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Lifecycle Management and Maintenance of Marine Bridge Engineering

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Abstract: Marine bridge engineering in China is continuously developing in offshore, deep-sea, long-distance, and large-scale directions. However, due to the harsh natural environments and complex geological and loading conditions, several problems in health monitoring, measurement technology, inspection technology, and marine bridge engineering lifecycle maintenance management still exist. Therefore, after summarizing the existing problems in bridge lifecycle management and maintenance, this study proposes several key technologies for marine bridge development, including health monitoring based on multi-parameter, high-reliability, large-capacity, and long-distance optical fiber sensing; space–air–ground–sea integrated measurement; automated inspection; and intelligent management and maintenance platforms. Furthermore, this study investigates the difficulties and development directions of these technologies and explores development strategies and recommendations for marine bridge engineering lifecycle management and maintenance technologies, thereby providing technical support for the construction and operation safety of marine bridge engineering.
Keywords: marine bridge engineering; lifecycle management; health monitoring; automated inspection; engineering mapping; intelligent maintenance

1 Introduction

With the construction and operation of cross-sea bridges such as the Donghai Bridge, Hangzhou Bay Bridge, Qingdao Bay Bridge, and Hong Kong–Zhuhai–Macao Bridge, marine bridge construction in China has continued to develop from conventional bridges to offshore deep-sea long links. However, water depth, rapid and turbulent flow, and frequent tidal impacts in areas where marine bridge projects are located, as well as construction complexity, hydrology and geology, and higher environmental loads due to strong winds, earthquakes, and wave forces mean that marine bridges face extremely high risks throughout their lives. Simultaneously, marine bridge engineering spans a large distance and is far from land; thus, direct use of existing measurement references is difficult. High-precision measurement and positioning techniques are also frequently restricted by the harsh environment. Additionally, high temperatures, high humidity, salt damage, freezing and thawing cycles, and sea fog, among other extreme natural conditions in addition to the traffic load, causes bridge structure performance to deteriorate more quickly and more severely. Therefore, marine bridge engineering faces severe challenges in the survey, design, construction, and operation of lifecycle maintenance management.

The main problems faced in marine bridge engineering lifecycle maintenance management are as follows:

(1) There is an urgent need to overcome the real-time online and long-term reliable technical challenges associated with marine bridge health monitoring. In recent years, increasing numbers of bridge structures have been installed with long-term health monitoring systems to identify bridge structural damage and predict and

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evaluate possible damages and disasters; however, providing long-term reliability monitoring for the stress state of bridge structures is difficult [1].

(2) There is an urgent need to quickly and accurately overcome the technical limitations associated with real-time marine bridge engineering measurement. Many conventional engineering measurement techniques and methods are unable to meet the quick, accurate, and real-time requirements of marine bridge engineering; therefore, there is a need for continuous, dynamic, synchronous, real time, and automated monitoring methods.

(3) There is an urgent need to overcome the technical limitations associated with automatic marine bridge engineering inspection. Bridge engineering inspections are mainly designed for inland bridge engineering, and the inspection process is mainly manual and supplemented by mechanized equipment. Therefore, the work efficiency is low and subject to various conditions, limiting the inspection scope [2].

(4) There is an urgent need to overcome the limitations associated with marine bridge engineering lifecycle maintenance-management platform. At present, bridge management systems are single systems that are developed independently and are not compatible with each other. Therefore, bridge information management systems cannot share data, making it difficult to reach scientific and reasonable maintenance-management decisions. Previous risk impact research conducted worldwide has mainly focused on large inland bridges, and current risk assessment systems must be improved for the evaluation of marine bridges [3].

To overcome the abovementioned limitations, cutting-edge technologies are used to focus on the development of optical fiber sensing, satellite navigation and positioning, and automatic inspection, among other new technologies and equipment. A multi-parameter, high-reliability, large-capacity, and long-distance fiber-optic health monitoring system with “space–air–ground–sea” integrated measurements, automated inspection, and an intelligent maintenance-management platform is proposed. Herein, we study the key problems and development directions of this system and explore the development strategy and recommendations of marine bridge engineering lifecycle maintenance-management technologies. To realize the automation, informationization, and intelligence of the marine bridge project maintenance management, safe operation and prolonged service life of marine bridge structures must be ensured.

2 Key points for developing a marine bridge project lifecycle maintenance-management research strategy

2.1 Health monitoring technology for marine bridge engineering based on optical fiber sensing

2.1.1 Key issues

Bridge engineering health monitoring technology has evolved from visual inspection to electrical measurements such as resistance strain gage, steel string strain sensing technology, and electromagnetic tests; however, it is still difficult to realize the long term and reliable detection of the stress state of a bridge structure. The development of optical fiber sensing technology has enabled real-time monitoring, thereby improving the long-term reliability [4]. Based on the global research status of bridge engineering health monitoring technology, three problems related to the technology have been identified as follows: (1) longevity and reliability of the marine bridge engineering lifecycle health monitoring system; (2) necessary measurement parameters not being comprehensive due to the technical condition limitations; and (3) effective use of monitoring data for early warning.

2.1.2 Technological development directions

(1) Long-life fiber sensing technology for marine environments

The harsh environment of the ocean leads to sensor durability requirements, such as high strength, corrosion resistance, and large temperature difference sensing characteristics. For marine bridges with complex structures and long construction periods, replacing online monitoring equipment can be difficult because it requires sensors with a longer life cycle [5]. Therefore, the following points should be considered while developing long-life special optical fiber for marine bridge engineering: (1) special fiber structure and component design; (2) special preformed optical fiber production process; (3) special fiber drawing process; (4) special fiber coating preparation and coating process; (5) special optical fiber grating preparation technology; and (6) special fiber grating online preparation equipment integration.

(2) Development of multi-parameter, high-reliability, high-capacity, and long-distance fiber-optic sensing components

Optical fibers have large sensing capacities, making them suitable for the monitoring of marine bridges as multi-parameter monitoring requires a wide variety of sensors. Additionally, small installation spaces require a

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small sensor size and provide technical requirements for the layout, adhesion, and protection of gratings in narrow spaces as well as the routing and installation of multiple gratings in complex structures. Based on the ultra-high-precision testing requirements of marine bridges and their construction equipment for physical parameters, such as temperature, strain and vibration, efficient coupling between complex physics and fiber-guided wave fields, sensor sensitization mechanisms, and multiphysical cross-sensitivity mechanisms are studied. The microfiber sensor package structure is designed using materials sensitized to specific parameters through 3D printing technology, and sensor responsiveness is optimized to achieve high-precision measurements of temperature, strain, and vibration, among other physical quantities.

(3) Omnidirectional, multiscale monitoring technology for marine environments

The advancement of construction technology and complexity of marine bridges' structural system dictate higher requirements for the comprehensiveness of health monitoring, including the marine geographical environment, sea breezes, ocean waves, temperature, wave force, and operational period structural information changes. To accurately determine the health of marine bridge structure, the collected information must be comprehensive and accurate and include structural static response, dynamic characteristics, and structural changes during the operation period [1]. Simultaneously, the monitoring scales of different parts of a bridge are not the same, with some parts such as cables and other stressed parts requiring local dense grid monitoring and others such as the main beam line shape and main tower offset requiring overall global monitoring [6]. Therefore, comprehensive and multiscale monitoring is required to meet the different monitoring needs of marine bridge structures.

(4) Marine bridge engineering health monitoring system

Factors such as material aging, environmental corrosion, and natural disasters can lead to varying degrees of damage to marine bridge structures during service, thereby posing a threat to the safety and service life of the bridge structure. Therefore, it is necessary to combine online health monitoring and automated inspection technologies to construct a comprehensive system integrating structural calculation analysis; computer, communication, network, and sensing technologies; information analysis, processing, and evaluation; and other hightech integration so that the marine bridge engineering lifecycle maintenance management can truly meet the needs of safe operation and maintenance management [2].

2.2 Integrated "space–air–ground–sea" measurement technology of marine bridge engineering

2.2.1 Key issues

Marine bridge engineering projects typically have large scales, novel structures, and unique geographical locations. Many conventional measurement techniques and methods in engineering surveys cannot meet the real time, fast, and accurate requirements of marine bridge engineering. However, satellite navigation and positioning technology is unique since it can meet these requirements. This advantage has become an inevitable trend, but there are still several engineering measurement problems to be solved in the survey design, construction, and operation management stages [7].

2.2.2 Technological development directions

(1) Surveying and mapping technology of the marine bridge engineering survey and design stage

Based on the BeiDou satellite navigation system (BDS) independently developed by China, the global positioning system (GPS), Russia's global navigation satellite system (GLONASS), and other satellite positioning systems, auxiliary multimode global navigation is possible. Global navigation satellite system (GNSS) technology possesses advantages such as high automation, all-weather operation, high precision, real-time operation, flexible layout, and convenient operation in establishing a control network in the bridge survey and design stage. GNSS can overcome the positioning of a single satellite system, which can be blocked by local signals, insufficient satellite coverage, and defects affecting positioning performance. GNSS technology assists in the measurement of underwater topography with centimeter-level or greater precision and it is necessary to conduct research on the GNSS vertical reference establishment and conversion technology of marine bridge engineering [8]. Simultaneously, the development of drone technology, which breaks through the limitations of traditional oceanographic terrain mapping methods, will greatly improve the work efficiency and automation.

(2) Surveying and mapping technology in the construction stage of marine bridge engineering

Marine bridge construction positioning technology based on GNSS possesses advantages such as all-weather, high precision, wide compatibility, and easy management. This technology can provide an intuitive, accurate, and continuous overview of ship position, heading, and construction area as well as continuous three-shift and all-weather operation for ship construction. Simultaneously, the 3D laser scanning technology can automatically verify component dimension correctness, presimulate the assembly process, check the construction quality, and evaluate the accuracy of bridge construction. Unmanned aerial vehicle (UAV) inspection technology can grasp the construction status in real time, enabling real-time construction monitoring and scheduling when combined with communications and geographic information system technologies.

(3) Surveying and mapping technology in the operation and management stages of marine bridge engineering

Combining multimode GNSS technology with network communication technology, computer technology, and sensor fusion technology, as well as other cutting-edge technologies such as the Internet of Things (IoT), big data, and cloud computing can realize the real-time online 3D deformation monitoring of marine bridges, significantly improving marine bridge operation management level and early warning capabilities. In key parts that are not measured by GNSS, the comprehensive application of GNSS and measurement robots can achieve comprehensive bridge monitoring. Additionally, 3D laser scanning technology is a powerful complement to GNSS automatic deformation monitoring that can use point cloud data acquired to obtain monitoring information on different pieces and higher density deformation monitoring data, which is not possible using other monitoring methods. Vigorously developing airborne and mobile 3D laser scanning applications and comprehensively applying GNSS monitoring technology and robot monitoring technology is conducive to the formation of 3D deformation monitoring technology system for marine bridges.

2.3 Automated inspection technology for marine bridge projects

2.3.1 Difficult problems

By inspecting the technical status of marine bridges, the type, extent, and location of bridge structural damage can be obtained. The technical status of the marine bridge can be assessed to provide reliable technical parameters for developing a maintenance strategy. However, the following two problems exist with technical inspections: (1) there is a lack of inspection technology systems for marine bridge engineering and (2) the degree of automation of maritime bridge engineering inspection equipment is low.

2.3.2 Technological development directions

(1) Establishing an automatic inspection technology system for marine bridge engineering

For extreme environmental and traffic loads such as high temperatures, high humidity, salt damage, freezing and thawing cycles, and sea fog, the content, frequency, and indicators of regular inspection can be determined for regular and special inspections of marine bridge projects based on the existing inland bridge inspection technical solutions and specifications, standards, and guidelines. Research can be conducted on inspection technical systems applicable to marine bridge engineering to ensure the rationality, timeliness, and professionalism of the technical inspection scheme.

(2) Marine bridge engineering automation inspection equipment

Research and development should focus on marine bridge engineering cable intelligent detection robots, beam bottom automatic detection robots, UAVs, and other automated inspection equipment and intelligent mobile terminal movements to improve the safety, comprehensiveness, reliability, and timeliness of marine bridge engineering inspection [9].

2.4 Marine bridge engineering lifecycle maintenance-management platform

2.4.1 Difficult problems

The life cycle of marine bridge engineering refers to the entire process from generating the project survey phase target to completing the project implementation phase to the project operation stage. Currently, China's construction project management model follows the traditional phased management model. However, the relatively independent management theories at each stage cannot meet the needs of implementing major projects such as marine bridges [10].

(1) The marine bridge engineering maintenance-management platform is insufficiently open and not standardized. Additionally, the degree of networking and mobility is insufficient. Therefore, the prediction and evaluation of bridge state is lacking.

(2) Existing research on marine bridge engineering risk is biased toward theoretical and subjective factors. Therefore, it is difficult to determine targeted risk-averse strategies in a timely and effective manner.

(3) Owing to the particularity of marine bridge projects and harshness and complexity of the environment,

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existing conservation technology programs are difficult to be fully applied to marine bridge projects.

2.4.2 Technological development directions

(1) Construction of a marine bridge engineering lifecycle management and maintenance platform

The marine bridge maintenance-management platform is a large-scale cloud-based information system that integrates basic data, design data, construction information, and monitoring data, which is used for state assessment, structural degradation prediction, and maintenance countermeasures and plans, among others. Additionally, the platform can store massive multidimensional information and deep excavation analyses in a large database to determine the current state of bridge and maintenance countermeasures and forecast and analyze future developments of the structure.

(2) Risk identification and evaluation system for the entire life of marine bridge engineering

The risk source of marine bridge engineering has objectivity, universality, and inevitability; however, the existing bridge engineering risk identification and assessment system does not easily meet the dynamic risk assessment needs of marine bridge engineering. With an aim of achieving a complete marine bridge risk assessment system, a whole life risk identification and evaluation system applicable to marine bridge projects is proposed. Using massive monitoring data and deep mining analysis of cloud technology, timely and effective risk avoidance strategies can be determined [11].

(3) Technical system for marine bridge engineering maintenance and repair

Preventive conservation is a proactive and active conservation method that can effectively delay the middle stage duration and overhaul and extend the service life of marine bridge projects. Till date, the maintenance technology of marine bridge projects has not yet formed a perfect technical system. Developing technologies for the conservation and maintenance of marine bridges and improving the professional level of maintenance personnel, the marine bridge engineering maintenance and maintenance decisions based on artificial intelligence and big data will provide professional support for bridge maintenance management decision-making.

(4) Cloud technology in marine bridge engineering maintenance management

As a special form of distributed computing, cloud technology introduces utility models to remotely supplied measurable and scalable resources that can perfectly meet the challenges associated with marine bridge engineering big data [12]. Therefore, vigorously developing cloud technology ensures rapid processing and deep excavation of massive data in marine bridge engineering and can accelerate the promotion of information management and intelligence of marine bridge maintenance management.

3 Strategic objectives of marine bridge engineering lifecycle management and maintenance research

This topic focuses on the key technical problems of the lifecycle maintenance management of marine bridge engineering. Through an extensive data review, on-site investigations, continuous discussions, analyses, and multiple expert consultations, the strategic focus on the marine bridge engineering lifecycle maintenance management technology’s development is proposed.

(1) Based on optical fiber sensing, satellite navigation and positioning, automated inspection, and intelligent mobile terminal technologies, we will vigorously develop the health monitoring and early warning system and marine bridge engineering equipment.

(2) We will develop long-life special fiber-optic sensing technologies for marine environments and multi-parameter, high-reliability, large-capacity, and long-distance optical fiber sensing components as well as omnidirectional and multiscale monitoring technology.

(3) We will establish a multimode satellite fusion positioning mechanism based on the BDS with other satellite navigation and positioning systems as a supplement. Measuring robots, 3D laser scanning, UAV surveying, and other modern measurement methods will be used to form a construction measurement system for multi-method integration and data fusion processing of marine bridge engineering. Integrated spatial information integration technology will be developed for “space–air–ground–sea” marine bridge engineering.

(4) We will establish an intelligent decision-making system for marine bridge engineering lifecycle maintenance management. We will build an information-based intelligent maintenance-management platform supported by big data to promote the automation, informationization, and intelligence of the lifecycle maintenance management of marine bridge engineering in China and realize intelligent marine bridge management.

4 Strategy development recommendations for marine bridge engineering lifecycle

management and maintenance research

We will vigorously develop new technologies, equipment, materials, and processes for the maintenance management of marine bridge engineering and encourage universities, research institutes, and enterprises, among other relevant institutions, to strengthen the research and application of full-life management and maintenance technologies for achieving technological breakthroughs in relevant and important scientific and technological fields. We will also promote the continued development of marine bridge engineering maintenance management including the following: (1) We will focus on developing an application of optical fiber sensing technology in marine bridge engineering monitoring, develop special optical fibers suitable for the marine environment, and establish all-round, multiscale marine bridge engineering health detection technologies. (2) We will focus on the development of BDS with other satellite navigation systems as a supplement to the multimode satellite fusion positioning technology and construct a “space–air–ground–sea” marine bridge project integrated space information integration technologies. (3) We will establish an IoT marine bridge platform supported by a big data center of marine bridge engineering to promote the automation, informationization, and intelligence of marine bridge engineering project lifecycle maintenance management and realize the “Smart Marine Bridge” strategy.

5 Conclusion

This study considered the harsh and complex variability of marine bridge project environments. Furthermore, in the middle of the marine bridge engineering survey, design, construction, and operation stages, the entire marine bridge structure’s safety and longevity must be considered. Optical fiber sensing and satellite navigation and positioning technologies can be combined with automated inspection and intelligent mobile terminal technology to achieve health monitoring and all-weather, high-precision spatial positioning of marine bridge projects. An intelligent marine bridge project maintenance-management information platform with deep information technology integration can be constructed to conduct marine bridge health monitoring, maintenance, and risk management, among other research tasks, and achieve intelligent management of marine bridges and marine bridge engineering automation, information, and intelligent maintenance-management purposes. Finally, the safety, reliability, and longevity of marine bridge engineering must be ensured throughout the project’s lifespan.

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