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REVIEW

Demands and challenges for construction of marine infrastructures in China

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ABSTRACT The oceans are crucial to human civilization. They provide core support for exploitation and utilization of marine space, resources, and energy. Thus, marine infrastructures are vital to a nation's economic sustainable development. To this end, this article first describes the main challenges in current ocean utilization, and then reviews the China's ocean engineering progress. As such, six major sectors are evaluated: 1) global climate change and marine environment, 2) comprehensive utilization of marine space, 3) marine transportation infrastructure interconnection, 4) ocean clean energy development and maricultural facilities, 5) ecological crisis and marine engineering countermeasures, and 6) marine infrastructure operation safety and maintenance. Finally, perspectives on future directions of ocean utilization and marine infrastructure construction in China are provided.

KEYWORDS marine infrastructures, ocean engineering, exploitation of marine resource, coastal development, emerging marine industries, technological challenges

1 Introduction

The oceans occupy 71% of the earth's surface, about 40% of the world's population lives within 100 kilometers of the coast, 70% of economic activities occur in coastal zones, and more than 80% of international trade is carried out by the seas. Meanwhile, the oceans contain abundant resources relating to biology, energy, minerals, medicine, water, space, etc. The demand for marine resources results in expansion of human activities, from coastal zones and continental shelf shallow waters to deep seas and polar regions. Furthermore, the oceans play an increasingly essential role in national political and economic strategies.

Marine infrastructures provide the key support for ocean space utilization, resources exploitation, and energy recovery. They, are crucial to the sustainable economic development and maritime defense security. Marine infrastructures mainly include seaports, artificial islands, coastal protection structures, oil & gas platforms, offshore wind power installations, mariculture pastures, cross-sea bridges, subsea tunnels, etc. [1]. These infrastructures are bulky, expensive, and operate in complex and harsh environments. Failures and instabilities of marine infrastructures may cause serious casualties, economic losses, and environmental pollution. Building maritime defense, advancing marine ecological civilization, and implementing the "Belt and Road Initiative", etc., have all created new demands for construction of marine infrastructures. The design, construction, and safe operation & maintenance of marine infrastructures are subjected to new technological challenges. To this end, this article assesses the urgent needs and technological challenges in construction of offshore infrastructures, with the aim of providing a perspective for future ocean utilization in engineering practices.

This article is organized as follows: Section 2 describes the challenges and recent progress made in marine utilization; Section 3 elaborates the urgent needs and development opportunities of marine infrastructure construction in terms of six key sectors. A summary then points out some future directions for technology innovation for marine development.

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2 Challenges and recent progress made in ocean utilization

Global climate change and marine-related human activities threaten the ecological environment and sustainable development of the oceans. Current ocean exploration systems are not perfect in terms of energy efficiency, environmental friendliness, and sustainability [2]. Ocean exploitation and utilization are facing brutal challenges from climate change and associated environmental issues including: 1) aggravating marine pollution and its associated secondary disasters; 2) misfunctioning of marine ecosystems; and 3) growing intensity and frequency of extreme sea conditions. For example, under the influence of global warming, the frequency of high-intensity storms is expected to rise, resulting an increased potential damage from extreme water levels such as storm surges. Sea level rise has been accelerating saltwater intrusion and water pollution in coastal areas and has increased the risk of coastal flooding and beach erosion [3]. Frequent occurrence of extreme sea conditions may lead to heavier environmental loads, damage of coastal infrastructures, and may threaten the safety of offshore engineering facilities [4]. Therefore, it is urgent to build an efficient, safe, stable, and environment-friendly marine development model and framework [5].

Offshore and coastal engineering facilities feature high-risk, high-investment, and high-tech characteristics and exhibit strong sensitivity and susceptibility to changes of ocean environments. First, the marine environment is highly complex, imposing a continuous, destructive, and uncertain load on man-made infrastructures. Secondly, marine infrastructures have various structural types for different water depths where strong fluid-solid coupling and interactions exist. Lastly, offshore construction and operation are highly risky and require high standards of safety design and disaster prevention. Specifically, wind, waves, currents, sea ice, etc., have a continuous coupling effect on offshore engineering facilities and require the high strength and durability of main structures. Besides, more unpredictable forces such as earthquakes, tsunamis, may also devastate some marine infrastructures. Marine infrastructures differ significantly in structural types for different water depths and sea conditions. It is difficult to uniform the safety assessment standards of various marine infrastructures, and there are high risks during construction and service operations. In addition, the global ocean governance system is not complete, and the development of ocean resources is treated as each country's own affair. Scientific development and ecological conservation concepts are still lacking in practice. Due to the lack of scientific and reasonable Marine Spatial Planning (MSP), the conflict between ocean resource development and ecological environment conservation, and that between short-term economic interests and long-term living environment, have not been well addressed. Present-day innovative capabilities of ocean technology and equipment are insufficient to cope with the harsh environment and the high-risk challenges of deep sea. It is urgent to raise the level of ocean awareness, innovate engineering technology, upgrade development concepts, develop new technologies, new equipment, and to boost the emerging ocean-related industries. It is imperative to boost scientific development and utilization of ocean resources and build fair and sustainable blue economic conditions [6] for 1) the harmonious coexistence of humanity and ecological resources, 2) the sustainable development of economic and ecological resources, and 3) the balancing of maritime infrastructure with spatial pattern and ecological resources. It is important to promote sustainable ocean development by switching from the “high-speed and large-scale” type to the “high-quality and high-benefit” type and to increase the marine “green GDP” [7].

At present, China has made remarkable achievements in ocean exploitation and utilization, especially in maritime transportation, marine equipment and facilities manufacturing, and the utilization of ocean renewable energy. For example, several cross-sea bridges (e.g., Hong Kong-Zhuhai-Macao Bridge, the Donghai Bridge) and subsea tunnels in coastal cities (e.g., Xiamen, Qingdao, and Shantou) have been put into service. In 2020, the “Striver” submersible dived 10909 meters, a record for China's manned deep diving, indicating that China has reached the world's leading level in the field of ultradeep manned diving [8]. Furthermore, up to 2020, China's total installed offshore wind power capacity ranked first in Asia and second in the world, and the annual installed capacity in 2020 reached 3.1 GW, ranking the first in the world [9]. In 2020, China's first independently developed 10 MW offshore wind turbine was connected to the national power grid at the Xinghua Bay Phase II offshore wind farm in Fuqing, Fujian. It is the largest offshore wind turbine in the Asia-Pacific region and the second largest in the world [10]. While breakthrough progress has been made in the design and construction of high-end offshore equipment, the fundamental science and technology that support the high-end equipment is still relatively weak, and need to be improved, especially for design and analysis software with independent intellectual property rights. The Statistical Bulletin of China's Marine Economy shows an overall upward trend of marine gross production value in the period from 2009 to 2020. However, the relative contributions from high-tech and value-added marine emerging industries are relatively low compared to those from traditional marine industries. Since emerging marine industries are based on the development of marine high-tech, they play a guiding role in the development of the marine economy for the whole country, especially in the Eastern and Southern coastal areas [11]. Therefore, increasing marine scientific and technological innovation and cultivating marine strategic emerging industries are the key directions of marine economic development in China.

3 Demands and opportunities in marine infrastructure construction

3.1 Marine infrastructure design standards under global climate change

Since 1970, global climate change has been rising. The average global temperature has increased by 1.1 °C compared to that before industrialization [12]. Global average sea level rise rate has increased from 1.4 mm per year from 1901 to 1990 to 3.2 mm per year from 1993 to 2019. China has exceptional sensitivity and vulnerability to the global warming and sea level rise. From 1951 to 2019, China's annual average temperature increased by 0.24 °C every 10 years, and sea level rising was at a rate of ~3.4 mm/year from 1980 to 2019, which is higher than the global average level in the same period.

Although it is still in debate, most studies have suggested that intensities and numbers of tropical cyclones are increasing [13,14]. Marine infrastructures thus may be exposed to a more destructive environment. Main design environmental parameters such as the wind, wave and currents are increasing. Traditional design standards are not safe enough under current climate conditions. On one hand, the design standards need to be upgraded, for example, from return period of 100 years to 1000 years or longer. On the other hand, more data from both observations and models are needed to enrich the parameter samples. Reanalyzed ocean meteorological and oceanographical data, such as the products by the European Medium-term Weather Forecast Center, the US Environmental Forecast Center, and the Japan Meteorological Agency are widely used in marine infrastructure design. However, these data usually have a low spatial resolution covering global oceans and may underestimate extreme wind speed or wave height [15,16]. Increased wind speeds give rise to enhanced global waves; for example, the extreme significant wave height growth rates of the Southern Ocean and the North Atlantic reached 1.0 cm per year and 0.8 cm per year, respectively [17,18]. New numerical schemes [19] and methods to estimate design values [20] are among the most active research topics in this area. In addition, sea ice and storm surges are also affected by climate change. Water levels and flow velocities are also key parameters for design of coastal infrastructures, and they are influenced by climate change and sea-level rise significantly [21].

Accompanied with the changing climate, return periods of extreme marine events have actually been shortening [22,23]. Extreme marine events have brought serious disasters to economies and lives. For example, marine hazards including storm surges, huge waves, and red tides in 2020 caused direct economic losses of 0.832 billion RMB, and 6 casualties (including missing) [24]. Design standards for coastal and marine infrastructures should be updated regularly in response to extreme events under climate change.

3.2 Comprehensive development and use of marine space

Coastal and marine infrastructures usually occupy a large amount of marine space. Meanwhile, different marine activities compete for limited marine space resources, resulting in serious problems [25]. With continuous expansion of marine development and utilization activities, conflicts between different marine activities, different stakeholders, development, and ecological conservation have become increasingly prominent. To achieve the integrated, effective, and sustainable development and use of marine space, it is necessary to plan and manage marine space, and fully consider the interactions among different activities, and the cumulative effects of these activities [26].

MSP is an internationally recognized transparent, adaptable, and sustainable marine planning and management tool, which can provide feasible solutions to various conflicts in marine development and utilization activities. Specifically, MSP is a comprehensive, holistic, adaptive, ecosystem-based, and transparent spatial planning process. It is based on a sound scientific basis, systematic analysis, and reasonable planning of current and future marine development use [27]. The purpose of MSP is to provide a platform for decision makers, stakeholders, and the public at all levels, based on management of multiple sustainable use, resolution of conflicts, and support for ecosystem-based marine management. The aim is to achieve balanced ecological, economic, and social goals [28].

The formulation and implementation of marine spatial planning is an adaptive cyclical process [29], which needs to be dynamically adjusted according to the implementation situation. Figure 1 shows the implementation process of marine spatial planning. In a specific implementation process, the following basic principles should be followed [27]: establishment of a management concept based on ecological priority, rational arrangement of multi-functional marine space and the utilization of multiple types of marine resources, enhancement of the public and stakeholders' participation in the implementation of

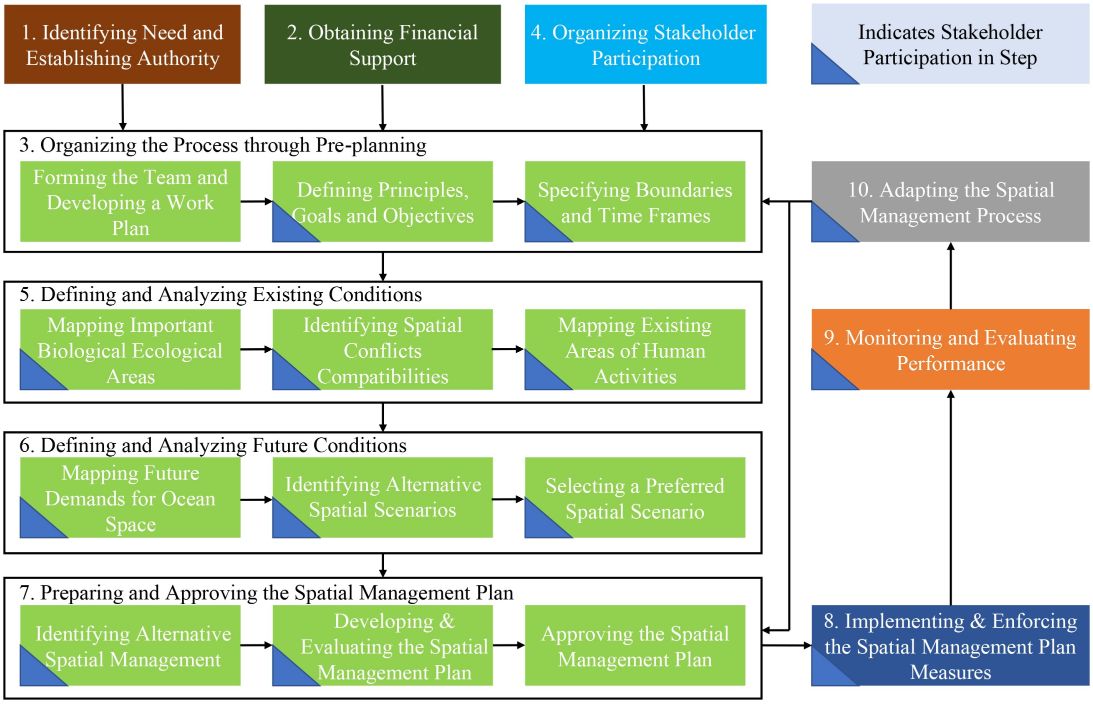

Fig. 1 Implementation process of marine spatial planning (reproduced from Ref. [28]).

supervision, establishment of cross-regional and cross-departmental coordination and management mechanisms. However, in the actual operation process, MSP still faces many challenges, such as major scientific and knowledge gaps, policy and legislative constraints, institutional fragmentation, environmental security and sustainable development, and the needs and expectations of stakeholder's coordination difficulties. [29]. For this reason, in the future use of MSP, the following should be given attention [27]: improvement of the ability to adapt to and recover from global climate change and the deterioration of the marine environment; adaptation of measures to local conditions; ecosystem conservation, renovation and restoration for different sea areas; strengthening of environmental observation and infrastructure construction of oceans, coasts and islands; promotion of marine scientific and technological innovation; improvement of ocean development, utilization and conservation capabilities.

Offshore oil and gas projects are taken as examples to further illustrate the importance of MSP and its comprehensive use in marine space. In the design and construction process of offshore oil and gas development facilities, it is necessary to formulate comprehensive indicators that consider factors such as safety, costs, and environmental conservation, and to comprehensively consider the process of construction, transportation & installation, as well as the decommissioning plan and its impact on the ecological environment. Projects are expected to achieve a balance of ecosystems, costs, and social benefits. In the early 20th century, the United States (US) began to exploit offshore oil, and the first abandoned oil wells appeared in the 1940s. People began to pay attention to abandoned oil wells after the 1980s. As of November 2020, more than 31000 offshore oil wells in the US alone have been permanently abandoned or suspended. In 2020, more than 600 offshore platforms worldwide are facing decommissioning; by 2040, there will be more than 2000 decommissioned offshore platforms worldwide. It will cost more than US$200 billion in the next 30 years to dismantle all abandoned offshore platforms worldwide [30]. However, research on the ecosystem around existing offshore facilities shows that compared with the surrounding natural environment, the number of fishes around the ocean platform is larger and the population is richer [31]. In other words, ocean platforms can play the role of features such as coral reefs in long-term operation, and the direct dismantling of ocean structures may cause new negative effects. For this reason, the former U.S. Marine Minerals Administration first proposed the concept of “Rigs-to-Reefs” (RTR), the purpose of which is to transform offshore platforms into artificial reefs to maintain the local existing marine ecosystem. As of 2018, more than 500 abandoned platforms in the Gulf of Mexico have been transformed into artificial reefs. Treatments to the local environment include maintaining, overthrowing, partially demolition and transferring of the current reef environment [32]. Through the transformation and utilization of abandoned ocean platforms, biological productivity has been increased, the conservation and restoration of deep-sea creatures have been promoted, and the cost of decommissioning and dismantling offshore oil and gas facilities has been greatly reduced.

3.3 Interconnection of maritime transportation infrastructures

Deep-water ports, islands and reefs, and cross-sea bridges and tunnels are key infrastructures for maritime transportation, which play a pivotal role in social and economic development [33,34]. The construction of maritime transport infrastructure is facing new technical challenges with more new requirements appearing such as promotion of the joint construction of the “21st Century Maritime Silk Road”.

The construction of maritime transportation infrastructure is one of the priorities of the Maritime Silk Road. However, the sea conditions along the Maritime Silk Road differ significantly from those of China’s offshore waters [35–37]. The main challenges lie in 1) exposure of construction sites to fully open seas with heavy design load, short construction window period, and high cost of operation and maintenance; 2) complexity of topography and geomorphology, with weak foundation carrying capacities and intense seabed erosion and depositions; 3) fragility of the ecological environment. The construction of the port project on the southwest coast of Indonesia along the Maritime Silk Road provides an example [38]. Offshore construction is subjected to long waves with periods ranging from 10 to 20 s, and the wave period and wave height have abrupt changes. Within 24 hours, wave periods can change from 10 to 20 s, and the wave height can change from 1 to 3.5 m. As a result, traditional construction techniques and equipment cannot be applied.

In response to the urgent needs and technological challenges mentioned above, new offshore construction technology, equipment, structure, and the corresponding engineering technology standard system are necessary for large-scale port construction in medium and long-period wave areas. In view of the special dynamic environment and evolution law of remote islands and reefs, it is necessary to carry out in-depth research on the long-term stability of islands and reefs as well as conservation technologies [39].

For the construction of cross-sea bridges and tunnels under complex and severe sea conditions, it is important to incorporate fundamental theories and design methods from multiple disciplines, including marine dynamic environment, marine geological exploration, marine engineering design and construction, and new marine engineering materials. In the meantime, it is indispensable to carry out exploration and research on new cross-sea passages such as large floating bridges and floating tunnels [40,41].

3.4 Ocean clean energy and mariculture engineering facilities

To fulfill the target of reaching peak carbons emissions by 2030 and carbon neutrality by 2060 in China, substantial efforts have been made in the development of marine renewable energy. Due to the advance of marine technology and increasing market demand, marine emerging industries are showing a leap-forward evolution [42]. However, the design of equipment for emerging industries remains challenging because of the complex marine environmental conditions and limitations in design theories. Offshore wind power and offshore aquaculture projects are the two main growth sectors of marine emerging industries.

The Chinese national carbon peak and carbon neutral long-term plans bring new opportunities for the development of the offshore wind power industry. However, the cost of offshore wind power is much higher than that of onshore wind power [43]. According to data from Bloomberg NEF, the cost of electricity per kilowatt-hour offshore in wind levels of major countries or regions in the world will reduce significantly before 2026 (Fig. 2). Reducing the design, construction, operation, and maintenance costs of offshore wind power under the premise of ensuring structural safety is the key to improving the competitiveness of offshore wind power. Large-scale implementation and Artificial Intelligence (AI) have become future development directions of offshore wind power. In the next 5 to 10 years, the single-unit capacity of offshore wind power will reach 15–20 MW. A higher hub, heavier superstructure, and larger wind turbine load require higher technical standards for offshore wind power support structures [44]. There will be further challenges to traditional design concepts. In addition, with the continuous increase of the design pile diameter of offshore wind power foundations, the traditional theory of pile-soil interaction is not applicable. There is still a lack of relevant theories for the behavior of foundation and soil degradation under long-term cyclic loading [45]. For this reason, the integrated design method of integrated foundation-support structure-upper fan is a key technology to reduce structural redundancy and ensure structural safety. On the other hand, offshore wind energy development is moving from coastal shallow water to offshore deep water. When the water depth exceeds 50 m, floating wind power technology will have better engineering economics. Norway, Japan, and other countries have already carried out projects regarding the demonstration and application of floating offshore wind power projects, but floating wind power technology in China is still at the infant stage. The operating environment of floating offshore wind power is more complex and harsher than the coastal areas. Under the action of environmental loads such as wind, waves and currents, there is a strong coupling between floating body movement, mooring deformation, tower elastic deformation and impeller rotation. Coupling analysis is still challenging for the design of offshore floating wind power [46,47]. With the aim to provide technical support for the

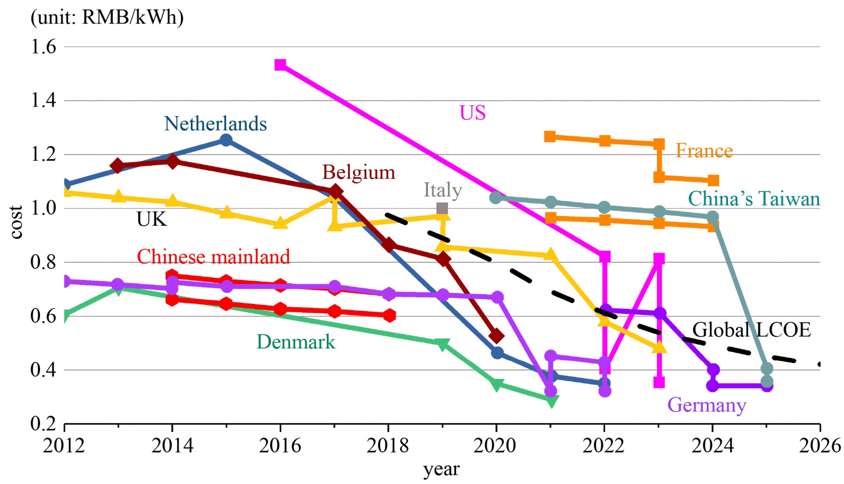

Fig. 2 Standardized cost analysis of global offshore wind levels (data source: Bloomberg NEF. Note that Chinese mainland and France include two lines, which represent two different estimates of cost officially released by each government).

design, construction and safe operation of wind power, there is a critical need to develop multi-physics, multi-floating bodies, and multi-scale coupling analysis and design methods for offshore floating wind power.

Under the influence of overfishing, environmental pollution, and decline in fishery resources, the world's fisheries are changing from a development model based on marine fishing to mariculture [48]. Mariculture engineering facilities are the basic guarantee for the development of the marine fishing industry, mainly including marine pasture construction and mariculture platform equipment. Traditional marine pasture construction and management are based on production experience, lacking systematic and scientific guidance. Modern marine pasture construction has significant multi-disciplinary characteristics, requiring comprehensive consideration of ecology and oceanography. It requires characteristics of standardization, information system, intelligence, systemization, etc., and relies on advanced technical support and management methods such as ocean ranch online monitoring system [49]. At present, the site selection and planning technology of marine ranches is not mature. It is necessary to comprehensively consider the suitability and carrying capacity of the ecological environment, to develop large-scale marine ranching platforms, and to improve the habitat creation mode and behavior control technology for biological resources. Compared to nearshore mariculture, deep-distance sea areas have high-water exchange rate and low pollutant content and have less effect on other marine activities such as shipping. For this reason, floating marine mariculture platform equipment is developing deep sea capability and showing a trend of large-scale application of AI. Figure 3 shows the typical deep-sea mariculture platform facilities designed and built in China and elsewhere. Under deep sea conditions, larger water depths with stronger currents and waves bring new technical challenges to floating mariculture platforms [50,51]. Therefore, it is necessary to develop new deep-sea mariculture equipment that adapts to complex sea conditions. At present, scholars at global level have made some progress in the research of the hydrodynamic characteristics of large-scale breeding platforms [52,53] and breeding ships [54]. However, the equipment's anti-wind and wave performance and the research on structural safety theory still have shortcomings. The technologies of automatic bait throwing, pollutant discharge, and catching are still not perfect. The anchoring and positioning control technology, electric propulsion and drive control technology are in urgent need of breakthroughs in terms of informatization, digitization, and intelligence. In addition, the deep-sea mariculture equipment is far from the shore and the energy supply is difficult. A new energy supply support system for the deep-sea mariculture platform has not been fully established [55]. The potential impact of deep-sea mariculture platforms on the ecological environment remains unclear. The competitive use of oceans and natural resources also needs in-depth study [56].

As the development of emerging marine industries continues to boom, their integration exhibits promising prospects. In the future, the combination of offshore wind power and offshore mariculture projects can share marine space resources for joint construction, operation, and maintenance. Offshore wind power can provide nearby power supply for offshore mariculture facilities, reducing the development and operation and maintenance costs. This will benefit the intelligent development of offshore wind power and marine mariculture [57]. Through the integrated development of offshore wind power projects and offshore mariculture projects, the intensive and efficient use of marine space resources can be realized, a new integrated marine development model can be formed, and other emerging marine industries will be promoted to explore the path of combined and integrated development.

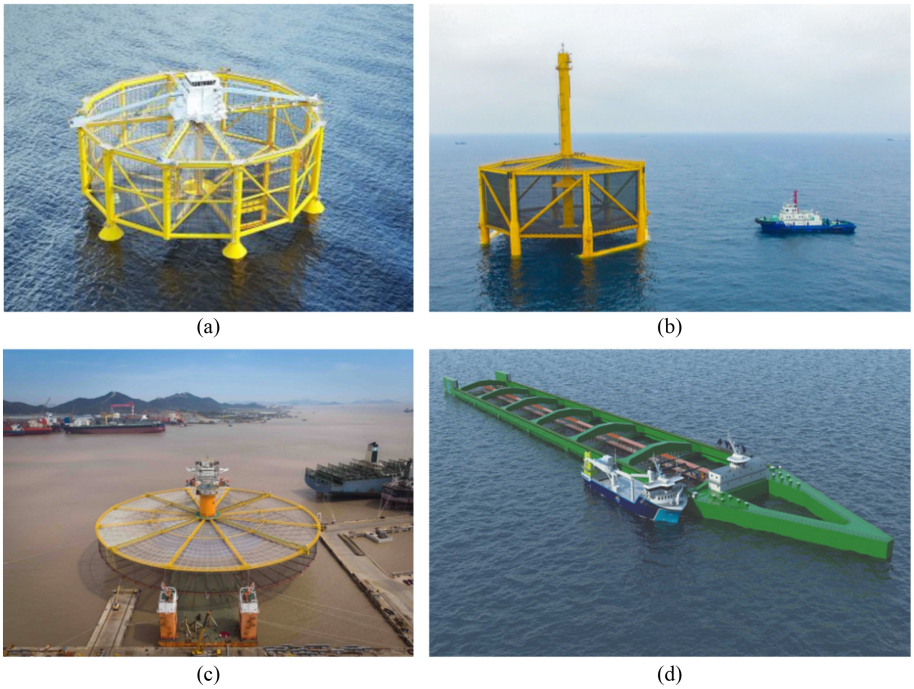

Fig. 3 Typical deep-sea mariculture platform facilities: (a) deep-sea fishery Ocean Farm 1 [58]; (b) deep Blue No. 1 [59]; (c) semisubmersible deep-sea fishery [60]; (d) deepwater mariculture ship Havfarm [61].

3.5 Marine ecological crisis and engineering countermeasures

In the early stage of marine development, people have tended to pay more attention to the short-term economic profits, while ignoring the values and services of the marine ecosystem in the long term. Uncontrolled development and resource utilization depleted marine biological resources, exacerbated marine pollution, and degraded the marine ecological functions.

Coastal and nearshore regions are the areas affected the most by human activities. Taking coastal wetlands as an example, types of these in China include salt marshes, mangrove swamps, coral reefs, seagrass beds, etc. With large-scale land reclamation and other coastal engineering activities, the total area of coastal wetlands has been declining year by year. The areas of temperate coastal wetlands and mangroves in China have decreased considerably since the 1960s [62]. In response to this issue, over the past five years, the Chinese government has renovated and restored 1200 km of coastlines and 23000 ha of coastal wetlands [63] by implementing various coastal ecology conservation plans such as the "Blue Bay" action. It is necessary for the government to make continuous progress in promoting coastal conservation and restoration projects and ensuring their sustainable development and utilization of coastal resources in the coming years.

Technologically, it remains challenging to strike a balance between marine utilization and environmental conservation. Engineering measures can be divided into two levels based on the project objectives and the prerequisites of marine environmental protection. The first level applies to the process of project planning and construction. The potential marine environmental impact is considered and precautions are taken during the construction. At this level, projects still focus on resource development and utilization, such as construction of ports or seawalls. Therefore, there remain some impacts on the surrounding ecological environment. The second level intends to promote the restoration of marine ecosystems by improving water quality and upgrading the functionality of the ecological services, such as providing habitats for local marine lives. The engineering measures adopted at this second level are to control, promote, and accelerate this process based on the full understanding of the local environment. They have been successfully applied to the coastal restoration and conservation projects such as beach maintenance, coastal salt marshes and mangrove restoration. While the two levels of engineering measures have different goals and utilize different methods, they are both indispensable for ocean development and conservation. Taking the Bohai Bay Shengli Oilfield Permeable Road Island Project and Rizhao China's first "Port to Beach" project as examples, the two levels of marine development and conservation projects are explained in detail.

The shallow water area of the Yellow River Delta in Bohai Bay (water depth < 5 m) is rich in oil and gas resources, but traditional offshore oil production platforms are not suitable there due to the unstable foundation. A novel "offshore oil extracted on land" mode was proposed and applied: artificial islands were built at the sites of oil wells and connected with the mainland through a sea-road (Fig. 4(a)). Considering that extreme sea states such as storm surges and high waves occur frequently at the Yellow River Delta, the sea-road must be stable under the attack of destructive oceanic forces. However, a solid sea road extending several kilometers to the shallow seas would have had a considerable impact on the surrounding ocean dynamics and environment. Considering the above contradictions, in the construction of the road island project in the "Qingdong 5 block", the adverse impact of the entrance to the sea on the marine ecological environment was considered in advance. A new type of sea-road structure with permeable piles (see Fig. 4(b)) was invented and applied to ensure the water exchange and environmental friendliness. To ensure the structural safety of the permeable sea-road, dynamic characteristics of the structure were tested under the influence of waves. The sea-road has experienced several severe storms and sea ice since being built and remains stable and safe. The new type of design minimized the environmental impacts from the initial engineering construction activity, and at the same time it saved about 1/3 of the project investment. This project is considered as a success in the balance between safety, environmental conservation and economy.

Rizhao Port in Shandong Province is a significant seaport for transportation of coal from the west to the east and from the north to the south of China. After years of development, the seaport has become an essential part of Rizhao city. However, the coal operation area of the port is close to local tourist attractions and residential areas. The urban ecological shoreline has been disrupted, damaging the integrity of the coastal ecology. In addition, the port seriously affects the environmental sanitation of the surrounding cities. In order to effectively solve the increasing interference between the development of the port and that of the city, in June 2016, with the support of "Blue Bay", Hailong Bay of Rizhao began to implement China's first "Port to Beach" project. Two 100000-ton coal terminals and coal operation areas in the east of Shijiu Port Area were relocated (Fig. 5(a)). Artificial beaches and water sports activity areas at the site of the original wharf were constructed to achieve the goal of "return the natural sea to the people". During the implementation of the project, with the help of numerical simulations and physical model tests on the local marine dynamic environment, long curved dikes and sand barriers were designed and constructed to protect the ecological conservation and coastal tourism functions of the artificial beach under the action of marine dynamics. In addition, dredged sand from the harbor channels was used to fill the beach. Equipment such as pollution barriers were deployed to protect the marine environment. The restoration project formed 1.8 km of ecological coastline and 450000 m^2 of artificial beach (Fig. 5(b)) and survived the attack of the Super Typhoon Lekima in 2019. The installations remain stable and functioning so far. The successful implementation of this project is a demonstration of optimization of the spatial layout of the port and the city. It has set up a prosperous example of promoting the transformation and upgrading of a used port.

3.6 Safe operation and maintenance of marine infrastructure

During operation, various offshore infrastructures are subjected to complex marine environmental effects such as waves, ocean currents, storm surges, scrubbing, corrosion, etc. Structural safety thus faces severe tests and structural failure can cause severe casualties, economic loss, and ecological destruction. To ensure the safety of offshore infrastructure, it is necessary to monitor the operating status of the structure, identify potential damage and performance degradation, propose maintenance and conservation plans, and predict remaining service life (Fig. 6). In an engineering project, the monitoring, evaluation, maintenance, and reinforcement of the entire life cycle of offshore infrastructure need to involve multidisciplinary concepts from mechanics, materials science, control theory, and computer science. In particular, , the engineering environmental conditions

(a)

(b)

Fig. 4 "Offshore oil and land production" road island project in Qingdong 5 block of Shengli Oilfield in Bohai Bay (photo source: Sinopec Petroleum Engineering Design Co., Ltd.). (a) Road island project; (b) open-air sea entry way.

Fig. 5 Hailong Bay "Port to Beach" Project in Rizhao City, Shandong Province, China. (a) Before the project remediation; (b) after the project remediation.

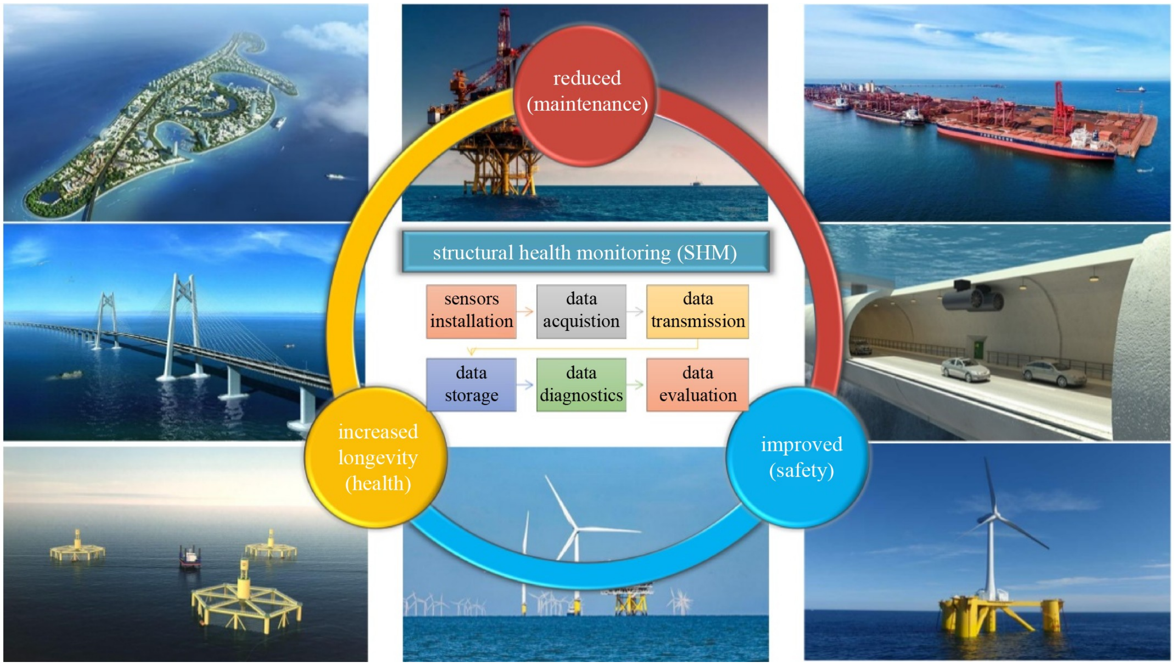

Fig. 6 Marine infrastructure health monitoring.

become more complicated in non-coastal waters and different standards are necessary for safe operation and maintenance of structures.

The health monitoring and damage diagnosis of offshore infrastructure require multiple modules including data collection, data transmission, and data evaluation [64]. The successful implementation of health monitoring requires reliable sensor data collection, reasonable health assessment algorithms and mathematical models [65]. Although the health monitoring methods of offshore infrastructures have been developing for many years, due to the complex nature of infrastructure structures and the harshness of the offshore environment the current systems are not yet mature. The following technical challenges exist. 1) Most existing methods require accurate finite element models (FEM), which is difficult to apply in ocean structures. Thus, to avoid continuous model updating and to reduce model errors, it is necessary to develop new models that have less dependence on the accuracy of finite element models [66]. 2) The structure of offshore infrastructures is usually complex and large, so it is necessary to effectively configure limited sensor resources, to optimize the location of sensors, and to build a low-cost and efficient structural health monitoring data collection system. In addition, the installation of sensors under water or mud is challenging and costly. Low measurement accuracy results from the lack of key underwater or mud information. Therefore, using limited sensor data above the water surface to derive the vibration information of the entire structure is a promising trend for offshore infrastructure health monitoring [67]. 3) The safety performance evaluation and life prediction of traditional structures require a quantitative determination of the damage location and extent. However, for offshore infrastructure, it is difficult to assess the entire structure due to dynamic constraint boundaries, nonlinear effects, and randomness of environmental loads.

In order to address these issues, we can resort to the modern technologies as briefly described below. The rapid development and wide application of computer technology and AI has ushered in new opportunities. The development of innovative technologies, such as smart sensors and smart algorithms, will provide more solutions to the challenges of health monitoring of marine infrastructure. AI technologies such as genetic algorithms, neural networks, and machine learning have the advantages of autonomous learning, model adaptation, and robustness, which can effectively overcome the shortcomings of traditional algorithms. The successful application of network plus technologies, such as engineering information models, cloud computing, Internet of Things, and big data, can remotely monitor the status of the structure in real time. This provides a new direction for the health monitoring system [68]. Digital Twin technology [69] can comprehensively use structural response history and model correction technology to predict the performance and possible future failures of a structure, and to conduct health monitoring and safety maintenance cost-effectively and efficiently throughout the life cycle.

Alternatively, interdisciplinary methods can be used to address these issues. For example, oil & gas pipeline FEM modeling based on beam theory in Ref. [70] is comparable with that for bridge beam structures [66]. In Ref. [70], the cutting-edge methods of prognosis using real-time data have been developed. Multiple issues and obstacles make the monitoring of subsea pipelines a challenging task. Problems may occur throughout the life of the pipeline because the long-term environment of a pipeline is highly complex and full of uncertainties. Taking the subsea pipelines as an example, the US DOT provides a broad classification of the major causes of failure in subsea oil and gas pipelines. They can be grouped into five categories: mechanical, operational, corrosion, natural hazards and the third party. The focus in this review is on the operational aspect as follows.

There are two ways to minimize damage due to the consequences of subsea pipeline failure, which are risk-based inspections and continually monitoring critical part of pipelines for potential sources of failure. For inspection, methods are not detailed here, and the reader is referred to the cited literature [65] for details. Based on the authors' experiences, the most important inspection method is magnetic flux leakage (MFL) pipeline inspection as detailed in Ref. [71].

Working structures are more commonly studied based on ambient operational loading alone, referred to as operational modal analysis (OMA) or output-only system identification. The use of OMA can diminish noise and provide real information without "false" data [70]. The research field concerning the OMA of civil structures has also experienced significant development [71].

The methods in Ref. [70] creatively integrate the concepts of Response Surface Method (RSM), OMA and FEM to avoid issues as mentioned earlier in this Section. In general, the analysis of nonlinear risers in the time domain is similar to that for beam-type bridges [66] due to use of the same beam theory. Direct calculation of probability of failure from the RSM in conjunction with FEM is very efficient.

In summary, new technologies from different disciplines have made it possible to obtain real-time data monitoring for marine structures. If the mechanical relationship between structural safety performance indicators and measured monitoring data can be established, the structural integrity evaluation objective function can be formed, and big-data processing and other methods can be integrated (e.g., combination of FEM, OMA, and RSM, etc.). Modern analysis technologies such as AI can also empower the transition from "inspection and evaluation" to "monitoring and evaluation" and provide new ideas for the safety performance evaluation of offshore infrastructures. The transformation from responsive maintenance to preventive maintenance to predictive maintenance is very efficient indeed and can be expected expanded in the future. To this end, establishing and forming new modes of safe operation and maintenance of offshore infrastructure can become a reality.

4 Conclusions and perspective

This article identifies and evaluates the demands and challenges for marine infrastructure construction in China from perspectives of sustainable exploitation of marine resources, global cooperation networks, development of emerging marine industries, etc. Motivations and inspirations for future ocean development, exploitation, and conservation are put forward. In response to the urgent demands of ocean development and utilization and environmental conservation, some important future perspectives include but are not limited to the following:

Planning the optimal use of marine space and resources, is crucial to marine sustainability and is essential to resolving the conflicts between marine utilization and protection. To recover from and deal with global climate change, there is a need for optimizing and harmonizing Marine Spatial Planning processes at both global and regional levels. Smart spatial planning concepts are capable of combining multiple-use objectives with effective resource and nature conservation needs. Noting the scarcity of valuable ocean space, especially competition in near shore areas, the concept of multiple use in a single location needs to be further explored. Examples of this can include use of multi-purposing windfarms for concurrent seaweed production, aquaculture, and tidal energy.

China has made great achievements for the development of marine clean energy during the past decades, such as offshore wind power and floating photovoltaics. While the potential of nearshore wind farms is now being actively explored, the development of offshore wind power can start to grow rapidly. The hybrid energy system combining offshore wind turbines, floating photovoltaics and offshore aquaculture has promising market potential. In addition, the demonstration of offshore photovoltaic projects is about to carried out nationwide and is expected to set a good example to the rest of the world. In view of the continuing emergence of new offshore structures and new modes of energy exploitation, the informatization and digitalization of the equipment operation and maintenance will grow rapidly as well.

In terms of the engineering construction projects, first, it is necessary to quantify the dynamics, uncertainties, and multifunctionality of current infrastructure against the current guidelines and standards. Then, infrastructure project evaluation guidelines and technical standards for planning, design, and construction need to be revised. Revised guidelines and standards would make it possible for practitioners to confidently explain the effects and benefits of the proposed infrastructure, thus making it more likely to be approved and funded. Finally, we encourage broader collaboration between stakeholders and designers, creating partnerships that may yield important advances in ocean management. This is particularly important because different local management goals necessitate different designs that should consider the ecosystem processes they influence.

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