Analysis on the current situation and key problems of artificial island development in China

J Zheng¹,², C H Pan¹,²,³, W W Yao¹,², J B Mu¹,² and X Zhao¹,²

¹Zhejiang Institute of Hydraulics and Estuary, Hangzhou 310020, China
²Zhejiang Provincial Key Laboratory of Estuary and Coast, Hangzhou 310020, China
³panch@zjwater.gov.cn

Abstract. The artificial island is an important way to develop and utilize the resources of sea areas, islands, and mudflats. The land formed by it has increased artificial shoreline. It is the way of reclamation with advanced concepts in the world and has been paid more and more attention. Based on the investigation and analysis of the current situation of artificial island development in China, the key problems of artificial island development were analyzed. The exploitation of artificial islands can be divided into 4 categories: industrial production land, transportation place, tourism and entertainment place, and urban construction land of comprehensive utilization. The key issues in the development of artificial islands include the fundamental data, site selection, plane shape, foundation treatment, seawall design, ecological environmental impact, full consideration of extreme events and abundant funds. Site selection is the core of the key problems of artificial island development, which is mainly restricted by functional requirements and also influenced by natural conditions.

1. Introduction
China's coastal areas have developed economies, dense population, and scarce land. And the exploitation of the mudflat resources by means of reclamation alleviates the contradiction between social and economic development and the shortage of land resources[1]. The traditional development way of the mudflat resources is an along-shore development one. This type of reclamation has relatively low investment and relatively little backfill. It is the main way to develop and utilize the mudflats in China at present, but it has a relatively great impact on the ecological environment. The artificial island is another important way to develop and utilize the resources of sea areas, islands, and mudflats, which can not only extend the artificial shoreline of newly formed land, but also retain the natural shoreline. It is the way of reclamation with advanced concepts in the world and has been paid more and more attention [2].

The artificial island is an artificially constructed island in the water. The artificial island in the broad sense includes various aquatic structures that can provide a certain site for human beings, such as pile or floating hydraulic structures. In the narrow sense, the artificial island refers to the land built in the sea in an artificial way. In this paper, the artificial island is defined as a narrow sense of an artificial island, and there are two ways to construct the artificial island. One is to build the artificial island completely independently, while the other is to expand the existing one or combine more small islands to form a certain amount of land. For the latter, this paper considers that the land area should be expanded by at least one time to be called an artificial island.
This paper investigates the artificial islands already built, under construction and to be built in China, and systematically analyzes the key problems and development experiences of the artificial island construction, so as to provide a reference for the future development of the artificial island.

2. The current situation of artificial island development in China

In the 1950s, in order to exploit oil and gas resources on the seafloor, foreign countries began to build artificial islands by industrialization and modernization on large-scale. With the rapid development of the society and the economy, the progress of reclamation construction technology and the in-depth development and utilization of marine resources by human beings, the artificial island development mode of land reclamation has gradually become the mainstream. The large-scale artificial islands around the world are mainly concentrated in East and Southeast Asia, the Persian Gulf, Europe, and the United States.

Since the founding of the People's Republic of China, China has experienced four major climaxes of reclamation [1, 3]. In the past, most of the reclamation methods used to extend the coast to the sea, truncate and straighten the bay for reclamation. Although it has the advantages of low cost, convenient construction and transportation, it has brought some problems, such as the reduction of the natural coastline, the disappearance of the bay, the destruction of the natural landscape and the ecological environment of the coastal waters to some extent. Therefore, the State Oceanic Administration issued a document of "several opinions on improving the plane design of land reclamation engineering" in 2008, which put forward three basic principles of improving the plane design of land reclamation engineering, namely, protecting the natural coastline, extending the artificial coastline and improving the landscape effect; and proposed three main ways of plane design of land reclamation engineering, including artificial island reclamation and multi-jetty reclamation and block group reclamation. Among them, the artificial island reclamation can not only extend the artificial shoreline of newly formed land to the maximum, but also not occupy the natural shoreline. In areas with suitable sea conditions, the artificial island reclamation should be the first choice. Since then, the domestic artificial island reclamation has developed rapidly.

The research on the construction of the artificial island in China started in the 1980s [4]. In August 1988, the artificial island of Yongshu Reef in Nansha was built, which was used to set up an ocean observation station, covering an area of more than 8000 m². In order to develop oil resources in the shallow sea of Bohai Bay, Zhangjiahe artificial island was built in 1992 in the Didao oilfield of Bohai Bay in China [5]. In 1995, the artificial island of Macao International Airport was built [6], which was designed and constructed by China, marking that China's artificial island research and design had entered a new stage. Since the beginning of the new century, there had been a boom in the construction of the offshore artificial island in China's coastal areas. The construction of the artificial island in Yangkou Port, Nantong, Jiangsu in 2008 [7], marked the successful construction of China's first no cover off-sea artificial island in China. In February 2010, the construction of the first ecological artificial island in Zhangzhou, China, Shuangyu artificial island was started [8], and the reclamation project was basically completed in August 2014. In January 2011, China’s largest offshore artificial island group—Longkou artificial island [9] officially was started in Longkou City, Shandong Province. In October 2018, the Hong Kong-Zhuhai-Macao Bridge combined with the bridge, artificial island and tunnel was completed and opened to traffic [10]. The artificial island in the sea has increasingly become an important means for China to develop marine resources. In recent years, due to the serious ecological and environmental problems of reclamation projects, the state strictly controlled the reclamation, and the development of artificial islands had entered a low tide.

According to incomplete statistics, the constructed, under construction and proposed artificial islands in coastal provinces are shown in Table 1. The table also lists the area, offshore distance, island site water depth and status of the artificial islands. According to their development function and use orientation, this article divides artificial islands into 4 categories: (1) industrial production land, such as the construction of offshore energy bases and offshore oil and gas field exploitation platforms (Table 1 is not included). (2) Transportation place, such as the construction of maritime airports, ports,
bridges, and tunnels, etc. (3) Tourism and entertainment place, such as the construction of seaside parks, green spaces, yacht bases, fishing grounds, and artificial seashores, etc. (4) Urban construction land of comprehensive utilization. From the perspective of use function, most of them are transportation places, urban construction lands of comprehensive utilization, and tourism and entertainment places. From the perspective of regional distribution, Hainan Province has the largest number of artificial islands, with as many as 12 under construction or constructed artificial islands (excluding artificial islands in Sansha sea area), except for the proposed Sanya New Airport as a transportation place, the rest are tourism and entertainment places, determined by the unique natural environment of Hainan. Both Yangshan Port and Daxiao Yushan artificial islands in Zhejiang Province are island expansion types, which are related to the natural conditions of many islands in Zhejiang Province.

3. Key problems and experiences of artificial island development

Compared with conventional coastal engineering, the natural condition of the development of an artificial island is more complex and more difficult. Therefore, a lot of research works have been carried out on the development of artificial islands at home and abroad, mainly including the natural condition and site selection of artificial island [11], plane shape and general layout [8, 12-14], design standard [8, 13], water and sediment impact [9, 14-16], disaster prevention and mitigation and engineering safety [17-20], land formation and foundation treatment [10, 21], revetment structure [7, 8, 13], construction technology [22], ecological environment impact and protection [3, 23-24], development benefit [1], etc. The key problems and experiences of artificial island development are analyzed as follows.

3.1. Basic data are the basis for the early research of artificial islands

The basic data mainly include factors such as tide and current, wave, typhoon surge, sediment, topography, geological condition, water quality, ecological environment, material source, and meteorology, etc., which have important influences on the use function, location, plane layout and shape, engineering safety, and construction cost, etc. of the artificial island and are the basis of artificial island development.

Compared with conventional coastal engineering, it is more difficult to obtain the basic data of the construction of the artificial island. Firstly, there is a lack of data accumulation in the open sea, which requires a lot of field observation and experimental research. Secondly, the construction standard of the artificial island is generally higher, and the requirements for the basic data are higher. The influence factors of artificial island construction are more complicated and more factors need to be considered. Therefore, a large number of basic surveys and special studies are often needed for artificial island construction projects to obtain detailed and accurate basic information.

3.2. Site selection and plane shape are the key factors to the early study of the artificial island

3.2.1. Site selection. Artificial island construction generally has a specific function, and its location is mainly limited by its functional requirement. For example, the airport artificial island is generally located near the city, which is mainly affected by the air route and surrounding restrictions; the port artificial island mainly considers the economic hinterland of the nearby land and the cargo transfer function; the auxiliary artificial island of the cross-sea channel is mainly determined according to the layout of the whole channel; the artificial island used for the comprehensive development and construction of the urban mainly considers its urban function, landscape, and environment; the tourism and entertainment artificial island mainly considers the regional tourism environment, convenient transportation, and a number of visitors, etc.
Table 1. Construction of artificial islands in China.

| No. | Name of artificial island                     | Use functiona | Region         | Offshore distance /km | Island site water depth /m | Artificial island area /ha | Status          |
|-----|-----------------------------------------------|---------------|----------------|-----------------------|----------------------------|---------------------------|-----------------|
| 1   | Macau International Airport                   | 2             | Macau          | 0.3                   | 2~4                        | 117                       | built           |
| 2   | Hong Kong-Zhuhai-Macao Bridge                 | 2             | Hong Kong, Zhuhai, Macao | 11~14                | 7~9                        | 330                       | built           |
| 3   | Hong Kong International Airport              | 2             | Hong Kong      | 0.3                   | /                          | 936                       | built           |
| 4   | Dalian Jinzhou Bay Airport                   | 2             | Liaoning       | 4.5                   | 5~8                        | 2100                      | Under Construction |
| 5   | Caofeidian                                    | 4             | Hebei          | 0.9                   | <5                        | 20600                     | built           |
| 6   | Yangkou Port Sun                              | 1             | Jiangsu        | 13                    | 12                         | 300                       | built           |
| 7   | Ruyi island                                   | 3             | Hainan         | 4.4                   | <4                        | 715                       | built           |
| 8   | Nanhai Pearl                                  | 3             | Hainan         | 2                     | 7                          | 265                       | built           |
| 9   | Haikou Bay Lighthouse Hotel                   | 3             | Hainan         | 0.6                   | <6                        | 35.4                      | built           |
| 10  | Haikou Millennium Hotel                       | 3             | Hainan         | 0.3                   | <5                        | 11.7                      | Basically completed |
| 11  | East Suburb Yelin Bay Marine Leisure and Holiday Center | 3             | Hainan         | 0.3                   | /                          | 25.5                      | built           |
| 12  | Wenchang Nanhai Resort                        | 3             | Hainan         | 0.2                   | /                          | 26.4                      | built           |
| 13  | Tanmen Fishing Port Reclamation               | 3             | Hainan         | 0.3                   | /                          | 48.9                      | Basically completed |
| 14  | Wanning Riyue Bay                             | 3             | Hainan         | 0.3                   | 2~7                        | 97                        | built           |
| 15  | Phoenix                                       | 3             | Hainan         | 0.4                   | 7                          | 83.9                      | built           |
| 16  | Yazhou Central Fishing Port                   | 3             | Hainan         | 0.5                   | 5~10                       | 49.6                      | Basically completed |
| 17  | Hailua                                        | 3             | Hainan         | 0.6                   | 1~8                        | 783                       | Basically completed |
| 18  | Sanya New Airport                             | 2             | Hainan         | 3.5                   | 22                         | 2398.7                    | proposed        |
| 19  | Longkou                                       | 4             | Sandong        | 0.6                   | 7                          | 3523                      | Basically completed |
| 20  | Haiyanglianli                                 | 3             | Sandong        | 1.5                   | 2~5                        | 183.9                     | built           |
| 21  | Zhaoyuan                                      | 4             | Sandong        | 0.6                   | 7                          | 1215.3                    | proposed        |
| 22  | Penglai                                       | 4             | Sandong        | 0.3                   | /                          | 502.6                     | Basically completed |
| 23  | Yantai Development Zone                       | 4             | Sandong        | /                     | /                          | 620                       | proposed        |
| 24  | Shuangyu                                      | 4             | Fujian         | 0.6                   | <5                         | 221.7                     | built           |
| 25  | Yangshan Port                                | 2             | Zhejiang       | 25                    | 12                         | 4500                      | built           |
| 26  | Daxiaoyunshan                                 | 1             | Zhejiang       | 8                     | 6~10                       | 4100                      | Under Construction |

a The use function of the artificial island can be divided into 4 categories: 1-industrial production land, 2-transportation place, 3-tourism and entertainment place, 4-urban construction land of comprehensive utilization.

The site selection of the artificial island is also constrained by natural conditions. The natural environment of the island's sea area will have a significant impact on the site selection of the artificial island. Generally, the artificial island is selected as far as possible in the middle and weak tide bays, with weak wave dynamics or semi-closed seas. For example, Caofeidian artificial island is located in Bohai Bay, Longkou artificial island group is located in Longkou Bay in Bohai Bay, Yangshan Port artificial island is located in Hangzhou Bay, Shuangyu artificial island is located in Xiamen Bay,
Nanhai Pearl artificial island, Haikou Bay Lighthouse Hotel artificial island and Haikou Millennium Hotel artificial island are located in Qiongzhou Strait, and Phoenix artificial island is located in Sanya Bay. According to the geomorphology, a naturally formed shoal or a seabed bulged reef tray shall be selected with high elevation. On the one hand, there is less filler, low construction risk and saving construction cost. On the other hand, it can be a natural way and the impact on the water and sand environment of adjacent sea areas is relatively small, such as Caofeidian artificial island, Yangkou Port artificial island, Phoenix artificial island, and Haihua artificial island. Port artificial island requires certain water depth conditions and stability of berth and channel, and its offshore distance may be relatively far, such as Yangkou Port artificial island in Jiangsu Province. The site selection of offshore oil and gas artificial island is mainly affected by the location of resource storage. Tourism and entertainment artificial island generally requires beautiful nearby coastal environment, good sense of water quality, developed sandy beach and comfortable climate condition. The island-expanded artificial island is restricted by the original island site. The island site should avoid the underground fault zone as much as possible, which will affect the safety of the artificial island and increase the construction cost at least. Therefore, the site selection of the artificial island shall fully consider the surrounding natural environment.

The offshore distance of the island site has a great influence on the construction cost and natural environment of the artificial island. Except for offshore oil and gas artificial island, harbor artificial island, cross-sea bridge auxiliary artificial island and island-expanded artificial island with large offshore distance constraints, all the other artificial islands are basically located in the offshore and shallow sea areas near the mainland. According to the statistical analysis in Table 1, the offshore distance of most artificial islands is within 1-2km. However, the offshore distance of the artificial island shall not be less than 1km in principle, otherwise, it will have a great impact on the ecological environment of the continental beach.

The water depth of the island site also affects the construction cost and environment around the artificial island. In terms of construction condition and investment, the shallower the water depth is, the easier the construction will be, and the smaller the backfill earthwork is, the smaller the load and disturbance on the seafloor will be, so the smaller the investment will be. But from the landscape condition and the disturbance to the mainland and the impact on the surrounding sea areas, certain water depth conditions are needed to meet it. So, the selection of the island’s water depth often needs to balance the needs of both, and at the same time, it is determined comprehensively after combining other natural conditions and use functions. According to the statistical analysis of the constructed artificial islands, except for the artificial islands with large location constraints such as the purpose for offshore oil and gas, cross-sea bridge, airport, and port required large water depth, the water depth of other artificial island sites generally do not exceed 10 m.

3.2.2. Plane shape. The plane shape of the artificial island can be divided into single island type and island group type. The single island type pays attention to the plane shape of the island itself, as the island group type pays more attention to the combination relationship between the islands.

The plane shape of the artificial island shall first meet the functional requirement, and the design principle of the plane shape of the artificial island with different functional positioning will be completely different. For example, the artificial island of tourism and entertainment and real estate development aims to pursue the space and landscape quality and maximize the length of the coastline, so the plane shape of the island is relatively free and organic. In China, such as Shuangyu artificial island [8] (a circle formed by two frolicking dolphins), Haihua artificial island (three petal shapes) [15], and Nanhai Pearl artificial island (a Tai Chi eight trigrams shape fully reflecting China's traditional culture) also have their own characteristics in a plane shape. In order to better adapt to the urban planning and layout, the artificial island of urban construction of comprehensive utilization generally adopts a grid network, such as Kobe sea artificial city in Japan has a trapezoidal plane shape, which is conducive to the urban layout planning. The layout of the Longkou artificial island group in Shandong Province is similar [9]. Airport and port artificial islands are mostly rectangular and quasi-
rectangular. Offshore oil platforms and industrial storage islands are generally round or nearly round in a plane shape to facilitate design, construction and save investment.

Secondly, the natural environment is also a key factor to be considered in the plane shape design, which includes the coastline shape and size of the adjacent sea area, geological landform and water depth condition, current velocity and its direction, wave protection, beach erosion and deposition, and environmental ecological impact around the artificial island and the adjacent sea. Generally, the artificial island is convex streamline type and shall avoid large intersection angle with the main flow direction as far as possible, so as to smooth the flow. If the artificial island has a breakwater, the entrance shall be arranged to avoid the main wave direction and avoid the shoal at the same time, so as to prevent sediment from entering the inside of the breakwater. In addition, the plane shape must also take into account the effects of extreme weather such as typhoon and storm surge.

Thirdly, the plane shape of the artificial island determines the length of the coastline, which is closely related to the cost.

In addition, building an artificial lake, increasing the water surface rate of an artificial island, as well as the beautiful, green, ecological and hydrophilic of the coastline, are also important contents of plane shape design [8], especially for the construction of urban construction land of comprehensive utilization and tourism and entertainment place.

In short, on the basis of meeting the functional requirements, the plane shape of the artificial island shall not only be conducive to the efficient use of land resources, but also fully consider the harmony between the artificial island and the surrounding environment.

3.3. Foundation treatment and seawall design are the key factors to cost control of the artificial island

When the site selection of the artificial island is determined, foundation treatment and seawall design are the key factors to the cost control of the artificial island. The formation of the land area of the artificial island requires a large number of backfill earthworks, which have a great influence on the project cost and construction time. The thickness of the backfill earthwork is composed of three parts: water depth of the original site, designed land elevation and settlement. The thickness of the backfill earthwork for each artificial island ranges from 10 m to 40 m. Such a huge amount of earthworks will definitely add a huge load to the foundation of the original seabed and have an impact on the geological condition of the local sea area, such as liquefaction of seabed silt, and even threaten the safety of artificial island in severe case. Therefore, it is necessary to grasp the geological data of the island site through actual exploration, and find out the geological condition of the reclamation area, and study the foundation treatment plan thoroughly. Generally, the foundation is consolidated through the selection of backfill material and foundation reinforcement treatment to ensure that the seabed can bear the huge load and guarantee the long-term stability of the artificial island.

The construction of the artificial island requires a lot of fillers. The source of the fillers is directly related to the construction cost of the artificial island. The mechanical characteristics of the fillers have significant influences on the difficulty of foundation treatment, construction time and cost of the artificial island. The hydraulic filling is generally used in the domestic artificial island backfilling project, and the fillers mainly come from the sand and mud formed by dredging the surrounding sea area and channel and excavating of the project itself.

Although there is no substantial difference between the seawall design of the artificial island and the land area, the seawall design of the artificial island has its characteristics, including the high requirement of an artificial island, a long coastline, complex natural condition, more soft soil foundation, difficult construction, especially the artificial island owning deep water and large wave. And the large wave climb and amount of wave overtopping discharge determine the higher seawall elevation, and at the same time, it must meet the requirements for the stability of the protective surface block and the erosion protection of the seawall bottom structure under strong hydrodynamic condition. Therefore, on the premise of meeting the standard of tide and wave prevention, considering the construction cost of seawall comprehensively, adapting to the harsh natural conditions in the open sea, and meeting the requirements of environmental protection, landscape, and hydrophilicity of seawall,
the study of new seawall structure is still one of the key factors to control the construction cost of the artificial island.

### 3.4. The eco-environmental impact is the key factor to the approval of artificial island

The ecological environmental impact caused by artificial island is the key factor in the approval of an artificial island project. The concept of protecting the ecological environment runs through the entire process of the project, including the preliminary research, design, construction and operation stage. It is necessary to pay full attention to the requirements of ecological and environmental protection on site selection, scale, plane shape, filling method, and filler selection of the artificial island. It is necessary as far as possible to minimize the impact of the construction of the artificial island on the surrounding ecological environment.

The site selection of artificial island shall avoid the marine ecological functional area, ecologically sensitive area, and ecologically fragile area, and shall not affect the overall pattern of topographic feature and important natural landscape in the sea area of the island site. The island site shall not be too close to the shore and shall be kept more than 1km away. Special attention shall be paid to the variation of water and sediment in the sea area between the artificial island and the mainland. On the one hand, the construction of the artificial island narrows the cross-section between the island and the mainland, resulting in the increase of velocity and coastal erosion. On the other hand, the construction of an artificial island produces a wave shadow area, and the effect of the wave will make the sediment transporting to the wave shadow area, and the loss of sand on both sides of the wave shadow area will form coastal erosion. In China, some artificial islands are too close to the shore, resulting in the scour or siltation of the nearby continental sand beach. Therefore, it is necessary to fully demonstrate the impact of the construction of the artificial island on hydrodynamic and sediment erosion and deposition. In addition, artificial island dike, reclamation and so on will have an impact on the ecological environment.

Therefore, during the construction and operation of the artificial island, it is necessary to strengthen the environmental ecological monitoring of the whole process, including various indicators such as water and sediment, water quality, sediment quality, biological quality, and marine ecology, so as to grasp the impact of the construction and operation of the artificial island on the surrounding natural environment in real time.

### 3.5. Fully considering extreme events is the foundation of safe operation of the project

The design standard of the artificial island is mainly determined by the functional positioning. At present, the standard of tide and wave prevention of most artificial islands in China is once in a hundred years. However, for extreme events beyond the standard, such as typhoon surge, typhoon wave, earthquake and tsunami, the structure of artificial island should allow a certain degree of damage, but it is generally required that most of the buildings can remain after the damage, and can be repaired on the original basis [13].

### 3.6. Abundant funds are the guarantee for the successful construction of the artificial island

For the construction of the artificial island, the cost is high, the development cycle is long, and the investment return is slow. Most of the domestic construction parties are local governments or large enterprises, such as Evergrande group of Haihua island, Hainan Airlines Group of Nanhai Pearl artificial island, etc. Some artificial islands have been shut down or changed project legal entities due to insufficient funds in China, so the capital strength of the construction unit is the key factor to guarantee the construction of the artificial island.

### 4. Conclusions

China’s artificial island development began in the late 1980s, and so far there are more than 30 artificial islands including built artificial islands, constructing artificial islands and proposed artificial islands. The development of the artificial island is mainly divided into 4 categories: industrial
production land, transportation place, tourism and entertainment place, and urban construction land of comprehensive utilization.

The key problems of artificial island development are as follows: basic data are the basis of the early stage study of the artificial island; site selection and plane shape are the key factors to the early stage study of the artificial island; foundation treatment and seawall design are the key factors to the cost control of artificial island; ecological and environmental impact is the key factor to the approval of artificial island; full consideration of extreme events is the basis for the safe operation of the project; abundant funds are the guarantee for the successful construction of the artificial island.

Site selection is the core of the key problems of artificial island development, which is mainly limited by its functional requirements and also greatly influenced by natural conditions. The site selection of artificial islands should avoid the marine ecological functional area, ecologically sensitive area, and ecologically fragile area, and should not affect the overall pattern of topographic features and important natural landscapes in the sea area of the island site. The artificial island should be located in the sea area with an offshore distance of 1-5km, water depth of no more than 10m, good shelter, enough earth and stone materials nearby and thin soft soil layer on the seafloor.

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