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Intelligent Bridge Maintenance and Management

Emerging Digital Technologies

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Preface

Bridges are critical structures as connecting nodes in modern transportation systems. While supporting social and economic activities, bridges are constantly subject to environmental attacks that deteriorate structural materials, hence shortening bridge life; in addition, bridges are threatened by extreme natural and technological events in their life cycles, which, although rare, may lead to catastrophic consequences. Traditionally, civil structural (bridge) engineers and researchers have attempted to develop various sensing, inspection, and monitoring technologies, as reflected in the plethora of literature on structural health monitoring (SHM) and non-destructive evaluation (NDE). Nonetheless, there are many reasons that prevent massive adoption of these (SHM or NDE) technologies for bridge maintenance and management. Not to criticize SHM or NDE technologies, which have greatly contributed to our understanding of the complex behavior of civil and other structures, we assert that they lack three *connectivity* attributes.

First, it is the disconnection between technology components that prevent the realization of *ad hoc* automation.[1] Entering the second decade of the twenty-first century, we are witnessing the movement of industrial automation in many industrial sectors. On the one hand, many ‘smart’ sensing or monitoring solutions exist in our community; on the other hand, it is evident that the deployment of these technologies is still labor intensive. Furthermore, visual analytics, if rendered, is often remote and latent.

Second, we recognize the disconnection between identifying, quantifying, and integrating local and global structural damage relative to the system-level functionality of bridge structures. To this end, most NDE technologies attempt to detect and localize damage at structural elements. On the other hand, most SHM technologies focus on global structural integrity; if a few SHM technologies are dedicated to local structural integrity, practical implementation and validated solutions are scarce. These technology-based local or global structural damage or integrity information are not systematically represented or synthesized for system prognosis or forecast.

[1] We define ad hoc automation as a specific-purpose automation in an (maintenance or management) process, not a fully or global automation for the integral maintenance and management process.

Last but not least and the most important one, disconnection is more severe between technologies and stakeholders. It is a fact that most existing technologies are still limited either by presenting incomplete visual analytics or overwhelming information to end-users. Added to this is the limitation in physical media for presenting information to end-users. It is noted that the common practice is still based on computer screens, the reporting is still textual or two-dimensional through illustrations or tables, and finally, the decision-making is often centralized, lacking situational awareness.

Toward the next-generation maintenance and management of bridge structures that ensure lifecycle sustainability and resilience, we call for the intelligent integration of traditional and emerging digital technologies. To integrate NDE, SHM, and other inspection and maintenance technologies, we believe that data-driven machine learning, advanced artificial intelligence, next-generation communication (e.g., IoT and 5G/6G), and robotic manipulation and actuation will play critical roles. To augment decision-making efficiency, efficacy, and situational awareness, it is crucial to develop advanced information fusion methods and platforms (e.g., via digital twinning) and novel human-infrastructure interfacing technologies (e.g., augmented reality).

We believe that many researchers and practitioners have recognized the lack of these connectivity attributes as well, or even in a more profound way. However, our humble opinion is that, to this end, there is no systematic exposure of these technologies in one book found in our communities. We admit that it is not necessarily a significant task if the focus is on introducing theories and methods underlying different technologies. We assert that it is the synthesis of theories, implementation of these methods and technologies in practice, and, better yet, the existence of case studies that render preparing a useful book as we will offer a much more challenging endeavor.

In this book, *Intelligent Bridge Maintenance and Management*, we strive to balance between background, theoretical foundation and methods, and practical implementation and case studies. Specifically for the latter, many of the implementation and case studies are from China. This is not incidental but is based on the substantial progress in China's civil infrastructure.

With the comprehensive coverage and the intended balance between theories and practice, this book aims to assist readers in not only understanding emerging digital technologies but also in adopting effective ones for maintaining and managing bridge structures in their life cycle. It is our intention to share with readers the vision that the next-generation bridge maintenance and management should be an intelligently integrated system that embraces physical structures, digital technologies, and stakeholders systematically toward a great degree of automation. The target audience for this book includes bridge engineers, decision-makers in the field, and students and researchers in universities and scientific institutions.

Ten chapters are included. For the interest of readers, they may start with reading Chaps. 1 and 2, then select technologies of their interest that are covered in Chaps. 3–9. Specifically,

- Chapter 1 introduces the background, definition, and main contents of intelligent bridge management and maintenance.
- Chapter 2 analyzes the practical feasibility of establishing an intelligent bridge management and maintenance system and introduces an emerging platform "IntelliBridge."
- Chapter 3 discusses the application of IoT technologies to bridge management and maintenance.
- Chapter 4 focuses on automation technologies and robotic detection for bridge inspection.
- Chapter 5 discusses the importance of cloud computing and other big data technologies applied to bridge management and maintenance, as well as the new opportunities brought by AI technologies to the development of bridge management and maintenance.
- Chapter 6 introduces machine learning for bridge evaluation and early warning.
- Chapter 7 introduces the application of computer vision technology for automating bridge maintenance.
- Chapter 8 presents multi-source data fusion, structural state assessment, virtual reality, and digital twin technologies for intelligent bridge management and maintenance framework.
- Chapter 9 discusses intelligent decision-making for bridge maintenance and management, and the role of AI.
- Chapter 10 summarizes and envisages the future of intelligent bridge management and maintenance.

This book is co-authored by Gang Wu of Southeast University, ZhiQiang Chen of the University of Missouri, and Ji Dang of Saitama University. Professor Gang Wu's team members Shitong Hou, Yujia Zhang, Jiao Dai, Yitian Han, Mida Cui, Tianyu Wang, Haochen Wang, Xiaoxiang Cheng, Fanqi Cong, Hongyu Lu, Jianhua Fan, Zhihong Xiao, Zhao Xu, Xi Chen, Yongcheng Bao, Wei Wang, Lu Zhang, Fengbo Ma, Shizhi Chen, Bin Dong, Huile Li, Shiqing Wang, Jinqiao Chen, Liuzhen Yao, Tianran Han, Xudong Chen, Zhuoran Li, Jianwu Pan, Jingwei Zhao, and Lu Chu contributed much in content writing and editing.

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Nanjing, China — Gang Wu
Columbia, USA — ZhiQiang Chen
Saitama, Japan — Ji Dang
November 2022

Executive Summary

This book, *Intelligent Bridge Maintenance and Management*, focuses on the application of digital technologies for enhancing the safety and serviceability of bridge structures. The selected technologies, many of which are emerging for applications in Civil Engineering, include the Internet of things, robotics, machine learning and artificial intelligence, and digital twins, among others. By introducing the theories, methods, case studies, and practical examples, this book aims to assist readers in not only understanding emerging digital technologies but also in adopting effective ones for maintaining and managing bridge structures in their life cycle. In the end, we expect to present the vision that next-generation bridge maintenance and management should be an intelligently integrated system that embraces physical structures, digital technologies, and stakeholders systematically toward a greater degree of automation. The target audience for this book includes bridge engineers, decision-makers, and other professionals in the field, besides students and researchers in universities and scientific institutions.

Contents

About the Authors

Gang Wu winner of the National Science Foundation for Distinguished Young Scholars, Distinguished Changjiang Chair Professor of the Ministry of Education, Lead Talent of Science and Technology Innovation under the National "Ten Thousand People Program," winner of Tencent Science Exploration Award, winner of China Science and Technology for Young Scientists Award, member of Standing Party Committee of Southeast University, Executive Vice President of Southeast University, President of China Young Science and Technology Professionals Association, Director of National and Local Joint Engineering Research Center for Smart Construction, Operation and Maintenance, etc. His research interests include intelligent construction, operation and maintenance of major infrastructure, new materials and new structural systems, and performance improvement of existing engineering structures. He has been ranked a world top 2% scientist and an Elsevier highly cited scholars in China. He has published 193 SCI papers, authored 74 patents (five international patents), published six monographs, and edited eight standards. Additionally, he has led two national key R&D projects, and more than 20 key National Natural Science Foundation projects and major instrument projects (free application). He has also won two second prizes of the National Science and Technology Progress Awards (ranked 1, 2), two first prizes of the Provincial Science and Technology Progress Awards and two second prizes of the National Teaching Achievement Awards.

ZhiQiang Chen is a Professor of Civil Engineering at the Division of Natural and Built Environment, University of Missouri-Kansas City (UMKC). At UMKC, he directs the interdisciplinary research lab of Disaster, Infrastructure, and Geointelligence Technology (DIGIT). Before joining UMKC in 2010, he received his Ph.D. in Structural Engineering from the University of California, San Diego (UCSD). He was a visiting professor at the University of California, Berkeley, in 2020 and a visiting professor at the Saitama University, Japan, in 2022. His research interests, in general, focus on Civil Systems Intelligence and Resilience, including multi-hazard performance and resilience computing for civil structures and the application and development of AI, remote sensing, and human-infrastructure interfacing technologies for disaster response and infrastructure management.

Ji Dang Professor of Department of Environmental and Social Foundation, Graduate School of Science and Technology, Saitama University, since October 2020. Bachelor and Master of Engineering from Southeast University (2002, 2006), Ph.D. from Aichi Institute of Technology (2010), Postdoctoral fellow of Aichi Institute of Technology (2010–2011), researcher of Kyoto University (2011–2013), and teaching assistant of Saitama University (2013–2020). In recent years, his main research directions in intelligent bridge operation and maintenance are: IoT bridge monitoring, development of smartphone applications for vibration monitoring; UAV-based bridge detection, performance-based UAV bridge detection and evaluation, Japan Strategic Innovation Program SIP; and development of damage recognition technology based on AI computer vision. He has published 41 papers and has won awards such as the Outstanding Presentation Award of the Japan Society for Civil Engineering (2016), and the AI and Digital Science Data Award (2021).

Chapter 1
Introduction

Abstract In this chapter, we offer a comprehensive review of the state of the practice with a global perspective and the current technologies for bridge maintenance and management. By discussing that the systematic goal of conducting bridge maintenance and management is to achieve lifecycle system goals, such as sustainability and resilience, we recognize the challenges pertinent to the state of the practice. To resolve these challenges, digital technologies, especially emerging ones, including the Internet of Things, Robotics, Cloud and Edge Computing, and Artificial Intelligence with Big Data, are described. The promise of adopting these technologies to realize the notion of intelligent bridge maintenance and management is then introduced.

1.1 State of the Practice and Definitions

As human beings' growth consists of youth, adolescence, and adulthood, bridges undergo the states of construction, normal service, and degraded services. Similarly analogous is the possibility that a person can be abruptly hurt or become sick, and a bridge can be damaged by extreme events, leading to disrupted services. One important argument is that bridge in-service life is not design life. In Japan, the proposed design life for highway bridges is 100 years; in the UK, it is 120 years; in other European countries, it is 100 years; the United States targets 75–100 years. In fact, the actual life spans of many bridges do not reach their design life due to premature degrading or disaster-induced sudden failure. Statistics from the United States show that the actual service life of bridges, with a design average life of 75 years, is about 40 years. These general statistics manifest that many, if not most, bridges have not been 'cared for' as a human being would be during their active life.

A special example is the I-35W bridge collapse in Minnesota, USA, in 2007. Three months before the collapse of I-35W, the bridge had just obtained its routine evaluation results after a full bridge inspection, leaving the doubt behind over either poor quality of the inspection process or improper use of technologies. This event has facilitated the transformation of bridge maintenance and management throughout the

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United States. Other examples of bridge collapse events, or more generally structural failure of different levels, can be found in the literature but are statistically rare due to the physical nature of such failure events. Nonetheless, in this book, we stress the abundance of case-history data related to bridge engineering practice in China, which is not incidental but due to the rapid development of China's civil infrastructure in the last 30 years.

1.1.1 Case-History Data in China

China's bridge industry has developed rapidly in the past 30 years, boasting the largest bridge inventory in the world. Up to the year 2023, China has built more than 800,000 highway bridges, more than 1000 long-span bridges, over 200,000 railway bridges, and over 10,000 km of high-speed railway bridges. However, bridges in China are no exception, as a very large percentage of them have entered their aging stage.

First, up to today, about 40% of China's highway bridges have been in service for more than 20 years. More specifically, there are nearly 50,000 bridges with a safety level of Class III or above on the national, provincial, and county roads, accounting for 16% of the total number of in-service bridges in China. In addition, more than 100,000 bridges are classified as dangerous. In addition, a large number of bridges built in the early 1990s are about to enter their maintenance period. Referring to the bridge maintenance experience of developed countries, numerous county, township, and village bridges will be overhauled or rebuilt in the next 5–10 years. In the next 10–15 years, many national and provincial bridges and long-span bridges will also need significant investment to ensure their safe operation (see Fig. 1.1).

Second, there are general distinctions between bridges of different sizes. It is observed that it is small- and medium-sized bridges that take on most traffic loads in transportation systems. These bridges are constantly faced with progressive degrading from material deterioration, geological foundation settlement, hydraulic scour, and artificial hazards from vehicle and ship collisions. Above all, these bridges are often subjected to traffic loads beyond their designed capacities due to regional economic booming and transportation burdens; structural fatigue or even sudden failure due to overloading is not rare.

As far as long-span (and other large-scale) bridges are concerned, the pursuit of "long, large, high, and exceptional" bridge types brought about much higher construction costs. In contrast, the quality of many long-span bridges was not directly proportional to the increase in project cost. Some bridges were overhauled shortly after they were completed, and some were resurfaced several years after they were opened to traffic. In addition, these structures may encounter extreme events that are beyond their code-based targets of risk levels, for example, high-intensity climatic events (flooding, strong wind, fire, etc.) as witnessed in recent years, which are partially attributed to global climate change. Indeed, risk from extreme climatic events is particularly prominent for long-span cable-stayed or suspension bridges

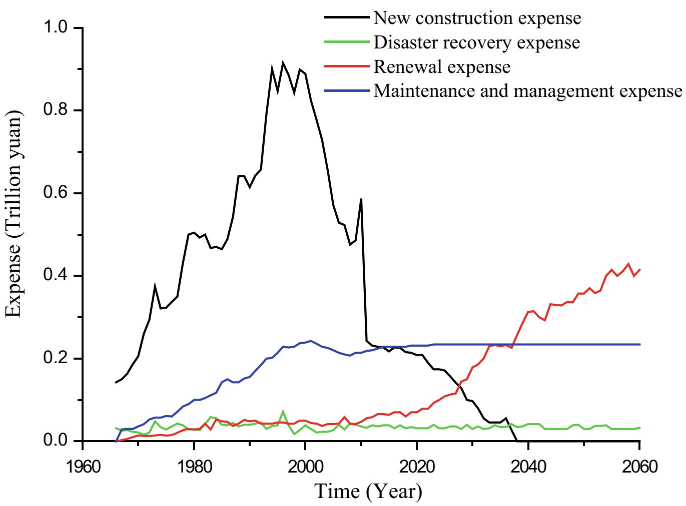

Fig. 1.1 Trend of bridge construction, maintenance, and management expenses in China

with high lateral flexibility, as well as some special-shaped bridges with abnormal static and dynamic responses.

As a result of the bridge condition status in China, it has been recorded that between 2007 and 2012, 37 bridges collapsed in China. On average, more than 6 'fatal' bridge events occurred every year, resulting in more than 180 deaths. It is worth noting that nearly sixty percent of these collapsed bridges were built after 1994, with an average age of less than 20 years.

1.1.2 Technical Standards-Based Practice

In general, technical standards, which are standardized knowledge bodies curated by professional organizations, are found globally related to bridge maintenance and management. These standards provide guidelines and provisions to direct a structuralized bridge maintenance process, including bridge inspection, monitoring, condition evaluation (including load rating), structural repair, and retrofitting. In the following, we comparatively describe the practice of adopting technical standards in China, Japan, and the United States (US).

1.1.2.1 China

Three relevant standards are adopted in China for governing bridge maintenance and management: the Technical Specifications for Urban Bridge Maintenance (CJJ99-2017) [1], the Evaluation Standard for Technical Conditions of Highway Bridges

(JTGT H21-2011) [2], and the Maintenance Specifications for Highway Bridges and Culverts (JTG H11-2004) [3].

With respect to the current bridge maintenance practices, the maintenance and retrofitting of bridges are mainly based on the results of bridge inspection and evaluation, so the rationality and practicality of the inspection and evaluation methods directly decide the maintenance, retrofitting, and management methods adopted by the maintenance personnel. Therefore, bridge inspection and evaluation specifications are the core subjects of bridge maintenance. Among the current specifications for bridge maintenance in China, the Code for Maintenance of Highway Bridges and Culverts [3] has the widest scope of application, while the Technical Code for Maintenance of Urban Bridges [1] has a smaller area of application, which primarily deals with urban bridge maintenance. The Standard for Evaluation of Technical Conditions of Highway Bridges [2] comprises the strengths of the previous two specifications. It classifies different bridge types and describes the distresses of each bridge type [2], and thus is currently the most complete specification for technical evaluations of bridge conditions in China.

As the leading specification, the Code for Maintenance of Highway Bridges and Culverts [3] provides the inspection and evaluation system for highway bridges and culverts, suggestions for maintenance of the upper and lower components, and suggestions for disaster prevention and retrofitting. It involves all stages of bridge maintenance and has the advantages of strong authority, small workload, simple operation, etc. However, there are some shortcomings with this standard, such as the fixed weights for the different components, the failure to divide the components according to the bridge type, and subjectivity and randomness in the technical evaluations of the bridge conditions. The specification is still the version revised in 2004, whose contents are relatively out of date. Subsequently, the Technical Code for Maintenance of Urban Bridges [1] was developed on the basis of the Code for Maintenance of Highway Bridges and Culverts [3]. The layered evaluation method and the weighted average method were adopted for the Technical Code for Maintenance of Urban Bridges [1]. At the same time, the criteria for grading component defects were specified, making the technical evaluations of bridge conditions more objective. However, the arithmetic average method is adopted for the scoring of the upper and the lower structures of the bridge with the potential risk of weakening the structural defects. Moreover, the classification of bridge types and components is insufficient, which is not suitable for the technical evaluation of the conditions of large bridges and complex bridges. In comparison, the Evaluation Standard for Technical Conditions of Highway Bridges [2] adopts the method of combining the layered comprehensive evaluation with five types of single control indicators. First, each component of the bridge is evaluated. Secondly, each part of the bridge is evaluated. Then, the deck system, the superstructure, and the substructure are evaluated sequentially. Finally, the overall technical conditions of the entire bridge are evaluated. The results obtained are highly objective. Besides, this specification proposes different distress types and weights for different bridge types, and for the first time, proposes that the weights of components not mentioned can be proportionally allocated to the existing components.

At present, the main problems with China's bridge inspection and evaluation specifications are (1) the specification uses fixed weights to evaluate bridges, which makes it impossible to correctly reflect the effects of malfunctions of components with small weights on the operational status of the whole bridge under evaluation; (2) the classification of bridge component types in the specification is unreasonably simplified; for some components on complex bridges, their corresponding weights are not clearly specified, and the stipulations are too vague in this respect; and (3) there is no quantitative evaluation method recommended in the specification, and the evaluations of bridge conditions are usually obtained from the subjective experience of the bridge evaluators through a rough qualitative analysis of the bridge. The knowledge and work experiences of the bridge evaluators greatly affect the bridge evaluation results. Besides, in different regions, evaluators have different understanding of distresses and their degrees. In summary, the differences in regions, units, and evaluators directly lead to the differences in computing measures used in evaluation.

1.1.2.2 Japan

Japan built a large number of bridges during its period of rapid economic development after World War II. Similarly, these bridges have entered the stage of maintenance and management, many of which exert an urgent need for these actions. In 2013, Japan passed an amendment to the Road Law, which clearly pointed out that bridge managers have an obligation to carry out preventive maintenance and management for the bridges under their jurisdiction and made clear the necessity of bridge maintenance and management. Subsequently, the Ministry of Land and Communications of Japan issued bridge inspection protocols to standardize the bridge maintenance and management practices under its jurisdiction.

Bridge inspections in Japan include regular inspections and intermediate inspections. The regular inspection is conducted once every five years. Intermediate inspection refers to the inspection conducted before the next regular inspection when damage is found during the previous regular inspection or maintenance or retrofitting, which needs to be confirmed. Intermediate inspection has no regular frequency, and the inspection content is also determined by the inspection parts and the inspection standards. Intermediate inspections are mainly manual on-site visual inspections, supplemented by limited detection tools. According to the regulations, the maintenance rating and the damage appearance rating will be given to each component of the bridge after the inspection.

In order to make the assessment more objective, the Japanese code includes photos of typical distresses of different damage categories and damage levels for reference. After the assessment, the engineers collected the standardized distress detection results and built a proprietary database for subsequent bridge maintenance and management decision-making according to the Japanese standard. Based on the Japanese codes, both the subjective maintenance rating and the objective existing damage rating are independently carried out, which enables the managers to cross-reference the two at the end and improve the credibility of the results.

1.1.2.3 United States

It is noted that the period of massive construction of highway bridges in the United States was much earlier than most other countries. As such, its history of technical standards and standards-based have been scrutinized over a longer period, hence much technically mature to this date. At present, a comparatively complete of private and public industrial sectors have been established that provide bridge inspection, evaluation, maintenance, and retrofitting with proven records of effectiveness.

In the US, related standards are documented in the National Bridge Inspection Standards (NBIS) [4], Guidelines for Bridge Management Systems (GBMS) [5] issued by the Federal Highway Administration (FHWA), and the American Association of State Highway and Transportation Officials (AASHTO). The current bridge technical condition evaluation system in the United States consists of six standards or manuals. According to American law, the National Bridge Inspection Standard (FHWA 2001) [4] is the highest standard, which was formulated by FHWA and passed by Congress and has become a law that must be complied with by all bridge maintenance and management practices. According to the specifications used in the United States, each component of the bridge is first scored on a scale of 0–9, and then the bridge parts are scored. The overall score is directly calculated based on the conditions of each component without weighting. The advantage of this evaluation method is that the decision-makers can easily see the distress of each component and each part of the bridge, which is conducive to bridge maintenance personnel paying more attention to key distresses.

At the same time, FHWA released the Recording and Coding Guide for Structure Inventory and Appraisal of Nation's Bridges (RCGSIANB), which stipulates that all bridge data must comply with this standard for recording bridge maintenance and management information in a standard way. After that, the National Bridge Inventory (NBI) is employed to completely and accurately master the basic composition, structure, function, management, maintenance status and other information related to the highway bridges in real time. FHWA also released a comprehensive manual (Bridge Inspector's Reference Manual, BIRM) on procedures, regulations and technologies for inspection and evaluation of various bridges. AASHTO also released the Manual for Bridge Evaluation (MBE) [6], which can be used to evaluate bridges from both the unit and the structure levels. Finally, in terms of bridge maintenance, repair and retrofitting, the United States adopts the AASHTO Maintenance Manual: The Maintenance and Management of Roads and Bridges [7] which corresponds to China's Code for Maintenance of Highway Bridges and Culverts [3] and Design Code for Strengthening of Highway Bridges [8], etc. As a whole, the US bridge inspection system has clearly classified various typical distresses for different components, so as to reduce the differences in evaluation results from subjective judgments of different inspectors. At the same time, more comprehensive consideration is given to the factors affecting the distress, and more in-depth cause analysis is made by the US system. Finally, more attention is paid to the refinement and standardization of the testing workflow and the corresponding safeguards by related US standards.

1.1.2.4 Remarks

Compared with the standard practice in China, Japan and the United States, it is stated that China is clearly still in the early stage in developing a complete bridge maintenance and management system. In terms of technical completeness, China's specifications and standards are still relatively inadequate. For example, there is no detailed regulation on the specific implementation of manual testing in Chinese standards.

Specific differences are observed. In the process of inspection, practitioners in Japan often carry out the inspection and evaluation of bridges at the component level, but the division of bridge components are not quite the same between the two countries. The main difference is that the United States only classifies the members according to the member type, while Japan makes a more detailed classification considering the location of the bridge span.

Finally, the current bridge maintenance specifications in various countries generally have strict requirements for subjective experiences of the bridge inspectors and a strong overview evaluation process. However, most of them aim to assess bridges qualitatively, and quantitative analysis and reporting of structural integrity or damage is desired but mandated. To overcome the disadvantage of inspectors' subjectivity, Japan and the United States have tried to establish authoritative image libraries of bridge distresses to help on-site inspectors with their identifications, but the objectivity brought in by using this approach is still limited. At the same time, the existing detection methods mainly use visual inspection with some auxiliary instruments. This combination mode will introduce a lot of subjective errors, resulting in limited credibility of the bridge evaluation results.

Last, we observe that in most standards of the three countries, structural inspection is largely limited to visual inspection, and less often, it recommends the use of nondestructive evaluation (NDE). Although researchers have undertaken a lot of investigations over various Structural health monitoring (SHM) technologies, which provide the advantage of producing more quantitative analytics, there is still a lack of relevant specifications to guide and standardize the maintenance works in practice. This void should be filled urgently to improve the efficiency and objectivity of bridge maintenance and management.

1.1.3 Definitions: Bridge Maintenance and Management

Bridges are lifeline facilities that ensure the development of the societal economy and facilitate public transportation. Reviewing the case-history of bridge performance and the current state-of-the-practice, particularly the standards adopted globally, we can state that the existing bridge maintenance and management practices have played an important role in ensuring the safety and uninterrupted services of existing bridges across regions and countries. In this section, formal definitions and descriptions of bridge maintenance and management are given. To characterize the connotation span (or space) of these two notions, we borrow the notion of resilience defined in four dimensions—technological, organizational, social, and economic (i.e., the TOSE dimensions)—originally proposed by Bruneau et al. [9]. Figure 1.2 illustrates how bridge maintenance and management sit in these dimensions.

As illustrated in Fig. 1.2, bridge maintenance is defined as a technology-centered process consisting primarily of four different technology-based means: inspection, monitoring, evaluation, and repair and retrofit (as a whole).

Specifically, bridge maintenance comprises the following phased processes:

- Inspection: A process that uses manual or technological methods to provide data about the condition, including damage or failure modes, of bridge structures. Typical inspection methods include manual (visual) checking and recording, non-destructive testing and evaluation (NDT&E), and imaging or vision-enabled inspection methods.
- Monitoring: A process that uses standalone or networked sensors to collect transient or dynamic responses of bridge structures. Typical methods and technologies are generally explored and developed in the sector of structural health monitoring (SHM).
- Evaluation: A process where engineers conduct empirical rules-based evaluation, structural load rating, or even rigorous structural analysis to identify the safety level of the bridges.
- Repair and retrofit: A process that, upon the decision of structural evaluation, provides solutions to fix, replace, strengthen, or reinforce structural elements in a bridge system.

With the definition and description of bridge maintenance and its four elemental processes above, we assert that maintenance is generally defined in the technological dimension of the multi-dimensional space of system resilience (Sect. 1.3 for

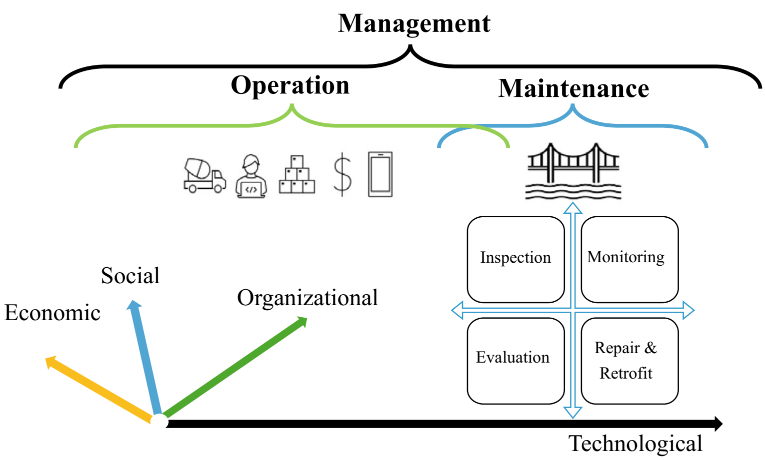

Fig. 1.2 Bridge maintenance and management in the TOSE dimensions

Life-cycle Resilience). Management, however, spans more than the technological dimension.

Broadly speaking, bridge management is a human-centered process that includes personnel training, planning, resource allocation, decision-making, and many other human activities, encompassing means, resources, and other assets, and spanning all TOSE dimensions. If one attempts to define a process describing the activities distinct from technology-centered maintenance activities, the notion of operation is commonly used. Namely, in a bridge management process, operation concerns the planning and distribution of all resources and assets relevant to bridge maintenance.

In this book, we limit the scope of management within the technological realm. Specifically, the notion of management is addressed in two aspects: technologies for various maintenance phases and technologies that contribute to better management for variables in other TOSE dimensions.

1.2 Bridge Maintenance Technologies

1.2.1 Inspection and Monitoring

The purposes of bridge inspection and monitoring are to (1) determine the bearing capacities and service conditions of new bridges; (2) evaluate the service performances and bearing capacities of existing bridges; and (3) study the mechanical behaviors of bridges with new structural forms or new materials and technologies to guide structural design and construction. Bridge inspection and monitoring is a technical discipline that directly serves engineering practices, involving structural design and calculation, testing technology and instrument performance, mathematical statistics and analysis, inspection personnel organization, etc. In terms of the conventional methods, bridge inspection and monitoring can be divided into patrol inspection, static load test, dynamic load test and non-destructive testing.

Patrol inspection does not need to configure any special measurement system on the bridge, but only needs an instrument that can support a variety of measurement operations. On the basis of specifying the inspection route, the data measurement and storage must be undertaken, and then utilized as a basis to subsequently evaluate the health of the bridge. As it is easy to carry out without many equipment, patrol inspection has become the most widely used conventional bridge inspection method. Static load test is a conventional inspection method that examines the static displacement, static strain, crack and other behaviors of the structure after static loads are applied to designated positions on the bridge, which can then infer the serviceability of the bridge under those loads. Dynamic load test is another conventional inspection method that is implemented by exciting vibration of the structure, and then measuring the natural frequency, damping ratio, vibration mode, dynamic impact coefficient, vehicle-induced response and other parameters of the structure to examine the overall structural stiffness and performance of the bridge bearing running vehicles. Non-destructive testing (NDT) is another important bridge inspection technique. It employs visual inspection without damaging the structural materials, or use acoustic, optical, thermal, electrical, magnetic, radiographic or other methods to measure the physical parameters concerning material properties so as to infer the material strength, defects, etc.

Bridge inspection technologies are of great significance for construction quality control, maintenance and management of existing structures, assessment of strength, durability and damage of existing structures, etc. However, the conventional bridge inspection technologies have technical problems themselves that restrict their wide applications. For example, for the static and the dynamic load tests to take place, the traffic need to be closed, and these inspection technologies are also prone to cause structural damages. Without traffic, the testing scenarios are different from the actual bridge operational conditions for these inspection technologies. Besides, the testing results can only reflect the overall mechanical behaviors of the structure, and cannot identify any local damage. NDT is complicated in operation, and its effectiveness largely depends on the damage assumptions of the inspectors.

Bridge structural health monitoring (SHM) practices integrate modern testing and sensing, network communication, signal processing and analysis, structural safety evaluation and decision-making, structural analysis and other technologies from different scientific fields, overcoming many shortcomings of the conventional bridge inspection. A bridge SHM system is usually divided into five parts: online testing module, real-time analysis module, damage diagnosis module, condition assessment module and maintenance oriented decision-making module. Firstly, the inspectors can conduct online testing for the bridge's actual working environments and its responses to various external loads using online testing module that relies on sensing, testing and network communication technologies. Secondly, the inspectors can transfer the measured data to real-time analysis module, and determine the current mechanical state of the whole bridge by finite element model updating and numerical simulation. Thirdly, the inspectors can use damage diagnosis module for damage warning, employing methods based on physical models or machine learning to locate and quantitatively identify the damage. Fourthly, in the condition assessment module, the inspectors can evaluate the safety and durability of various components of the bridge and the whole structure according to the updated indexes. Finally, the maintenance decision-making module will provide suggestions for the current bridge operation, management, maintenance and repair.

Due to the importance of the structure and the economic value, SHM systems are usually installed on selected long-span bridges. The application of bridge SHM systems began in the 1980s, when long-term monitoring instruments and automatic data acquisition systems were installed on Foyle Bridge, UK, to verify the design practice of the time and to study the impact of vehicle, wind and temperature changes on the dynamic behaviors of the bridge. Subsequently, several countries established SHM systems on some newly-built or existing large bridges, incorporating some advanced sensing technologies, computer and communication technologies, and signal analysis and processing technologies.

In recent years, with the enrichment of practical applications and the development of scientific researches, some progresses have been made in bridge SHM technologies which are reflected in: (1) practicing engineers can acquire more comprehensive monitoring information and content; (2) monitoring instruments are more diversified with more complete functions; (3) theory and method of structural damage identification have been improved; and (4) a variety of safety assessment methods has been applied to bridge SHM systems. However, the current bridge SHM technologies are still not perfect, and the following two scientific issues continue to perplex the engineering circle that need to be addressed urgently. Firstly, the structural uncertainties and the bridge's complex working environments have adverse effects on the sensitivity of the structural response, which is difficult to eliminate. Secondly, there is a lack of in-depth research on the changes in the structural characteristics of the bridge during its service life, so it is difficult to establish an objective structural evaluation standard. The conventional monitoring technologies also have the following technical problems: (1) SHM systems based on point contact sensors are of high costs and can only provide scarce data; (2) in terms of communication technologies, there is a lack of networks with large throughput and low latency, and a lack of data transmission protocols with low energy consumption and long life; (3) there is no mature and robust local damage identification method in terms of structural analyses; and (4) SHM systems based on remote sensing technologies lack structural details and elevation perceptions.

1.2.2 Evaluation Methods

Using data obtained from bridge inspection and monitoring, engineers can evaluate the health of the bridge with effective methods. Conventional bridge health evaluation methods can be roughly divided into two categories: deterministic evaluation methods and uncertainty evaluation methods. Deterministic health evaluation methods include those based on appearance survey, methods based on design specifications and methods based on load tests. Uncertainty health evaluation methods include those based on structural reliability theory and methods based on interval analysis.

The method based on appearance survey is the simplest and the most widely used bridge health evaluation method. Based on practical experiences, engineers and technicians have established various types of visual evaluation systems.

The evaluation method based on design specifications has a solid theoretical basis. However, due to differences between the structural design and the health evaluation, it is inappropriate to directly apply bridge design specifications to the evaluation of bridge bearing capacity, and engineers need to correct the structural resistant capability and loading effects according to the information obtained from field investigations. Therefore, the basic steps of bridge health evaluation methods based on design specifications should include: (1) establishing the bridge structure's finite element model according to the measured structural geometric parameters, material properties, support conditions, etc.; (2) applying the design vehicle loads modified according to the field investigation on the finite element model; and (3) comparing the load effects calculated with the updated structural resistance to assess the structure's reliability.

Load test method evaluates the bridge health through field tests. Specifically, this method uses the static and the dynamic responses of the structure under different levels of loads measured on site to identify the geometric parameters, material properties and support conditions of the actual structure. It then uses numerical analyses to estimate the normal service bearing capacity and the ultimate bearing capacity of the actual structure so as to quantify the integrity of the structure. In practice, the reliability of this method largely depends on whether the geometric, material and other parameters of the actual structure are accurately identified by finite element model updating and other technologies.

Health evaluation method based on structural reliability theory uses the failure probability or the reliability index to estimate the safety level of the structure. This method is based on probability and statistics theories, which can effectively take into account the uncertainties of the load and the resistance. Compared with the deterministic evaluation method, this method is proposed within a more reasonable theoretical framework for bridge health evaluation. The integrity evaluation method based on structural reliability theories can be subdivided into the direct evaluation of reliability index method, the sub item safety factor method, the analytic hierarchy process method, etc.

Probability model is not an ideal health evaluation tool for uncertain cases with few statistical data and less accurate computational model. Some scholars proposed a non probabilistic convex set model, which considers uncertain parameters as bounded quantities contained in a convex set, and obtains the range of structural response through set operation. Interval analysis is a representative convex set model-based method. At present, interval analysis method has been introduced into bridge integrity evaluation, but its effectiveness still needs substantial validations by incorporating it into real-world engineering applications.

To sum up, deterministic bridge health evaluation methods are widely used because of their simple processes for easy evaluation of bridge structures under specific conditions. However, these methods all make certainty assumptions for uncertain parameters in the evaluation process, leaving behind potential problems. The uncertain health evaluation methods consider various reasonably uncertain factors in the process of integrity evaluation, which are more mature in theory. However, these methods are not widely used due to their complexity, and their effectiveness in practical use remains to be assessed. In addition, both deterministic and uncertainty evaluation methods have the following common problems: (1) life cycle evaluation has not been realized; (2) visualization and dynamic interaction are not realized for results obtained; and (3) prediction has not been combined with structural health evaluation.