}{N} P(\bar{e}_{i\to j}, e_{j\to i}) + \frac{Num(G|\bar{e}_{i\to j}, \bar{e}_{j\to i})}{N} P(\bar{e}_{i\to j}, \bar{e}_{j\to i}), m = 4,5,6\end{aligned} \tag{4}$$

where $Num(G|\cdot)$ represents the number of connected states to the bridge network, given the state of edge $e_{i\to j}$ or edge pair $(e_{i\to j}, e_{j\to i})$ in N samples.

Figure 8 shows the importance ranking of all edges (equivalent bridges) with non-zero failure probability in the directed bridge network during 2018. It can be observed that the importance of the upstream and downstream edges of an edge pair is not equal. It is related to the position and direction of the edge and the failure probabilities of single- and double-deck bridges. It is proved that the proposed index can effectively distinguish the relative importance of all edges in a network, thereby providing important guidelines for the designing novel network-level maintenance strategies.

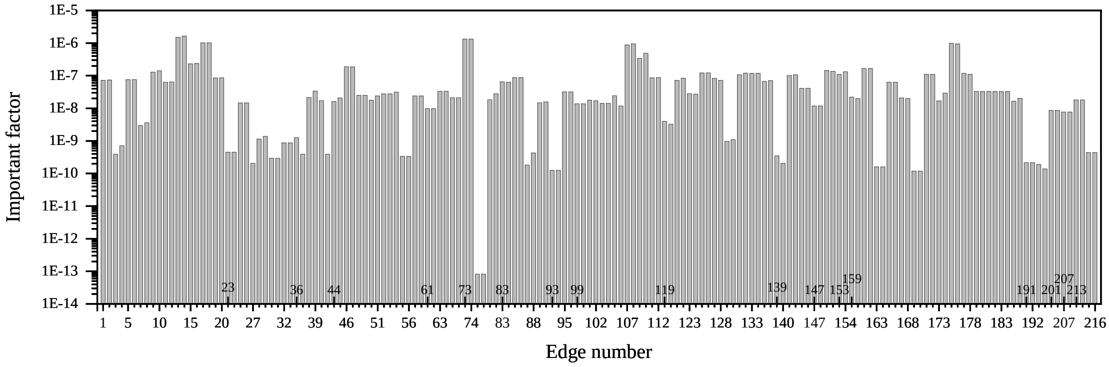

Figure 6. Important index of the directed urban bridge network.

KEY WORDS: Bridge clusters; Service performance; Graph network representation; Intelligent evaluation.

REFERENCES

[1] Frangopol, D. M., & Bocchini, P. (2012). Bridge network performance, maintenance and optimisation under uncertainty: accomplishments and challenges. Structure and Infrastructure Engineering, 8(4), 341-356.
[2] Fiorillo G, Ghosn M. Risk-based life-cycle analysis of highway bridge networks under budget constraints. Structure and Infrastructure Engineering. 2022;18:1457-71.
[3] Liu, D. (2009). Probability-based network-level performence assessment of exiting bridges. (master's thesis). Hnnan University, Changsha, China.
[4] Wang X, Dai J Y, Liu X. A spatial-temporal neural network based on ResNet-Transformer for predicting railroad broken rails[J]. Advanced Engineering Informatics, 2025, 65: 103126.