STUDY OF EFFICIENCY STRATEGIES FOR ROAD BRIDGE MAINTENANCE

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Overview

In order to promote the ongoing upkeep of the road network through efficient management of an increasing number of steadily deteriorating road bridges, road authorities in Japan have set up a systematic framework for checking the condition of bridges throughout the country and identifying degradation and failure, involving the collection of detailed data on all structures.

This paper describes the utilization and ongoing refinement of a data-driven maintenance and management framework for road bridges in Japan, particularly with respect to the development of condition evaluation indicators for road bridges and bridge management systems for the relevant national highways.

1. Introduction

The road network in Japan has an increasing number of road bridges and structures that are steadily aging. In order to maintain the road network at a suitable level of performance, it is necessary to keep these structures in good condition. To this end, structures are inspected periodically. The inspections generate detailed data, which is used to identify deterioration and/or failure and determine the required repairs and/or reinforcement work.

This approach, which involves attending to faults identified via visual inspection, is inherently inefficient and uneconomical, since repair work is always being carried out after the damage has occurred. Work is now underway to develop a comprehensive management system as the basis for effective, low-cost prediction modeling, involving collection of detailed data and use of simulation techniques such as degradation prediction.

A management system that makes predictions based on averaged data at the macro level is effective for broad predictions at the national or prefectural level, but cannot generate the required level of precision for individual structures with respect to the nature and timing of repair work. The management system is not being utilized in the preparation of repair programs in the field, either because it is not considered useful or

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because discrepancies with budgetary restrictions in the form of macro estimates prevent proper estimation of the extent of work required.

This paper discusses the development and refinement of the maintenance and management system for road bridges in Japan, and also describes the way of the future.

2. Inspection data

A periodic inspection program has been developed to provide detailed data on road bridges on the national highway system throughout Japan. Table 1 shows changes in bridge structures classified in 26 categories, based on periodic inspections conducted every five years. Data for structural members is further sub-divided, and each category is evaluated on a five-point scale. Even an ordinary single span bridge with 30 meter span length would generate over 1,000 data items. Generally, the supervising engineer is responsible for assessing the need for repairs and determining the timing and type of work required, based on this enormous volume of data. In this sense, it can be said that large volumes of detailed information are not being utilized effectively.

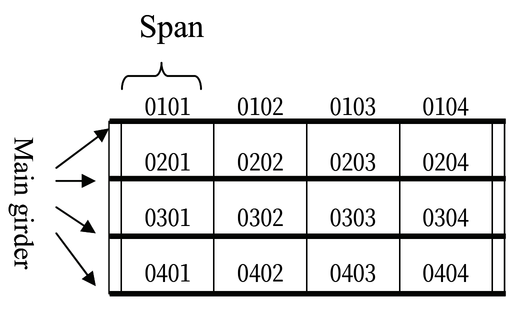
TABLE 1. EVALUATION UNDER PERIODICAL INSPECTION GUIDELINES — SCOPE AND CRITERIA

Damage to steel members	Corrosion	e	Corrosion causing general reduction in thickness
		d	Corrosion causing localized reduction in thickness
		c	General surface corrosion
		b	Localized surface corrosion
	Cracking	e	Linear cracks
		c	Splits/small cracks in paint film
	Looseness/falling	e	Very loose/many missing portions
		c	Slightly loose/some missing portions
	Rupture	e	Ruptured
	Deterioration of corrosion-proofing function	e	General spot rust
		d	Localized flaking of membrane
		c	Discoloration of membrane, localized lifting

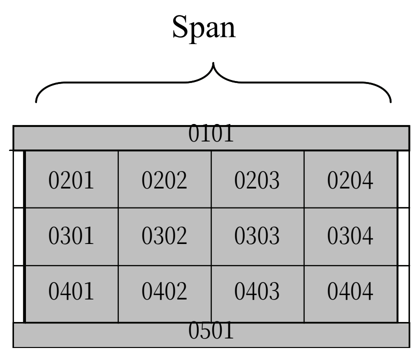
Damage to concrete parts	Cracking	e	Width = large, minimum interval = less than 0.5 m
		d	Width = medium, minimum interval = less than 0.5 m/width = large, minimum interval = 0.5 m
		c	Width = small, minimum interval = less than 0.5 m/width = medium, minimum interval = 0.5 m
		b	Width = small, minimum interval = 0.5 m or more
	Peeling and exposure of reinforcing bars	e	Reinforcing steel exposed and corroded
		d	Reinforcing steel exposed only
		c	Flaking only
	Leakage and free lime	e	Extensive water leakage/free lime/rust effluent
		d	Free lime
		c	Water leakage only
	Falling out of place	e	Missing
	Damaged concrete reinforcement	e	Extensive damage to reinforcing material
		c	Minor damage to reinforcing material
	Deck slab cracking	e	Continuous corner flaking including over 0.2 mm
		d	Localized corner flaking at lattice
		c	Mainly less than 0.2 mm before lattice
		b	Mainly less than 0.1 mm and in the same direction
	Lifting	e	Lifting

Other damage	Problems		e	Openings too wide, girder contact
			c	Openings out of alignment, not symmetrical
	Unevenness of road surface		e	Level difference of 20 mm or more
			c	Level difference of less than 20 mm
	Paving problems		e	Cracks, granulation
	Deteriorated bearing function		e	Displacement tracking function affected
	Others		e	Damage

Common damage	Anchor problem		e	Flaking of attached concrete sections/cable damage
			c	Rust effluent
	Discoloration/deterioration		e	Discoloration
	Leaking or collecting water		e	Inundation
	Abnormal noise/vibration		e	Unusual sounds/vibrations
	Abnormal deflection		e	Abnormal deflection
	Deformation/missing material		c	Severe deformation/missing sections
			e	Localized deformation/missing sections
	Sediment blockage		e	Blockage
	Settlement, displacement, inclination	Substructure	e	Subsidence/movement/inclination of substructure
		Support point	e	Subsidence of support point
	Scouring		e	Severe scouring
			c	Minor scouring



Evaluation unit for main girder



Evaluation unit for deck slab

To this end, a data stocking and updating environment has been developed (see Figure 1) to promote full utilization of the various forms of maintenance data, including inspection data, repair information and structural dimensions. Similarly, the data is also being used to develop decision-making tools for maintenance and management (see Figure 2), such as a bridge condition evaluation system (e.g., from present to future).

3. Bridge condition evaluation method based on inspection data

3.1 Conventional damage analysis

The frequency and impact of road bridge damage varies considerably depending on the sections and/or structural members involved. In order to develop an efficient and reliable evaluation system using as little data as possible, typical degradation damage was analyzed to identify common patterns of damage by section and/or member. This information was then used to prepare a data extraction model for evaluating the overall condition of a bridge.

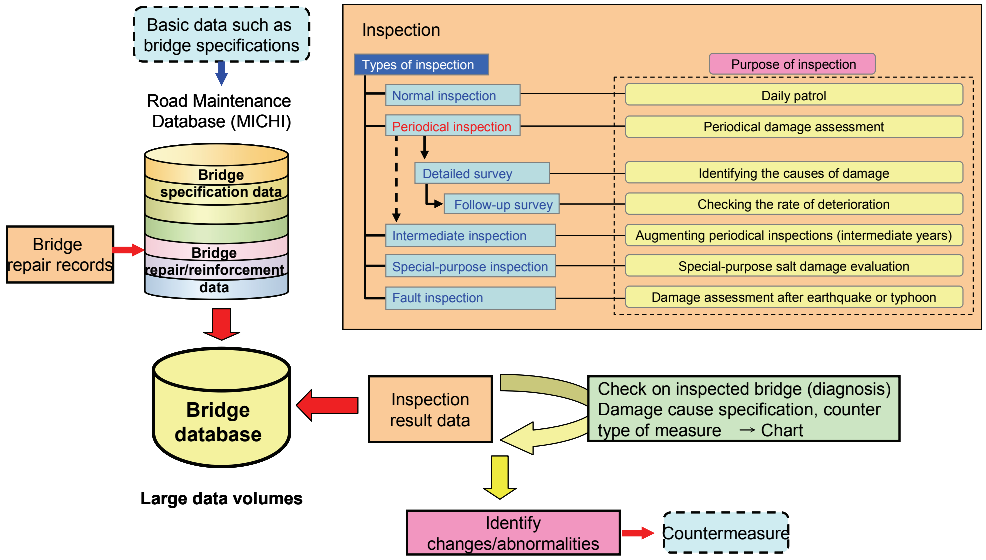


FIGURE 1. ROAD BRIDGE DAMAGE ASSESSMENT DATA — COLLECTION AND UTILIZATION

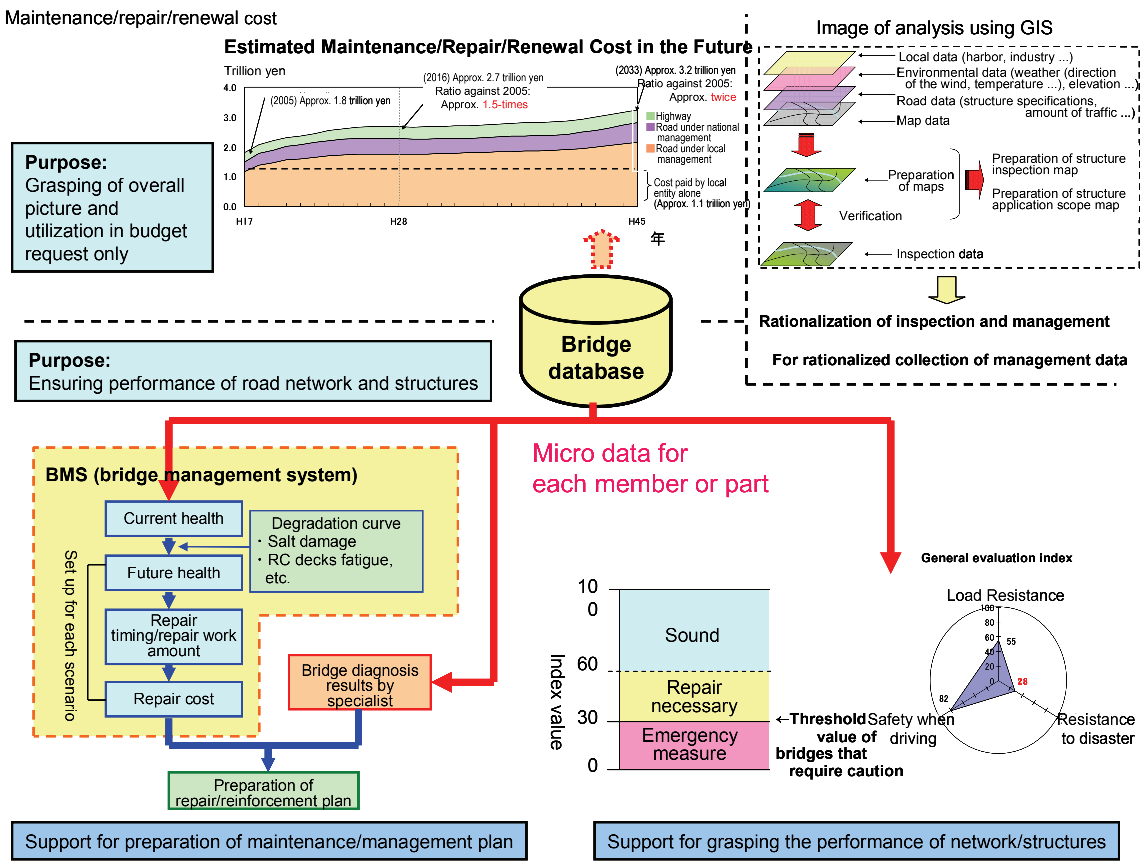
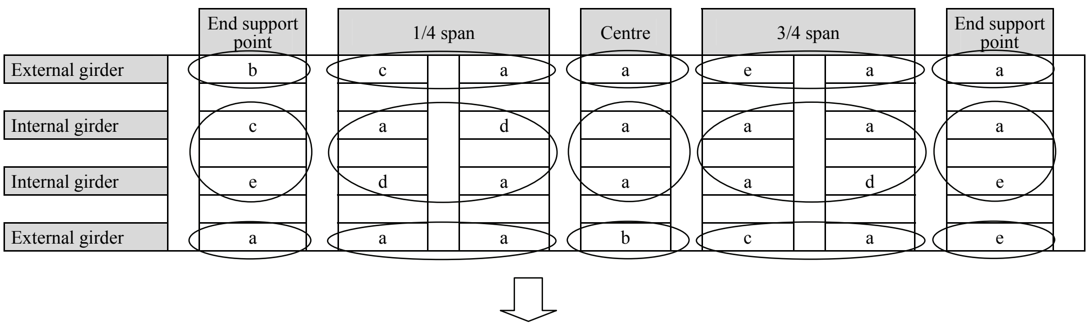


FIGURE 2. UTILIZATION OF THE INSPECTION DATA

Patterns of damage to structural members identified in the analysis were standardized in the form of planar position information. To assess girder corrosion, for instance, each bridge was plotted as a grid consisting of five sections in the bridge axis direction and three sections in the transverse direction, as shown in Figure 3. The damage evaluation (performed in accordance with the Periodical Inspection Guidelines for Bridges) was converted to a five-point rating scale (from "a" = good condition to "e" = worst condition) as shown in Table 2. The analysis findings are presented in Figures 4 to 6.



	End support point	1/4 span	Centre span	3/4 span	End support point
External girder	b	c	b	e	e
Internal girder	e	d	a	d	e
External girder	(b)	(c)	(b)	(e)	(e)

FIGURE 3. INTEGRATION OF DAMAGE CONDITION DATA

TABLE 2. DAMAGE RATING SCALE

Extent of damage	a	b	c	d	e
Rating score	1	2	3	4	5

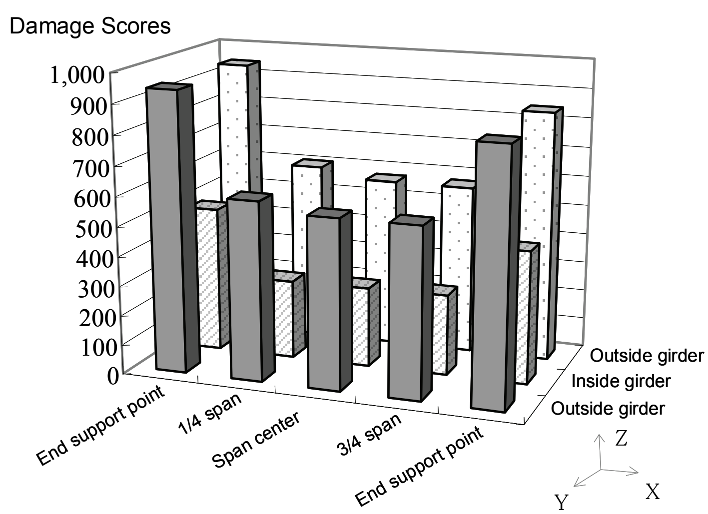


FIGURE 4. CORROSION DAMAGE SCORES, BY SECTION

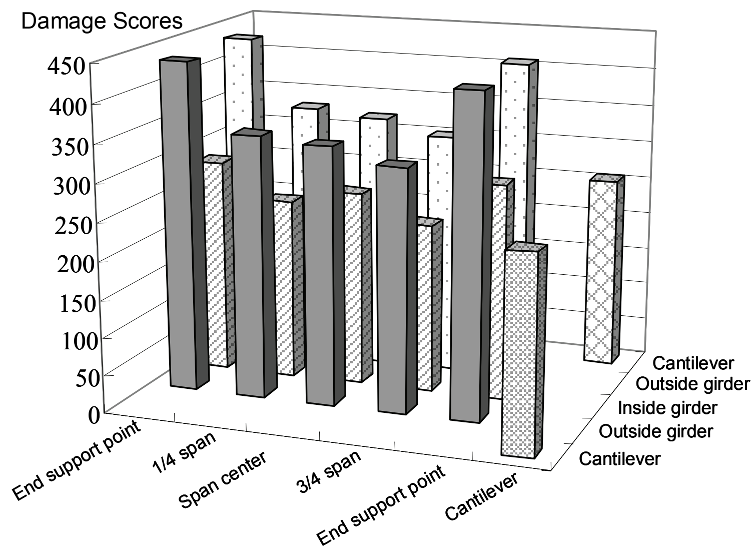


FIGURE 5. RC DECK CRACKING DAMAGE SCORES, BY SECTION

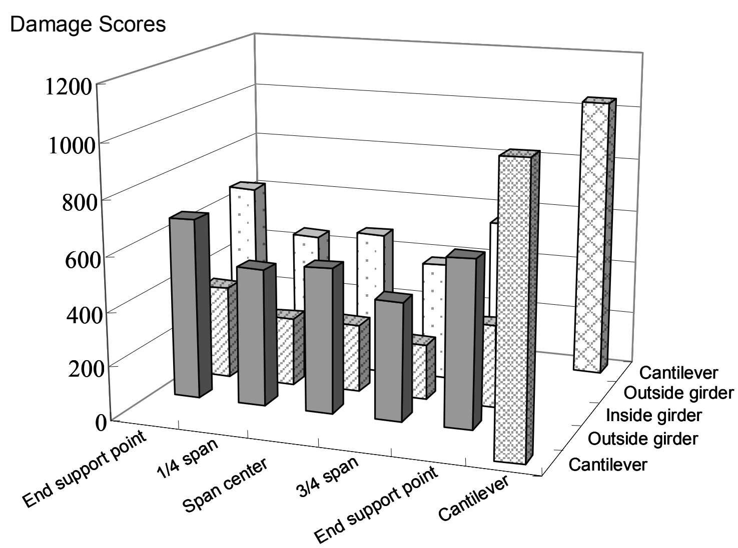


FIGURE 6. RC DECK WATER LEAKAGE AND FREE LIME DAMAGE SCORES, BY SECTION

The analysis demonstrated the veracity of using conventional analysis based on inspection data to identify areas (such as end support points) with a high probability of damage on the basis of past history and experience. By utilizing this information and employing representative data for certain sections, it is possible to evaluate the overall condition of a bridge without the need for detailed data on all sections and members. The result is a more efficient evaluation system involving less risk and reduced data collection.

3.2 Bridge condition evaluation indicators

Quantitative evaluation of the condition of a road bridge with respect to a set of standard criteria is best achieved by using indicators of damage. Road bridges must be capable of facilitating a safe and efficient flow of traffic, and must also be designed to absorb the forces generated by natural disasters such as earthquakes without sustaining critical damage, in order to ensure speedy restoration of service. However it is not feasible to create an indicator that encompasses these as well as the many other performance requirements of bridges. For this reason, a condition evaluation indicator was developed based on three key criteria selected on the basis of universal applicability to all bridges and impact on safety. The three criteria are load resistance, resistance to disasters and safety when driving. Three categories were defined, as shown in the left-hand diagram in Figure 7. The main emphasis with accuracy was on the category of selection rather than relative relationships within categories.

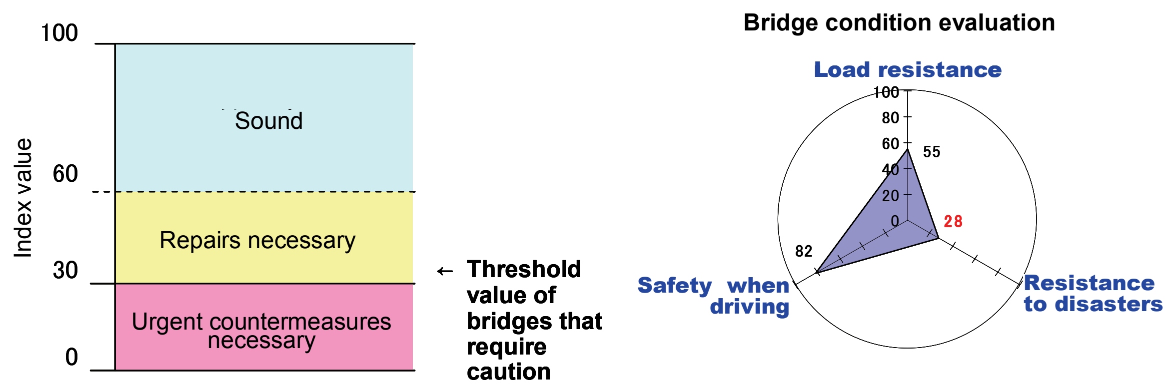


FIGURE 7. EXAMPLE OF ROAD BRIDGE CONDITION INDICATORS

The following considerations were taken into account in the calculation of the indicator.

(1) Importance of member

Weighting factors for members were specified for normal use (load resistance) and in the event of earthquake (resistance to disasters). The load resistance weighting was converted to numerical form based on the vertical load transmission mechanism and the function and importance of the member. The earthquake weighting was similarly converted with respect to the impact associated with destruction of the bridge. The two weighting factors were determined through a process of trial and error involving varying a number of different coefficients for the model bridge, as well as analysis of damage data for actual bridges.

(2) Damage evaluation of member

Each member was evaluated using either the worst-case value or the average value, depending on the relative importance of the member to the overall structure.

Table 3 shows the overall damage evaluation system and member weighting factors. Figure 8 shows the process of calculating the bridge condition evaluation indicator.

TABLE 3. COMBINED DAMAGE EVALUATION AND WEIGHTING FACTOR FOR SECTIONS

		Load resistance		Resistance to disaster		Safety when driving	
		Combined method	Weighting factor	Combined method	Weighting factor	Combined method	Weighting factor
Superstructure	Main girders	**Worst-case value**	1.0	Average value	0.4	Average value	0.2
	Deck	Average value	0.6	Average value	0.2	**Worst-case value**	1.0
	Cross beams	Average value	0.2	Average value	0.2		
	Vertical girders	Average value	0.2	Average value	0.2		
	Brace frame	Average value	0.2	Average value	0.2		
	Horizontal frame	Average value	0.2	Average value	0.2		
Substructure		Average value	0.2	**Worst-case value**	1.0		
Supports		Average value	0.2	**Worst-case value**	0.8	Average value	0.2
Expansion mechanism						**Worst-case value**	0.8

3.3 Indicator precision versus inspection results (and classification criteria)

A comparison with the classifications produced by an experienced engineer (as stipulated in the Periodical Inspection Guidelines for Bridges) was performed in order to evaluate the precision and feasibility of the proposed indicator, using data from the period 2003 – 2005. Table 4 show the classification system used for maintenance and administration purposes. A classification is given for each member, indicating whether repair work is required and if so the level of urgency. Although the classification system and the proposed indicator do not correspond exactly, there are general similarities if E1 and E2 are excluded. For instance, S and M would be somewhere between B and C, indicating that further investigation or maintenance work is required. The general order indicating the overall extent of damage to a bridge would thus be A – B – S, M – C.

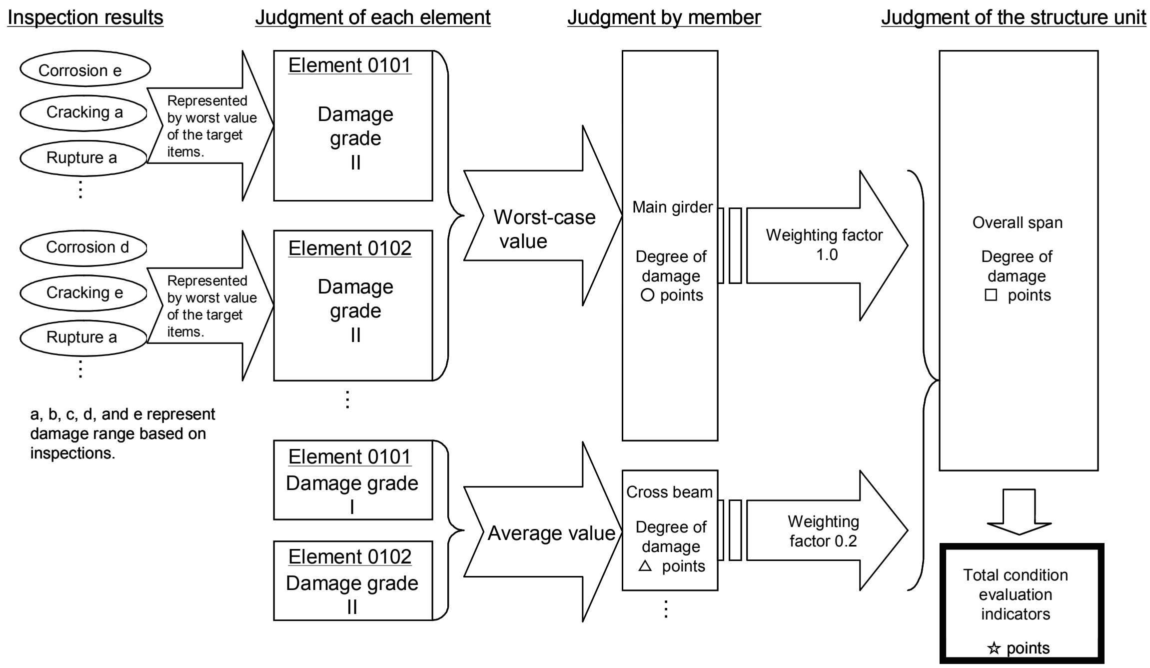


FIGURE 8. CALCULATION FLOW OF CONDITION EVALUATION INDICATORS

TABLE 4. COUNTERMEASURE CLASSIFICATIONS BY PERIODICAL INSPECTION GUIDELINES FOR BRIDGES (DRAFT)

Classification	Contents of judgments
A	No damage, or the damage is so minor that repair is unnecessary.
B	Repair is necessary according to circumstances.
C	Prompt repair etc. is necessary
E1	Emergency response is necessary to maintain safety of the bridge structure
E2	Other emergency repair is necessary
M	Maintenance work is necessary.
S	A detailed survey is necessary

For the purpose of comparison, the worst-case indicator values in the damage evaluation method shown in Table 3 were used: load resistance for the main girders, traffic safety for the deck and resistance to disaster for the substructure and supports. Figure 9 shows the analysis findings for the bridge (main girder). Indicator values of 100 (good) were generated for both B and C classifications. This discrepancy can be attributed to the influence of factors such as declining anti-corrosion performance, damage to concrete reinforcement, lifting, and water leakage/inundation.

The analysis was repeated with these values removed. The criterion for inclusion was increased to all bridges of length up to 15 m in order to boost the sample size. As Figure 10 shows, the new analysis generated satisfactory results overall. Despite the inherent limitations of accuracy and reliability associated with mechanical calculation of inspection data, the analysis nevertheless demonstrated that the overall bridge condition indicator should be suitable for quantitative evaluation purposes.

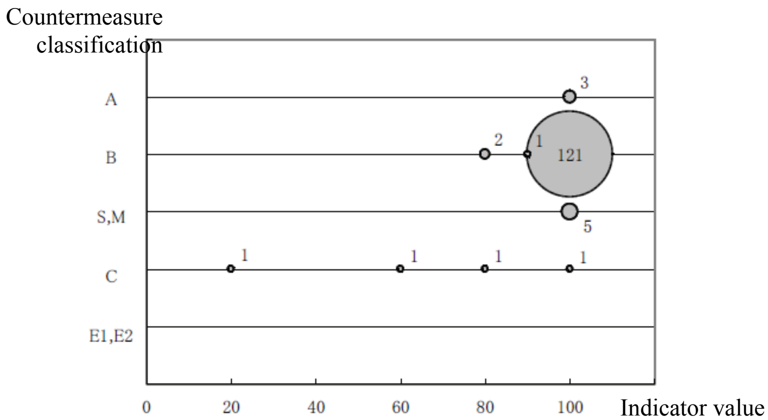


FIGURE 9. STEEL BRIDGE (MAIN GIRDERS) ANALYSIS RESULTS

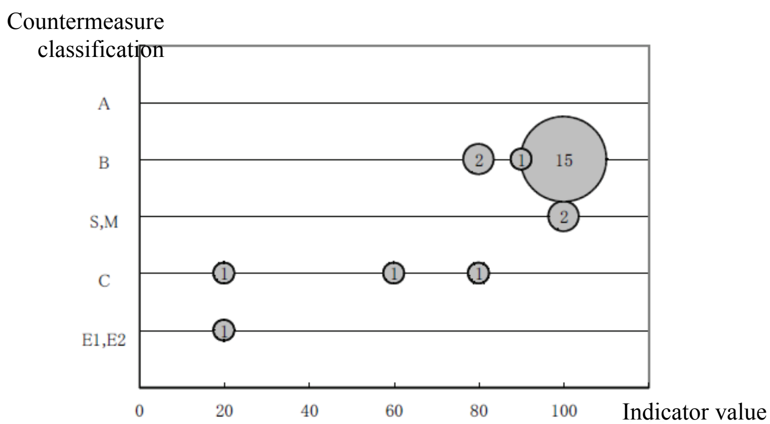


FIGURE 10. STEEL BRIDGE (MAIN GIRDERS) RE-ANALYSIS RESULTS

3.4 Networked evaluation

Figure 11 shows a plot of results generated by the proposed bridge condition indicator for a series of bridges on an actual highway route. It provides a visual indication of which bridges in which locations are potentially affected by damage. This information can be combined with other elements such as traffic volumes and road conditions (e.g., detours and emergency transport routes) to draw up a systematic maintenance and administration program incorporating priority rankings and work measurement and description.

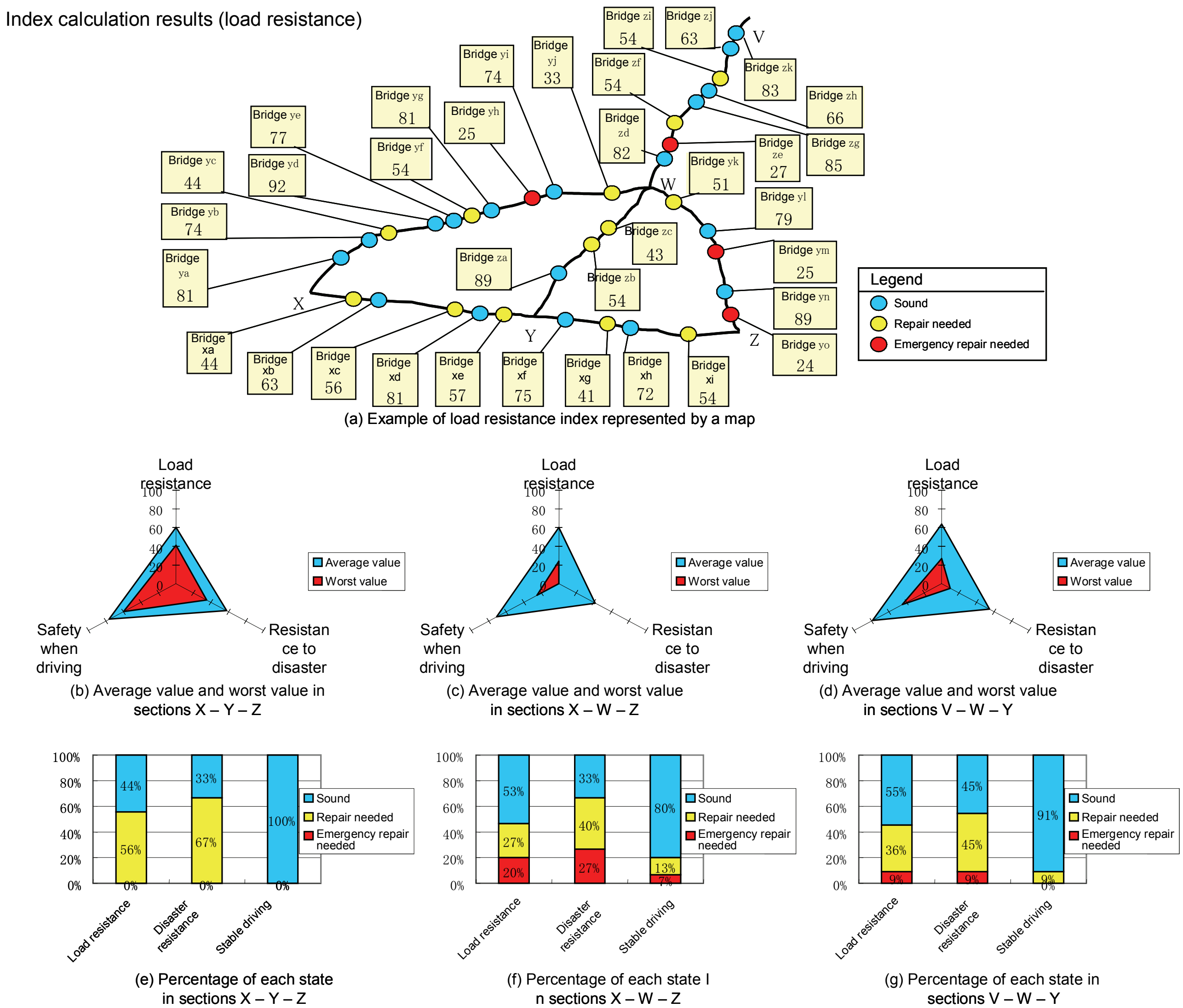


FIGURE 11. EXAMPLE OF BRIDGE GROUP MAINTENANCE CONDITION, BY ROUTE

4. Macro management (BMS development)

Amidst ongoing changes in the condition of the road network, the ability to determine the number of structures requiring maintenance and/or repairs and estimate the associated budgetary requirements will be critical to the development of sound maintenance and management strategies and procedures. To this end, an investigation has been carried out on the development of Japanese version of BMS, the bridge management system featuring future forecasting and estimation based on inspection data.

4.1 Japanese version of BMS

The Ministry of Land, Infrastructure and Transport is developing a Bridge Management System (BMS) to assist with systematic management of road bridges. The BMS provides a range of features based on data extracted from various sources, including bridge dimensions and other statistics, inspection data, and repair history databases. Figure 12 illustrates the concept of the BMS.

Ideally, road bridge management programs would consist of a combination of both qualitative and experiential evaluation, and quantitative and objective evaluation based on empirical data. To date, management programs have been almost entirely dependent on qualitative evaluation. The introduction of BMS will augment this with prediction-based quantitative and objective evaluation information.

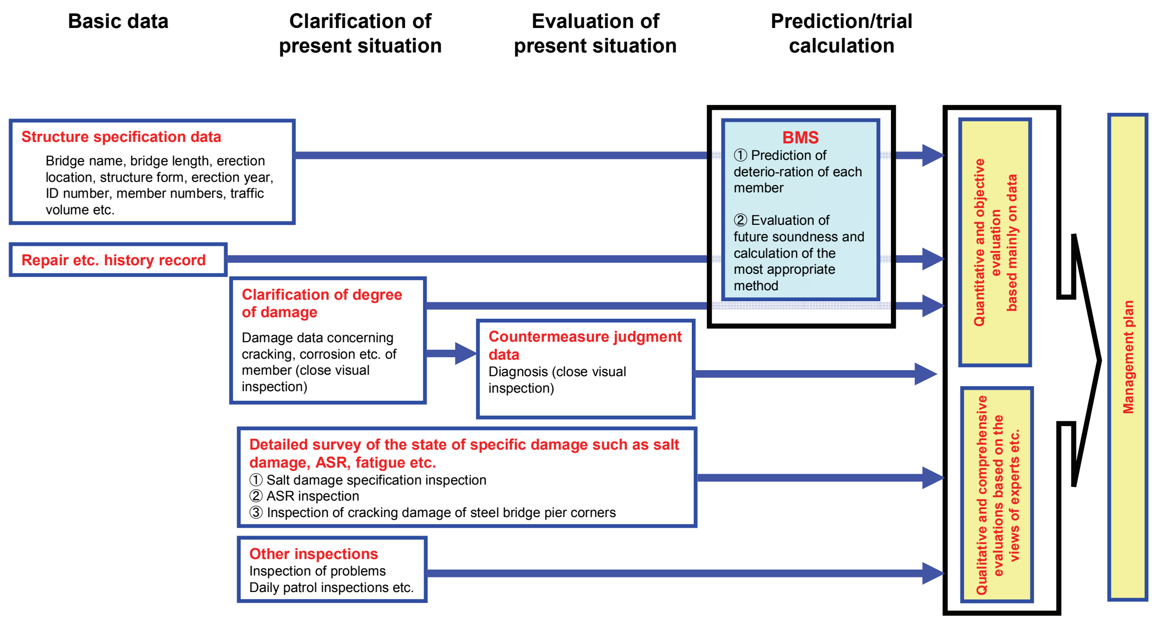


FIGURE 12. ROLE OF BMS IN BRIDGE MANAGEMENT PLANING

The first process in the BMS involves evaluating current damage levels for the purpose of generating predictions about the condition of the bridge into the future. On those bridges where prediction is considered feasible, the current bridge condition is given a rating from I to V, as shown in Figure 13 (1), on the basis of the extent of damage as described in periodical inspection reports. For salinity damage to concrete, for example, formulae are defined for converting the salinity concentration and volume fraction for steel materials (based on the degradation process and theoretical expressions provided by the Japan Society of Civil Engineers) to a bridge condition rating.

Where prediction is not practicable, the bridge condition evaluation shown in Figure 13 (1) is not performed. A fixed replacement cycle is assumed, with repair work based on the classification results from the damage evaluations during periodical inspections.

The next step involved development of a degradation prediction method for each degradation factor in the prediction process. Degradation can be predicted by various methods, including the usable life of the bridge, a theoretical formula for predicting degradation, transition probability, and statistical analysis of inspection records. In the future, it should be possible to select a prediction method based on the available data and objectives; however, for the time being it will be necessary to rely on theoretical prediction formulae, due to the lack of inspection data obtained in accordance with the draft Periodical Inspection Guidelines for Bridges and the fact that degradation factors such as salinity damage and fatigue are not in the form of quantifiable inspection data.

At the present point in time, the BMS components are: paint degradation on steel members; fatigue of RC deck; and salt damage. For elements such as elongation mechanisms and supports where prediction is not applicable, the replacement cycle will be determined based on the estimated usable life.

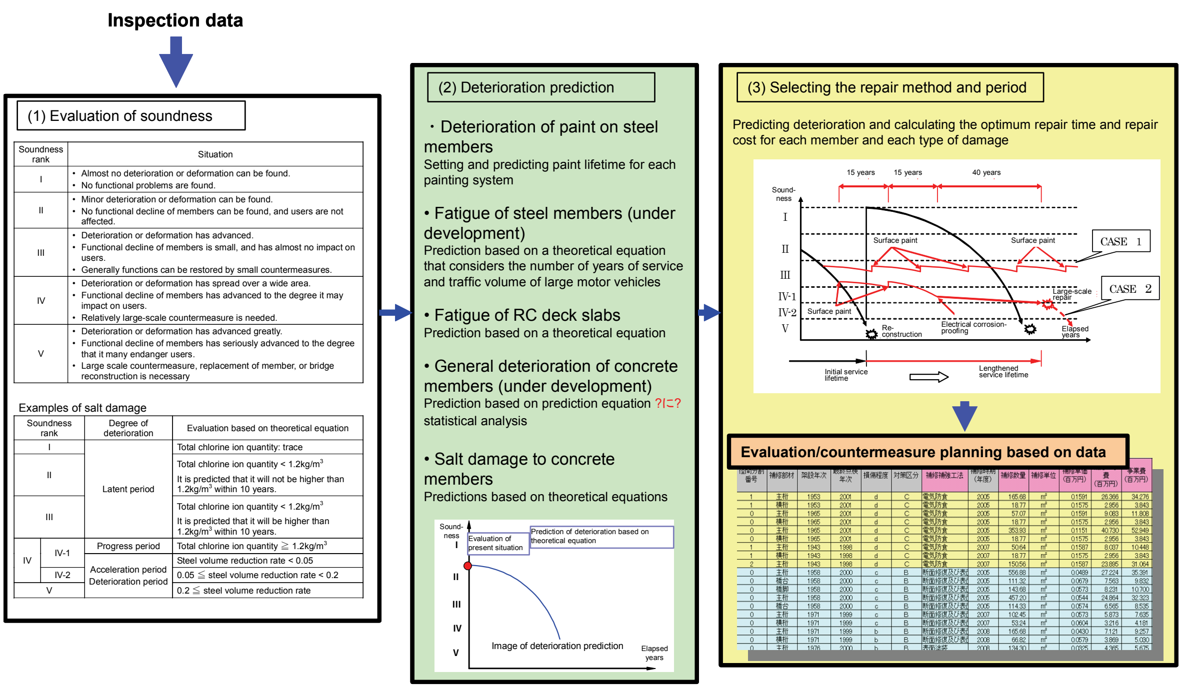


FIGURE 13. CALCULATION PROCESS BY BMS

The degradation predictions and current condition evaluations outlined above are used to determine the timing and cost of repairs for each member and damaged section and to develop an overall repair program. Where prediction is not practicable, a fixed replacement and repair cycle is assumed for the purpose of calculating maintenance expenses, although in practice the timing of repairs will be governed by inspection results and other considerations.

4.2 Ongoing development of BMS

The BMS has been deployed on a trial basis at several local bureaus to analyze the advantages and disadvantages compared to conventional maintenance and administration program. The analysis findings are being used to modify current bridge condition evaluation procedures, degradation prediction methods and calculation of repair timing cycles. Given that there are still significant discrepancies between BMS results generated through systematic calculation and the judgments of experts in the field, it will be necessary to identify the limitations of the system and expand the scope of applicability to include more types of damage and a greater range of members. Similarly, it is important to improve both prediction accuracy and descriptive power, particularly with respect to functionality for networks and areas that can be evaluated.

5. Future issues

We will continue to investigate the utilization of detailed data on individual members and sections (primarily data from inspections) in order to develop a genuine maintenance and management system for road bridges and structures, as depicted in Figure 2. The above information will be integrated with GIS map information such as meteorological, environmental and topographical information and traffic data to create an efficient framework for generating maintenance programs, that can also be used to revise the relevant design standards.

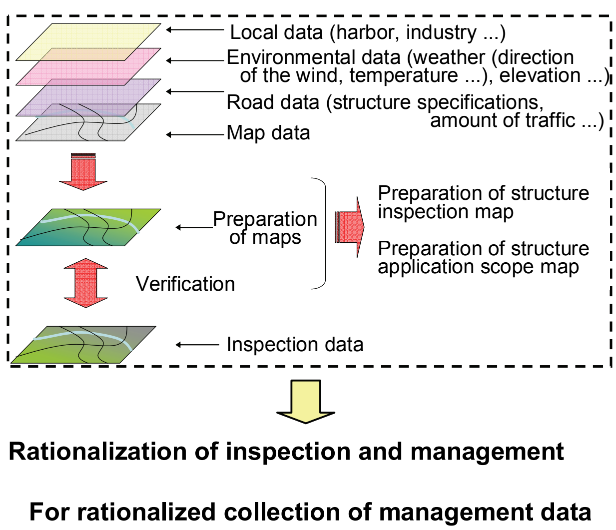


FIGURE 14. IMAGE OF ANALYSIS USING GIS