POST-DISASTER PRIORITIZATION OF BRIDGES FOR DAMAGE INSPECTION AND REHABILITATION

[1]MUSTAPHA JALLOW, [2]HSIEN-KE LIAO, [3]NIE-JIA YAU, [4]YU-HAN CHUANG, [5]JYUN-HAO HUANG

Institute of Construction Engineering and Management, National Central University[1], Taiwan
[2] Construction Management Association of The Republic of China, Taiwan
[3] Institute of Transportation, MOTC, Taiwan
E-mail: Jallowm12@gmail.com, 943402019@cc.ncu.edu.tw, yau@ncu.edu.tw, yuhan@cc.ncu.edu.tw, herry@mail.ihmt.gov.tw

Abstract— Management of existing bridges has become a major social and economic concern in Taiwan. This is due to the critical conditions of bridges driven by post-disaster deterioration and the controlled funds available to timely repair their deficiencies. This paper presents the development of a decision-support model, which proposes a method to facilitate post-disaster prioritization of bridges by virtue of their structural vulnerability and strategic importance to implement damage inspection and rehabilitation. The proposed model is a flexible framework that is applicable to earthquakes, typhoons, and floods events, which involve abrupt damages to transportation facilities where decisions on rehabilitation strategies must be made promptly. Specifically, it provides the user with a simplified and systematic approach to assess bridges by addressing the critical parameters of safety and cost-benefit in prioritizing resources and work allocation.

Index Terms— AHP, Bridge Management, Damage Inspection, MR&R, Natural Disaster, Priority Ranking.

I. INTRODUCTION

Bridges form an essential part of the infrastructural development in Taiwan, facilitating its social and economic growth by allowing free movement of people and goods between remote locations in the shortest possible interval. These bridges are considered as inseparable aspects of the transportation network that in addition to safety issues, their failure cause inefficiency of the network. Inefficiency may lead to significant economic consequences such as the cost of rehabilitation and reconstruction. On the contrary, these bridges are exposed to natural hazards, like adverse weathers, earthquakes, typhoons, torrential rains, floods, etc., as the major causes of deterioration. Strong floods and frequent earthquakes in urban areas damage critical infrastructural assets, predominantly bridges and culverts, which gradually decrease the level of services provided by such structures. Due to these distressing concerns, bridge safety and management have become important matters to the bridge authorities in Taiwan, which led to the initiation to inspect, maintain, and repair bridges. Bridges in Taiwan are endangered not only by forces of nature but also traffic volumes, overweight trucks etc.

With an inventory of 33,275 bridges, maintaining them within acceptable limits of safety have become extremely critical. Maintenance, Repair, and Rehabilitation (MR&R) of damaged bridges are very expensive and time-consuming, yet, the authorities responsible for their maintenance are usually constrained by limited resources.

The aforementioned conveys the need to develop a model to help bridge authorities prioritize damage inspection and rehabilitation needs accordingly. The proposed model is employed to determine cost-effective repair strategies and their time of execution while maintaining acceptable bridge condition rating under various disaster constraints.

II. LITERATURE REVIEW

A. Bridges prioritization for maintenance operations

Bridge prioritization is simply the process of using optimal and proper models, which the status of each bridge is being rated and then based on that rating, maintenance operations for the bridge will be prioritized [1]. Models for prioritizing inspection and rehabilitation require a reliable database for data processing. These models can rank the existing bridges numerically and accurately compare their conditions.

Various priority-ranking models have been successfully developed and applied to numerically prioritize and rank existing bridges' needs for rehabilitation operations. Some of the models were applied to compare their structural conditions precisely.

Depending on specific criteria in various regimes, some experts consider certain parameters more imperative in prioritizing bridges for rehabilitation needs. Such parameters are under the influences of the environment, geography, regulations, design codes, etc.

In the UK, Ryall developed an index to determine the

Maintenance Priority Number (MPN) for bridges [1]. MPN is calculated based on three indices: Condition Factor (CF), Location Factor (LF), and Route Factor (RF). Weights are assigned to these factors and substituted in (1). Prioritization of bridges is done by ranking the MPN values in a decreasing order. A bridge with the highest MPN value gets the highest priority for maintenance operations.

$$MPN = CF \times LF \times \frac{RF}{14} \quad (1)$$

Rashidi from Australia developed a model for prioritizing bridges' maintenance needs in two phases [2]. The first phase calculates the Priority Index (PI) while the second incorporates a Multi-Criteria Decision-Making (MCDM) process for selecting the best maintenance strategy. As illustrated in (2), the PI is a simple summation of three-factor weightings: Structural Efficiency (SE), Functional Efficiency (FE) and Client Impact Factor (CIF). This model ranks bridges in a decreasing order of PI values.

$$PI = 0.6(SE) + 0.2(FE) + 0.2(CIF) \quad (2)$$

B. Decision Analysis Tools

MCDM tools are employed to deal with problems that involve various criteria simultaneously and to achieve objectivity in decision-making processes [3]. Different decision-making tools have been investigated in this study and Analytical Hierarchy Process (AHP) was identified as the most applicable. The AHP as a decision support tool is applied to complex decision problems to incorporate both subjective and objective data into a logical hierarchy framework [3]. This is due to its mathematical characteristics and the fact that input data can be easily analyzed through a set of pairwise comparisons. In this study, identifying the appropriate parameters through disaster-risk analysis and weighting are highlighted in the following sections.

III. METHODOLOGY

In the AHP process, the research issue is broken down into two independent hierarchies: Vulnerability of Damage (V_D) and Impact of Damage (I_D). Each hierarchy comprises six attributes as shown in Fig. 1 and Fig. 2. V_D is expressed as a function of the structural probability of a bridge's component, or the entire structure to be subjected to damages due to natural disasters. I_D is an evaluation of the consequences a damaged bridge would effect on safety, socioeconomic activities, and traffic flow.

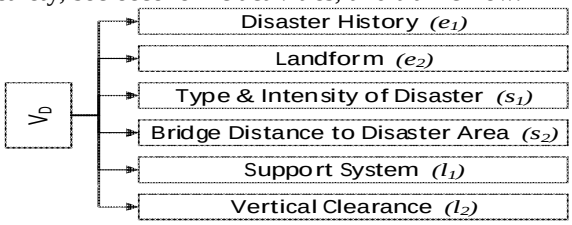


Fig. 1. Hierarchy structure of V_D

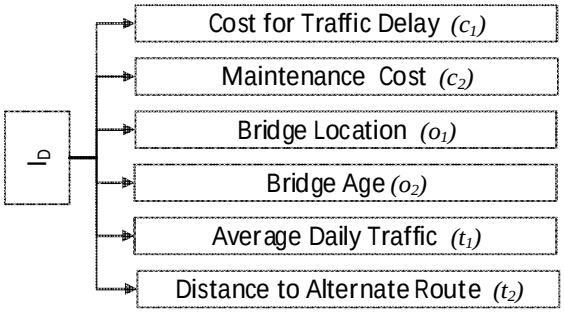


Fig. 2. Hierarchy structure of I_D

Through the study of bridge design codes, regulations, guidelines, and applied research in different countries, parameters were extracted and used to build the decision hierarchies. Sources such as Bridge Inspector's Reference Manual (BIRM) [4], Bridge Management in Europe (BRIME) [5], and other related articles such as reports and technical notes were reviewed. Each hierarchy has two levels: goal and attributes. The first level of the structure is the overall goal of the ranking. The second contains the attributes defined to achieve the main goal. Each parameter has a unique weight that indicates its relative importance to the identified goal. These weights were defined by experts through a pairwise comparison approach embedded in the AHP. Eight experts averaging 14 years' experience in bridge maintenance and management in Taiwan were requested to provide the inputs through interview sessions.

The AHP permits experts to perform a consistency check for their judgments. Thus, all the judgments integrated into this study were consistent (CR>0.1). The AHP method has been conducted to estimate the Vector of Priority (VOP) for each attributes based on the experts' judgments. The eigenvector of the AHP matrix presented in the following:

$$VOP_{V_D} = \begin{bmatrix} 0.1721 \\ 0.1240 \\ 0.2701 \\ 0.3204 \\ 0.0811 \\ 0.0323 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ s_1 \\ s_2 \\ l_1 \\ l_2 \end{bmatrix} \qquad VOP_{I_D} = \begin{bmatrix} 0.3264 \\ 0.2236 \\ 0.1017 \\ 0.1138 \\ 0.1505 \\ 0.0840 \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ o_1 \\ o_2 \\ t_1 \\ t_2 \end{bmatrix}$$

IV. MODEL DEVELOPMENT AND IMPLEMENTATION

C. Developing the Priority Indices (P_I and P_R Values)

Having completed the consistency tests and determining that the matrices were acceptable, the overall priority values were calculated by simple summation of the weights of the attributes. The priority values represent the importance of the attributes with respect to the goal. The VOP matrices

indicate that 'Bridge Distance to Disaster Area (s_2)' and 'Vertical Clearance (i_2)' are the highest and lowest contributing factors for V_D respectively. Whereas for I_D, 'Cost for Traffic Delay (c_1)' is the highest contributing factor while 'Distance to Alternate Route (t_2)' is the lowest. Hence, a multi-criteria analysis and the scoring model was adopted to calculate the indices for both V_D and I_D as given in (3) and (4) respectively.

$$V_D = \left(w_{e_1} c_{e_1} + w_{e_2} c_{e_2}\right) + \left(w_{s_1} c_{s_1} + w_{s_2} c_{s_2}\right) + \left(w_{l_1} c_{l_1} + w_{l_2} c_{l_2}\right) \quad (3)$$

$$I_D = \left(w_{c_1} c_{c_1} + w_{c_2} c_{c_2}\right) + \left(w_{o_1} c_{o_1} + w_{o_2} c_{o_2}\right) + \left(w_{t_1} c_{t_1} + w_{t_2} c_{t_2}\right) \quad (4)$$

Substituting the VOPs for each attribute in (3) and (4) yields (5) and (6) respectively.

$$V_D = \left(0.17 c_{e_1} + 0.12 c_{e_2}\right) + \left(0.27 c_{s_1} + 0.32 c_{s_2}\right) + \left(0.08 c_{l_1} + 0.03 c_{l_2}\right) \quad (5)$$

$$I_D = \left(0.33 c_{c_1} + 0.22 c_{c_2}\right) + \left(0.10 c_{o_1} + 0.11 c_{o_2}\right) + \left(0.15 c_{t_1} + 0.08 c_{t_2}\right) \quad (6)$$

Where w_x is the weight for attribute x, c_x is the significance rating of attribute x. The denotations of e_x, s_x, l_x, c_x, o_x and t_x are defined in Fig. 1 and Fig. 2. The criteria significance of the attributes are then allocated ratings of 1–4, based on the conditions defined in Table 1 and Table 2 accordingly; where 1 is the lowest rating and 4 is the highest. Priority ranking values are grounded on the consideration of bridge safety, functionality and expected damage rates. P_I and P_R, as well as their priority categories, are automatically determined through an MS-Excel application using actual data inputs for each bridge (Table 4).

The entire prioritization process involves two independent stages. P_I calculates the priority index for inspection and P_R calculates the index for rehabilitation. In this process, bridges can be ranked for inspection needs by using (7) and then their P_I values are recorded in a descending order. Bridges with higher P_I values are further prioritized to determine their order of rehabilitation by using (8).

$$\rightarrow P_I = \frac{V_D}{4} \times 100\% \quad (7)$$

$$\rightarrow P_R = \frac{I_D}{4} \times 100\% \quad (8)$$

The values of P_I and P_R are expressed as a score of 100, with the least possible outcome of 25. The former situation is only possible if the manager assigns a criteria significance rating of 4 for each attribute. A P-value (P_I and/or P_R) of 25 is however attainable, provided that each attribute is assigned a significance rating of 1. Nonetheless, both aforementioned conditions are very unlikely since some parameters would be much more significant to the bridge engineer/manager than others are. In this case, the P-values range on a scale of 25 to 100 as defined in Table 3.

Table 1. Criteria significance rating for V_D

	Environmental Factor		Safety Factor				Structural Factor	
Rating			Earthquake (Magnitude)	Precipitation (mm/24hrs)	Earthquake (Distance to nearest fault)	Precipitation (Distance to nearest rain station)		
	c_{e1}	c_{e2}	c_{s1}	c_{s1*}	c_{s2}	c_{s2*}	c_{l1}	c_{l2}
4	Frequent	Slope	c_{s1}=7	c_{s1*}>500	c_{s2}≤2km	c_{s2*}>12km	Single column	c_{l2}≤2m
3	Moderate	Mountain	c_{s1}=6	350<c_{s1*}≤500	2<c_{s2}≤7km	12≤c_{s2*}<7km	Multiple column	2<c_{l2}≤4m
2	Seldom	Plain	c_{s1}=5	200<c_{s1*}≤350	7<c_{s2}≤12km	7≤ c_{s2*}<2km	Wall pier	4<c_{l2}≤6m
1	Rare	Others	c_{s1}=4	c_{s1*}<200	c_{s2}>12km	c_{s2*}≤2km	Single span	c_{l2}>6m

Table 2. Criteria significance rating for I_D

Rating	Economic Factor		Bridge Location & Age		Traffic Access Factor	
	c_{c1}	c_{c2}	c_{o1}	c_{o2}	c_{t1}	c_{t2}
4	Very high	Very high	c_{o1}≤5km	c_{o2}>40	Very high	c_{t2}>30km
3	High	High	5<c_{o1}≤10km	20<c_{o2}≤40	High	15<c_{t2}≤30km
2	Medium	Medium	10<c_{o1}≤15km	5<c_{o2}≤20	Medium	5<c_{t2}≤15
1	Low	Low	c_{o1}>20km	c_{o2}<5	Low	c_{t2}<5km

Table 3. Definition of Priority Categories

Priority Category	Priority Description	Index Range (P-value)	Priority Code	Actions
Critical	Bridges whose damage or failure would impose a disastrous impact on the network.	P≥80	P_1	Immediate inspection and repair works are required. Bridges under critical category must be closed to public access for safety.
Urgent	Bridges whose structural reliability, safety, functional, or serviceability may be ceased by disaster effects.	80>P≥60	P_2	Prompt actions must be taken when inspection details and maintenance crew become available.
High	Bridges that are direct indicators of disaster vulnerability.	60>P≥35	P_3	Rehabilitation is required when inspection shows that damages on primary structural components directly affect traffic safety.
Low	Bridges that do not meet any of the strategic, critical, or high vulnerability criteria.	P<35	P_4	The inspection should be performed within regular work schedule or as programmed in the periodic work schedule.

D. Bridge Importance

Bridge importance defines the strategic significance (priority index) of a bridge in a network. In this study, four categories were specified for bridge importance: critical, urgent, high, and low priority for prioritizing post-disaster inspection and rehabilitation operations. However, these priorities represent an urgency-definition hierarchy; therefore, remedial actions (inspection, repair, rehabilitation etc.) that are not completed in a timely manner will potentially evolve to a higher priority. The priority definitions are as follows:

1. Critical (P_1) - Bridges whose failure would impose negatively on public safety, structural vulnerability and strategic importance for rehabilitation, and emergency management. Bridges categorized as 'critical' are closed to traffic, inspected, and placed to receive immediate remedial actions.
2. Urgent (P_2) - A bridge categorized as "Urgent" is one whose structure, safety or serviceability may be ceased by disaster effects. As soon as inspection details and maintenance crew become available, prompt remediation must be taken to upsurge the functionality of the bridge.
3. High (P_3) - The rationale for the selection of "high" priority is to identify factors that are direct indicators of disaster vulnerability. Normally, a minor nonstructural damage could eventually develop into a higher priority if not timely repaired. Thus, rehabilitation is required when inspection shows that damage to primary structural components could directly affect traffic safety.
4. Low (P_4) - "Low" priority bridges are those that do not meet any of the critical, urgent or high vulnerability conditions. This study proposes that bridges that are characterized by 'low priority' require neither damage inspection nor rehabilitation, except if deemed necessary by decision-makers. The priority definitions are further elaborated in Table 3.

This model can be implemented by using disaster information provided by the Central Weather Bureau (CWB) and maintenance crew. With bridge data stored in the inventory module of Taiwan Bridge Management System (TBMS), decision-makers can prioritize bridges located in the disaster vicinity for inspection and rehabilitation accordingly. Having collected all the necessary data, the developed model is applied to determine the numeric values of P_I and P_R respectively. The P-values (index range) are then used to set priorities to the selected bridges, which enable decision-makers to determine the level of importance of a bridge as well as to determine what actions to perform in the shortest time. Using this technique, all bridges are sorted in a descending order of their index values and the required actions are carried out until the allocated funds are exhausted.

V. CASE STUDY – 2018 HUALIEN EARTHQUAKE

In an effort to demonstrate the usefulness of the developed model, a case validation was supposed very necessary. The validation study highlights the practicability of the model to rank bridges for inspection and rehabilitation based on their determined P-values. Herein, Hualien, a disaster-prone county in Eastern Taiwan was chosen to demonstrate the process of prioritizing bridges using the proposed model.

On February 6, 2018, the northern offshore of Hualien was struck by an earthquake of 6.4 magnitude. The quake resulted in major infrastructural damages, with several bridges closed for safety precautions. These concerns made the county under intensive traffic control by transport officials until inspections and assessments were completed. For these motives, this research identified this concern as a study case by evidence of the vulnerability to frequent disasters in this area. Although the 2018 Hualien Earthquake struck 4 months before this research was completed, the validation study enabled the researchers to simulate a decision-making practice on bridge prioritization for remediation using genuine data records. Therefore, the results of the validation study would be substantial to benchmark potential bridge prioritization for a similar disaster in the same vicinity.

Precisely, the first step of the validation study was a

selection of 27 bridges in Hualien County. Using the bridge information and the developed MS Excel program (Table 4), the P-values of each bridge was simply obtained by assigning criteria significance ratings (Table 1 and Table 2) to the attributes. All data were processed independently and P-Values for each bridge were determined and sorted, where bridges with greater needs for inspection and rehabilitation were given the highest priority accordingly (Table 5). The overall prioritization process in this study involves two phases (Fig. 3). First, the inspection indices (P_I) for all bridges were determined and ranked. The priority categories: P_1–P_3 were judged and arranged for rehabilitation needs. This is because P_4 category gets the least priority and generally do not require immediate remediation. For top-ranked bridges in the inventory, the deemed MR&R strategies can be carried out considering the overall score and cost as the main constraint.

By identifying the bridges that are likely to be the most vulnerable to damages due to natural disasters, bridge officials can potentially save significant resources by avoiding across-the-board inspection and assessment of their entire bridge inventory. Moreover, since data obtained from the TBMS are standardized, the methodology incorporated in the proposed model could readily be adapted by various bridge agencies in Taiwan.

The analyses of the case study indicates that the developed model quantifies the priority levels of each bridge and suggests valid decisions regarding the operation of rehabilitation needs for bridge improvement. Similarly, the validation study proved that bridges with higher priority for inspection needs (P_I) do not essentially imply a higher priority for rehabilitation needs (P_R) and vice versa. This argument testifies to the need to prioritize bridges for inspection and rehabilitation independently.

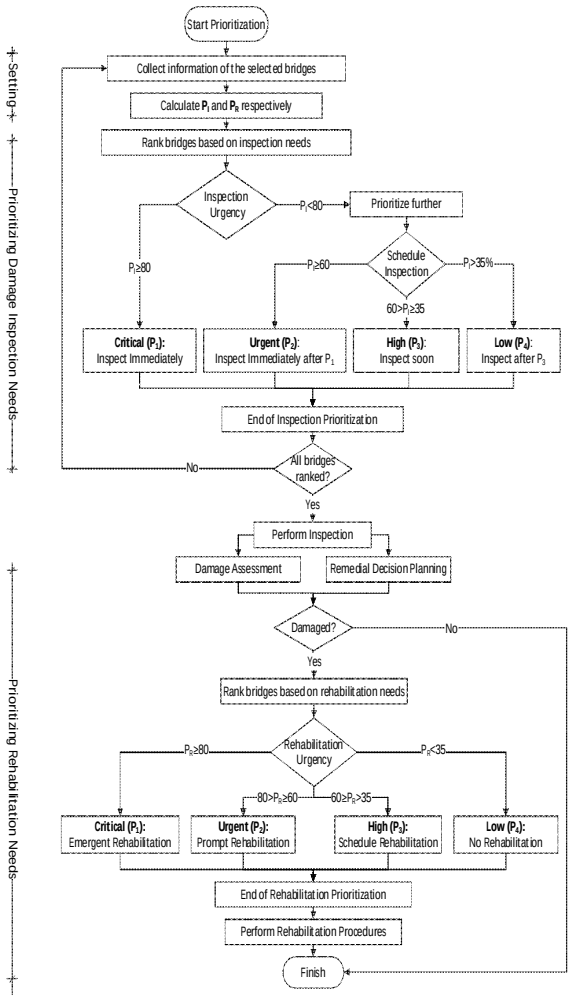


Fig. 3. Schematic layout of prioritization process

Table 4. Determination of P-values and Priority Category using MS Excel (Bridge ID: 9796)

Vulnerability of Damage (V_D)				Impact of Damage (I_D)			
Attribute	Weight	Criteria Significance (c_s)	Attribute Index	Attribute	Weight	Criteria Significance (c_s)	Attribute Index
e_1	0.17	3.00	0.69	c_1	0.33	4.00	0.98
e_2	0.12	3.00	0.37	c_2	0.22	3.00	0.67
s_1	0.27	4.00	1.08	o_1	0.10	2.00	0.20
s_2	0.32	3.00	0.96	o_2	0.11	4.00	0.11
I_1	0.08	3.00	0.08	t_1	0.15	2.00	0.45
I_2	0.03	4.00	0.03	t_2	0.08	2.00	0.17
V_D = 3.30		Priority Category		I_D = 3.10		Priority Category	
P_I = 82.56		P_1 (Critical)		P_R = 77.60		-	
		-				P_2 (Urgent)	
		-				-	
		-				-	

Table 5. Ranking of 27 bridges for inspection and rehabilitation in Hualien County

No.	Inspection Prioritization (P_I)				Rehabilitation Prioritization(P_R)			
	Bridge ID	P_I	P_I Ranking	Priority Category	Bridge ID	P_R	P_R Ranking	Priority Category
1	34427	90.57	1		9829	84.82	1	
2	9832	87.47	2		9832	81.31	2	P_1
3	32965	84.64	3		32965	81.23	3	
4	34428	84.09	4		9796	77.60	4	
5	9796	82.56	5	P_1	34427	76.56	5	
6	9844	81.75	6		26014	72.43	6	
7	9829	81.49	7		26015	69.58	7	
8	13603	81.49	8		26017	69.11	8	P_2
9	9842	80.95	9		9844	68.22	9	
10	26017	79.46	10		9842	67.48	10	
11	9837	78.92	11		34428	63.28	11	
12	27578	78.65	12		26016	62.97	12	
13	9834	78.51	13		13603	61.72	13	
14	9856	77.85	14		9837	55.42	14	
15	9836	77.75	15		26018	55.42	15	
16	26015	75.82	16		9836	55.12	16	
17	26016	75.82	17	P_2	34768	52.96	17	P_3
18	26018	75.82	18		26100	47.26	18	
19	26014	74.60	19		9856	45.87	19	
20	27587	74.60	20		34769	45.43	20	
21	9857	73.79	21		34776	42.59	21	
22	26100	73.79	22		9834	41.67	22	
23	34776	73.79	23		27578	41.67	23	
24	34768	72.98	24		9857	33.13	24	P_4
25	34769	72.98	25		27587	33.13	25	
26	27818	59.03	26	P_3	27818	33.13	26	

CONCLUSION

The main scope of this research was to develop a quantitative decision support model to prioritize the needs for damage inspection and rehabilitation after natural disasters. Based on the achieved developments, decision-makers could readily make the best use of their limited budgets to enhance bridge safety and manage all disaster-related risks.

REFERENCES

[1] M. Ryall, "Bridge management," CRC Press, May 2010.
[2] M. Rashidi, B. Samali, and P. Sharafi, "A new model for bridge management: Part B: decision support system for remediation planning," Australian Journal of Civil Engineering, vol. 14, no. 1, pp. 46-53, December 2015.
[3] T. L. Saaty, "Decision making with the analytic hierarchy process," International Journal of Services Sciences, vol. 1, no. 1, pp. 83-98, January 2008.
[4] H. A. Ryan T., Mann J., and Danovich J., "Bridge Inspector's Reference Manual (BIRM), Volume 1(6). U.S. Federal Highway Admin, February 2012.
[5] R. Woodward, et al, "Bridge Management In Europe (BRIME)-Deliverable D14-Final Report," March 2001.

★★★