DEVELOPMENT OF VARIOUS BRIDGE CONDITION INDICES FOR TAIWAN BRIDGE MANAGEMENT SYSTEM

Hsien-Ke Liao[1]* and Nie-Jia Yau[2]

[1] *Department of Civil Engineering, National Central University, Taiwan*
[2] *Graduate Institute of Construction Engineering & Management, National Central University, Taiwan*
** Corresponding author (943402019@cc.ncu.edu.tw)*

ABSTRACT: Taiwan is an island exposed to various natural disasters. Currently inventory and inspection data of the existing 28,000 bridges in Taiwan are managed by the Taiwan Bridge Management System (T-BMS). Thus, this research aims at developing a mechanism for fast and automatic evaluation of bridges' abilities to resist possible damages caused by the natural disasters as well as by traffic loads. Four individual condition indices, in the term of "degree of resistance" are defined first for floods, mudflows, earthquakes, and for traffic loads. A final evaluation of the bridge's overall ability of resistance is determined accordingly. The developed mechanism is being verified and modified and will be completed in a few months.

***Keywords**: Bridge Management System, Condition Index, Visual Inspection, DER&U*

1. INTRODUCTION

Taiwan Bridge Management System (T-BMS) is a nation-wide bridge management system used by all the bridge management agencies in Taiwan. The first version of T-BMS was completed and online in year 2000. T-BMS now has 28,000 bridges, including highway and railway bridges, in its inventory with yearly or bi-yearly inspection data and maintenance records. The large amount of bridges can be explained by the fact that Taiwan is a mountainous island with numerous short rivers running rapid streams.

Natural hazards such as typhoons are common during summer time in Taiwan. Torrential rains brought by typhoons causing floods and mudflows are huge threats to the bridges. On August 8, 2009 Typhoon Morakot struck the south part of Taiwan and brought the worst floods in that last 50 years. There were 129 bridges seriously damaged or completely destroyed by floods or mudflows (debris flows).

In addition to typhoon, since Taiwan lies in a complex tectonic area near the Yangtze Plate, the Okinawa Plate, and the Philippine Mobile Belt, earthquakes are fairly common in the region. On 21 September 21, 1999, a 7.3 magnitude earthquake, known as the "Ji-Ji Earthquake" or "921 Earthquake," hit and seriously damaged central Taiwan. Twenty-nine bridges collapsed due to the earthquake.

Aging and deterioration are also inevitable for all bridges. There are more than 4,000 bridges over 30 years old, in which 2,500 bridges were built in 1970s when Taiwan government invested huge amount of budgets on infrastructure. Daily traffic loads worsen the conditions of these old bridges therefore maintenance of them has become a crucial task for bridge management agencies.

In the light of the above the main hazards and threats toward the bridges in Taiwan, it is the intention of this research to explore a mechanism that can perform fast evaluation of a bridge's ability to resist these extreme natural forces and traffic loads using existing data available in the T-BMS.

2. BRIDGE INSPECTION

Bridges in Taiwan are regulated to be visually inspected at least once every two years. In addition, a special inspection should be performed after extremely heavy rains or severe earthquakes exceeding intensity IV. The special inspection is a quick and simple inspection just to check if any obvious damage occurs while regular inspection inspects 21 components of a bridge, including its river course. Regular inspection is performed by trained inspectors with naked eyes and hand-carry tools. The inspectors get close to the bridge by walking, climbing, or by taking boats or special vehicle.

In Taiwan, the methodology of regular inspection is called DER&U. Based on DER&U, the inspection of a concrete girder bridge includes 21 components, for cable-stayed bridges there are 23 components and for arch bridges there are 24 components, as shown in Table 1 [1]. DER&U has four indices to evaluate the conditions of a bridge's components: "D" represents degree of deterioration; "E" represents extent of the deterioration; "R" implies relevancy to safety of the deterioration; and "U" depicts urgency for repairing of the deterioration. All of these indexes are numerically rated on an integer scale from 0 to 4. Index rated as 0 means the component does not exist or unable to inspect. Index rated as 1 stands for good condition while 4 stands for extremely serious condition. I.e., larger index values indicate worse conditions.

Table 1 Bridge components

No	Component Description	Remark
1	Approaching embankment	
2	Approaching guardrail	
3	Waterway	
4	Protection works for the embankment	
5	Abutment foundations	
6	Abutments	
7	Retaining walls	
8	Pavements	
9	Superstructure drainages	
10	Sidewalks	
11	Guardrails	
12	Scouring protection for piers	
13	Pier foundations	
14	Piers and columns	
15	Bearings	
16	Earthquake brakes	
17	Expansion joints	
18	Longitudinal girders	
19	Transversal beams	
20	Decks & slabs	
21	Others	
22	Pylon & anchor	*Cable-stayed Bridge only*
23	Cable & anchor	*Cable-stayed Bridge only*
24	Arch rib	*Arch Bridge only*
25	Crossbeam	*Arch Bridge only*
26	Spandrel or suspender	*Arch Bridge only*

The DER&U ratings are obtained for calculating the condition index (CI) of the bridge. First, a component condition index Ic_{ij} is calculated based on the evaluated integers of D, E, and R for each component. The calculation is based on a point-deduction mechanism, i.e., deficiencies of a component will deduct points from a perfect score of 100. Equation (1) shows the formula for calculating an Ic_{ij} value for the "*j*" item of component "*i*". Notably, "*a*" is an integer in this equation, usually denoted as 1, and it can vary if the user desires.

$$Ic_{ij} = 100 - 100 \times \frac{D \times E \times R^a}{4 \times 4 \times 4^a} \qquad \text{Equation (1)}$$

Further, the condition index Ic_i of a component "*i*" will be an average value of all similar items, as calculated by Equation (2).

$$Ic_i = \frac{\sum_{j=1}^{n} Ic_{ij}}{n} \qquad \text{Equation (2)}$$

The overall bridge condition index CI can be calculated once condition indices of all components are obtained. CI is a weighted average of all components, as shown in Equation (3). Where m equals 21 for concrete girder bridge, m equals 23 for cable-stayed bridge, and m equals 24 for arch bridge. w_i is the corresponding weight of component i represents its importance, and each w_i was obtained and predefined by bridge experts.

$$CI = \frac{\sum_{i=1}^{m} Ic_i \times w_i}{\sum_{i=1}^{m} w_i} \qquad \text{Equation (3)}$$

3. TAIWAN BRIDGE MANAGEMENT SYSTEM

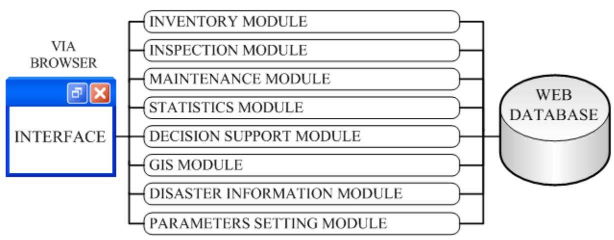

Fig. 1 Major Modules of T-BMS

Funded by the Ministry of Transportation and Communications (MOTC), the T-BMS was developed by the Center for Bridge Engineering Research (CBER), National Central University (NCU) in 2000. T-BMS is a web-based system thus every agency can login via web browsers if the computer is connected to the Internet.

As illustrated in Figure 1, the major functions of T-BMS are: (1) Inventory Module; (2) Inspection Module; (3) Maintenance Module; (4) Statistic Module; (5) Decision Support Module; (6) GIS Module; (7) Disaster Information Module; and (8) Parameters Setting Module. Functions of these modules are described below [2].

(1) The Inventory Module is the core of T-BMS; all system functions are meaningless without bridge inventory. In T-BMS, each bridge is characterized by 57 fields that are categorized into five types including photos, they are: (i) Management Data; (ii) Geometry Data; (iii) Structure Data; (iv) Design Data; and (v) Photos. Using coordinates of Global Positioning System (GPS) to Google Map, the bridge's aero view can be automatically displayed.

(2) The Inspection Module is designed to record inspection data, such as DER&U inspection records and special inspection records.

(3) The Maintenance Module stores bridge maintenance contracts and maintenance data when the deteriorated components are repaired.

(4) The Statistic Module provides the statistics of bridge inventory, inspection, and maintenance records including number of bridges, average age, length, slab area, number of bridges need inspection, and number of repaired/unrepaired components, etc.

(5) The Decision Support Module includes several functions: (i) Cost Estimate for Bridge Inspection; (ii) Cost Estimate for Bridge Repairing; (iii) Prioritization of Repairing; and (iv) Distribution of Repairing Funds. T-BMS provides different levels of unit prices for different DER&U inspection results. The user may select the bridges intended for estimation then system will sum up the costs automatically. For a certain type of deterioration, T-BMS can estimate a repairing cost using a pre-determined unit price, based on the repairing method and amount suggested by the inspector. Prioritization of repair is based on a danger classification of each bridge. The classification is determined by the latest inspection data recorded in Inspection Module. According to the prioritization of repair, system can distribute the budget to necessary bridges.

(6) The GIS Module allows displaying a bridge on the map to show its surroundings. The users also can pin-point to a particular bridge to obtain its inventory data.

(7) The Disaster Information Module is linked to the databases of Central Weather Bureau and Institute of Water Resources in Taiwan to obtain real time data of rainfalls and water levels on certain rivers. Users are allowed to set a warning water level and a warning amount of rainfalls for a bridge. Exceeding any of the warning thresholds will trigger displaying of a warning message in the module and sending warning text messages to cell phones of two responsible officers of the bridge management agency.

(8) The Parameters Setting Module allows the system administrator to change various parameter settings in T-BMS, such as rights of system users, repairing methods and their corresponding unit costs, and contents of pull-down menus, etc.

4. DEGREE OF DISASTER PREVENTION

The condition index (CI) of a bridge is calculated based on the DER&U inspection results and is an indication of the overall bridge condition. However, CI could be misleading since it is an "averaged" deterioration value of all the components and has its deficiencies in revealing danger when certain key components of the bridge, e.g., one pier being seriously scoured, are in critical condition.

Thus, this research aims at establishing a mechanism for fast evaluation of a bridge's abilities in resisting natural disasters such as floods, mudflows, earthquakes, and man-made traffic loads. A Degree of Disaster Prevention (DPP), shown as Equation (4), is defined to determine the bridge's abilities to prevent failure or collapse:

$$DDP = \frac{Min[DF, DM, DE]}{100} \times \frac{DL}{100} \times 100 \qquad \text{Equation (4)}$$

Where

DF : Degree of Flood Resistance

DM: Degree of Mudslide Resistance

DE: Degree of Earthquake Resistance

DL : Degree of Load Resistance

All of these degrees are evaluated in a 0-100 scale where higher degree represents better ability of resistance.

4.1 Degree of Flood Resistance (DF)

The Degree of Flood Resistance (DF) represents a bridge's ability to resist possible damages caused by floods. DF is calculated by Equation (5), in which K and Rs are parameters used for deduction and have a maximum value of 1. DF is calculated only for river-crossing bridges, otherwise DF should equal to 100.

$DF=SSI\times K_{pier}\times K_{Protection}\times R_{uncover}\times R_{clearance}$ Equation (5)

Where

SSI: Scouring Stability Index (SSI) of a bridge is calculated in the way similar to CI, but only worst DER ratings, instead of an averaged rating, among same components are used. In addition, only a few components related to scouring are incorporated. They are Waterway (3), Abutment foundations (5), Abutments (6), Scouring protection of piers (12), Pier foundations (13), and Piers and columns (14). Numbers in the parentheses are the component number listed in Table 1. Equation (6) shows the formula for calculating SSI.

$$SSI=\frac{\sum_i Ic_i\times w_i}{\sum_i w_i}, i=3,5,6,12,13,14 \quad \text{Equation (6)}$$

K_{pier}: For multi-column piers K_{pier}=1; for double column piers K_{pier}=0.9; for single column pier K_{pier}=0.8.

$K_{Protection}$: For pier foundation that is in covered condition, FP=1; for pier foundation that is uncovered with scouring protection, FP=0.9; and for pier foundation that is uncovered without scouring protection, FP=0.8.

$R_{uncovered}$: Adjustment ratio for uncovered height of foundation. According to the report published by National Center for Research on Earthquake Engineering (NCREE), the uncovered height of pile foundation generally cannot exceed half of the height of the pile [3]. Thus, for pile foundation, $R_{uncovered}$=(1-2×h/H), where h is the uncovered height of pile and H is the full length of the pile. Notably, if $h\geq H/2$, $R_{uncovered}$=0.1 (for pile) for a maximum deduction. For caisson foundations, $R_{uncovered}$=(1-1.43×h/H), and if $h\geq H/1.43$, $R_{uncovered}$=0.1.

$R_{Clearance}$: Adjustment ratio for the clearance between the bottom of beam and highest-ever flood water level. According to the book "*Bridge Inspection Method and Practice*" published by the Ministry of Transportation and Communication, the clearance must exceed 2 meters [4]. If so, then $R_{Clearance}$=1, otherwise $R_{Clearance}$ =[(Elevation of bottom of beams)-(Elevation of highest-ever flood water level)]/2.

4.2 Degree of Mudflow Resistance (DM)

The Degree of Mudflow Resistance (DM) represents a bridge's ability to resist possible damages caused by mudflows. DM is calculated by Equation (7), in which Rs are parameters used for deduction and have a maximum value of 1. Again, DM is calculated only for river-crossing bridges, otherwise DM should equal to 100.

$DM=SSI\times R_{Span}\times R_{Riverbed}\times R_{Flow}$ Equation (7)

Where

SSI: Scouring Stability Index, as depicted in section 4.1.

R_{Span}: Adjustment ratio for span length. According to the report published by Construction and Planning Agency Ministry of the Interior, if the minimum span of the bridge exceeds 35 meters, the bridge is deemed to have enough section space for mudflow to pass through [5]. Thus, if so, then R_{Span} =1, otherwise R_{Span} =Min[Span length]/35.

$R_{Riverbed}$: Adjustment ratio for the distance from the bottom of bridge beams to the river bed. According to the report published by Construction and Planning Agency Ministry of the Interior, if the distance exceeds 10 meters, the bridge is deemed to have enough section space for mudflow to pass through [5]. Thus, is so, then $R_{Riverbed}$ =1, otherwise, $R_{Riverbed}$ =Min [Distance from bottom of beams to riverbed]/10.

R_{Flow}: Adjustment ratio for the distance from the bridge to the nearest river or creek which has potential to induce mudflows. It is deemed to be a safe distance exceeding 500 meters. Thus, if so, then R_{Flow}=1, otherwise R_{Flow}=[distance from bridge to mudflow rivers]/500.

4.3 Degree of Earthquake Resistance (DE)

The Degree of Earthquake Resistance (DE) represents a bridge's ability to resist possible damages caused by earthquakes. DE is calculated by Equation (8), in which *Ks* and *R* are parameters used for deduction and have a maximum value of 1.

$DE = ASI \times K_{Design} \times K_{Device}$ Equation (8)

Where

ASI: Anti-Seismic Index (*ASI*). Again, *ASI* is calculated similar to CI but only taking into account the worst DER ratings of the components related to resistance of earthquake force. The components vary by bridge types, as listed in Table 2. Equation (9) shows the equation for calculating *ASI*.

$$ASI = \frac{\sum_i Ic_i \times w_i}{\sum_i w_i} \quad \text{Equation (9)}$$

Table 2 Components used by *ASI* for different types of bridges

No	Components	Girder	Sable-stayed	Arch
5	Abutment foundations	use	use	use
6	Abutments	use	use	use
13	Pier foundations	use	use	use
14	Piers and columns	use	use	use
15	Bearings	use	use	use
16	Earthquake brakes	use	use	use
17	Expansion joints	use	use	use
18	Longitudinal girders	use	use	use
19	Transversal beams	use	use	
22	Pylon & anchor		use	
23	Cable & anchor		use	
24	Arch rib			use
25	Crossbeam			use
26	Spandrel or suspender			use

K_{Design}: Earthquake design factor, ranging from 0.5 to 1.0, is determined by required design acceleration based on the bridge locations listed in the bridge design manual published by the Ministry of Transportation and Communication.

K_{Device}: If earthquake-resistance device exists, K_{Device}=1, otherwise K_{Device}==0.8.9

4.4 Degree of Load Resistance (DL)

The Degree of Load Resistance (DL) represents a bridge's ability to resist possible damages caused by traffic loads. DL is calculated by Equation (10), in which *Ks* are parameters used for deduction and have a maximum value of 1.

$DL = DI \times K_{Age} \times K_{Liveload}$ Equation (10)

Where

DI: Danger index. *DI* is obtained based on an index termed *JI*, developed by Join Engineering Corp. and shown in Table 3. *JI* was determined by experienced bridge inspection experts in that company. *DI* of a bridge is then calculated by Equation (11) for all of its 21 components, where w_i is structural safety factor, s_i represents traveler's safety factor [6]. The structural safety factors are same as the weights used in the DER&U methodology, while the traveler's safety factors, shown in Table 4, are designed to magnify the influence of certain components which may cause injury to the travelers.

$$DI = Min\left[JI \times w_i \times s_i\right] / \left[Max(w_i) \times Max(s_i)\right] \quad \text{Equation (11)}$$

Table 3 *JI* values determined by inspection results.

D	E	R	*JI*	D	E	R	*JI*	D	E	R	*JI*
1			100	3	2	2	65	3	4	3	29
2	1	1	98	4	1	2	63	4	3	3	27
2	2	1	96	2	4	2	60	4	4	3	25
3	1	1	94	3	3	2	58	2	1	4	23
2	3	1	92	4	2	2	56	2	2	4	21
3	2	1	90	3	4	2	54	3	1	4	19
4	1	1	88	4	3	2	52	2	3	4	17
2	4	1	85	4	4	2	50	3	2	4	15
3	3	1	83	2	1	3	48	4	1	4	13
4	2	1	81	2	2	3	46	2	4	4	10
3	4	1	79	3	1	3	44	3	3	4	8
4	3	1	77	2	3	3	42	4	2	4	6
4	4	1	75	3	2	3	40	3	4	4	4
2	1	2	73	4	1	3	38	4	3	4	2
2	2	2	71	2	4	3	35	4	4	4	0
3	1	2	69	3	3	3	33				
2	3	1	67	4	2	3	31				

Table 4 Traveler safety factor

Importance	Component number	Condition	Safety factor
Major	5, 8, 11, 13, 14, 18, 20	D=4, R=4	3
Average	1, 2, 3, 4, 6, 9, 10, 15, 16	All	2
Minor	7, 12, 19, 21	All	1

K_{Age}: Factor for deduction due to aging. According to the report published by Construction and Planning Agency, Ministry of the Interior, if a bridge's age exceeds 30 years, it is defined as old bridge. Thus, if so, K_{Age}=0.8, otherwise K_{Age}=1.

$K_{Liveload}$: Factor for designed live load. If the bridge's designed live load exceeds HS20+25% then $K_{Liveload}$ =1; If the bridge's designed live load is between HS20+25% and HS20 then $K_{Liveload}$ =0.9; otherwise $K_{Liveload}$ =0.8.

4.5 Discussion of Degree of Disaster Prevention (DDP)

It can be seen from historical records that Taiwan's bridges were mainly damaged by natural disasters or by overloaded traffics. Thus, in Equation (4), DF, DM, and DE are defined first to represent the bridge's ability to resist possible damages caused by natural disasters, while DL is defined to show the ability to resist man-made traffic loads. Under the worst situation, when multiple disasters occur, the bridge should be firstly damaged by its weakest resistance to a certain type of disaster. However, there could be also traffic loads at the time when a disaster occurs. Thus, it is deemed reasonable to obtain DDP as a multiplication of minimum of DF, DM, and DE by DL.

A threshold of DDP representing sufficient resistance to disaster is temporarily determined at 64. The rationale behind is that when an individual degree of resistance exceeds 80, it means that the bridge has sufficient ability; thus when all the degrees of resistance to natural disasters or traffic loads are rated at 80, DDP will be calculated as 64 by Equation (4). By the same rational, an individual degree of resistance below 40 is deemed definitely insufficient, thus when DDP scores below 16, the bridge is in a dangerous condition.

5. CONCLUSION

Taiwan is an island exposed to various natural disasters. This research develops a mechanism for fast evaluation of a bridge' resistance to possible damages caused by floods, mudflows, earthquakes, and by traffic loads using inventory and inspection results recorded in the Taiwan Bridge Management System (T-TBMS). The evaluation mechanism can be programmed into the T-BMS for an automatic evaluation and identification of dangerous bridges among the existing 28,000 bridges in Taiwan. Verification and modification of the developed mechanism are being conducted now and are expected to be completed in a few months.

ACKNOWLEDGEMENT

This research is sponsored by the National Science Council of Executive Yuan in Taiwan under the project "Adaptation Strategies of Bridge Engineering in Response to Compound Disasters Caused by Extreme Weather Conditions" (Project no. NSC 99-2218-E-008-014).

REFERENCES

[1] Nie-Jia Yau and Hsien-Ke Liao, "Visual Inspection and Evaluation for Special Bridges", *Proceedings of 2007 International Symposium on Integrated Life-Cycle Design & Management of Infrastructures*, pp. 195. 2007.

[2] Nie-Jia Yau and Hsien-Ke Liao, "Development of Bridge Management System in Taiwan", *Proceedings of the 5th International Conference on Construction Project Management & 2nd International Conference on Construction Engineering and Management*, pp. 92. 2007.

[3] Kuo-Chun Chang, Yi-Chao Tsai, and Dyi-Wei Chang, *Seismic Assessment and Retrofit Manual for Highway Bridges*, NCREE, Taiwan, 2009. (In Chinese)

[4] Chinese Institute of Civil and Hydraulic Engineering, *Bridge Inspection Method and Practice*, Scientific & Technical Publishing Co., Ltd., Taiwan, 2010. (In Chinese)

[5] Construction and Planning Agency Ministry of The Interior, *The Research of Bridge Inspection, monitoring, rehabilitation and management at Urban Planning Districts*, CPAMI, Taiwan, 2005. (In Chinese)

[6] Nie-Jia Yau and Hsien-Ke Liao, "Development of bridge maintenance decision support module of Taiwan Bridge Management System", *Bridge Maintenance, Safety, Management, Health Monitoring and Informatics*, pp. 166. 2008.