Comparison of Bridge Inspection Methodologies and Evaluation Criteria in Taiwan and Foreign Practices

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Abstract –
The reliability of structural performance of bridges in Taiwan are affected by both in-service loading and material deterioration due to extreme environmental factors. With an inventory of 27,895 bridges and culverts in Taiwan Bridge Management System (TBMS), there are more than 8,840 bridges that are over 30 years and around 8,877 whose built years are still unknown. Government officials noticed this issue in recent years and placed thoughtful attention. Not only did they establish the maintenance mechanism for regular bridge inspections and maintenance, but developed maintenance systems to upsurge the competence of bridge management. However, this strategy only focused on data recording and was not able to notably improve maintenance efforts. Thus, it is essential that engineers refine their inspection and assessment techniques.

Bridge inspection data recorded in TBMS are frequently analysed, to determine failure causes. According to the "Validation of bridge inventory data in TBMS" project, funded by Ministry of Transportation and Communications (MOTC) in 2010, the accuracy of bridge inspection data was lower than that of inventory. Consequently, MOTC proposed to enforce a new and detailed inspection program after 2015.

This research reviewed the state-of-the-art for inspection methodologies in practice to assess condition of bridges in Taiwan, Japan, South Africa, USA and Europe. Concisely, the findings, including description, categorization of deterioration, and assessment method of bridge conditions were collected to provide bridge inspectors and engineers with more reliable assessment approach. Recommendations for enhancing bridge inspection standards and qualifications for inspectors in Taiwan are also discussed in this paper accordingly.

Keywords: Bridge Management System, Condition Rating, DER&U Methodology, Evaluation Criteria, Visual Inspection.

1 Introduction

Taiwan owes its formation, shape and frequent rate of earthquakes to the complex interaction of the Eurasian and Philippines Sea plates. In a geological time-scale, the 35,563 km^2 (13,731 mi^2) island has virtually erupted from the ocean floor as the Philippines Sea Plate drives Northwestward into the Eurasian plate at a rate of about 7 centimeters per year.

On September 21, 1999, Chi-Chi Earthquake of magnitude 7.3 struck Central Taiwan, leaving subsequent aftershocks with four of which measured a magnitude greater than 6.5 on the Richter scale. The devastating incident caused severe infrastructural damages and casualties to the affected region.

Furthermore, torrential rains brought by typhoons causes floods and mudflows which are huge threats to bridges in particular. On August 8 2009, Typhoon Morakot struck southern Taiwan and brought about the worst flood recorded for the past 50 years, whereas 129 bridges were seriously damaged. Due to these alarming issues, bridge maintenance, rehabilitation, and repair (MR&R) have become important matters to MOTC and Local Governments [1].

Different versions of BMS packages have been developed to administer bridge-related issues in Taiwan. However, it was until 2000 that Taiwan Bridge Management System (TBMS) was established by the Center for Bridge Engineering Research (CBER) at National Central University (NCU). This project was funded by MOTC and is currently maintained by the Graduate Institute of Construction Engineering and Management at NCU [2].

2 Overview of International Inspection Methods

2.1 Taiwan

According to the Manual for Enhancement and Inspection of Highway Concrete Bridges (2015) regulated by the MOTC, there are three types of bridge inspections, namely:

1. *Daily Patrol*– performed as regulated by the Road Maintenance Manual (2012), whereby two inspectors drive over a bridge to check for defects.
2. *Regular Inspection*– performed by trained inspectors using naked eyes and essential tools to examine the overall condition of a bridge and its river course. This inspection is operated span-by-span and is performed once every two years.
3. *Damage Inspection*– an unscheduled inspection to assess structural damages resulting from floods, typhoons, earthquakes, fire, etc.

Regular and Damage inspection may involve the usage of heavy instruments such as bridge inspection trucks, cherry pickers and inflatable boats.

The methodology for visual inspection in Taiwan is abbreviated as DER&U. DER&U is a national standard for regular bridge inspection and evaluation; which is an effective, reliable and economical way to examine bridges. Herein, "D" stands for degree of deterioration; "E" represents extent of the deterioration; "R" implies relevancy to safety of the deterioration; and "U" depicts the urgency for repairing of the deterioration. All of these indices are numerically rated on an integer scale ranging from 0 to 4, as shown in Table 1. While rating, the inspector may state his/her personal remarks if deemed necessary [3].

Table 1. DER&U evaluation criteria

	0	1	2	3	4
D	Not exist	Good	Fair	Bad	Serious
E	*U/I	<10%	10~30%	30~60%	Over 60%
R	Uncertain	Minor	Limited	Major	Large
U	**N/A	Routine	In 3 yrs.	In 1 yr.	Immediate

*U/I – Unable to Inspect, **N/A – Not Applicable

After inspection, each component (deck, girder, pier, joint, abutment etc.) of the bridge is rated. A component condition index Ic_{ij} is calculated based on the evaluated integers of D, E, and R for each component. This 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'*.

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

Where *'a'* is an integer usually denoted as 1 for the *'i'* component of item *'j'*.

The condition index I_{ci} of component *'i'* is an average value of all similar items as deduced in Equation (2) below.

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

The overall bridge condition index, *CI* is a weighted average of all components as shown in Equation (3); where m=21 for concrete girder bridge, m=22 for cable-stayed bridge and m=23 for both suspension bridge and arch bridge [2].

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

2.2 Japan

In Japan, each element in the structure is evaluated based on every single kind of defect, such as cracking, corrosion, etc., then a demerit rating is assigned to each element in a tabular format [4].

According to the Regular Inspection Procedure for Road Bridge (2014) regulated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), there is basically one inspection type; *Regular Inspection*.

Based on this regulation, all bridges in Japan bridges with a span longer than 2 meters must be inspected at least once every five years. *Regular inspection* in Japan is a hands-on visual inspection of components or elements in a close distance [5].

For every structural member in each span, the condition is translated into either of the maintenance urgency ratings listed in Table 2.

Table 2. Health rating of bridges in Japan

Condition		Description
I	Good	No obstacle to the function of the structure.
II	Preventive maintenance phase	There is no obstacle to the function of the structure, but it is desirable to take preventive maintenance.
III	Early rehabilitation phase	There is a possibility that the function of the structure may be hindered, so a rehabilitation strategy must be taken.
IV	Emergency repair phase	Presence of an obstacle to the function of the structure, or a possibility of occurrence is extremely high. An urgent action must be taken.

Maintenance urgency ratings are diagnoses given by experienced engineers in a very subjective manner, recommending to bridge owners the needs for action by the time of the next inspection. Engineers are required to interpret the maintenance urgency for each member, taking into account the damage type, location of damage, direction of crack, earlier remedial work history, etc. Moreover, numeric criteria like crack width and length are specified for maintenance urgency ratings.

2.3 United States of America

The National Bridge Inspection Standards (NBIS 2009) set the criteria for proper inspection and evaluation of all highway bridges in the United States. According to the American Association of State Highway and Transportation Officials (AASHTO) manual for Condition Evaluation of Bridges, the overall condition rating is assigned for 3 major components: deck, superstructure and substructure which are further divided into various elements.

In the U.S., there are eight types of bridge inspections (Table 3) [5]. Federal regulations address bridge inspection population, inspection intervals, inspection methods, inspection personnel, and inspection reporting. Federal requirements are presented primarily in the Code of Federal Regulations [6].

Table 3. Types of bridge inspection in the U.S.

Inspection	Description
Initial	First inspection of a bridge as it becomes a part of the bridge inventory to determine baseline structural conditions.
Routine	Regularly scheduled inspection consisting of observations and/or measurements needed to determine the physical and function condition of the bridge.
Damage	Unscheduled inspection to assess structural damage resulting from environmental factors or human actions.
In-Depth	A close-up inspection which investigates deficiencies that were not detected during Routine Inspection.
Special	An inspection scheduled at the discretion of the bridge owner, used to monitor a particular known defect or suspected deficiency.
Underwater	Inspection of the underwater portion of a bridge substructure and the surrounding channel.
Hands-on	Inspection within arm's length of the component. Inspection uses visual techniques that may be supplemented by NDT.
Fracture-Critical Member	A hands-on inspection of a fracture-critical member or components that may include visual and other non-destructive evaluation.

NDT: Non-destructive Test

Table 4. NBI condition rating system

Rating	Description
N	Not Applicable.
9	Excellent Condition.
8	Very good Condition – no problems discovered.
7	Good Condition – some minor problems.
6	Satisfactory Condition – structural elements show some minor deterioration.
5	Fair Condition – all primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
4	Poor Condition – advanced section loss, deterioration, spalling, or scour.
3	Serious Condition – loss of section, deterioration, spalling or scour have seriously affected primary structural elements.
2	Critical Condition – advanced deterioration of primary structural elements.
1	Imminent Failure Condition – major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability.
0	Failed condition – out of service.

The U.S. methodology for rating values during inspection is a very subjective approach. The inspector visits the site and looks at every component of the bridge, then gives an assessment value ranging from 0 to 9 for the whole structure (Table 4) [7]. The ratings provide information on the severity of a condition but do not identify or quantify the extent of the deterioration. For this reason, this rating system has a limited value in determining repairs and rehabilitation needs.

Moreover, a descriptive condition rating in terms of 'good/fair/poor/not applicable' is given by the inspector for each element (waterproofing, painting, road surface etc.) of the component, based on the deficiencies found on the individual element [8]. Table 5 illustrates the descriptive rating for bridge elements.

Table 5: Descriptive condition rating for elements

Condition	Description
Good	Element is limited to only minor problems.
Fair	Structural capacity of element is not affected by minor deterioration, spalling, cracking etc.
Poor	Structural capacity of element is affected by advanced deterioration, section loss, spalling, cracking or other deficiency.

2.4 United Kingdom

The Structures Management Information System determines maintenance needs based upon structural adequacy or safety rather than solely on the condition state of the structures for UK's Highways Agency. The requirements for inspecting highway bridges in the UK are defined in Volume 3, Section 1, Part 4 of the Design Manual for Roads and Bridges (BD 63/07) (Highways Agency, 2007) [9].

According to UK. Highways Agency, there are five types of inspections for bridges and can be used in combination depending on inspection needs (see Table 6).

The methodology of visual inspection in U.K. is primarily based on *Severity – Extent* code prescribed procedure set out by the Highway Agency. *The severity* defines as the degree of damage while *extent* is a measure of the length, area, or number of defects of the bridge element. [10].

Table 6. Types of bridge inspection in the UK

Inspection	Description
Acceptance	Performed for new bridges, newly repaired bridges, and newly start of a new maintenance contract.
Superficial	Checks for outstanding defects that pose a risk to safety are highlighted and action taken immediately to remedy them.
General	Applies to bridge elements that are easily accessible.
Principal	All bridge elements, including those that are difficult to access. This may sometimes require specialist access machinery or tools.
Special	Detailed investigation of a particular bridge component. Bridges that have been strengthened using plates bonded to them also require special inspections.

Table 7. UK Bridge condition rating system

Code		Description
Extent	A	No significant defect.
	B	Slight, less than 5% of length/area affected.
	C	Moderate; 5% – 20% of area/length affected.
	D	Wide, 20% – 50% affected.
	E	Extensive; over 50% of surface area/length.
Severity	1	As new, or has no significant defect.
	2	Early signs of deterioration, minor defect.
	3	Moderate, some loss of functionality expected.
	4	Severe defect and/or element is close to failure.
	5	The element is non-functional/failed.

These codes are used in a scale of 1-5, describing the degree of deterioration, from minor (structurally sound) to a collapsed state (non-functional). Table 7 presents permissible combinations of Severity and Extent.

2.5 South Africa

The inventory and inspection of bridges is done by the South Africa National Roads Agency Limited (SANRAL) for bridges on national roads, 9 Provincial departments of transport for bridges on provincial roads and municipal transport agencies for bridges on municipal roads. South African maintenance practice includes five types of inspections (Table 8) [11].

Similar to Taiwan, the defects are rated for their Degree, Extent, Relevancy and Urgency (DER&U) as it is previously discussed (see Table 1). This system is a visual inspection and evaluation method for bridges jointly developed by Join Engineering Consultants, and South African CSIR Company

The DER&U rating system identifies defects and prioritizes them by evaluating their relative importance to the structural integrity of the bridge. It is important to note that the ratings are not directly associated with the elements but with the damage. [12].

Table 8. Types of bridge inspections in South Africa

Inspection	Description
Monitoring	A quick check on the new defects and the status of the previously known defects. A monitoring inspection does not produce any condition rating.
Principal	A thorough examination and record of a bridge for all defects.
Verification	Are performed annually by SANRAL in order to verify the accuracy of inspection data.
Project-level	Inspection to collect information for contract documents.
Acceptance	Inspection of work during and after a contract.

2.6 Denmark

The Danish Road Directorate used a computer-based BMS, called DANBRO, to manage their bridges. DANBRO has been in place throughout Denmark since 1988 and is reported as fulfilling its main purpose of aiding bridge management at all levels.

DANBRO identifies eight types of bridge inspections (Table 9). For each defect reported, the inspector will recommend a repair scheme, its year of application, and also estimate the costs for repair actions.

Table 9. Types of bridge inspections in Denmark

Inspection	Description
Inventory	Collect bridge data and baseline conditions.
Daily*	Cursory examination noting failure, damage, debris, etc.
Routine—Extended	Planning and checking routine cleaning and maintenance.
Reports from Users	Reports of: impact damage, vandalism, debris on bridge or road and erosion damage.
Principal	Thorough and systematic visual inspection of all the components of the bridge.
Special	Collection of more detailed information for decisions on maintenance actions.
Economic Special Inspection	Preparation for major repair project for a bridge.
Technical Special Inspection	Damage investigations, Special investigations, Load-carrying capacity evaluations.

* | Not a formal part of the Directorate Bridge Inspection Program.

Recommendations on the interval of visual inspections depend on the age, average daily traffic (ADT), location, existing conditions, and special features of the bridge.

Condition ratings in Denmark (Table 10) are built up from three contributors: damage (3 points), function (1 point), and consequence (1 point). The overall rating scale is 0-5, with '0' meaning no damage and '5' implying that the component can no longer fulfil its function [13].

Table 10. DANBRO condition rating system

Rating	Description
0	Insignificant deterioration; little or no damage.
1	Minor deterioration; damage with a very slow rate of development.
2	Damage is at an early stage of development or there are a few fully developed defects.
3	Damage has developed to such a degree and/or extent that it is likely that within a short time the component will no longer fulfil its function.
4	The component is severely deteriorated, such that its capacity to fulfil its function has or will soon disappear. Repair is necessary in the near future.
5	The component has completely deteriorated and can no longer fulfil its function.

2.7 Sweden

The Swedish Road Administration (SRA), maintain guides and manuals for bridge design, construction, and inspection. Sweden does not have national regulations for bridge inspection, thus, work performed by SRA includes strategic management, planning of projects, specifications for bridge works, procurement of bridge works, and supervision of contract work. SRA executes about half of all bridge inspections, with other inspections done by consultants. SRA has four levels of routine inspections: Regular, Superficial, General, and Major (Table 11) [12].

Table 11. Types of bridge inspections in Sweden

Inspection	Description
Regular	Quick visit to detect significant new conditions.
Superficial	Verify that maintenance requirements are met.
General	Follow-up on damages detected at the last major inspection.
Major	Arms-length, visual inspection of all components.
Special	Further investigation of defect or deterioration.

In addition, SRA performs Special inspections of known defects, suspected defects, and deterioration mechanisms, as needed.

SRA collects ratings and other data on conditions of bridge components during General, Major, and Special inspections. The quantity and the method of its measurement are fitted to the type of damage, structural element, material, and other considerations (e.g., mode of action of element). Functional condition is reported on a 0 to 3 rating scale, with '3' being the worst condition (Table 12). Functional condition is related to the time until the defect is expected to impair the service of the bridge [9].

Table 12. SRA condition rating

Rating	Physical Condition	Functional Condition
3	Repair needed now	Service impaired now.
2	Repair within 3 years	Service impaired within 3 years.
1	Repair within 10 years	Service impaired within 10 years.
0	Repair after 10 years	Service greater than 10 years.

2.8 Germany

Germany performs bridge inspections at two levels called Major Test and Minor Test (Table 13) [15]. Major tests are arms-length (DIN wording is "touching-distance") inspections of all elements with access to all parts. Minor tests are done three years after each major test. Minor tests use findings of the previous major test and focus on known damage and defects.

In Germany, condition rating scales run from 0 (good) to 4 (very poor). Each bridge component is assigned three ratings; one each for structural damage, traffic safety, and bridge durability. In this paper, the rating for structural damage is shown in Table 14 [16].

To ensure a standard approach for the evaluation of damages, inspection teams will be equipped with catalogues containing detailed example of damage evaluation. A total of 6 levels of bridge condition ratings are defined whose descriptions are shown in Table 15. The possible damages are graded (0 to 4), assigned to stability, safety and durability

Table 13. Types of bridge inspection in Germany

Inspection	Description
Major Test	Arms-length inspection of all components; uses access equipment and includes underwater inspection.
Acceptance	*Major test.*
Guarantee	*Major test.*
Minor Test	Verification of current state of known damage and defects.
Superficial	Cursory inspection for safety.
Ad Hoc	After significant events, such as storms, floods, etc.; also for known, severe damage.
Systems	Inspection of electrical or mechanical systems.

Table 14: Condition ratings for structural damage

Rating	Description
0	Defect has no effect on the strength of the element or structure.
1	Defect affects the strength of the structural element, but does not affect the strength of the structure.
2	Defect affects the strength of the structural element and has little effect on the strength of the structure.
3	Defect affects the strength of the structural element and the structure. Structure does not have adequate strength.
4	Structural strength of the structural element is lost. Structure does not have adequate strength. Repair or rehabilitation is needed.

Table 15. Ratings for Components in Germany

Grade	Description
1.0–1.4	Very good structural condition.
1.5–1.9	Good structural condition, but may have less long-term durability.
2.0–2.4	Satisfactory structural condition, but may have less long-term durability.
2.5–2.9	Unsatisfactory structural condition. Traffic safety may be affected.
3.0–3.4	Critical structural condition. Traffic safety is affected.
3.5–4.0	Inadequate structural condition. Traffic safety is not adequate.

3 Discussion and Suggestions

3.1 Bridge Inspection Intervals

The condition of any bridge can be quite alarming even when slight deteriorations are yet to be visually identified. In this respect, defined inspection interval for different types of bridge inspection and condition assessment is significant in assuring a suitable structural healthiness of the bridge.

However, inspection intervals vary from one country or agency to another (see Table 16). The depth and frequency to which bridges are inspected in Taiwan depends on factors such as age, traffic characteristics, state of maintenance or known deficiencies. The evaluation of these factors is a sole responsibility of the individual or agency in charge of the inspection program. Thus, it is necessary to innovate solid criteria for assessment of a bridge's general condition in accordance to a defined frequency for visual inspection. Conversely, structural assessments and reliability models can be developed using established methods and integrate them into prioritization techniques to better improve bridge condition modelling with time.

Considering the necessity to ensuring safety of bridges and determination of a suitable MR&R at a lower cost, it is suggested that the regular inspection in Taiwan be refined into; (1) *Minor*–biannual inspection of a bridge to determine its maintenance urgency. This inspection can be performed by applying the Japanese methodology for health rating of bridge components. (2) *Major*–assessment of all bridge components using the DER&U rating system. A major inspection should be performed after two consecutive minor inspections (6 years). Despite the fact that inspection data are seen to be subjective, this ideology will enable engineers to achieve a target level of reliability of inspection results.

On the other hand, a review of international practices emphasizes that underwater material damage, and scour-related deterioration may not be apparent above water until the damage has become so severe that remedial actions are extremely expensive. Based on this argument, there is a need for an additional underwater inspection to the inspection program in Taiwan. Practising this inspection type can reduce the cost of in-water repair work. Furthermore, it is also considered necessary to perform initial inspections on new bridges, or when existing bridges are entered into the database. This inspection provides a foundation for all future inspections or modifications to the bridge.

These strategies can baseline a framework to support engineers and bridge managers in decision-making processes for prioritizing inspections, maintenance actions and budget allocations.

3.2 Inspection Qualification & Certification

In foreign practices, most entry-level jobs require a high school diploma and certification. Advanced positions may require higher education such as a bachelor's or master's degree in civil engineering. Depending on the inspection type being active for a certain service, different inspectors are employed upon the guiding principles of the inspecting agency (Table 17). Herein, some influential codes of practice are discussed consequently.

In the U.S., the federal regulations do not establish qualifications for inspection team members working under the direction of an inspection team leader. An Inspection team leader in the U.S. must be a professional engineer, complete a Federal Highway Administration (FHWA) approved comprehensive bridge inspection training courses and has at least five years of bridge inspection experience. Apart from underwater inspectors, all Danish inspection personnel are engineers. Denmark conducts annual refresher training for all bridge inspectors. Individuals performing General or Major inspections in Sweden must hold an engineering degree, have experience with bridge design and construction, and must complete a one-week training course offered by the SRA. In Germany, bridge inspectors must have formal education as civil engineers and complete a federal training course lasting one week that covers all aspects of inspection.

It’s observed that, most of the practices reviewed hold a regulation governing qualifications for certain inspection processes. This strategy is yet to be practiced in Taiwan as it is still under development by MOTC. Meanwhile, it would be reasonable to propose periodic training workshops for inspectors and engineers all over the country.

The training should be directed towards all features of inspection, deterioration processes, rating systems and assessment methods. Moreover, the participants must hold a degree in civil engineering before being accepted to this program. In so doing, inspectors will be able to recognize indications projecting to harmful influence of deterioration even before visible signs appear on bridge surfaces.

3.3 The DER&U Methodology

The DER&U is a condition assessment methodology invented in 1994 by two consulting companies, CSIR and Join Engineering of South Africa and Taiwan respectively. It has since become a national standard for regular bridge inspection and evaluation, deemed an effective, reliable and a cost-effective method for assessment of bridge conditions in Taiwan. During condition assessment of bridge structures, defects are rated for their Degree, Extent, Relevancy and Urgency, as previously illustrated in Table 1.

The DER&U is a subjective technique because, two defects may look the same to the inspector and have the same extent, but their impact on the reliability of the bridge may be different. Hence, the relevancy of the distress helps the inspectors capture information beyond ordinary visual ratings by assessing the impact of each distress on the overall structural integrity of the bridge.

Table 16. Summary of inspection types and their respective intervals

Occurrence	Taiwan	Japan	USA	UK	South Africa	Denmark	Sweden	Germany
Frequent	Patrol			Superficial		Daily	Regular	
3 Months								Superficial
1 Year					Monitoring	Routine	Superficial	
2 Year	Regular		Routine	General				
3 Year							General	Minor
5 Year		Regular	Under water		Principal			
6 Year				Principal		Principal	Major	Major
Other	Damage		Damage, In-depth, Special	Special	Verification, Project	Users Report, Special	Special	Ad Hoc

Table 17. Summary of inspection types and corresponding personnel qualification

Personnel	Taiwan	Japan	USA	UK	South Africa	Denmark	Sweden	Germany
Non-Certified Inspector	Regular			Superficial	Monitoring	Routine	Superficial	Superficial
Certified Agency			Routine					Minor
Inspector			-Routine -In-depth					
Engineer		Regular		Principal	Principal	-Economic -Special	General	Major

4 Conclusion

This paper briefly discussed the state-of-the-art for bridge inspection, evaluation and management methods being used to assess the performance of bridges in Taiwan and other countries. The findings outline the inspection types, condition description, and structural evaluation for bridge conditions.

It is observed from foreign practices that, with the exception of Japan and Taiwan, the combination of bridge complexity and inspector qualifications determines a matrix for inspection intervals. In this regard, bridge inspection certification scheme should be established to upsurge the competency of inspectors and engineers in Taiwan. Moreover, reformation of inspection level and frequency for inspections such as initial, underwater, damage, and special inspections should be considered in prospect researches in Taiwan.

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