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Wave Current Force Action and Foundation Scour of Marine Bridges

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Abstract: With marine bridges extending to the deep sea, the problems of bridge foundation wave force and bridge foundation scour have become a critical factor threatening bridge safety. To ensure the rationality of bridge design and safety of construction and operation, this paper systematically classified ten significant problems that marine bridges face in terms of wave force and foundation scour. Furthermore, the paper emphasizes that marine bridges need to be developed using a high-precision prediction method, an environmental prediction system and pre-warning system, multi-factor environmental coupling, scour numerical simulation technology, a wave force calculation method, and other aspects, and proposes ten developmental directions. This study demonstrates that the research on wave action and foundation scour is an important endeavor to ensure the safety of marine bridges. This paper recommends eleven countermeasures from three aspects of macroscopic management, industrial application, and academic technology.

Keywords: marine bridge; wave force; foundation scour; development direction; countermeasure

1 Introduction

With the Belt and Road initiative and the Ocean Power strategy proposed, the construction of marine bridges has ushered in a peak period of development, bridges are increasingly being built on the important channels along the coast of China. With the continuous extension of marine bridges to the deep sea, the wave and current loads have an expanding influence on the substructures of the bridges. The wave and current forces have become the controlling loads of marine bridges [1]. Monographic studies on the wave forces on bridge substructures have been carried out on many marine bridges currently under construction or those that have been completed, such as Hong Kong-Zhuhai-Macao Bridge [2], Pingtan Strait Bridge [3], Donghai Bridge [4], and Yueqing Bay Bridge [5]. Distinctive from beam bridges and other small span bridges, marine bridges are typically cable-stayed bridges, suspension bridges, and other large span bridges. These bridges have the characteristics of an extensive span, small global stiffness, and substantial structural deformation, which makes marine bridges more significantly affected by wave and current forces and foundation scour. Therefore, it is urgent to study the developmental directions of wave and current forces and foundation scour of marine bridges.

Furthermore, extreme weather such as typhoons and tropical cyclones occur frequently along the coastal areas of China. According to statistics, there have been as many as 59 typhoons landing in China from 2011 to 2018. In this period, 2018 was the year with the most typhoons landing in China, with approximately nine typhoons; 2014 had the least and there are 5 times. Typhoons often bring massive waves and torrents and can cause disastrous

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storm surges, which pose a considerable threat to the construction and operation of bridges. The study of wave and current forces and foundation scour is an indispensable part of the strategy for marine bridges, and also a fundamental assurance for the rational construction and safe operation of the bridges. How to improve the accuracy and efficiency of wave and current forces prediction? What is the difficulty in the foundation scour of complex bridge substructure? What are the development directions of marine bridges? To further elaborate on these problems, this study deeply analyzes the existing challenges presented by wave and current forces and the foundation scour of marine bridges, highlights the developmental directions of marine bridges in this field, and finally, presents corresponding countermeasures and suggestions, which can provide a vital reference for the study of wave and current forces and the foundation scour of marine bridges.

2 Problems and challenges

2.1 Insufficient measured data of wave

There are quite a number of buoys on the ocean off the coast China, but the density of buoys is limited. When typhoons and other extreme weather occur, the accuracy of the traditional methods for calculating the wave characteristics of the bridge site with high sea waves is limited. More abundant and direct wave data are needed to understand the wave characteristics of bridge sites. Furthermore, the buoys belong to different organizations, making it difficult to query the buoy data. The data availability of each organization is seriously insufficient, and there is no centralized data-sharing platform for buoys. The installation of wave gauges at the bridge site could supplement certain wave data, but the instrument is easily disturbed by environmental factors and its output is inconsistent. There are often many missing and erroneous data in the measured sequence, especially in the harsh ocean environment such as strong winds and waves.

2.2 Low accuracy of wave calculation and prediction in bridge site area

Current studies on wave height generally have been focused on the relationship between wind and waves. However, in nearshore areas, the change in wave height is primarily controlled by the terrain, and the study on the practical mechanisms of a nearshore wave propagation in a complex terrain is relatively rare. The predicted wave propagation and deformation for nearshore terrains in the *Code of Hydrology for Harbour and Waterway* [6] is calculated by multiplying the shoaling coefficient and refractive coefficient under ideal parallel isobaths. This method has been widely used for flat beach terrains; however, its calculation accuracy cannot meet the engineering requirements for complex reef terrains. The empirical formula proposed based on the measured wave data has a very limited range of application due to the unique terrains of the various bridge sites [7]. Although the wave propagation law obtained from the test can be extended to certain types of terrains, it is not yet universal because it is often simplified and is greatly affected by the test conditions. The numerical calculation method can improve the accuracy; however, it requires considerable time, and time and accuracy are inversely correlated; reducing the time will reduce the accuracy. Therefore, more improvements are necessary to accurately predict the waves in the bridge site area.

Furthermore, the marine bridge is a large strip structure project, and the interaction between the bridge superstructure, pier, and wave field is very complex. Moreover, based on the differences in the structural forms of the bridge during different stages, the influence of the wave field on the bridge during the construction and operation stages is different. However, the strip's precise measurement and the prediction platform for the construction and operation for a marine bridge has not been found. Additionally, from the perspective of bridge design, construction, and operation, more attention should be paid to the wave field at the bridge site and the interaction between different piers and columns, which will determine the magnitude of the direct force acting on the bridge structure. Therefore, small-scale and short-term wave forecasting has very important implications, but most current forecasting models are for large-area forecasting, with low forecasting accuracy, which cannot meet practical requirements.

2.3 Difficulties in calculating wave characteristics of bridge site in complex ocean environment

The study of the wave characteristics at bridge sites in complex ocean environments not only needs to consider the complex terrain effects, but also to study the role of extreme climates. Presently, the most commonly used analytical method is the mathematical statistics method based on measured data. The return period of the design wave element in harbor engineering code is based on the mathematical statistics method, which is calculated using

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long-term data. However, there is no design standard for marine bridge engineering, and a determination method of design wave element and its return period has still not been clear. The numerical simulation can better realize the coupled calculation of the terrain, wave, and wind, but the computational cost of the numerical simulation is high. For high accuracy, the required time will be very high. To reduce the time cost, the computational accuracy must be reduced, which results in a significant deviation between the numerical solution and the actual value. The South China Sea and southeast coast of China are areas with frequent typhoons. It can take fewer than 5 days from the generation of a typhoon until it reaches China's coastal areas. The time from the determination of the general path of a typhoon until it makes landfall is even shorter. It is challenging to simulate the impact of a typhoon on the safety of bridge structures and take protective measures in such a short time. Because of the limitation of test conditions, it is often only possible to simulate the action of conventional wind, and it is difficult to simulate severe storm impacts; therefore, it is impossible to restore the real complex ocean environment.

2.4 Morison equation needs to be improved

The drag coefficient and inertial force coefficient in the Morison equation depend on *Re* number and the *KC* number. The influence of the two parameters on the drag coefficient is greater than that on the inertial force coefficient, but the exact results require additional analysis. In the Morison equation, the drag force is proportional to the square of velocity, but in the process of calculating the wave force with the Morison equation, it is necessary to linearize the term of drag force to simplify the calculation. However, to calculate the result accurately, the influence of the second-order force should also be considered. Therefore, there is no unified theory on the treatment method. Engineering examples of structural failure of ocean engineering piers caused by wave force are common [8]. As the main calculation method of wave force on deep-water bridge pier, the Morison equation requires further study on its accuracy and reliability.

2.5 No clear method for calculating wave forces on complex structures

The complexity of a marine bridge is mainly reflected in three aspects: large-scale and small-scale structures coexist; the structural combination of the pile group and pier group is varied; and the sections of structures are irregular. Small-scale structures of marine bridges primarily refer to piers, pile foundations, and other structures. These structures, especially piers, contain sections that are often non-standard shapes (e.g., rectangular with rounded corners, dumbbell-shaped). Presently, there is no clear formula and method for calculating the wave forces on these structures in the design code of ocean-crossing bridges. Therefore, as the foremost controlling external forces, the wave forces have become a concern for bridge structural design. Large-scale structures of marine bridges mainly refer to caps, cofferdams, and other similar structures. The code can only calculate circular sections and rectangular sections with aspect ratios less than 1.5. There is no clear calculation method for building such complex sections. Moreover, the interaction between the composite structures is not considered in the calculation process. Additionally, the existing wave force calculation methods for large-scale piers and small-scale piles are based on theoretical analysis and the numerical calculation of piers extending from the seabed to the water surface. To apply this method to the calculation of wave forces on pile foundations, caps, and piers, it is necessary to study the influence of wave forces on the calculation results. The basic assumption of the Morison equation used in the calculation of wave force on pile foundation is that the existence of structures does not affect the wave propagation. Because of the large size of the upper cap and pier, the wave field around the structure will change. The applicability of the Morison equation in the calculation of a bridge pile foundation needs to be further demonstrated.

2.6 Lack of multi-factor coupling analysis for ocean-crossing bridges under wave action

Because of the flexibility and vastness of the foundation, the dynamic characteristics and responses of the structure calculated on the assumption of a rigid foundation are different from those calculated based on the foundation and structure as a whole. Therefore, it is necessary to consider the influence of a multi-factor interaction of the seabed, foundation, and structure. Nonlinear and non-uniform excitation problems are particularly important in multi-factor coupled systems. For non-linear problems, the influence of non-linear factors, including the non-linear theory of waves, the non-linear interaction between waves and the second-order wave force, is not taken into account when calculating wave forces. Moreover, the non-linear factors must be considered in the dynamic calculation regarding the shallow water areas and ocean engineering structures affected by these factors [9]. Furthermore, owing to the large span of ocean-crossing bridges, inconsistent excitation such as the traveling wave effect and spatial coherence effect will be involved when the wave force is used as random excitation input, which are worth studying.

2.7 Mechanism of wave-current interaction is not clear

The actual velocity and direction of the change in current in real time and the elements of the wave are transient changes, resulting in complex forms of wave-current interactions, especially in coastal shallow water area where wave-current interactions are easily recognizable. For example, at high tide, the current into the estuary flushes out the waves; at low tide, when the current enters the estuary, the waves become steeper and often break, which affects the offshore navigation. Additionally, when waves spread from the high sea to the shore, a parallel coastal current is formed between the broken wave line and the shoreline. In the broken wave zone, a narrow strip flowing in the direction of the deep ocean will be formed, which is called the offshore current. Tidal waves, runoff, wind-driven circulation and wave interaction, solitary wave and current, and interfacial wave and current interactions are the typical forms of wave and current interactions. Additionally, many other natural phenomena, such as wave set-up and rip current, are also affected by wave-current interactions. With the exploration of the oceans, wave-current interactions have become key problem in the development of the oceans in the complex environment, and has attracted the attention of scientific researchers in China and abroad.

2.8 Inadequate research on interaction between tsunami wave and bridge

Tsunami research in China has been a relatively recent development, primarily focusing on the causes, warning and monitoring, risk and the division of hazardous areas, numerical simulations of tsunami propagation, and the interaction between the tsunami and structures [10]. Among the areas studied, the interaction between the tsunami and structures has been studied the least, and the research focus has been primarily concentrated on the destructive effects of tsunamis on building structures. Some guidelines for escape structures have been formulated abroad and are gradually being incorporated into the Chinese code. However, there are no guidelines for bridge–tsunami interactions. The guidelines or codes regarding tsunami forces are mostly associated with residential buildings or coastal engineering; they are not applicable for marine bridges. For example, the expression of tsunami force estimation provided in Federal Emergency Management Agency (*FEMA P-646 (2012)*) does not consider the buoyancy varying with time during the rapid advance of tsunami waves and the gradual variation in the pore water pressure in the foundation soil. There are no guidelines for the calculation of tsunami forces in China nor in relevant codes. In domestic offshore projects, tsunami forces only have been considered and monitored for nuclear power plants; other offshore infrastructure ventures have not considered the tsunami force.

2.9 Scour mechanism of marine bridge foundation is complex

When designing ocean-crossing bridges, navigation requirements, large main spans, large self-weight of superstructure, more complex and large bridge foundation, deeper water depth, and more complex and changeable seabed geological conditions should be considered in the construction of ocean-crossing bridges, all of which are important factors that affect the foundation scour. The environmental loads generated by severe meteorological events and the hydrology of the deep-water foundation in the ocean are much more significant than the impacts on deep-water foundations in the inland rivers. Therefore, the foundation scour caused by typhoons, massive waves, and springs is a more serious concern in the design and construction in off-shore projects. The flow direction of the ocean’s deep-water foundation is much more complex than that of an inland river, where the flow direction is relatively fixed, while the flow direction in the ocean environment is relatively random. Furthermore, the influence of global ocean current movements and other related factors should be considered, which will greatly increase the complications in predicting the scour depth of the bridge foundation in an ocean environment. Scour mechanisms, morphologies, and processes are different because the scour caused by water flow and waves are two distinct types. Therefore, it is necessary to focus on the research of the scour of marine bridge foundations. To reduce the unsafe and economic loss caused by scour in the process of marine bridge foundation construction, it is particularly important to study the scour of marine bridge foundation.

2.10 Inadequate numerical and experimental techniques for scour of marine bridge foundations

Many researchers have carried out experiments and studies on local scour impacts on structures including piers, pile groups, and caissons. The results obtained have been consistent with the results of empirical, semi-empirical,

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and semi-theoretical formulas, and can also provide a scientific basis for practical engineering. However, the test results can only be used as a reference, and the gap between the measurements and the actual results of the project is substantial. The selection of relevant test parameters, the accuracy of measurement, the scale effect, and the improvement in test methods remain the issues for further development of scour testing [11]. Compared with the empirical method, the numerical model method has the following advantages: (1) it can simulate for the size of the prototype to avoid the scale effect; (2) it can be precisely arranged, especially for complex conditions, for which the empirical method cannot accommodate; (3) it can provide detailed and comprehensive observations of scour mechanisms and behavior from different perspectives; (4) the operating environment is simple, and there is no need for a special test site and many experimenters. Although many numerical simulations of the local scour have been carried out, the mechanism of local scour, especially the mechanism of bridge foundation scour in the ocean environment, requires further study, and the research on the movable bed scour and three-dimensional two-phase simulations must be strengthened.

3 Developmental direction

3.1 High-precision prediction method for wave characteristics along marine bridges

Ocean forecasting research in China has begun only recently, but the research has developed rapidly and has made considerable progress in forecasting, early warning methods, and quality. However, the operational wave forecast for the general public is far from meeting the prediction requirements that should be considered for marine bridge construction. The subsequent key research directions are hereby proposed. (1) The spatial resolution of the operational wave forecast must be improved and the wave height of the major construction control points should be predicted accurately for a large marine bridge. (2) It is necessary to consider the inshore propagation process of ocean waves. Marine bridges often need to connect and span over islands. The bridge sites are located in complex island areas and are influenced by the complex island topography; thus, a series of complex and changeable physical processes will occur in the propagation process of ocean waves. (3) The space scale of general operational wave prediction is too large, and the pertinence is low. This needs to be built on a super computer cluster, and the system is very complex; hence, its computational efficiency. It is necessary to develop multi-station ocean buoys to be three-dimensional and have high-density. Further, the number of buoys must be increased and the degree of data opening should be improved.

3.2 Development of a joint probability model of wind and wave environment elements for engineering application

The probability method or reliability method has been widely used in designing offshore engineering structures in China and abroad; however, it still has some limitations. For instance, for the probability distribution of wave height and period, generally, the best fitting model is chosen according to the sample data, and then the return period are calculated according to the model. However, this model is built on the basis of independent and identically distributed data, and the measured data are relevant; therefore, the traditional probability analysis of the multivariate distribution function is limited considerably. Thus, it is necessary to explore a new probability distribution function for practical simulations. There are many limitations of the joint probability model , such as the lack of measured data and design wave elements of uncertainty. Therefore, it is necessary to study the joint probability distribution model for wind and wave environmental factors, establish a combination method for wind and wave environmental loads on marine bridge structures, and improve the technical standards and risk assessment mechanism of marine bridge engineering design.

3.3 Establishment of marine bridge environmental prediction system and early warning system

The construction and operation of bridge engineering is a long-term process. In particular, during the construction of bridges, a stable ocean environment is necessary. Thus, it is important to study wave characteristics in the bridge site area and clarify the role of waves in the bridge structure urgently. Thus, under extreme climatic conditions, unilateral or multifaceted early warning standards such as disaster energy level, structural overall stability, driving stability and component level failure are still unclear, and a risk assessment mechanism for the management of marine bridges has not been developed yet. For the development of marine bridges, it is important to study high-precision prediction methods for wave characteristics along these bridges and to provide real-time ocean environment prediction and early warning systems for major ocean channels.

3.4 Improving the numerical simulation technology of small-scale and short-term wave prediction

In the construction and operation stage of bridges, the wave characteristics near the bridge also change. The wave characteristics in large areas cannot accurately represent the wave characteristics of each structure. Furthermore, the small-scale and short-term wave prediction will play a key role in the construction safety and emergency measures of the bridge; therefore, it is necessary to study small-scale and short-term wave prediction.

3.5 Understanding the influence of pile group effect on wave field

Presently, the study of pile group effect mostly focuses on the case of four pile arrays, while the pile foundation of ocean-crossing bridge has various arrangement forms, including inclined piles. These complex pile group coefficients, which originate from the pile group effect in actual engineering, have not been studied sufficiently. However, considering the influence of the overall structure of pile group-cap and pier on the wave flow field, there is almost no research on the influence of the wave flow force on the structures of ocean-crossing bridges. Therefore, it is necessary to extensively study the pile group effect of marine bridges and clarify the interaction mechanism of pile groups.

3.6 Study the time domain and frequency domain methods for calculating wave force of large-scale and small-scale structures

The dynamic response of wave force can be obtained from the time and frequency domains. The time domain can solve any non-linear problem. However, for a long history, its calculation efficiency is considerably low, while the frequency domain is limited to solving dynamic problems of linear structures. Presently, considering the characteristics of deep-water long-span bridges, time-domain and frequency-domain calculation methods for wave forces of marine bridges should be proposed to improve the accuracy and efficiency of wave forces calculation. Bridge composite structure should be studied considering the influence of nonlinear terms and the interaction between adjacent structures to improve the Morison equation, and the correlation between components must be clarified.

3.7 Research on dynamic response and multi-factor coupling of large marine bridges

For structures located in the deep sea area, the structure has greater flexibility (areas where the offshore ocean-crossing bridge is not at great depths; however, the pier foundation size is smaller, making it flexible). It is more sensitive to the wave dynamic load, and the dynamic response is also significant; therefore, the structure must be analyzed dynamically. It is important to study the traveling wave effect, spatial coherence effect, fluid-solid interaction, and other non-uniform excitations of the wave load. Further, the influence of structure-pile-soil dynamic interaction, fluid-solid interaction, wave theory, wave direction, and other factors on large marine bridges should also be studied.

3.8 Study on wave interaction and wave impact mechanism

Wave-current interaction is a very complex non-linear problem. Its flow mechanism and characteristics have not been fully explored thus far. Its experimental research consumes considerable manpower, material, and financial resources, and it is difficult to carry out large-scale and systematic research under different working conditions. The analytical method is essentially limited to the special flow velocity profile conditions such as uniform flow and shear flow. However, to explore oceans, wave-current interaction has become a key problem in ocean development in complex environments, which has attracted the attention of researchers at home and abroad.

The process and mechanism of wave impact are very complex, involving strong non-linearity, instantaneous effect, fluid viscosity, turbulence characteristics, water-air mixing, and other factors. Existing studies have not sufficiently clarified the mechanism of wave impact on buildings. Therefore, this problem is still one of the difficult problems to be addressed in the field of coastal engineering. Presently, most scholars still use semi-empirical and semi-theoretical method to study the impact problem. First, the calculation formula of the impact pressure is given based on theoretical research, and then the main parameters are determined in a physical model test. The existing calculation formulas have mainly been derived for regular wave conditions. Although the results of these formulas are in good agreement with the experimental data, they have certain limitations owing to the complexity of offshore structures. Thus, it is necessary to study wave impact methods and theories applicable to marine bridges.

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3.9 Study on mechanism of tsunami wave and bridge interaction

Thus far, no tsunami-resistant design has been proposed for bridges in China and abroad, and there have been no provisions for tsunami-resistant design in bridge engineering codes. This is mainly because the understanding of the tsunami threat is not sufficient, and the nature of the tsunami force and the mechanism of bridge damage have not been studied thoroughly. The interaction mechanism between the tsunami and the structure under stable climate conditions must be analyzed through numerical simulations or experiments. Furthermore, guidelines or codes for tsunami force calculation in China must be compiled. These guidelines or codes need to learn from existing studies and summarize them to provide an understanding of tsunami research results. This work will have very important applications.

3.10 Study on the scour mechanism and local scour simulation technology of marine bridges

The scour of bridge foundation is a key problem to be considered in the designing and construction of marine bridges. Because the bridge foundation scour mechanism of the ocean environment research is very scarce, scour mechanism is still not sufficiently thorough, there are very few bridge foundation scour calculation formulas in the ocean environment, and there has been no pure theoretical derivation. These formulas are empirical or semi-empirical and semi-theoretical formulas. Therefore, it is necessary to study the scour mechanism of marine bridge foundation, improve the understanding of the characteristics of scour flow field and sediment movement of marine bridge foundation, and compile a scour code of bridge foundation under ocean environments. Additionally, to solve practical engineering problems, the scour physical test model is usually used to provide a scientific basis and reference for practical engineering. For other purposes, it is necessary to establish different bridge foundation scour test models. However, the scour test still has some limitations, such as the experimental scale effect, the scouring during construction and the experimental modeling of actual topography. Considering the complexity and variability of the ocean environment, it is necessary to study the coupling effect between the scour of bridge foundation and other factors, and to further study the simulation technology of local scour test, underwater detection method, and anti-scour measures for bridge foundation under complex ocean dynamic environments, to provide a basis for construction.

4 Countermeasures and suggestions

The study on wave-current force and the foundation scour of marine bridge engineering is important in the development of strategies for marine bridges, and it will also ensure the safety during the construction and operation of marine bridge. Based on this, the present study proposes policy suggestions for the development of wave-current force and foundation scour research on three levels.

4.1 Macro management level

(1) Strengthen the layout of monitoring points for the proposed major ocean channels, integrate the monitoring data of various agencies, build a data platform, open and share real-time data and historical data through specific channels, and provide comprehensive raw data for engineering design and scientific research units.

(2) Set up a major project to study marine bridges, establish a research platform for the development of marine bridge technology, study basic scour using wave and current forces, and improve technical standards and risk assessment mechanisms to design marine bridges.

4.2 Industry application level

(1) To provide disaster warning services for the construction and operation of marine bridge projects, add special marine bridge line forecast, and improve the forecast accuracy and real-time forecast of ocean conditions.

(2) Study wave propagation near shores, wind-wave-current coupling mechanism, wave-current protection measures and a joint probability model of wind-wave environmental factors and improve bridge design codes.

(3) Formulate design standards for tsunami resistance of bridges to provide support for engineering design.

(4) Study the scour mechanism of marine bridge foundations, improve the analysis methods of scour flow field characteristics and sediment movement of marine bridge foundations, and compile the scour criteria for bridge foundations under ocean environments.

4.3 Academic and technical level

(1) Propose a time domain and frequency domain method for calculating the wave force of large-scale and small-scale structures of marine bridges and improve the calculation accuracy and efficiency.

(2) Study substructures of marine bridge, dynamic response, dynamic reliability, and traffic safety of large marine bridge, and clarify the correlation between components.

(3) Carry out systematic tsunami wave–bridge interaction tests, and explore the mechanism of tsunami wave interaction, providing a reference for numerical simulations and theoretical analysis.

(4) Study the coupling effect between the scour of the marine bridge foundation and other factors considering the complexity and variability of the ocean environments.

(5) Further study local scour test simulation technology, underwater detection method, and anti-scour measures of bridge foundation under complex dynamic ocean environments to provide a basis for practical construction.

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