8-27-2021

Maritime safety supervision and navigation service of offshore wind farms in China

Zhimin Zhang

World Maritime University
Dalian, China

MARITIME SAFETY SUPERVISION AND NAVIGATION SERVICE OF OFFSHORE WIND FARMS IN CHINA

By

ZHANG ZHIMIN
The People's Republic of China

A dissertation submitted to the World Maritime University in partial
Fulfillment of the requirements for the award of the degree of

MASTER OF SCIENCE

(MARITIME SAFETY AND ENVIRONMENTAL MANAGEMENT)

2021

DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

Signature: ________________________

Date: ________________________

Supervised by: DR. LIU Zhengjiang
Vice president and Professor of
Dalian Maritime University

ACKNOWLEDGEMENTS

Time really flies, the fifteen-month MSEM program is coming to an end. I'll be leaving this beautiful campus, the palace of knowledge, and saying goodbye to my dear professors and fellow students. Thinking about this has been making me sad over and over again, but more than sad, my heart is filled with gratitude.

Firstly, I am sincerely grateful to China MSA for offering me this splendid opportunity to study in Dalian, China. Many thanks to my superior leaders for releasing me from my regular work to complete my postgraduate study with undivided attention.

Secondly, I am deeply thankful for my supervisor Prof. LIU, Zhengjiang, Vice President of DMU, for guiding me through this dissertation and providing me with invaluable advice and insight into the subject matter. His profound and rich knowledge will be conducive to my profession and whole life.

Thirdly, I truly appreciate all professors in WMU and DMU, inter alia, Prof. SUN Peiting, Vice President of DMU, Prof. MA, Shuo, Vice President of WMU, Prof. Emeritus Proshanto K. Mukherjee, Prof. ZHAO, Jian and ZHAO, Lu, etc., for their interesting teaching, kindly guidance and thoughtful arrangements which indeed have maintained the high quality of the program. My heartfelt gratitude also goes to my fellow students who have kept me company during the programme.

Fourthly, I am very grateful to my beloved parents who have been encouraging me all the time by offering their full support, especially my dear wife who has been taking care of the whole family during my long absence and sharing happiness with me all along. Last but not least, my sincere appreciation goes to all the authors of literature that I had the honor to read and cite.

ABSTRACT

Title of Dissertation: **Maritime Safety Supervision and Navigation Service of Offshore Wind Farms in China**

Degree: **MSc**

Offshore wind power is clean energy that has drawn tremendous attention and grown rapidly over the past decade in China. In comparison with other energies, offshore wind power has several advantages, inter alia, no occupancy of land space, abundance in wind resource and suitability of large-scale development. However, the development of offshore wind farms (OWFs) unavoidably have profound impacts on navigation environment. A majority of OWFs have been established in the offshore sea areas, while inappropriate siting, insufficient distances to shipping routes, inadequate safety mitigation measures and unsuitable marking of wind turbines are undoubtedly detrimental to safety of navigation.

In the first chapter, this dissertation introduces the state of the art on the risk management of OWFs both at home and abroad from different perspectives, and identifies three unsettled issues that are clarified subsequently. In the second chapter, the impacts of OWFs on the navigation environment are illustrated from the design, construction, operating and decommissioning phase of offshore wind farm, and three salient risk factors are identified and analysed thereafter. In chapter three, taking the Binhai Offshore Wind Farm as an example, a quantitative navigational risk assessment is conducted. In chapter four, based on the achievements of the navigational risk assessment and the analyses, risk control options have been proposed from the perspectives of maritime safety supervision and navigation service to enhance safety of navigation around OWFs. Finally, the author wraps up the dissertation by summarizing essential risk factors and risk mitigation measures, and puts forward the practical solutions that involves cooperation of both the maritime authorities and OWFs developers in order to promote a harmonious coexistence between shipping industry and offshore energy industry in the use of marine spaces.

KEY WORDS: Offshore Wind Farm; Maritime Safety Supervision; Navigation Service; Risk assessment; AIS; Risk Control Options.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AtoNs	Aids to Navigation
AIS	Automatic Identification System
ADA	Average Distance of Approach
COLREGs	International Regulations for Preventing Collisions at Sea
CLV	Cables Laying Vessel
DCA	Distance of Closest Approach
E	East
ENE	East North East
ESE	East South East
GIS	Geographic Information System
GMDSS	Global Maritime Distress and Safety System
HLVs	Heavy Lift Vessels
HAT	Highest Astronomical Tide
IMO	International Maritime Organization
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IWRAP	IALA Waterway Risk Assessment Program
IPS	Intermediate Peripheral Structure
Km	kilometre
LAT	Lowest Astronomical Tide
mm	millimetre

m/s	metres per second
MSA	Maritime Safety Administration
MSP	Marine Spatial Planning
MBS	Maritime Buoyage System
MSI	Maritime Safety Information
MW	Mega Watts
N	North
NE	North East
NNE	North North East
NW	North West
NNW	North North West
NRA	Navigational Risk Assessment
NM	Nautical Miles
OWFs	Offshore Wind Farms
OSVs	Offshore Support Vessels
PVs	Piling Vessels
RCOs	Risk Control Options
S	South
SE	South East
SSE	South South East

SSW	South South West
SW	South West
SPS	Signification Peripheral Structure
SAR	Search and Rescue
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNCLOS	United Nations Convention on the Low of the Sea
VTS	Vessel Traffic Service
W	West
WNW	West North West
WSW	West South West
WFO	World Forum Offshore Wind
WTIVs	Wind Turbine Installation Vessels
ZoP	Zones of Potential

Chapter 1 Introduction

1.1 Background

Currently, the GHG emission generated by human activities are still rising each year. The 13th Sustainable Development Goal for addressing climate change called for affordable and effective solutions from all countries to ensure the health and resilience of national economies. China has been taking strong measures to address climate change and is committed to peaking the CO_2 emission as soon as possible by 2030 and accomplishing carbon neutral by 2060. Due to the impact of GHG emission restrictions and implementation of environmental protection policies, the demand for renewable energy has been increasing dramatically. Wind energy compared with the conventional coal-fired power generation is a renewable and clean energy source with zero CO_2 emission. The use of onshore wind energy had been close to saturation along with its continuous development, which gave rise to offshore wind energy. With a series of advantages of abundance in resources, high power generation efficiency, no occupation of land, small impact on the ecological environment, no consumption of non-renewable energy sources and suitability for large-scale construction, the offshore wind energy generation has been attracting lots of attentions (ZHANG, 2014). Since the construction of the first commercial offshore wind farm (OWF) in Denmark in 1991, offshore wind power has grown rapidly in

Europe (CHEN, 2020). And China commenced developing its first commercial OWF in 2010, lagging behind for almost twenty years in the offshore wind energy exploitation has not held China back. According to the statistics from WFO[1], China's offshore wind sector continued to grow rapidly with a total capacity of 4.4 GW under construction in 2020. Despite the supply chain disruption due to the outbreak of COVID-19, the global offshore wind industry continued to grow strongly with more than 5.2 GW of added offshore wind capacity in 2020, as illustrated in Figure 1.1 (World Forum Offshore Wind, 2021).

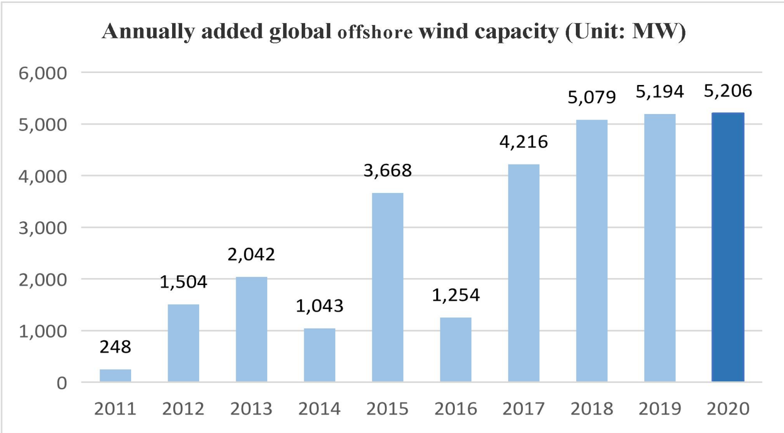


Figure 1.1 Global offshore wind growth despite COVID-19

From "Global offshore wind report-2020", by WFO, 2021, p.3. https://www.wfo-global.org

However, the rapid development of offshore wind industry has also posed profound influences to the maritime industry (HE, 2016). In the operating phase, the OWF brings the impacts of fragmentation and tridimensional exclusivity to the use of the sea area, leading to the loss of compatibility of the sea resources, and permanently affects the safety of navigation. The presence of OWF will complicate the navigation environment of the adjacent waters. For examples, inadequate distance to shipping routes, waterways and anchorages may present a risk of collision between ship and

[1] World Forum Offshore Wind (WFO) is the world's first organization 100% dedicated to fostering the global growth of offshore wind energy.

wind turbine, unsuitable establishment and maintenance of Aids to Navigation (AtoNs) may confuse the navigators and induce improper handling of ships, and the electromagnetic radiation generated during the operating phase of OWF may affect the navigational equipment on board ships (LIANG, 2018).

1.2 Research purpose and significance

From the point of view of maritime safety concerns, based on the previous researches and achievements, this dissertation aims to carry out a comprehensive study on the impacts of OWF on safety of navigation of ships, and then proposes risk mitigation measures as references for the maritime authorities in China to enhance safety of navigation and protection of marine environment.

1.3 Literature review

1.3.1 Research status on risk management of OWF

Regarding to the impact of OWF on safety of navigation of ships, REN et al. (2010), discussed the potential risks of the commercial vessels and infield support vessels affected by wind and current, and the drifting patterns of vessels not under command due to wind and current. The authors laid down ship's safe navigation and preventive measures according to the characteristics of the offshore wind farm. GU, E.K. (2015) discussed the impact of OWF in each phase on the navigation environment and put forward technical countermeasures in the development process of OWF from the perspective of maritime supervision. YU et al. (2018) proposed a framework to characterize the influence of an OWF on maritime traffic and on a specific route by means of a statistical analysis of AIS data, which provided a data-based approach for future works on OWF siting, collision/allision risk analysis and management. LIU et al. (2010) studied the the influence of OWFs on the radar, showing that the shaded area had little impact on radar at a distance more than 200 metres to wind turbine, but it was difficult for radar to detect the objects inside and in close vicinity of OWF, and the authors concluded that OWFs posed certain threat to safe navigation of ships. ZHANG, M. (2014) studied the impacts of OWF on vessels, AtoNs, VHF, Radar, magnetic compass, GPS, AIS and other maritime communication signals, eventually raised safety measures during the OWF operating phase.

Regarding to the risk assessment of OWF during construction and operating phases. LI et al. (2013), established risk assessment criteria and risk assessment model during operating phase using fuzzy network analysis and support vector machine, providing reliable basis for risk management of OWF during operating phase. XIE, Z.Z. (2013), put forward OWF risk assessment criteria system including natural hazards, accidents, breakdown of facilities, management risks and market risks. And she proposed the OWF risk assessment model using support vector machine, which provided a calculable tool better than conventional methods in terms of convenience and accuracy for OWF risk management. Similarly, JIANG et al. (2014), proposed the OWF risk assessment criteria system, including natural conditions, traffic conditions, AtoNs, turbine conditions, VTS, emergency response, etc., and then the authors conducted comprehensive assessment using fuzzy comprehensive evaluation method. Moulas et al. (2017), developed a nonlinear finite element analysis (NLFEA) approach to identify various collision scenarios and evaluate the damage to offshore wind foundations stricken by infield vessels. The results of this research provided an insight on how the next generation of wind turbine foundations can be designed in a more "collision-friendly" way. Torres et al. (2020) presented the concept of a methodology for the indicator-based assessment of the safety of OWFs, which employed key performance indicators as well as key risk indicators. These indicators enabled not only the online monitoring of the infrastructure, but also the exploration of its response to hazardous events–a fundamental requirement for resilience assessment.

Regarding to OWF siting. LI et al. (2014), based on the traffic characteristics of the Fujian planned OWFs sea area, the authors identified primary maritime risk factors around OWFs sea area, and then carried out qualitative and quantitative analyses using expert inquiry, preliminary hazard analysis and fuzzy comprehensive evaluation methods. The degree of navigation safety impacts of the eighteen planned OWFs were sorted out from highest to lowest, providing reference for the construction of OWFs. JIANG (2012), analysed the navigation safety of a planned OWF with a mathematical model established by combining fuzzy mathematics and analytic hierarchy process, which could be used for site optimization of OWF. CHEN et al. (2017), from the perspective of navigation safety, analysed the factors affecting the safety of navigation around OWF, built a model utilizing analytical hierarchy process, entropy evaluation method and grey correlation analysis method, which was used to select the site with minimum impacts on the safety of navigation. The informed decision of OWF siting can be made through the application of this model. Kim et al. (2016), put forward four categories of siting criteria, including energy resources and economics, conservation areas and landscape protection, human activities, and the marine environment and marine ecology. The authors conducted a study on feasible evaluation of OWF siting around Jeju island utilizing marine spatial techniques from GIS.

Regarding to the minimum safety distance between OWF and waterway, customary route, recommended route, anchorage, obstructions, etc. Many scholars had developed different models to recommend minimum safety distance. NIE et al. (2019), based on Monte Carlo simulation, developed the ship-OWF collision probability model considering the influence of ship type, position, speed, wind and current. Then, the authors analysed the correlation between collision probability and distance between OWF and waterway, and obtained the acceptable safety distance ranging from 1,300 to 3,000 metres. WANG et al. (2020), considering characteristics of ships, safety area required for normal operation of wind turbine, wind-induced drift and current-induced drift, etc., developed the calculation model of the safety distance between OWF and waterway based on the improved drift model of ships not under command, eventually worked out the minimum safety distance of 2,800 metres without collision accident incurred by ships not under command. The UK Maritime and Coastguard Agency (MCA, 2016) recommended a minimum safety distance of no less than 0.5 nautical miles between OWF boundary and waterway. Rawson et al. (2015), suggested that the distance should be longer than 1,000 metres to reduce collision risks (as cited by YU et al. 2019). In order to ensure the navigation safety of ships in waterways, a safety distance of at least 3 miles to OWFs was defined by Spyridonidou & Vagiona (2020).

Regarding to the navigation service[2]. JIANG & LI. (2019) studied on the AtoNs placement scheme for OWF during construction and operating phases to facilitate safe navigation of ships. Basically, "*Maritime Buoyage System, China, GB 4696-2016*" and IALA related recommendations were referred. During the construction phase of an OWF, special marks (mainly light buoys) were established with Morse "O" light characteristic. During operating phase, light beacons were established on Significant Peripheral Structures and Intermediate Peripheral Structures with Morse "C" light characteristic. CHEN.J.J. (2017), taking Gui Shan OWF for instance, analysed the standardability and reasonability of OWF AtoNs

[2] Navigation service under China's maritime regulatory regime consists four areas of business: Aids to Navigation, Maritime communication, Maritime surveying and Mapping. This thesis mainly focuses on Aids to Navigation service.

placement during operating phase. “*Maritime Buoyage System, China, GB 4696-2016*”, *“The Regulation for Marking of Offshore structures in China, GB17380-1998”* and IALA Recommendation R0139 “*The Marking of Man-Made Offshore Structures*” were applied. The Significant Peripheral Structures and the Intermediate Peripheral Structures were fitted with special marks, yet differently for conspicuity and distinction. Morse “C” Yellow 12 s for the former, Morse “U” White 15 s for the latter.

1.3.2 Summary of the research status

Plenty of researches on OWFs risk assessments had been conducted, providing good references for risk management of OWFs during design, construction and operating phases. But those researches are for the benefit of OWF enterprises and ship users. It’s undeniable that more attention should be brought to the enhanced maritime safety supervision and navigation service to ensure safety of navigation in the vicinity of OWFs. Based on the literature review at home and abroad, navigational risk assessment (NRA) has been applied in different levels and aspects, including OWF siting, minimum safety distance analysis. However, there are still some technical problems needing further researches.

First, it’s widely recognized that the navigational risk assessment should be duly carried out during the design, construction and operating phase of an OWF, providing valuable information for decision makers on matters of OWF siting and minimum safety distance, etc. Although many authors have presented risk assessment models from different perspectives, it seems that the use of assessment models are multifarious. The government and construction parties using different risk assessment models could obtain quite different results.

Second, “*The Marking of Offshore Structures in Chinese Sea Areas, GB17380-1998*” was formulated more than twenty years ago, most of the marking techniques were out of date which made this regulation inapplicable to current offshore activities. Generally speaking, regarding the marking of OWFs, two contradictory approaches were applied. Most of OWFs were marked according to IALA Recommendation R0139, but quite a few OWFs were still marked according to GB17380-1998. The problem of different marking techniques is that Mariners perhaps would get confused and have difficulty in identifying the navigational marks and result in misoperation.

Third, based on the literature review, very little attention were given to the decommissioning of OWFs both at home and abroad. From the point of view of maritime safety, the decommissioning of an OWF should be treated as a reverse process of installation, only it's a removal of marine structures. And it's possible that some wind turbines may be dismantled wholly or partially, leaving the foundation untreated or even abandoned in extreme cases, in this regard the marine structures will become obstructions for safety of navigation.

1.4 The main research contents and key problems to be solved

- The current research status of maritime safety supervision and navigation service on OWFs at home and abroad.
- Introduce the OWF's impacts on navigation environment, analyse particular risk factors that severely affect safety of navigation.
- Assess and analyse the impact of one specific OWF to the safety of navigation of ships during the operating phase.
- Propose a series of risk control options based on the risk assessment and research from the regulatory and service perspective respectively corresponding to the design, construction, operating and decommissioning phases of OWF.

1.5 Research programme

- Literature reading and analysis. Through extensive reading of relevant papers, journals, books, reports and other materials, a comprehensive knowledge about navigational risk assessment methods, the impacts of OWF on safe navigation of ships and current risk mitigation measures will be gained, laying foundation for further research of this dissertation.

- Expert consultation and questionnaire research. Invite experts from maritime authorities, navigation safety agencies, port authorities, OWF development and construction parties, pilots and mariners to carry out expert consultation. Send questionnaires to AtoNs departments to acquire the general status on the marking of OWFs in China.

- Risk assessment theoretical research and application. Carry out a study on different navigational risk assessment methods used by different countries and organizations, and then choose an appropriate model and a specific OWF site with available data to conduct risk assessment.

1.6 Main points of innovation

A novel navigational risk assessment model has been developed. It is an AIS data-based quantitative method that can be used to calculate the distance of closest approach and average distance of approach of ships navigating in a waterway to the obstructions such as wind turbines, isolated hazards, etc. Eventually, risk of navigation can be analysed and assessed.

Chapter 2 Risk Analysis of OWFs

2.1 Overview of offshore wind farm

2.1.1 The introduction of OWF

OWF is a way of generating electricity through large-scale construction of wind power plants in the sea that captures wind energy and transforms them into electric energy. According to the characteristics of the sea areas, OWFs can be generally categorized into intertidal zone and subtidal zone wind farm, nearshore wind farm and deep-sea wind farm. The intertidal zone and subtidal zone wind farm are usually situated in sea areas with depth of water less than 5 metres in theoretically lowest tide level. The nearshore wind farm is usually situated in sea areas with depth of water between 5-50 metres in theoretically lowest tide level. And the deep-sea wind farm is usually situated in sea areas with depth of water more than 50 metres in theoretically lowest tide level. Currently, most of OWFs in China have been installed offshore in intertidal zone and subtidal zone. An OWF usually consists of wind turbines, meteorological mast, substation, submarine cables and centralized control center. There are different kinds of foundations including monopile, tripod, jacket and floating foundations, among which monopile undoubtedly is the most popular choice of foundation for offshore turbines (Wright et al., 2016). Different foundations applicable to various water depths and bottoms have diversified impacts on navigation environment.

2.1.2 The development of OWFs in China

China is rich in wind energy in many coastal provinces such as Liao Ning, Shan Dong, Jiang Su, Zhe Jiang, Fu Jian, Guang Dong and Hai Nan, providing favorable premise for developing OWFs. Statistics show that the exploitable reserves of wind resources in China's coastal areas are approximately 750 million KW (YI, 2004). The electricity supply shortage of eastern coastal areas could be effectively relieved if the kinetic energy of the wind were to be exploited adequately. "*The Renewable Energy Law of China*" came into force on January 1, 2006. In September 2007, the *National Development and Reform Commission* proposed the "*Medium-and Long-term Program for Renewable Energy Development*". In 2010, the *National Energy Administration*, together with the *National Oceanic Administration*, issued the "*Interim Measures for the Management of Offshore Wind Power Development and Construction*". These early regulations have offered both guidance and stimulation for the development of OWFs. China started its first experimental prototype in Bohai Bay in 2007, and then completed the construction of its first OWF in July 2010 (LIU, 2020). Since then, China has been putting tremendous efforts in developing OWFs. By the end of 2020, China's cumulative installed capacity of offshore wind power had broken through 9 GW, as illustrated in Figure 2.1. According to *Global Offshore Wind Report 2020*, global offshore wind capacity in operation surpassed 32 GW, in particular, China poised to overtake Germany as the world's second largest offshore wind market. As shown in Table 2.1, nearly 10 GW of offshore wind capacity was under construction worldwide by the end of 2020, among which 51.8% was being installed in China[3] (WFO, 2021).

[3] On January 3, 2020, Ministry of Finance, China announced the abolition of state subsidies for offshore wind power after 2021, which led to surge in construction of OWFs as we have seen through the statistics.

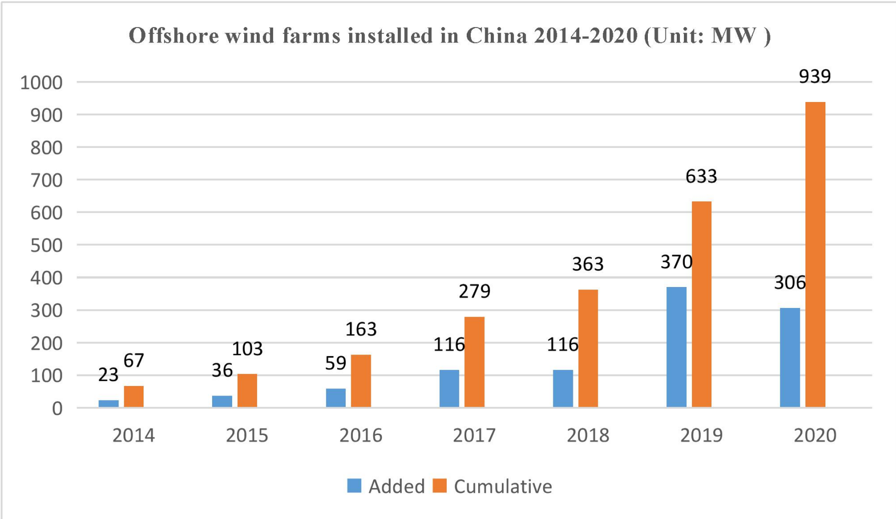


Figure 2.1 OWFs installed in China between 2014 and 2020

Adapted from "In-depth report of China's offshore wind industry-2020", by Bei Ji Xing Wind Power Grid, 2021, p.26. https://news.bjx.com.cn/html/20210322/1143271.shtml

Table 2.1 Global OWFs under construction worldwide

NO.	Wind Farm	MW	Location
1	Borssele 5	19	NL
2	Kincardine – Phase 2 (floating)	48	UK
3	Southwest Offshore Demonstration Phase 1	60	KR
4	Changhua Phase 1	109	CH
5	Fujian Fuqing Haitan Strait	154	CH
6	Longyuan Putian Nanri Island Phase 1	200	CH
7	Fujian Putian City Flat Bay (Zone F)	200	CH
8	Pingtan Changjiangao	204	CH
9	Daishan 4	234	CH
10	Fuqing Xinghuawan Offshore Wind Phase II	280	CH
11	Datang Jiangsu Binhai	300	CH
12	Zhuhai Jinwan	300	CH
13	Tangshan Area 6 Phase 2	300	CH
14	Sheyang H1	300	CH
15	CTGNE Yangjiang Shapa Phase 1	300	CH
16	Yangjiang Nanpengdao	300	CH
17	Windpark Fryslan	383	NL
18	Jieyang Shenquan	400	CH
19	Three Gorges Renewables YangXi II	400	CH
20	Neart na Gaoithe	450	UK
21	Shanwei Houhu Offshore Wind Phase I	500	CH

22	Kriegers Flak	605	DK
23	Yunlin	640	CH
24	Triton Knoll	857	UK
25	Moray East	950	UK
26	Hornsea 2	1400	UK
Total		9893	

Source: Adapted from "Global offshore wind report-2020", by WFO, 2021, p.8. https://www.wfo-global.org

2.1.3 The impacts of OWFs on navigation environment

OWFs have specific issues where they are in conflict with traditional activities such as navigation of ships. Particular aspects of OWFs that need to be considered include: OWFs are situated in open water, where seafarers don't expect to encounter obstacles; OWFs have both fixed parts and moveable parts, and have parts both under and above the water surface; OWFs are individual constructions, formed into an array; OWFs are interconnected with electrical and data transmission marine cables; OWFs are strategic energy infrastructure, making them sensitive to damage; and OWFs generate invisible perturbations in the form of electromagnetic radiation.

Generally, the entire life circle of an OWF can be categorized into four phases, which includes the design phase, construction phase, operating phase and decommissioning phase. Each phase involves various types of waterborne activities that last for long period of time. This will inevitably affect navigation environment and create major conflicts with safety of navigation. The OWF's influences on navigation environment are complex and varied. Problems emerging from each phase may lead to incidents. Hence as the first thing to do it's essential to get an idea of those impacts on navigation environment.

(i) In the design phase. This phase involves certain waterborne activities such as hydrographic survey, geological prospecting and wind resources survey that require ship operations, which will increase the traffic density of the operation sea area and affect the safety of navigation of ship in the vicinity. The engineering practice shows that OWF has the attribute of exclusiveness, which breaks the compatibility with other maritime activities. Only considering the self-development needs and wind resources will result in improper planning of OWF siting that will lead to conflicts with customary route, anchorage and military exercise area, etc. To make things worse, the planned areas of OWFs were too large that they unavoidably occupied and squeezed the congested navigable waterways. Take Shanghai for example, by 2020, Shanghai's planned area of offshore wind power is 374.5 km^2, accounting for 10.7% of its total sea area; in the long run, the percentage will rise up to 41.4% (LIU et al., 2015).

(ii) In the construction phase. The construction phase is a period of time that has a great influence on navigation, including frequent deployment of various types of construction vessels for dredging of sea bottom, transportation and installation of foundations and turbines, and laying of marine cables.

First, the Offshore Support Vessels (OSVs) navigating between port and designated construction area will aggravate the navigation density, and have a certain impact on traffic organization especially where the towboats are needed for transportation.

Second, the influence of foundation and wind turbine installation on navigation. The piling vessel (PV) needs to anchor to maintain relatively static positions for piling operation. Under normal circumstances, the PV is anchored with two pairs of reversed open moorings, and ordinary moorings fore and aft, and the length of anchor chains range from 150 to 500 metres. As a result, the vessel will occupy a rounded water area with a radius of 150-500 metres centred on the foundation, as shown in Figure 2.2. The anchor chains thrown by the vessel will become the potential factor to induce accident thus hinder the navigation of the ships in the vicinity. After the foundation is done and before the wind turbine is installed, the foundation becomes a new offshore structure, without proper marking it would bring huge impact on safety of navigation. During the wind turbine installation process, the anchoring method is roughly the same with foundation installation process, but only with comparatively small water area occupied and less impact on safety of navigation.

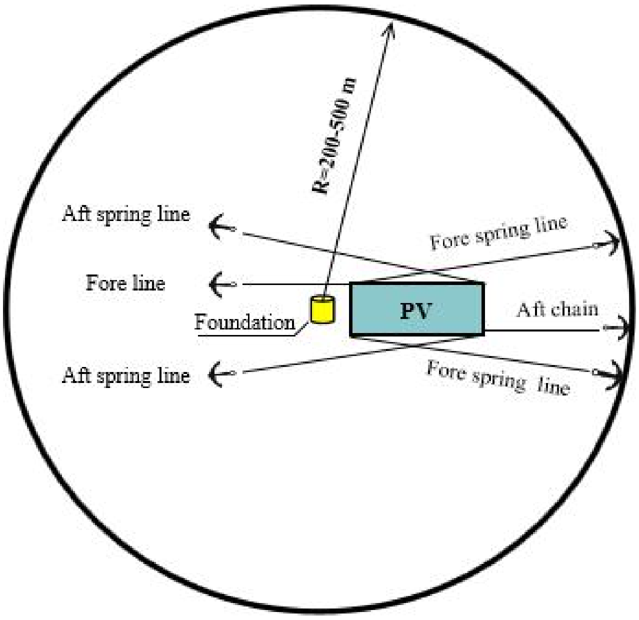


Figure 2.2 Anchoring drawing of the PV

Source: Reproduced from "The Study on the Construction and Vessel Navigation Safety of Offshore Wind Farms", by LIU, J.L. 2021, p.28.
http://kns.cnki.net/kcms/detail/detail.aspx?FileName=ZSUX20200 7013&DbName=CJFQ2020

Third, the influence of marine cable laying on navigation. The Cables Laying Vessel (CLV) is non-self-propelled vessel, which is usually assisted by towboat and anchoring system to control its position. This maneuverability restriction makes CLV hard to keep clear of other vessels effectively. When the vessel is operating in waterway or customary route of ships, it's necessary to take measures to close off navigation in such water, which will affect the normal navigation of ships. After the marine cables are laid, the waters perhaps will be prohibited from anchoring so as to protect the cables, which will certainly change the navigation environment permanently.

(iii) In the operating phase. Once an OWF completes its construction, it probably will be in operation for more than twenty years, during which period of time it poses profound influence to navigation environment.

First, the wind turbine's interference on radio equipment such as radar, VHF, AIS, etc. It is considered that the operation of the wind turbine makes it difficult for radar to detect the target located in the wind farm, the accuracy of target tracing inside and near the wind farm using ARPA radar can't be guaranteed, and a certain shaded area will be generated if the radar is close to wind turbine (LIU et al., 2010).

Second, the existence of an OWF has a certain impact on the surrounding natural environment, for example, the operation of wind turbine will change the surrounding wind field, the foundation of wind turbine will change the flow field and this in turn will change the erosion and deposition trend of the seafloor. All those will directly or indirectly affect the navigation environment of the adjacent waters.

Third, the OWF itself takes up a large amount of navigable water that will permanently change the surrounding navigation environment by reducing the navigable width and depth of waterway. In cases where ships navigating near the OWF are subject to current-induced drift or human elements, there are chances that the ships will collide with wind turbines.

(iv) In the decommissioning phase. After 20 to 25 years' of service, an OWF will reach its final phase - Decommissioning (Kerkvliet & Polatidis, 2016). When an OWF approaches the end of its service life, its owner can either choose to extend its service life by repowering it, or decommission it. Most of OWFs' decommissioning are expected to begin in 2030 to 2035 since the first China's OWF was established in 2010. Very little attention has been given to decommissioning of OWFs because the need of decommissioning is not pressing yet. And very few empirical data are available so far except the limited experience from the decommissioning of oil and gas installations. From the point of view of engineering, this phase can be deemed as the reverse process of the construction phase. Therefore, the top structures of a wind turbine will have to be removed first as shown in Figure 2.3, followed by the dismantling of foundation, and ultimately the cables will be recovered. Several challenges in decommissioning of an OWF must be given due considerations including the working vessel availability, the impacts on safety of navigation and marine environment. Inappropriate decommissioning approaches can be estimated to be not only money consuming and but also detrimental to marine environment and safety of navigation. The decommissioning cost of an OWF is estimated to be around 3% of the total capital cost (Beinke et al., 2018). There are chances that the poorly managed OWF might be abandoned by the owner.

Figure 2.3 The decommissioning of the world's first OWF - Vindeby

Source: From "EU Offshore Wind". https://mp.weixin.qq.com/s/ydwNp4rb9nQ4bBiKpS3C_w

Various types of vessels will be used constantly during the decommissioning procedure. Typically used vessels in the construction phase of an OWF such as Wind Turbine Installation Vessels (WTIVs), Piling Vessels (PVs), Heavy Lift Vessels (HLVs), Cables Laying Vessels (CLVs) and Offshore Support Vessels (OSVs) are also best alternatives for decommissioning activities. On one hand, these working vessels are rare kind and hard to find due to the rapid development of offshore wind industry. On the other hand, the continuous involvement of those vessels will inevitably take up wide navigable waters and increase the traffic density, hence jeopardize safety of navigation. Comparatively, the dismantling of foundations is more challenging than the removal of top structures and the recovery of marine cables. The key factor to be considered removing substructure of the foundation is whether it's to be dismantled completely (complete removal) or any parts are to be left behind (partial removal). The baseline of international law and obligations, e.g. UNCLOS, is complete removal of offshore installations, with exceptions according to the IMO guidelines. The IMO guidelines set out six key components that should be taken into account when deciding how much (if any) of a structure should be left on the seabed (Gjødvad & Ibsen, 2016). The complete removal of the substructures of an OWF is costly and not necessarily a sure card in that the substructures of an OWF (including wind turbines, meteorological mast and substation) may have become the perfect habitats for marine wild-lives such as reefs, fishes and crustacean as presented in figure 2.4. Thus the compete removal may destroy the marine environment that have been built naturally over the years. As opposed to complete removal, partial removal has both environmental and economic benefits. Nonetheless, if the substructure were to be dismantled partially leaving a considerable part below the LAT and above the seafloor, it would probably endanger safety of navigation of ships with deep draught, or engaging with bottom trawling. While wind turbines have a designed lifespan of 20-25 years, the marine cables could last for 50 years. Those cable are generally buried 1-2 metres under the seafloor, hence the complete removal requires excavation and pulling out of the trenches. In view of their sheer length, this would result in a major marine disruption as well as notable costs. Therefore, the marine cables could be left in situ (Eva et al., 2019), but this is in conflict with the notion of “restitutio in integrum”, meaning that the site should be restored to the shape as it was before the project was implemented. It can be concluded that the emerging conflicts and challenges are attributed to be the absence of relevant maritime regulatory framework.

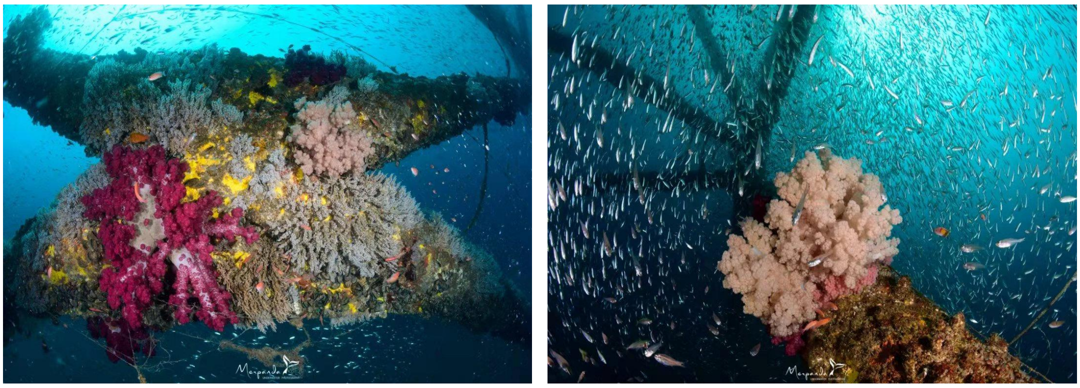


Figure 2.4 Substructure as habitat for reefs and fishes

Source: From “Diving strategy of a meteorological mast in Huizhou, Guangdong” . https://mp.weixin.qq.com/s/RHaESJtRN3GAD3B8B6Wx1g

2.2 Analyses of particular risk factors

Conceptually, risk is the probability of an unwanted event causing unintended consequences, and it’s also a combination of the likelihood and consequences of a particular dangerous situation (R = P x C, herein R means risk, P means probability or likelihood, and C means consequences). As Prof. Schröder-Hinrichs (2019) stated in his lecture, “no system or process is ever truly risk-free” (p. 7). An OWF involves a lot of risks in its entire service life, all of which are derived from nature, port, traffic, management and OWF itself.

However, this dissertation only intends to identify and analyse three salient but non-exhaustive risk factors from the perspective of safety of navigation of ships. In other words, those risk factors in question are also relevant to the problems that have been identified in the aforementioned literature review, which will be discussed further in the following subsections of this chapter.

2.2.1 OWF siting

Siting is the core component of the design phase of an OWF. The common practice for OWF siting in China generally contains three steps. First, the national and local energy authorities draw up a plan for potential sites of OWFs, examine and approve specific OWFs developers. Second, the approved OWFs developers apply to the department of Marine administration for a license for the use of sea areas. Finally, the approved OWFs developers apply for construction permit from MSA prior to the construction phase. The National Energy Administration and State Oceanic Administration jointly issued the "*Detailed Rules for the Implementation of the Interim Measures for the Management of Offshore Wind Power Development and Construction*" in July 2011, which aims to standardize and improve the construction and management procedures of offshore wind power and promote the healthy and orderly development of offshore wind power. It is explicitly stated that the OWFs shall be sited in sea areas where the offshore distance is not less than 10 km, and the depth of water is not less than 10 m if the width of intertidal zone is more than 10 km. This basic OWF siting principle specifies the development path of China's offshore wind power, which has contributed to coordinating each sector in the need of sea areas.

However, the engineering practice of OWF development reflects that the regulatory regime doesn't adapt to the rapid development of OWF. Just excluding the sensitive areas of relevant regulations does not mean the planned potential sites are technically feasible, nor does it mean that maritime related laws and regulations are met. In fact, the maritime authorities should get actively involved in the OWF siting process, otherwise the potential sites would probably be in conflict with safety of navigation.

Take the meteorological mast construction of Zhuhai Jiapeng for example, Guangdong MSA suggested to adjust its original position because it was very close to customary route, but the developer refused to do so, which resulted two collision accidents. In the end, the developer had no alternative but to start from scratch. Take the game between Taiwan's maritime sector and energy sector for another example. The energy sector announced 36 Zones of Potential (ZoP) on July 2, 2015 (Thousand Wind Turbine Project, 2021). Unfortunately, the plan didn't take the ship's routeing announced by the maritime sector into account. As a result, twelve ZoP were rejected by maritime sector, the preparing work in early stage and resource investment of developers came to nothing. Figure 2.5 shows that the twelve ZoP were canceled due to overlapping of routeing scheme and ZoP. Figure 2.6 gives the revised ZoP that the maritime sector and energy sector agreed upon eventually.

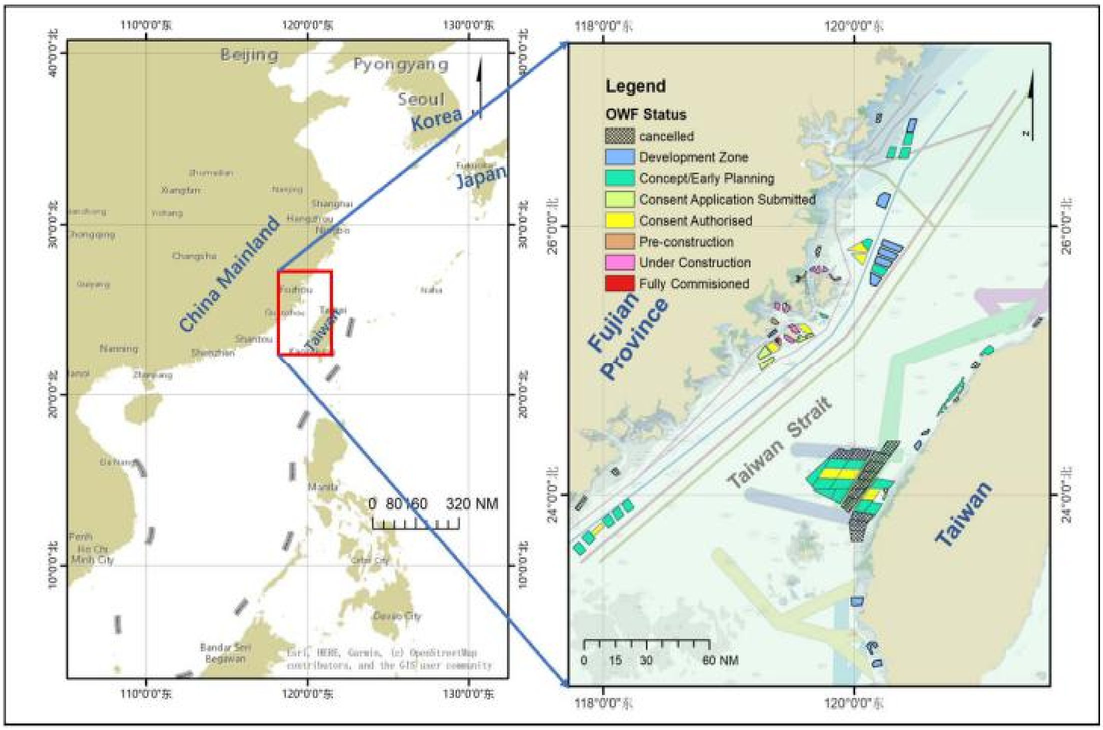


Figure 2.5 Cancellation of 12 ZoP

Source: From "Thousand Wind Turbine Project". https://www.twtpo.org.tw/index.aspx

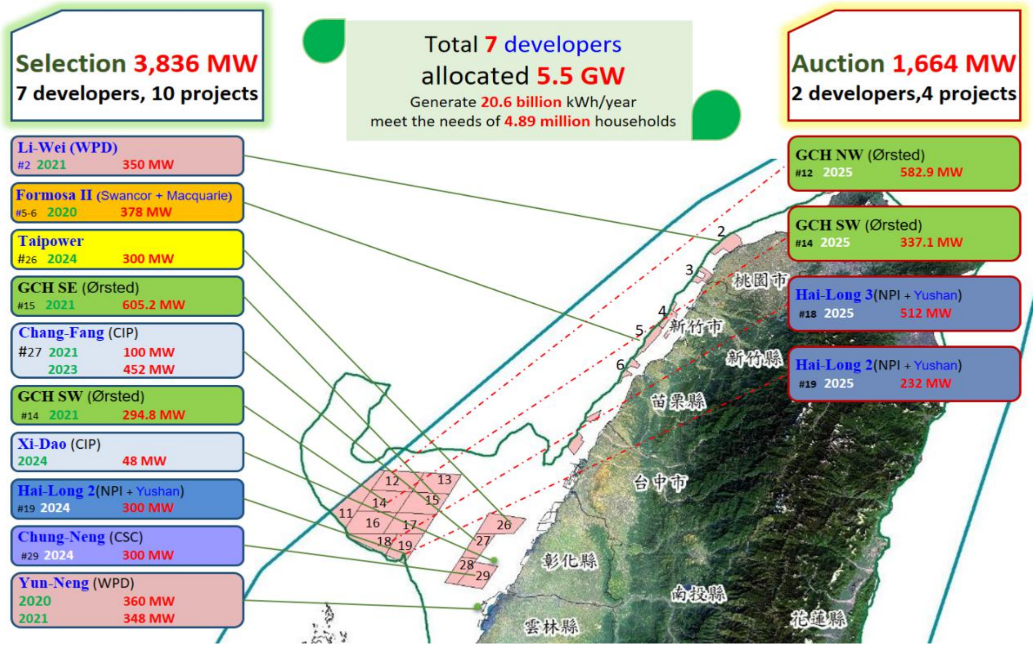


Figure 2.6 The revised ZoP

Source: From "Thousand Wind Turbine Project". https://www.twtpo.org.tw/index.aspx

Regarding OWF siting in the light of sustainable development in the already heavily used offshore marine realm, a holistic approach - Marine Spacial Planning (MSP) has been applied in many countries. MSP is defined by UNESCO as a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that are typically specified through the political process. Historically, MSP has been driven by the need to preserve ecological zones and was started as a management approach for nature conservation in the Great Barrier Reef Marine Park over 30 years ago. More recently, it has been adopted in the more crowded seas of European countries and several countries in Asia, including China and Vietnam, which are now using MSP to achieve both economic and environmental objectives (The World Association for Waterborne Transport Infrastructure, 2018).

The GIS-based framework is a suitable tool to analyse synergies regarding marine space issues among different users, to offer guidance to stakeholders and assist decision-makers in determining the most suitable sites for pilot projects. The co-location of OWF and aquaculture might be seen as a milestone towards sustainable MSP in the German EEZ (Gimpel et al., 2015). Tercan et al. (2020) developed an integrated methodology which combined multi-criteria decision making methods and GIS and was implemented in Greece and Turkey. This spatial suitability analysis may contribute to providing some useful recommendations for the MSP at the regional scale, as well as for the preliminary assessment of new OWFs in both countries. Apart from countries above, Spain (Rodríguez-Rodríguez et al., 2016), USA (Smythe et al., 2019), Belgium (Douvere et al., 2007), UK and the Netherlands (Stephen, 2010) have also implemented MSP approach in the OWF siting.

2.2.2 The minimum safety distance

The determination of minimum safety distance from an OWF to the recommended route, customary route and anchorage is crucial for both safety of navigation and OWF, through which the maritime authorities can exercise effective traffic control. Different minimum safety distance models have been proposed from different perspectives. First, from the perspective of vessel drift induced collision, WANG et al. (2020) established a minimum safety distance calculation model based on improved not-under-command drift model, considering the characteristic of the vessel itself, safety zone required for normal operation of wind turbine, wind induced drift and current induced drift, etc. Then take the 150,000-ton bulk carrier, 50,000-ton container ship, 150,000-ton oil tanker and 50,000-ton chemical tanker navigating in sea areas of Ru Dong, Jiang Su province for examples, calculations of safety distances in different combination of wind and current were conducted, and eventually the minimum safety distance of 2,800 m was determined for the not under command vessels to avoid collision with wind turbine. Second, from the perspective of the collision probability between ship and OWF, NIE et al. (2019) developed a ship-OWF collision probability calculation model. The test result showed that the collision probability was closely related to the distance between OWF and waterway, based on which the probability can be reduced by supervising the distance between OWF and waterway. The authors adopted the German acceptable risk criterion for collision risk studies on offshore installations, setting the acceptable probability to 0.0067 ships/year. Thereby the safety distance calculation model was formulated within the acceptable collision risk level, and the safety distance of 1,300 ~ 3,000 m between OWF and waterway was finally calculated. Third, from the perspective of collision avoidance regulations, one Working Group convened by Maritime Navigation Commission of PIANC produced a report (PIANC, 2018) on the interaction between OWFs and maritime navigation, among which acknowledged experts based on COLREGs regulations and guidelines proposed the minimum safety distance model between shipping route and OWF as follows:

(1) Starboard side of any route: 0.3 NM + 6 ship lengths + 500 m; and

(2) Port side of any route: 6 ship lengths + 500 m.

Notes:

- 0.3 NM is the distance that a ship deviates from original track right before it starts a round turn.
- 6 ship lengths is determined as the diameter of a round turn.
- 500 m is the safety zone[4] for protection of OWF structure.

Moreover, OWFs generate radar interference in addition to the effect of swapping targets. The safety distance to avoid interference has been determined by deep sea pilots to be 0.8 NM and surveys have identified a minimum distance of 1.5 NM from a OWF is necessary to minimise the interference on ship born radar and the

[4] According to UNCLOS Article 60 paragraph 4, the coastal State may, where necessary, establish reasonable safety zones around such artificial islands, installations and structures in which it may take appropriate measures to ensure the safety both of navigation and of the artificial islands, installations and structures. And the reserved safety zone has been defined as 500 metres.

automatic radar plotting acquisition (PIANC, 2018).

Yet, the pending question is left for maritime authorities to recommend how much is the distance considered to be safe and minimum, and eventually the mariners have to decide how near they can endure to pass clear of a wind turbine.

2.2.3 The marking of OWF

An OWF is usually formed by a wide array of wind turbines, arranged in a regular way that they will inevitably pose risks to safety of navigation and reshape traffic flow. In order for ships to avoid collision with wind turbines, the OWF shall be appropriately marked with AtoNs, such as light buoys, light beacons, AIS AtoN and fog signals. AtoN is a device, system or service, external to vessels, designed and operated to enhance safe and efficient navigation of individual vessels and/or vessel traffic. According to SOLAS chapter V, regulation 13, each Contracting Government undertakes to provide, as it deems practical and necessary either individually or in cooperation with other Contracting Governments, such aids to navigation as the volume of traffic justifies and the degree of risk requires (IMO, 2018).

There are three national and international regulations for reference when it comes to the marking of OWFs in China. First, *Maritime Buoyage System, China, GB 4696-2016*; Second, *The Regulation for Marking of Offshore structures in China, GB17380-1998*; Third, IALA Recommendation R0139, "*The Marking of Man-Made Offshore Structures*". Based on a survey conducted within the AtoN departments of China[5], a majority of OWFs have been marked in accordance with GB 4696-2016 and IALA Recommendation R0139, only a minority have been marked in accordance with GB 17380-1998. Table 2.2 lists different markings of some representative OWFs in China.

---

[5] In China, AtoN department from the organizational level perspective is a three-level organ affiliated under Ministry of Transport , meanwhile is subject to superior management of China MSA.

Table 2.2 The markings of some representative OWFs in China

NO.	OWF	Characteristics of light	
		Light buoys	Light beacons
1	Long Yuan 480 MW OWF	M “C” Y 12 s	M “C” Y 12 s
2	Shanghai East Bridge 100 MW OWF	M “P” Y 12 s	M “C” Y 15 s
3	Putian Pinghai Bay 50 MW OWF	M “O” Y 12 s	NIL
4	Binhai H2 Meteorological Mast	NIL	M “C” Y 12 s
5	Leting Yuetuo Island Meteorological Mast	M “O” Y 12 s	NIL
6	National Electric 5# Meteorological Mast	M “C” Y 12 s	NIL
7	Zhuhai Jiapeng Meteorological Mast	NIL	M “U” W 12 s

Source: Compiled by the author based on survey.

Notes: M = Morse; Y = Yellow, W = White, representing light colour; s = seconds, representing light rhythm; C means the special mark for offshore structure in GB 4696-2016; P means the special mark for prohibited area; O means the special mark for marine operation area; and U means special mark for offshore structure in GB 17380-1998.

It can be seen from the table that the markings of OWF and isolated meteorological mast were inconsistent due to the adoption of different regulations. For OWFs using M “C” Y 12 s, IALA Recommendation R0139 was adopted. For OWFs using M “P” Y 12 s and M “C” Y 15 s, both GB 4696-2016 and IALA Recommendation R0139 were adopted. For meteorological masts using M “O” Y 12s and M “C” Y 12 s, GB 4696-2016 was adopted. For meteorological masts using M “U” W 12 s, either GB 17380-1998 or IALA Recommendation R0139 was adopted. The problem arising from this inconsistency of adoption of regulations is that AtoN users particularly mariners would be really confused in observing and identifying the diversified markings of OWFs including isolated meteorological masts. Undoubtedly, this ambiguity or inconsistency will undermine the efficacy of AtoNs.

Chapter 3 Navigational Risk Assessment of Offshore Wind Farm

3.1 Introduction of risk assessment models

There are plenty of risk assessment methods developed so far, all of which basically fall within two kinds: quantitative methods using "objective" data and qualitative methods using "subjective" expert judgement (Schröder-Hinrichs, 2020). Quantitative risk assessment methods include Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Preliminary Hazard Analysis (PHA) and Risk Contribution Tree (RCT), etc. Qualitative risk assessment methods include Failure mode, effects and criticality analysis (FMEA/FMECA), Hazard and Operability Analysis (HAZOP), Fuzzy Comprehensive Evaluation (FCE) and Bayesian Networks (BN), etc.

Risk assessment models, on the other hand, are replications of real-life systems and processes. Many scholars, over the years, have developed risk assessment models for many scenarios (Mehdi & Schröder-Hinrichs, 2016). For examples, Mehdi et al. (2020) proposed a dynamic risk assessment model to address safety of navigation concerns around offshore renewable energy installations, it could be used by operational users such as VTS operators, pilots, shore-control centers and seafarers to make better and risk-informed decisions during the operation of vessels near OWFs in restricted, high-traffic-density areas. YU et al. (2020) developed a semi-qualitative risk model to assess the ship-wind turbine collision risks by incorporating Bayesian networks (BN) with evidential reasoning (ER) approaches. However, it has been acknowledged that the NRA conducted by different organizations have received discrepant results for the same OWF. This discrepancy in calculations arises because different countries and organizations use different calculation models and procedures (Mehdi & Schröder-Hinrichs, 2016). Table 3.1 gives a comparison of the NRA processes in eight countries. Currently, the China's management provisions on safety of navigation of water borne activities are general terms, and there is no recommendation on which NRA models or tools could be used. Thus, the use of models or tools during NRA is diversified, the OWF developer may have to use a qualitative approach with experts judgement, but could the invited experts represent the interests of all relevant stakeholders? Or the developer may have to choose a quantitative model, but is the model transparent? The report of Ellis et al. (2008) implied that it was impossible to replicate the calculation results of certain models, as the equations and data values being used were not evident (as cited by Mehdi & Schröder-Hinrichs, 2016). The real issue of this diversification is that different assessment results could be achieved at the same OWF using different models. Additionally, it may be also a bureaucratic burden for the developers because they need to follow different assessment procedures. This is clearly an issue that needs to be addressed urgently.

Table 3.1 Comparison of NRA process in the eight countries

No.	Question	UK	DE	DK	NL	BE	SE	US	CN
1	Is a marine licence necessary for OWF approval in your country?	Yes							
2	Is a NRA necessary for OWF approval in your country?	Yes						No, but generally included.	Yes
3	Who is responsible for conducting this NRA?	OWF Developer			Maritime authority	OWF Developer			
4	Do you have any national guidelines on NRA?	Yes		Internal only	Yes				
5	Do you require the use of any specific models, tools or methods when a NRA is conducted?	No. Recommend FSA; ANATEC's COLLRISK Model commonly used often by developers to compare base case vs. future case risk.	Yes. German Hazardous Incident Ordinance, the British Safety Case Regulations for offshore installations, IMO regulations for risk assessment to be followed. Models from DNV GL most commonly used by developers to compare base case vs. future case risk.	No. Recommend FSA; DNV MARCS model, and models from COWI and Rambøll most commonly used by developers to compare base case vs. future case risk.	No. Recommend FSA; MARIN's SAMSON model used most commonly to compare base case vs. future case risk.	No. Recommend FSA; MARIN's SAMSON model used most commonly to compare base case vs. future case risk.	No. Recommend IWRAP MKII model; SSPA model most commonly used by developers to compare base case vs.future case risk.	No. Recommend 'What-if' analysis amongst other tools.	No. Recommend assessment approaches as follows: comprehensive analysis of data; mathematical model; simulation; sea trials; expert consultation.
6	Are there any specific factors that must be considered in a NRA -e.g. - specific ship type, size,speed, weather conditions, etc.?	Ship traffic, speeds and types through AIS data, dynamic (wind, wave, tides, currents, etc.) and static (bathymetry, hydrographic features, layout of channels, etc.) environmental conditions, OWF location and layout.							
7	Are there any guidelines for approving a wind farm with regards to navigation safety?	No. Case by case basis.	Yes. turbine must be collision friendly, and not rupture hull of a predetermined vessel drifting into it at 2m/s.	No. Case by case basis. *In DK, turbine must be collision friendly.					

Notes: UK = United Kingdom, DE = Germany, DK = Denmark, NL = The Netherlands, BE = Belgium, SE = Sweden, US = United States of America, CN = China.

Source: Adapted from "Improving the coexistence of offshore wind farms and shipping: an international comparison of navigational risk assessment processes", by Mehdi et al., 2018, p.407. https://doi.org/10.1007/s13437-018-0149-0

3.2 The navigation environment of the research waters

3.2.1 Overview of Binhai OWF

Binhai OWF is situated in the offshore sea area between Zhongshan Estuary and Binhai Port, northwest of harbour boundary of Binhai Port. It generally contains two blocks of OWFs that have been established separately in around 2017 and 2018. The general location of the two blocks (H1 OWF & H2 OWF) is delineated in Figure 3.1. The Binhai H1 OWF consists of twenty-five rectangularly distributed wind turbines with unit capacity of 4.0 MW and total installed capacity of 100 MW. The offshore distance is about 7.5 km, the topography of the sea floor changes gently with the water depth ranging mostly between 7-13 metres. The Binhai H2 OWF consists of a hundred polygonally distributed wind turbines with unit capacity of 4.0 MW and total installed capacity of 400 MW. The offshore distance is about 22 km, and the depth of water ranging from 15 to 18 metres.

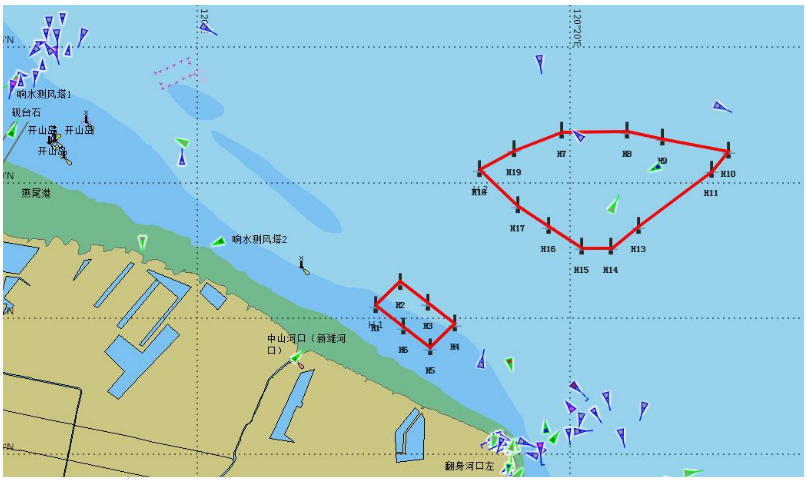


Figure 3.1 The siting of Binhai OWF

Source: Produced by the author.

3.2.2 Meteorological conditions

The OWF is located in the middle latitudes of the northern hemisphere. The humid monsoon climate dominates in this area, and the wind direction varies drastically seasonally, with southeasterly winds prevailing in summer and northeasterly winds in winter. The following data are based on the statistics of annual observation of Binhai meteorological station over the years.

(1) Temperature

The average temperature: 14.1 ℃;
The extreme maximum temperature: 38.5 ℃; and
The utmost lowest temperature: -15 ℃.

(2) Precipitation

The average precipitation: 949.5 mm; and
The maximum annual precipitation: 1381.2 mm.

The region is rainy in summer and dry in winter. The precipitation is mainly concentrated from June to September, accounting for 66% of the total annual precipitation. The maximum annual precipitation is 1381.2 mm, and the maximum precipitation per day is 162.5mm (it appeared in June 1999). The average annual precipitation days are 121.5 days.

(3) Wind condition

According to the observation statistics of the Binhai Oceanic Station, the strong wind direction is E, with measured maximum wind speed of 23.0 m/s. The second strong wind direction is ENE with speed of 21.3 m/s. The directions with the maximum wind speed above 20 m/s include NNE, NE, ENE, E, ESE and SE. The direction of the maximum average annual wind speed is NNE with the average annual speed of 7.14 m/s. The direction of prevailing wind is SE with the occurrence frequency of 10.9 %. The occurrence frequency of N~E~S directions is more than 7 %, and the total occurrence frequency of these directions is about 70 %. The frequency of NNW~W~SSW in all directions is relatively small, less than 6.3 %. The annual average gale of force 6-7 in the sea area is about 60~70 days, and the number of days of force ≥7 gale is 14.8 days. Based on the wind statistics of Binhai Oceanic Station between September 1997 and December 2006, Table 3.2 (the average and maximum wind speed in each direction), Figure 3.2 (frequency rose in each direction) and Figure 3.3 (wind rose) are produced as follows.

Table 3.2 The average and maximum wind speed in each direction by Binhai Oceanic Station (unit: m/s)

Direction	N	NNE	NE	ENE	E	ESE	SE	SSE
Average value	6.34	7.14	6.55	6.35	5.34	5.28	5.61	6.13
Maximum value	18.9	20.7	21	21.3	23	20.6	20.3	20.5
Direction	S	SSW	SW	WSW	W	WNW	NW	NNW
Average value	5.44	4.02	3.89	4.16	3.73	4.2	4.32	5.25
Maximum value	14.9	14	13.5	13.5	16	12.3	13.9	17.6

Source: Reproduced from "Aids to Navigation Project Design of Binhai OWF".

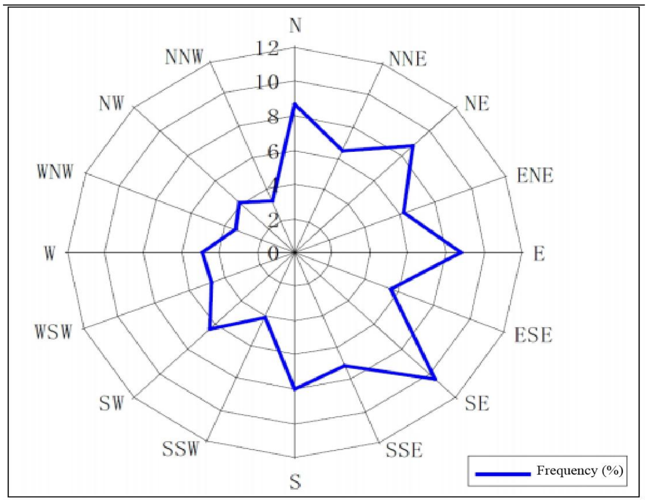


Figure 3.2 Frequency rose of wind in each direction
Source: Reproduced from "Aids to Navigation Project Design of Binhai OWF".

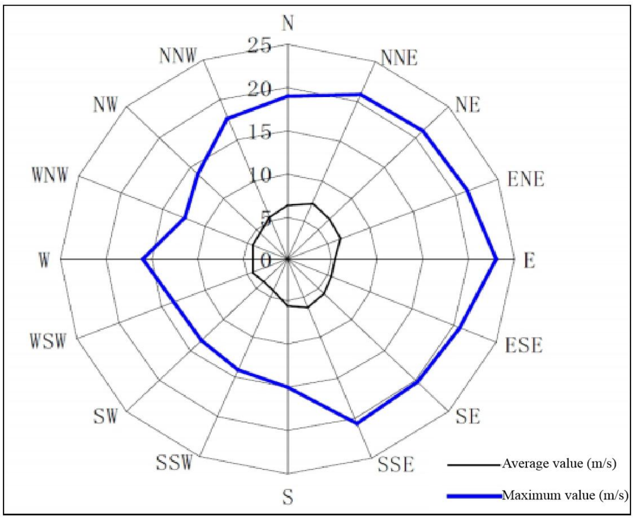


Figure 3.3 Wind rose in each direction

Source: Reproduced from “Aids to Navigation Project Design of Binhai OWF”.

(4) Fog

Fog in this sea area usually occurs in the turn of the spring and summer, or the autumn and winter. According to meteorological statistics of Xintan Salt Farm, the average number of foggy days over the years is 39.9 days. According to the statistics of Binhai Oceanic Station from 2000 to 2003, the foggy days with visibility ≤ 1 km are 14 days and the longest duration is 83 hours.

(5) Thunderstorm

The average number of thunderstorm days over the years in this region is 25.8 days, and the maximum number of thunderstorm days in the past years is 30.0 days, with the most occurring in June to August.

(6) Typhoon

In recent years (1997~2015), a total of 53 tropical cyclones had affected Jiangsu Province, among which twenty made a large impact. The coastal areas of Jiangsu Province are likely to be affected by tropical cyclones from May to November every year. The sea area where the OWF is located is offshore and wide open. The wind speed and strength are both greater than those in the land.

3.2.3 Hydrologic conditions

(1) Wave

The usual wave direction is ESE, with a frequency of 25.39 %, followed by E, ENE and NE, with a frequency of 18.85 %, 10.96 % and 10.81 % respectively. This is related to the prevailing southeast monsoon in the sea area of northern Jiangsu. There are no offshore waves in SSW, SW and WSW. The strong wave directions include NW and NE with NE being the strongest direction. Figure 3.4 shows the frequency rose of wind direction.

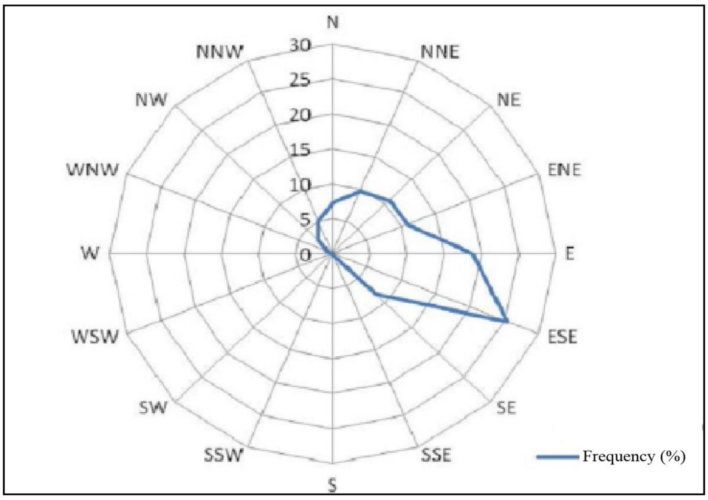


Figure 3.4 The frequency rose of wind direction
Source: Reproduced from "Aids to Navigation Project Design of Binhai OWF".

(2) Tidal current

The tidal current in this sea area is dominated by rectilinear current. The flood tide is from northwest to southeast, the ebb tide is from southeast to northwest. The directions of flood tide are between 105° ~ 156°, and the directions of ebb tide are between 253° ~ 33°. The maximum velocity of the tidal current at measurement point during the spring and autumn is 1.91 m/s and 1.58 m/s respectively, and the maximum velocity of ebb tide is 2.06 m/s and 1.79 m/s respectively.

3.2.4 Port conditions

Binhai port is situated in between south and southeast of Binhai OWF with a straight-line distance of 5 NM approximately. According to the “Development Plan of Jiangsu Coastal Areas”, Binhai port has been designated to serve the development of port industries primarily energy industries. By the beginning of 2018, seven berths ranging from 35,000 tons to 100,000 tons had been completed. Hopefully, the 300,000-ton deep-water terminal will be accomplished in the near future. Currently, Binhai port is a category-two port, accessible for ocean-going vessels of Chinese nationality.

3.2.5 Shipping routes conditions

According to “Shipping Route Planning of Jiangsu Coastal Waters”, there are generally four shipping routes adjacent to Binhai OWF as delineated in Figure 3.5.

(1) The deep-water route approaching Guanhe kou northbound. Way point 1: 33°22.5' N / 123°E; Way point 2：33°47.4' N / 122°38' E; Way point 3：34°14' N / 122°15' E; Way point 4：34°30.5' N / 121°31' E；Way point 5：34°34' N / 120°41' E; and Way point 6：34°37.2' N / 120°0.4' E. The closest distance to Binhai H2 OWF is 3.1 NM.

(2) The shallow-water route approaching Guanhe kou northbound. Way point 1: 31°37' N / 123°E; Way point 2：32°29.7' N / 122°33.6' E; Way point 3：33°48.5' N / 121°52.5' E; Way point 4: 34°34' N / 120°41' E; and Way point 5: 34°37.2' N / 120°0.4' E. The closest distance to Binhai H2 OWF is 3.1 NM.

(3) The two-way route between Guanhe kou and Binhai. Way point 1: 34°29′32.4″N

/ 120°20′16″E ; Way point 2: 34°21′12″N / 120°20′23″E; and Way point 3: 34°17′15″N / 120°20′23″E. The closest distance to Binhai H1 OWF is 1.8 NM. The closest distance to Binhai H2 OWF is 3.8 NM.

(4) The shallow-water route approaching Lian Yungang northbound. Way point 1: 31°37′N / 123°E; Way point 2: 32°29.7′N / 122°33.6′E; Way point 3: 33°48.5′N / 121°52.5′E; and Way point 4: 34°53′N / 119°58′E. The closest distance to Binhai H2 OWF is 3.7 NM.

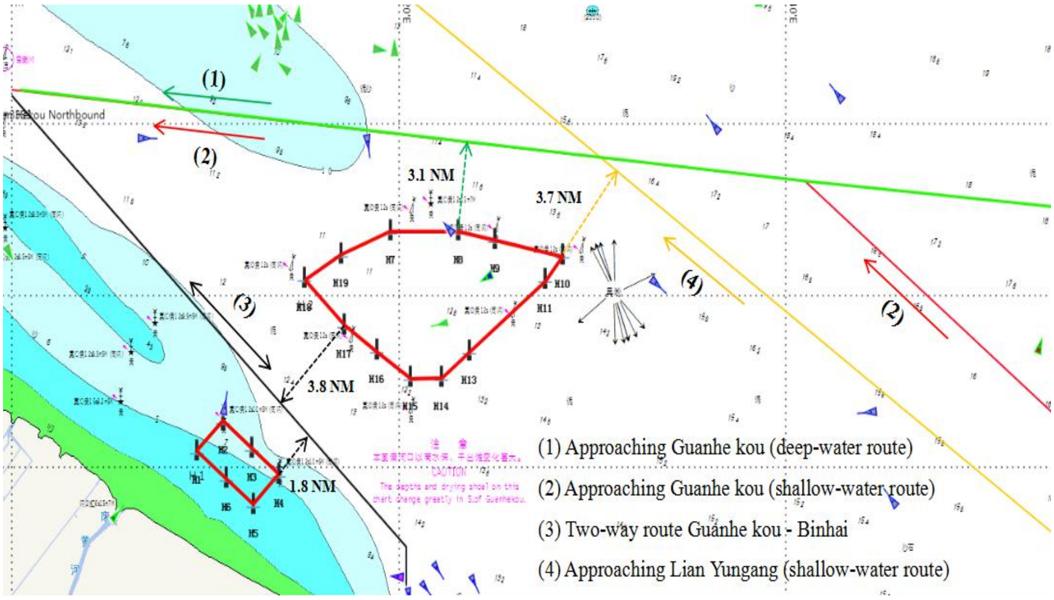


Figure 3.5 The shipping routes adjacent to Binhai OWF

Source: Produced by the author based on the "Shipping Route Planning of Jiangsu Coastal Waters".

3.2.6 Statistical analysis of water traffic accidents

According to the statistical analyses of water accidents carried out by Lian Yungang MSA covering the coastal area of Lian Yungang (coastline: 582.3 km) and the coastal area of Yan Cheng (coastline: 176.5 km), there were twenty-one accidents occurred throughout 2019 as shown in Table 3.3, among which two were major accidents, six were ordinary accidents and thirteen were minor accidents as shown in Table 3.4. All accidents fell into six types including collision, grounding, allision, fire explosion, foundering, operational pollution and else as shown in Table 3.5.

Table 3.3 The statistics of water traffic accidents throughout 2019 in the jurisdiction sea area of Lian Yungang MSA

	Number of accidents	Financial loss (Ten thousand yuan)	Number of sunken ships	Loss of lives	Number of punishment	Fine (Yuan)
Total	21	2606.60	2	16	0	0

Source: Reproduced from "Statistics of water traffic accidents of Lian Yungang MSA in 2019", by Lian Yungang MSA, 2019. http://www.lyg.msa.gov.cn/ssjtaq/49360.jhtml

Table 3.4 Grading of water traffic accidents

	Extraordinarily serious accidents	Major accidents	Ordinary accidents	Minor accidents
Total	0	2	6	13

Source: Reproduced from "Statistics of water traffic accidents of Lian Yungang MSA in 2019", by Lian Yungang MSA, 2019. http://www.lyg.msa.gov.cn/ssjtaq/49360.jhtml

Table 3.5 Types of water traffic accidents

Types	Collision	Grounding	Stranding	Allision	Swell damage
Total	14	1	0	6	0
Types	Fire explosion	Wind damage	Foundering	Operational pollution	Else
Total	2	0	6	3	1

Source: Reproduced from "Statistics of water traffic accidents of Lian Yungang MSA in 2019", by Lian Yungang MSA, 2019. http://www.lyg.msa.gov.cn/ssjtaq/49360.jhtml

Among the twenty-one accidents in 2019, there was one particular accident relating to OWF. On March 25, 2019, the cargo ship "Su Lian Yungang 8866" was on its way from Qingdao, Shandong Province to Fan Shenhe fishing port in Binhai, Jiangsu Province. At 2354 hours, the ship collided with the foundation of No. 38 wind turbine of Binhai H2 OWF in the southern waters of the Yellow Sea (34°30′.6 N /

120°15′.1 E) as shown in Figure 3.6, causing the sinking of "Su Lian Yungang 8866", death of three crew members and missing of the other three crew members, left the foundation with slight damage as shown in Figure 3.7. This collision accident constituted a major water traffic accident. The accident investigation report announced by Lian Yungang MSA provided a comprehensive analysis of the causes of the accident as follows, determining that the accident was the fault of one party, "Su Lian Yungang 8866" took full responsibility.

(1) Failed to keep proper lookout;

(2) Failed to take early actions to avoid collision;

(3) The ship was not seaworthy;

(4) The crew members were not competent;

(5) The registered operator of the ship failed to perform the duty of safety management; and

(6) The actual owner and operator of the ship failed to perform safety and pollution prevention responsibilities.

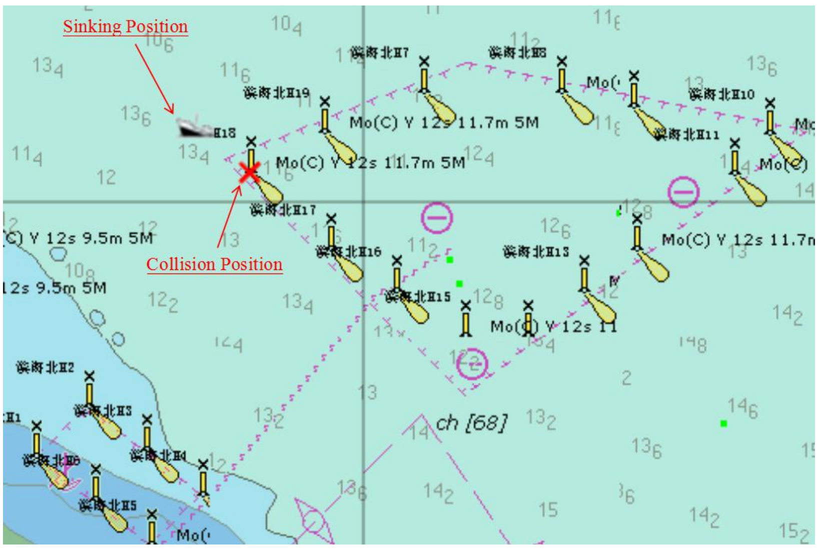


Figure 3.6 Collision and sinking positions of " Su Lian Yungang 8866"

Source: Reproduced from "Accident investigation report of the collision between Su Lian Yungang 8866 and No. 38 Wind turbine of Binhai H2 OWF", by Lian Yungang MSA, 2019, p.10. http://www.lyg.msa.gov.cn/html/ssaqsgxx/20191210/48300.html

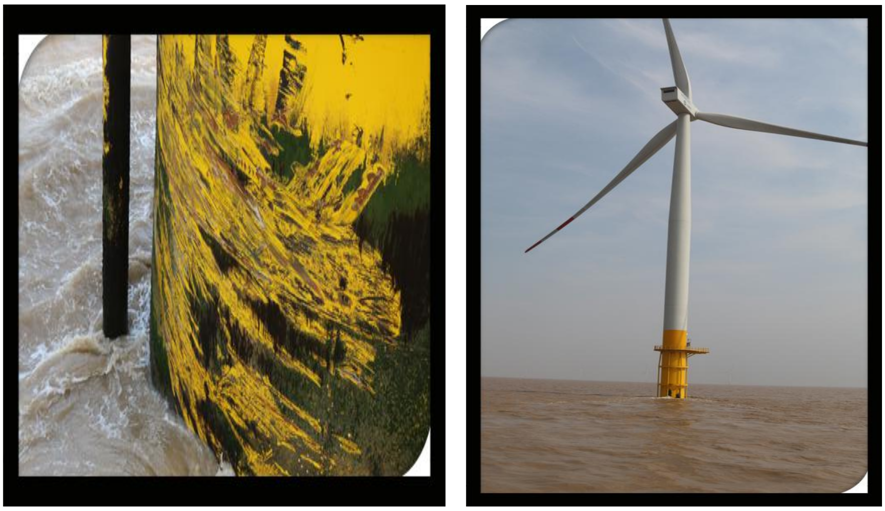


Figure 3.7 The damage incurred by the collision accident
Source: Reproduced from "Accident investigation report of the collision between Su Lian Yungang 8866 and No. 38 Wind turbine of Binhai H2 OWF", by Lian Yungang MSA, 2019, p.18. http://www.lyg.msa.gov.cn/html/ssaqsgxx/20191210/48300.html

3.3 Navigational risk assessment of Binhai OWF

OpenCPN is a concise and robust Chart Plotter Navigating software program that meets the requirements of IMO. It supports the functions of worldwide standard S57 and encrypted S63 vector chart display, AIS input with full target-tracking and collision alerting, route planning and route navigation with ship tracking functions, etc. The functionalities of OpenCPN can be expanded with plugins, for instance, the statistical platform of vessel traffic flow characteristics based on AIS data can be developed and plugged in. The static and dynamic information of ships can be extracted from the AIS data. Studies on vessel traffic volume, density, trajectory, speed and distance can be conducted using AIS data, from which the relevant vessel traffic flow characteristics could be mined. This software is conducive to the rapid statistics of vessel traffic flow characteristics, providing data support for the navigational risk assessment procedure. Therefore, OpenCPN is used in this dissertation to facilitate the navigational risk assessment of Binhai OWF.

3.3.1 Statistical analyses of vessel traffic flow

First, a rectangular working area has been selected covering the whole Binhai OWF, the four vertexes coordinates of the rectangular working area are presented in Table 3.6. Second, the AIS source data of ships within a certain time frame (between September 25, 2020 and April 5, 2021) in the selected sea area were extracted from Lian Yungang AtoN department, and then got parsed. Finally, the parsed data were imported to OpenCPN, and risk assessment results were obtained as follows.

Table 3.6 The four vertexes coordinates of the rectangular working area

Vertex	**Coordinates (CGCS-2000)**	
	N	**E**
1	34°22'33.00"	120°09'19.00"
2	34°22'33.00"	120°28'29.00"
3	34°32'34.00"	120°28'29.00"
4	34°32'34.00"	120°09'19.00"

Source: Produced by the author.

(1) The historical trajectories of all the ships navigating inside the working area within the certain time frame were synthesized and illustrated in Figure 3.8. It can be seen from the chart that plenty of ships were navigating within and in close vicinity of Binhai OWF.

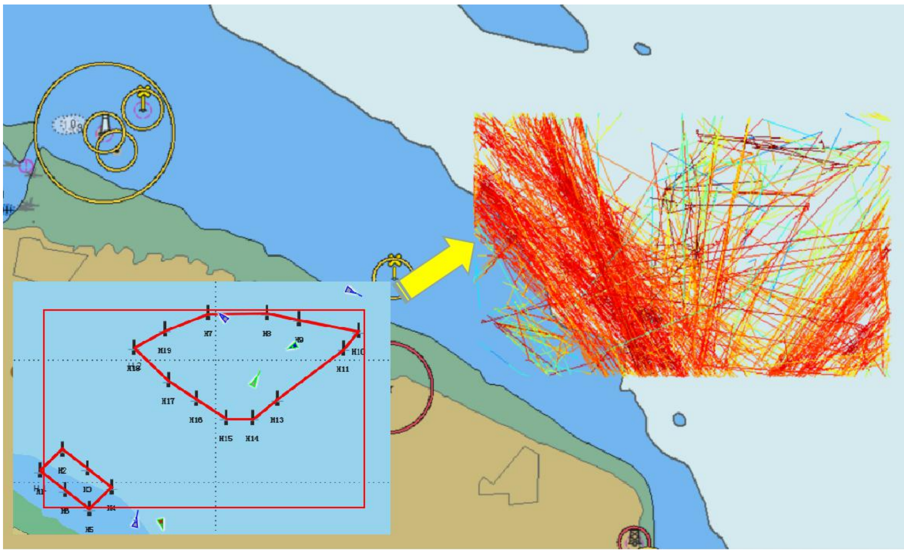


Figure 3.8 The historical trajectories of ships in the working area between September 25, 2020 and April 5, 2021

Source: Assessment result exported from OpenCPN.

(2) For statistical purposes, three cross sections have been established as shown in Table 3.7. Cross section 1 passes through the inshore shipping route between Guanhe and Binhai, cross section 2 passes though Binhai H1 OWF, and cross section 3 passes through Binhai H2 OWF.

Table 3.7 The coordinates of the three cross sections

Cross sections		Coordinates (CGCS-2000)	
		N	E
1	A	34°24′44″	120°12′25″
	B	34°29′	120°17′12″
2	A	34°24′44″	120°12′25″
	C	34°23′ 42″	120°11′05″
3	B	34°29′	120°17′12″
	D	34°31′ 28″	120°28′28″

Source: Produced by the author.

The distributions of vessel traffic flow at the first cross section is presented in Figure 3.9. The types of vessels and quantities have been analysed as shown in Table 3.8, and the dimensions of vessels and quantities are given in Table 3.9, among which the largest vessel passing by had the overall length of 270 m, breadth of 30 m.

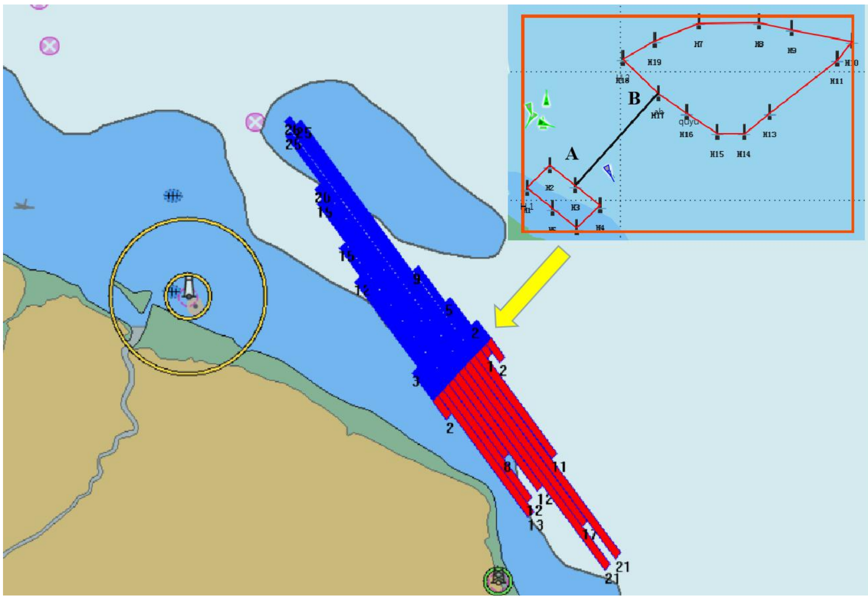


Figure 3.9 The distributions of vessel traffic flow at the first cross section
Notes: The blue area represents the northbound vessels and the red area represents the southbound vessels.
Source: Assessment result exported from OpenCPN.

Table 3.8 Statistics on vessels by type at the first cross section

Types of vessels	Quantity (ship)	Proportion	Traffic flow (ships)
Cargo vessel	64	56.6%	177
Fishing vessel	25	22.1%	46
Towboat	8	7.1%	14
Container vessel	2	1.8%	4
Tanker	4	3.5%	19
Recreational vessel	2	1.8%	3
Law enforcement vessel	1	0.9%	2
Other vessels	7	6.2%	13
Total	113	100%	278

Source: Produced by the author.

Table 3.9 Statistics on vessels by dimension at the first cross section

Dimensions of vessels (m)	**[0-30]**	**[30-50]**	**[50-90]**	**[90-180]**	**>180**
Quantity (ship)	14	26	34	36	3
Proportion	12.4%	23.0%	30.1%	31.8%	2.7%

Source: Produced by the author.

The distributions of vessel traffic flow at the second cross section is presented in Figure 3.10. The types of vessels and quantities have been analysed as shown in Table 3.10, and the dimensions of vessels and quantities are given in Table 3.11.

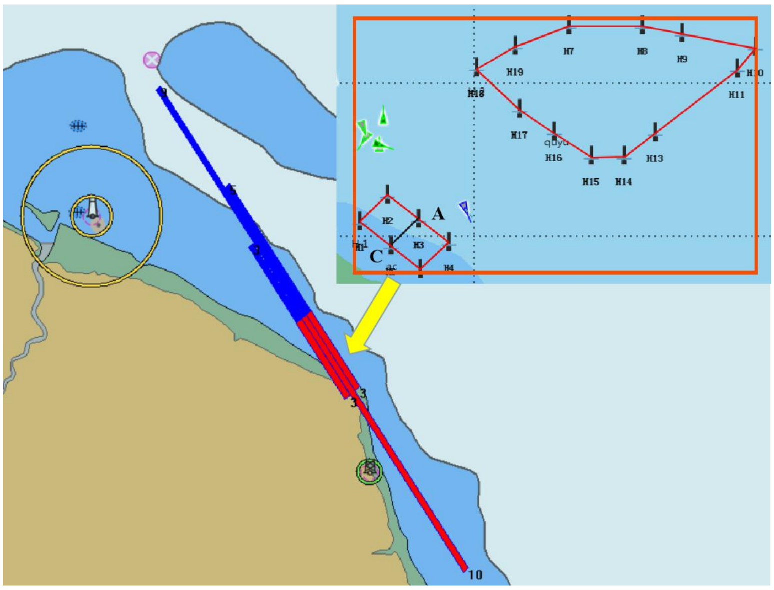


Figure 3.10 The distributions of vessel traffic flow at the second cross section
Notes: The blue area represents the northbound vessels and the red area represents the southbound vessels.
Source: Assessment result exported from OpenCPN.

Table 3.10 Statistics on vessels by type at the second cross section

Types of vessels	**Quantity (ship)**	**Proportion**	**Traffic flow (ships)**
Cargo vessel	2	33.33%	4
Fishing vessel	2	33.33%	21
Other vessels	2	33.33%	8
Total	6	100%	33

Source: Produced by the author.

Table 3.11 Statistics on vessels by dimension at the second cross section

Dimensions of vessels (m)	[0-30]	[30-50]	[50-90]	[90-180]	>180
Quantity (ship)	3	1	2	0	0
Proportion	50.0%	16.7%	33.3%	0.0%	0.0%

Source: Produced by the author.

The distributions of vessel traffic flow at the third cross section is presented in Figure 3.11. The types of vessels and quantities have been analysed as shown in Table 3.12, and the dimensions of vessels and quantities are given in Table 3.13.

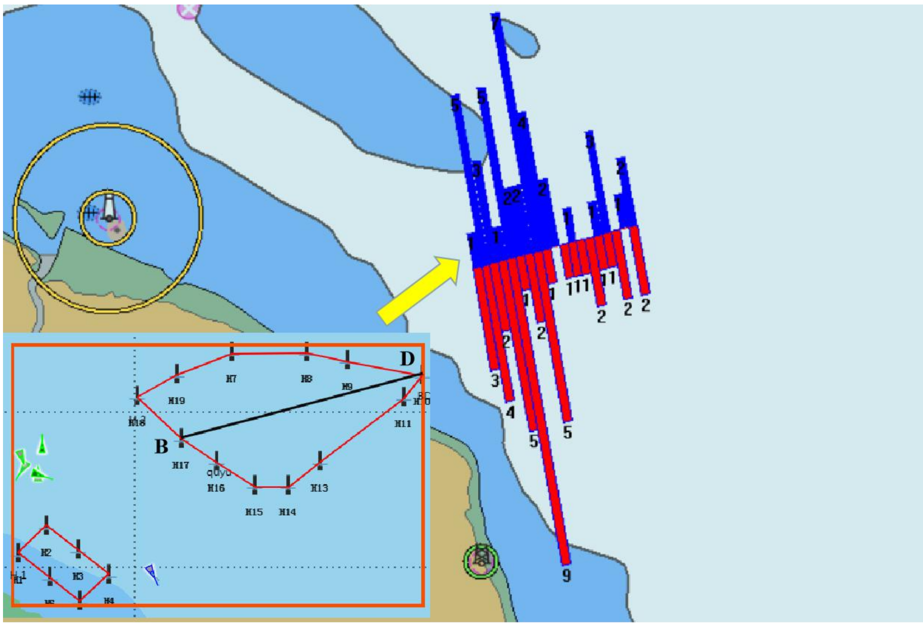


Figure 3.11 The distributions of vessel traffic flow at the third cross section
Notes: The blue area represents the northbound vessels and the red area represents the southbound vessels.
Source: Assessment result exported from OpenCPN.

Table 3.12 Statistics on vessels by type at the third cross section

Types of vessels	Quantity (ship)	Proportion	Traffic flow (ships)
Cargo vessel	11	35.5%	30
Fishing vessel	16	51.6%	39
Offshore support vessel	2	6.5%	9

Tanker	1	3.2%	4
Recreational vessel	1	3.2%	1
Total	31	100%	83

Source: Produced by the author.

Table 3.13 Statistics on vessels by dimension at the third cross section

Dimensions of vessels (m)	**[0-30]**	**[30-50]**	**[50-90]**	**[90-180]**	**>180**
Quantity (ship)	8	12	8	3	0
Proportion	25.8%	38.7%	25.8%	9.7%	0.0%

Source: Produced by the author.

3.3.2 The novel mathematical calculation of DCA and ADA

The above statistical analyses on vessel traffic flow characteristics using Open CPN have provided us with visual and intuitive cognition on the navigation status of ships in the vicinity of Binhai OWF. In order to learn more about risk of navigation through an objective way, this dissertation puts forward for the first time a mathematical method to calculate the Distance of Closest Approach (DCA) and Average Distance of Approach (ADA) between passing ships and OWF based on AIS data of the ships.

All the vessels of displacement that are traveling will leave trails in the water by fueling the waves. Simultaneously, the trails or rather trajectories could be also logged electronically in the AIS-based systems, then displayed graphically on ECDIS, OpenCPN, etc. The AIS data extracted from Lian Yungang AtoN department contain the trajectories of the vessels that have navigated in the inshore shipping route between Guanhe and Binhai, and passed through the first cross section. The accumulated lines of trajectories have formed a "Trajectory Plane" as illustrated in Figure 3.8 and 3.9. The theory of this novel method and practical application are elaborated as follows.

First of all, establishment of the calculation formulas. Suppose the horizontal line segment MN is a cross section that crosses a shipping route, and a ship is projected vertically on the plane as shown in Figure 3.12. The point O at the centre of the breadth of the ship is the point where GPS antenna is installed, in other words, O presents the GPS position of the ship. The heading course of the ship is C when she crosses the MN, and the breadth of the ship is B. If the positioning error, leeway and drift are ignored, the distance between M and P (the intersection point of MN and port side of the projection), and between N and S (the intersection point of MN and starboard side of the projection) can be expressed as:

$$\text{MP} = |MO| - \frac{B}{2\sin(90-C)} = |MO| - \frac{B}{2\cos C};$$

$$\text{NS} = |NO| - \frac{B}{2\sin(90-C)} = |NO| - \frac{B}{2\cos C}.$$

Note： the unit of B is metre, the unit of C is degree.

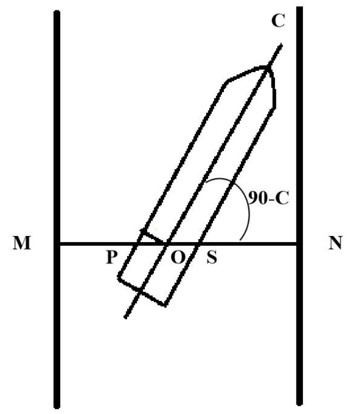


Figure 3.12 The cross section MN and vertical projection of a ship
Source: Produced by the author.

If the cross section is not horizontal, and there is an angle β between the cross section and latitude as shown in Figure 3.13, thus the discussions are divided into three scenarios.

(1) The latitude of N is higher than that of M. The distance between M and P, and between N and S can be expressed as:

$$\mathrm{MP} = |MO| - \frac{B}{2\cos(\beta + C)}; \qquad \mathrm{NS} = |NO| - \frac{B}{2\cos(\beta + C)}.$$

(2) The latitude of N is lower than that of M, and C>β. The distance between M and P, and between N and S can be expressed as:

$$\mathrm{MP} = |MO| - \frac{B}{2\cos(C - \beta)}; \qquad \mathrm{NS} = |NO| - \frac{B}{2\cos(C - \beta)}.$$

(3) The latitude of N is lower than that of M, and C<β. The distance between M and P, and between N and S can be expressed as:

$$\mathrm{MP} = |MO| - \frac{B}{2\cos(\beta - C)}; \qquad \mathrm{NS} = |NO| - \frac{B}{2\cos(\beta - C)}.$$

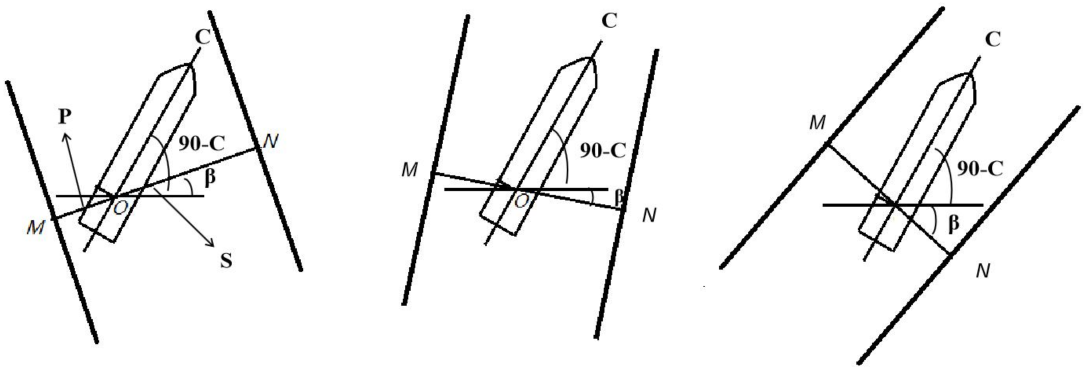


Figure 3.13 Positional relation between heading course and MN
Source: Produced by the author.

Now the calculations for the first cross section can be carried out using the formula above. The Vertexes A and B are the points located on the peripheries of Binhai OWF. The required values of related vessels such as heading courses, coordinates and breadth of vessels have been fetched. Ultimately, the distance of closest approach to

Binhai H1 OWF and Binhai H2 OWF, the average distance of approach to Binhai H1 OWF and Binhai H2 OWF have been calculated and shown in Table 3.14.

Table 3.14 The calculation results for Binhai OWF using the novel method

	DCA (m)	ADA (m)
The distance to Point A of Binhai H1 OWF	506.5	2482.3
The distance to Point B of Binhai H2 OWF	555.4	9969.5

Source: Produced by the author.

As can be seen from the calculation results, some vessels passed the OWF with a very small distance of 0.27 NM approximately, which is certainly not a safe passing distance that are recommended by various scholars as mentioned in chapter 2. This novel mathematical method has provided a potential quantitative approach for the maritime authorities to carry out navigational risk assessment.

Chapter 4 Recommendations on Maritime Safety Supervision and Navigation Service

Chapter 1 Article 3 of the *Maritime Traffic Safety Law of the People's Republic of China*, states that "the use of the sea for transportation is protected by the country pursuant to the law". China MSA in accordance with the law performs the maritime supervision duties, maintains the order of maritime traffic and ensures the safety of navigation of domestic and foreign ships navigating in the vicinity of OWFs. In December 2017, to serve the development and construction of OWF, China MSA drafted the *Guidance on Enhancing Maritime Safety Supervision of OWF,* which specifies the concept of "Feedforward, Concurrent and Feedback Control", realizing entire process management of OWFs.

This chapter will, from the perspectives of maritime supervision and navigation service, work out risk control options (RCOs) that are designated for improving safety of navigation of ships in the vicinity of OWFs. The RCOs are categorized according to four phases of OWF, the RCOs for design, construction and decommissioning phases are general measures, applicable for common OWFs. In light of the result obtained in the navigational risk assessment of Binhai OWF, the RCOs prescribed in the operating phase will be more nichetargeting and specific.

4.1 RCOs in the design phase of OWF

The OWF siting after completion of construction will have long-term implications for safety of navigation. Currently, the improper siting of OWFs is the immediate causation of increase of traffic density, which mediately induces maritime accidents. On the other hand, it is the energy authority in China who has the national power to decide and approve the siting of OWFs, and the maritime authority usually has no much say in this. Therefore, it is recommended that the maritime authorities should proactively participate in the OWF siting as early as possible, preferably during the project approval process and the processes thereafter, in order for the OWF leading authority to be aware of maritime concerns, needs and risks. Apart from the active participation in the institutional level, the maritime authorities could play a much bigger role in the technical level.

One one hand, enhance the involvement of MSP. The main purpose of MSP is to achieve a balanced approach towards safety of navigation, protection of environment, and effectiveness of economy and society (IALA, 2017). It could be a perfect tool for coordination and harmonisation of the use of marine spaces among various stakeholders. The MSP requires the GIS to organise and present data, the most essential data source derives from maritime data including ship traffic densities (AIS data), routes, accidents, expected growth (of density and/or ship sizes), intended routeing measures, etc., which should be provided in such a way that it may easily be imported into the GIS. Hence, the maritime authorities should make the maritime data readily accessible to facilitate the MSP in the process of OWF siting.

On the other hand, formulate the maritime criteria of OWF siting based on engineering practice and relevant studies. Generally speaking, the OWF siting should keep clear of shipping routes, anchorages and prohibited areas, and it’s a good practice to design the OWF in such a manner that the array of wind turbines are in parallel to the shipping route. Specifically speaking, a NRA should be conducted in the siting optimization process. Although this responsibility belongs to OWF developer, the maritime authorities can't just walk away, both parties should play a crucial part in the risk assessment. It is suggested that the use of NRA models should be harmonised, the transparency should be improved and more representative stakeholders should be involved. Generally, the data-based quantitative risk assessment approach is preferable to the qualitative risk assessment approach in view of objectivity and accuracy. Regarding the minimum safety distance from OWF to shipping route, anchorage, etc., there shouldn't be a fixed distance suitable for all circumstances. On the contrary, the minimum safety distance at the design phase of an OWF should be determined on a case by case basis, taking into account the differentiated traffic conditions such as volume, tonnage, cargo, sea conditions, etc.

All in all, the siting of OWF requires the critical input from the maritime authorities both in institutional and technical levels. The maritime authorities should optimize the sites on the basis of traffic conditions and navigation resources, to eliminate or mitigate the negative impacts of OWFs to navigation environment from the origin.

4.2 RCOs in the construction phase of OWF

The construction of an OWF usually takes up more than one year, during which period the working environment is harsh due to the hostile natural environment such as bad weather and rough sea, not to mention the complex traffic flow. Besides, the offshore construction makes it hard for maritime safety supervision. In order to ensure the safety of navigation during the construction phase, the following RCOs are recommended.

On one hand, it is recommended to establish a special regulation applicable to OWF maritime safety supervision in order to maintain the traffic order during the construction phase, and protect safety of navigation, property, lives and marine environment. The regulation should be an overarching framework consisting a wide range of matters including management requirement on construction vessels, crew members and temporary staff, the issuance of marine license, the use of guardship, contingency planning and emergency response, etc. In particular, the supervision over the seaworthiness of construction vessels and the competency of crew members should be strengthened due to frequent operations against relevant regulations such as the use of substandard vessel, insufficient manning level, improper lookout and violation of collision avoidance rules, etc. A feasible supervision program can be initiated based on the construction plan to effectively conduct supervision over the operations that pose major threat to navigation environment. A guardship can be deployed to safeguard the construction water and prevent passing vessels from entering the water accidentally. The maritime safety information (MSI) should be made available to the construction vessels for implementing safety measures, and the reporting system should be established to be informed of the dynamic conditions of the construction vessels.

On the other hand, it is suggested to establish the marine Aids to Navigation for OWF rigorously. During the construction phase, the marking of construction site is absolutely necessary. Generally speaking, there is no doubt about using the Special Marks as AtoNs in the construction phase of an OWF, however inconsistency arises as to the use of different light characteristics. Special marks as is shown in figure 4.1 and Table 4.1 are used to indicate a special area or feature whose nature may be apparent from reference to a chart or other nautical publication. They are not generally intended to mark channels or obstructions where MBS[6] provides suitable

[6] MBS is an abbreviation for IALA Maritime Buoyage System, which is an internationally recognised buoyage system and has been adopted by lighthouse authorities from more than 50 countries. It aims to harmonise the AtoN markings of all coastal countries since its inception in the 1970s.

alternatives. A majority of the special marks were fitted with Morse "O" lighting rhythm, as the construction sites were considered as marine operation areas. Some were fitted with Morse "C" lighting rhythm, as the construction sites were considered as established offshore structures. And a few were fitted with Morse "P" lighting rhythm to indicate that the construction sites were prohibited from entering. A variety of lighting rhythms are presented in figure 4.2. But, in order to avoid ambiguity, the markings of OWFs in the construction phase should be harmonised. In this regard, the Morse "O" lighting rhythm is recommended based on the following considerations. First of all, viewing the construction site as prohibited area is not reasonable in that the OSVs constantly shuttle between port and the site, which perhaps brings misunderstanding to other passing vessels. Then, the Morse "C" lighting rhythm fitted on established offshore structures, obviously an OWF in the construction phase is not completed yet. Last but not least, only the Morse "O" lighting rhythm marking the area of operation provides explicit caution without ambiguity.

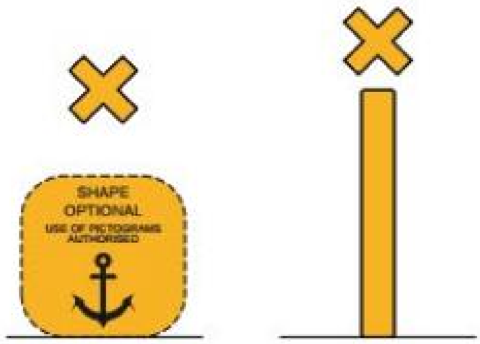


Figure 4.1 Special marks

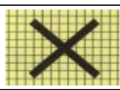
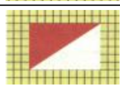
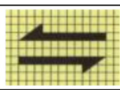
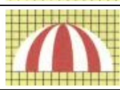
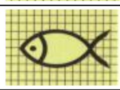
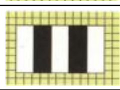
Source: From "R1001 the IALA Maritime Buoyage System", by IALA, 2017, p.21. https://www.iala-aism.org/product/r1001-iala-maritime-buoyage-system/

Table 4.1 Description of Special Marks

Description		
Colour		Yellow
Shape of buoy		Optional, but not conflicting with Lateral marks.
Top-mark (if any)		Single yellow “X” Shape
Light (when fitted)	Colour	Yellow
	Rhythm	Any, other than those reserved for cardinal, isolated danger and safe water marks.
Pictogram		The use of pictograms is authorised, as defined by a competent authority.

Source: adapted from “R1001 the IALA Maritime Buoyage System”, by IALA, 2017, p.21. https://www.iala-aism.org/product/r1001-iala-maritime-buoyage-system/

Table 4.2 Usage of different light rhythms for special marks

Category	Sign		Light Characteristics		
	Colour	Pictogram	Colour	Rhythm	Period “s”
Anchorage	Black		Yellow	M “Q” – –.–	12 s
Prohibited area	Black			M “P” .– –.	
Marine operation area	Red and White			M “O” – – –	
Traffic Separation	Black			M “K” –.–	
Offshore structure	Black			M “C” –.–.	
Recreational area	Red and White			M “Y” –.– –	
Aquatic area	Black			M “F” ..–.	
Crossing area	Black and White			M “Z” – –..	
Remarks: 15 s can be an alternative					

Source: From “Maritime Buoyage System, China”, by Ministry of Transport, 2016, p.8. http://jtst.mot.gov.cn/search/std?q=

4.3 RCOs in the operating phase of OWF

An OWF after completion of construction usually will be operating for more than 20 years. The OWF will exert long-term and permanent influence on safety of navigation, which requires effective and sufficient RCOs from the maritime authorities. The establishment of AtoN is an essential probability reducing RCO. However, the AtoNs established so far in China during the operating phase of OWFs are lack of uniformity as illustrated in the chapter 2. SOLAS Chapter V Regulation 13.2 states that, "In order to obtain the greatest possible uniformity in aids to navigation, Contracting Governments undertake to take into account the international recommendations and guidelines when establishing such aids". Hence, it is suggested that IALA Recommendations R0139 on the Marking of Man-Made Offshore Structure should be followed. In fact, the outdated GB 17380-1998 had been revised in the past few years achieving great uniformity with R0139, which will come into force by the end of 2021. Generally speaking, the Significant Peripheral Structure (SPS)[7] of an OWF shall display Morse "C" Yellow, with a nominal range of 5 NM. The Intermediate Peripheral Structure (IPS)[8] of an OWF shall be marked with Morse "C" Yellow, the lighting rhythm shall be distinctly different from those displayed on the SPS, with a nominal range of 2 NM. See figure 4.2 for better comprehension how an OWF should be marked. The Substation or Meteorological Mast, if considered to be a composite part of the OWF, shall be included as part of the overall OWF marking, otherwise it shall be marked as an isolated offshore structure, which is Morse "U" White ≤15s with a nominal range of 10 NM.

[7] A Significant Peripheral Structure is the 'corner' or other significant point on the periphery of the OWF.
[8] An Intermediate Peripheral Structure is Intermediate structures on the periphery of an OWF other than the SPS.

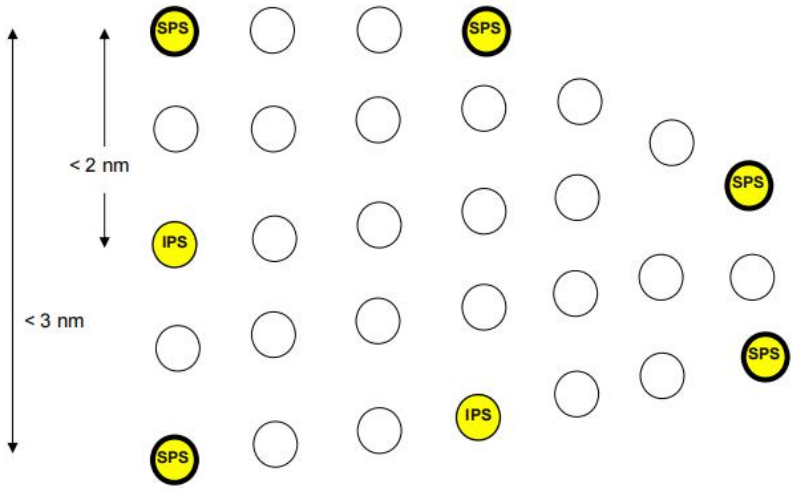


Figure 4.2 Sample marking of an OWF

Source: From "R0139 The Marking of Man-Made Offshore Structures", by IALA, 2013, p.14. https://www.iala-aism.org/product/marking-of-man-made-offshore-structures-o-139/

Apart from the proper markings of OWF, this subsection will illustrate the existing RCOs in the Binhai OWF, and then put forward additional RCOs based on the risk assessment result obtained in chapter 3.

4.3.1 The existing RCOs in the operating phase of Binhai OWF

In terms of maritime safety supervision, the RCOs in this phase resemble that of construction phase, inter alia, seaworthiness of operation and maintenance vessels, competency of crew members, reporting system, promulgation of MSI, traffic control and SAR. In particular, the OSVs used for transporting OWF maintenance personnel are given much attention due to some safety concerns such as replacing the maintenance vessel with substandard fishing boat, unqualified crew members, insufficient manning, overloading, etc. Moreover, "routeing scheme" can be also applied to the OSVs considering their relatively fixed routes, which is also beneficial for emergency SAR operation.

In terms of AtoN service, fixed marks have been established on the platforms of the wind turbines in accordance with IALA R0139. First, colouring and numbering of wind turbines. The structures were painted yellow all around from the level of HAT up to 15 metres. The structures were numbered black with the height no less than 1 metre. Second, fixed light beacons. The Binhai OWF generally contains two blocks (H1 & H2), consisting a total of 125 wind turbines as delineated in Figure 4.3. The Binhai H1 OWF have been marked with six light beacons, among which four light beacons were fitted on ＃1, ＃5,＃21 and ＃25 wind turbines that were viewed as significant peripheral structures, and two light beacons were fitted on ＃11 and ＃15 wind turbines that were viewed as intermediate peripheral structures. All the six light beacons display Morse "C" Yellow 12 s with synchronised flashing. The Binhai H2 OWF have been marked with thirteen light beacons, all of which were viewed as significant peripheral structures because all the wind turbines in the second block were distributed in such a way that they formed a polygon. The thirteen light beacons display Morse "C" Yellow 12 s with synchronised flashing. Third, AIS AtoN. In order to enhance the identification of the OWF under poor visibility, four wind turbines in Binhai H1 OWF and five wind turbines in Binhai H2 OWF were also installed with AIS AtoNs providing comprehensive navigation service. Detailed technical data are given in Table 4.3 and Table 4.4.

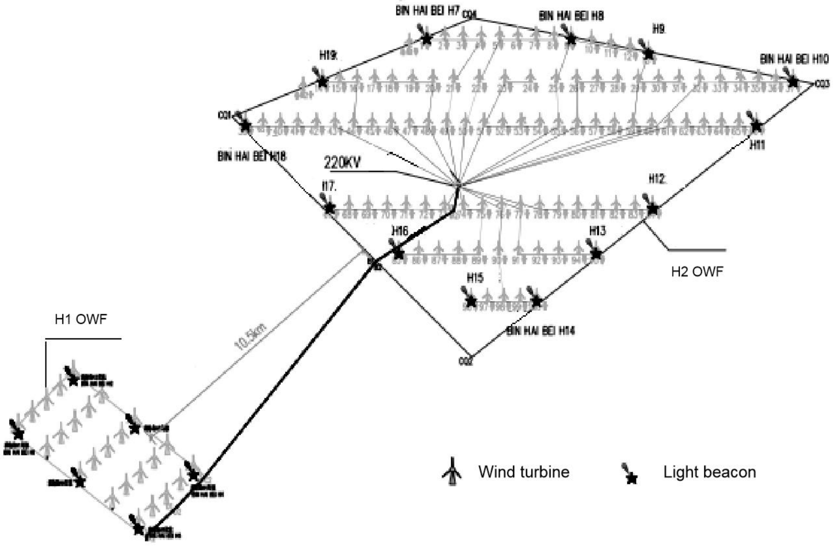


Figure 4.3 Site plan of Binhai OWF

Source: Adapted from "Aids to Navigation Project Design of Binhai OWF".

Table 4.3 AtoNs Technical data of Binhai H1 OWF in the operating phase

NO.	Name	Character	Coordinates (CGCS-2000)		Light characteristics	Location
			N	E		
1	Binhai H1 light beacon	Special Marks	34°24′36.07″	120°09′33.63″	M "C" Y 12 s Synchronised flashing	# 1 wind turbine
2	Binhai H2 light beacon		34°25′38.89″	120°10′53.68″		# 5 wind turbine
3	Binhai H3 light beacon		34°24′42.57″	120°12′23.27″		# 15 wind turbine
4	Binhai H4 light beacon		34°23′47.10″	120°13′48.53″		# 25 wind turbine
5	Binhai H5 light beacon		34°22′44.31″	120°12′28.47″		# 21 wind turbine
6	Binhai H6 light beacon		34°23′39.77″	120°11′03.21″		# 11 wind turbine
7	Binhai H1	AIS	34°24′36.07″	120°09′33.63″		# 1 wind turbine
8	Binhai H2		34°25′38.89″	120°10′53.68″		# 5 wind turbine
9	Binhai H4		34°23′47.10″	120°13′48.53″		# 25 wind turbine
10	Binhai H5		34°22′44.31″	120°12′28.47″		# 21 wind turbine

Source: Adapted from "Aids to Navigation Project Design of Binhai H1 OWF".

Table 4.4 AtoNs Technical data of Binhai H2 OWF in the operating phase

NO.	Name	Character	Coordinates (CGCS-2000)		Light characteristics	Location
			N	E		
1	Binhai H7 light beacon	Special Marks	34°32′19.6″	120°19′32.8″	M "C" Y 12 s Synchronised flashing	# 1 wind turbine
2	Binhai H8 light beacon		34°32′19.0″	120°23′03.6″		# 9 wind turbine
3	Binhai H9 light beacon		34°32′01.1″	120°24′56.6″		# 13 wind turbine
4	Binhai H10 light beacon		34°31′27.5″	120°28′27.6″		# 37 wind turbine
5	Binhai H11 light beacon		34°30′36.5″	120°27′33.6″		# 66 wind turbine
6	Binhai H12 light beacon		34°28′59.7″	120°25′01.5″		# 84 wind turbine
7	Binhai H13 light beacon		34°28′07.0″	120°23′38.8″		# 95 wind turbine
8	Binhai H14 light beacon		34°27′11.5″	120°22′11.7″		# 100 wind turbine
9	Binhai H15 light beacon		34°27′11.8″	120°20′36.2″		# 96 wind turbine
10	Binhai H16 light beacon		34°28′07.9″	120°18′50.8″		# 85 wind turbine
11	Binhai H17 light beacon		34°29′01.0″	120°17′10.8″		# 67 wind turbine
12	Binhai H18 light beacon		34°30′38.6″	120°15′07.6″		# 38 wind turbine
13	Binhai H19 light beacon		34°31′29.7″	120°17′00.0″		# 14 wind turbine
14	Binhai H7	AIS	34°32′19.6″	120°19′32.8″		# 1 wind turbine
15	Binhai H8		34°32′19.0″	120°23′03.6″		# 9 wind turbine
16	Binhai H10		34°31′27.5″	120°28′27.6″		# 37 wind turbine
17	Binhai H14		34°27′11.5″	120°22′11.7″		# 100 wind turbine
18	Binhai H18		34°30′38.6″	120°15′07.6″		# 38 wind turbine

Source: Adapted from "Aids to Navigation Project Design of Binhai H2 OWF".

4.3.2 Additional RCOs for Binhai OWF

As indicated in chapter 3, there were many cargo vessels navigating in close vicinity of the OWF, and a lot of fishing vessels were navigating inside of the OWF. This force of habit of navigation not only endangers the vessels themselves but also poses a threat to the OWF. In order to reduce the risk of collision, the following RCOs are recommended.

First, establish Safety Zone, Safe Passing Distance and Recommended Route. Pursuant to UNCLOS Article 60, a Safety Zone of 500 metres in breadth could be established for protection of wind turbines, all ships including fishing vessels must respect and implement the Safety Zone with generally accepted international and domestic regulations regarding navigation in the vicinity of wind turbines and Safety Zone. Based on the simple and practical calculation model produced by PIANC, the Safe Passing Distance between wind turbines and shipping route can be calculated. Considering that the ships are navigating between the two blocks of Binhai OWF, meaning that wind turbines are situated on both sides of ships, therefore the calculation model "Starboard side of any route: 0.3 NM + 6 ship lengths + 500 m" should be applied. As is learned from the navigational risk assessment result in chapter 3, the maximum length of ship navigating in the vicinity of Binhai OWF is 270 m, taking the future maximization trend of ships and depth of water into account, the length of 300 m is taken in this case. Eventually, the proposed Safe Passing Distance = 0.3 NM + 6 × 300 m + 500 m ≈ 1.5 NM. The local maritime authority should publicise this information as soon as it is adopted through identification on the nautical charts and publications and promulgation of MSI. Based on the "General Planning of National Coastal Shipping Routes" , Jiangsu MSA announced the "Shipping Route Planning of Jiangsu Coastal Waters" in 2012. The shipping route between Guanhe and Binhai port is as follows: A ship after passing clear of the safe water mark of Guanhe kou should alter its course to 145 ° , and proceed to the position (34°21′12″N / 120°20′23″E), and then turn to 180°, and proceed to the position (34°17′15″N / 120°20′23″E), arriving at the entrance light buoy of Binhai

Port. Vice versa for the shipping route from Binhai Port to Guanhe kou. The voyage planning shows that the shipping route passes the H1 & H2 OWF in between. It is suggested to develop a Recommended Route based on this shipping route that could facilitate safety of navigation in the vicinity of Binhai OWF. The proposed Recommended Route starts with the position (34°30′11.30″N / 120°10′12″E), and ends with the position (34°21′12″N / 120°20′23″E), with the depth of water 12 metres approximately. In view of the navigational risk assessment result, the number of vessels using the route is around 556 ships per year. Based on an AIS study by Maritime Institute Netherlands (MARIN), a traffic lane which accommodates 556 ships per year with a maximum size of 300 metres should be at least 1200 metres wide (=2 × 2 × 300 m). Considering the sufficient width of navigable waters, the width of the Recommended Route is expanded to 2 NM. The Safety Zone and Recommended Route are indicated in Figure 4.4.

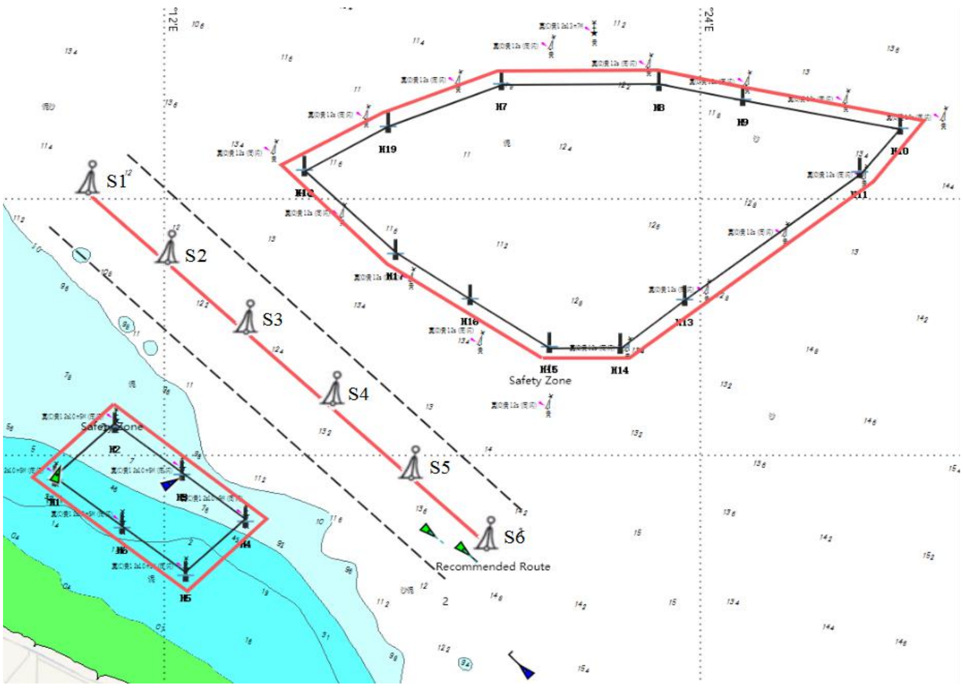


Figure 4.4 The Safety Zone and Recommended Route of Binhai OWF
Source: Produced by the author.

Second, the marking of Recommended Route and adjustment of light characteristics of light beacons. The proposed Recommended Route can also be marked with Safe Water Marks to indicate navigable waters of the waterway and separate the two-way traffic flow. Six safe water marks can be installed in the centreline of the Recommended Route as delineated in Figure 4.4. The technical data of the six safe water marks can be found in Table 4.5. As mentioned above, the lighting rhythm of light beacons on IPS shall be distinctly different from those displayed on the SPS, nevertheless the four light beacons fitted on SPS and two light beacons fitted on IPS display identical lighting rhythm. For easy identification of the OWF, it's suggested to adjust the lighting rhythm of the two light beacons fitted on IPS from 12 s to 15 s, and the nominal range from 5 NM to 2 NM.

Table 4.5 The technical data of the six safe water marks

NO.	Name	Character	Coordinates (CGCS-2000)		Light characteristics	
			N	E	Colour	Rhythm
1	S1 light buoy	Safe Water Marks	34°30′11.30″	120°10′12.00″	White	Isophase, occulting, one long flash every 10 s or Morse "A"
2	S2 light buoy		34°28′23.40″	120°12′14.28″		
3	S3 light buoy		34°26′35.50″	120°14′16.60″		
4	S4 light buoy		34°24′47.54″	120°16′18.92″		
5	S5 light buoy		34°22′59.48″	120°18′21.07″		
6	S6 light buoy		34°21′12.00″	120°20′23.00″		

Source: Produced by the author.

Third, eliminate the blind spots of maritime safety supervision by establishing complementary AIS, VHF, Radar and CCTV equipment. Affected by the operating distance of shore-based AIS stations and the signal interference of OWF, the loss of AIS signal and intermittent loss of communication occur frequently in ships navigating inside and in the vicinity of the OWF. According to GMDSS, Sea Area A1 is defined as "An area within the radiotelephone coverage of at least one VHF coast station in which continuous DSC alerting is available". A1 covers a sea area up to about 25 NM from the coast station in China. The nearest coast station is situated in Lian Yungang covering an area with the center coordinates ‘34°44′ N, 119°21′ N’ and a radius of 25 NM as delineated in Figure 4.5. Obviously, the Binhai OWF is beyond the coverage of Lian Yungang coast station. Shore-based Radar is an essential facility in provision of vessel traffic services. The Binhai OWF is also beyond the reach of Binhai port VTS as shown in Figure 4.6. CCTV system has been used by the maritime authorities in major ports and waterways, enabling visual surveillance of traffic flow. In view of the demand analysis, it’s suggested to install AIS base station, VHF base station, Radar and CCTV equipment on the platform of substation (uninterrupted power supply, maintenance friendly) to enhance the AIS, VHF, Radar and video signal coverage around the OWF. Figure 4.7 shows the approximate signal coverage of the proposed AIS and VHF base stations. All data can be fed into VTS center of the local maritime authority so as to improve the identification accuracy of ships, enhance VTS public service and realize continuous supervision and management of both static and dynamic information of ships.

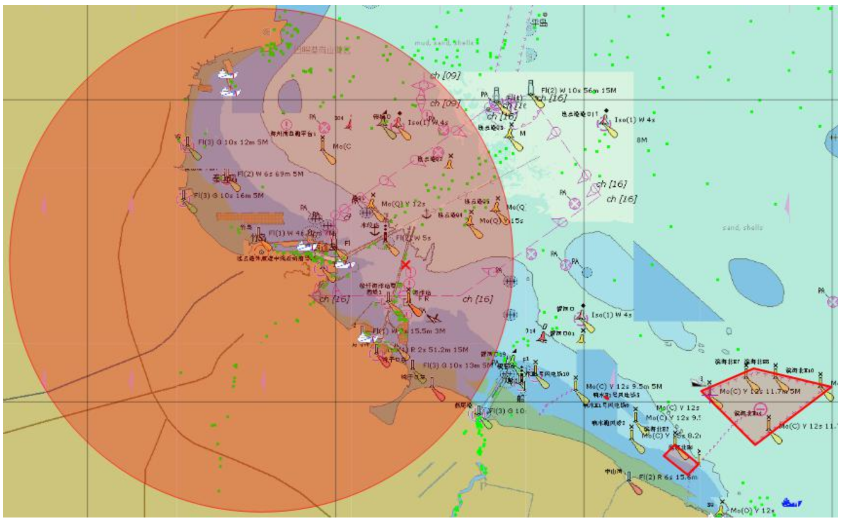


Figure 4.5 Signal coverage of Lian Yungang coast station

Source: Produced by the author.

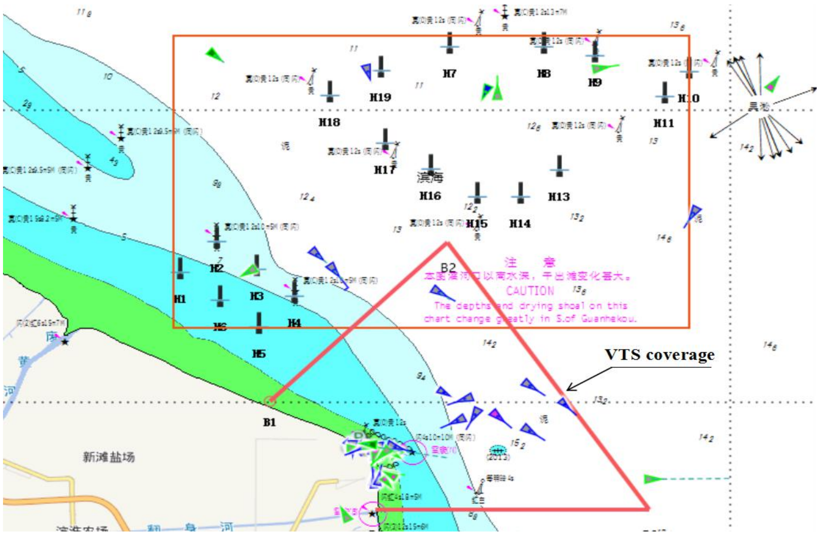


Figure 4.6 VTS area of Binhai Port

Source: From "Vessel Traffic Services Guide, Yancheng MSA".

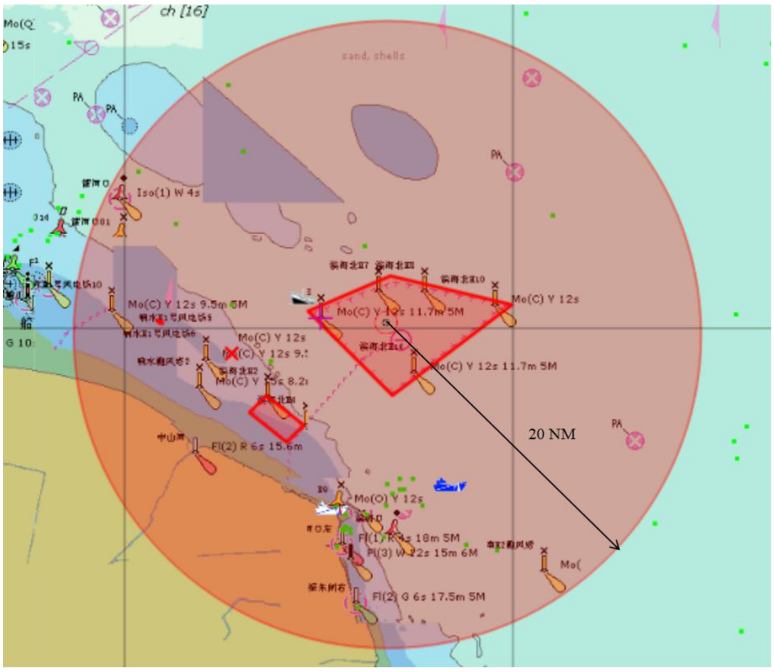


Figure 4.7 Signal coverage of AIS and VHF base stations

Source: Produced by the author.

Furthermore, an Electronic Fencing System integrating AIS, Radar, VHF, CCTV and acousto-optic alarm devices can be also established on the substation. It could effectively capture, warn, call and expel all errant vessels, ensuring safety of navigation around Binhai OWF. The AIS, Radar and CCTV devices are used for capturing static and dynamic information of ships navigating around the OWF. And VHF and acousto-optic alarm devices can be used for warning of ships entering the warning areas of the OWF. Main components of the electronic fencing system are listed in Table 4.6. Three levels of warning areas can be set up on the periphery of the OWF at a distance of 500 m, 1000 m and 1500 m respectively. The three level early warning mechanism of Binhai OWF is shown in Figure 4.8. Should a ship cross the level 1 warning line, Radar and AIS would capture its information, and a warning message would be broadcast through VHF radiotelephone notifying the ship to keep clear. Should the ship proceed to cross the level 2 warning line, the early warning system would be activated automatically warning the ship to keep away. If the ship were to defy and cross the level 3 warning line, CCTV would be initiated monitoring the dynamics of the ship in real time, and VTS involvement would be needed at this time to expel the ship and collect the evidence in case of any accident incurred.

Table 4.6 Main components of the electronic fencing system

NO.	**Components**	**Coordinates (CGCS-2000)**		**Location**	
		N	**E**		
Acousto-optic alarm device					
1	No.1 acousto-optic alarm device	34°24′36.07″	120°09′33.63″	＃1 wind turbine	H1 OWF
2	No.2 acousto-optic alarm device	34°25′38.89″	120°10′53.68″	＃5 wind turbine	
3	No.3 acousto-optic alarm device	34°24′42.57″	120°12′23.27″	＃15 wind turbine	
4	No.4 acousto-optic alarm device	34°23′47.10″	120°13′48.53″	＃25 wind turbine	
5	No.5 acousto-optic alarm device	34°22′44.31″	120°12′28.47″	＃21 wind turbine	
6	No.6 acousto-optic alarm device	34°23′39.77″	120°11′03.21″	＃11 wind turbine	
7	No.7 acousto-optic alarm device	34°32′19.60″	120°19′32.80″	＃1 wind turbine	H2 OWF
8	No.8 acousto-optic alarm device	34°32′19.00″	120°23′03.60″	＃9 wind turbine	
9	No.9 acousto-optic	34°32′01.10″	120°24′56.60″	＃13 wind	

	alarm device			turbine	
10	No.10 acousto-optic alarm device	34°31′27.50″	120°28′27.60″	＃37 wind turbine	
11	No.11 acousto-optic alarm device	34°30′36.50″	120°27′33.60″	＃66 wind turbine	
12	No.12 acousto-optic alarm device	34°28′59.70″	120°25′01.50″	＃84 wind turbine	
13	No.13 acousto-optic alarm device	34°28′07.00″	120°23′38.80″	＃95 wind turbine	
14	No.14 acousto-optic alarm device	34°27′11.50″	120°22′11.70″	＃100 wind turbine	
15	No.15 acousto-optic alarm device	34°27′11.80″	120°20′36.20″	＃96 wind turbine	
16	No.16 acousto-optic alarm device	34°28′07.90″	120°18′50.80″	＃85 wind turbine	
17	No.17 acousto-optic alarm device	34°29′01.00″	120°17′10.80″	＃67 wind turbine	
18	No.18 acousto-optic alarm device	34°30′38.60″	120°15′07.60″	＃38 wind turbine	
19	No.19 acousto-optic alarm device	34°31′29.70″	120°17′00.00″	＃14 wind turbine	
AIS base station					
20	AIS base station	34°29′32.4″	120°20′16.00″	Substation	
Radar					
21	Radar	34°29′32.4″	120°20′16.00″	Substation	
VHF base station					
22	VHF base station	34°29′32.4″	120°20′16.00″	Substation	
CCTV					
23	No.1 camera with pan-tilt system	34°25′38.89″	120°10′53.68″	＃5 wind turbine	H1 OWF
24	No.2 camera with pan-tilt system	34°24′42.57″	120°12′23.27″	＃15 wind turbine	
25	No.3 camera with pan-tilt system	34°23′47.10″	120°13′48.53″	＃25 wind turbine	
26	No.4 camera with pan-tilt system	34°27′11.80″	120°20′36.20″	＃96 wind turbine	H2 OWF
27	No.5 camera with pan-tilt system	34°28′07.90″	120°18′50.80″	＃85 wind turbine	
28	No.6 camera with pan-tilt system	34°29′01.00″	120°17′10.80″	＃67 wind turbine	
29	No.7 camera with pan-tilt system	34°30′38.60″	120°15′07.60″	＃38 wind turbine	

Source: Produced by the author.

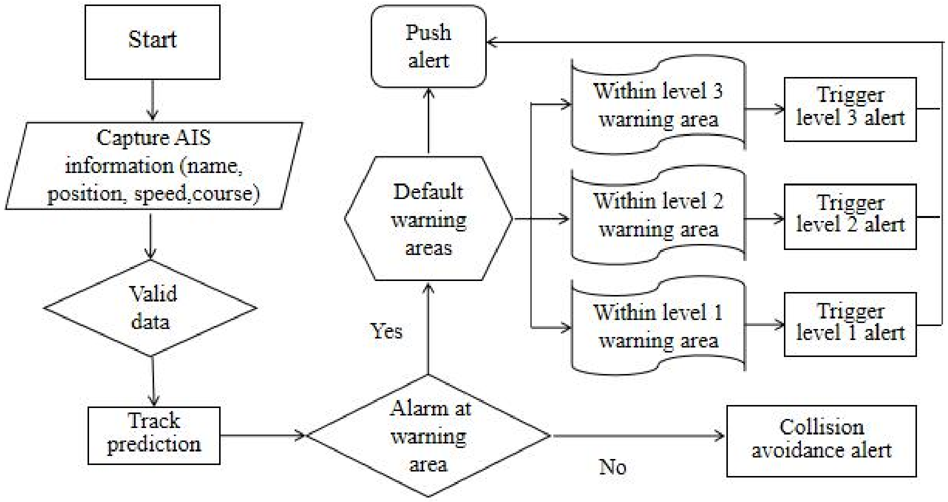


Figure 4.8 The three level early warning mechanism of Binhai OWF

Source: Reproduced from "Safety Assurance Method of Offshore Wind Farm Based on Electronic Fencing and Acousto-optic Early Warning System", by SUN et al. 2020, P.62. http://doi:10.13646/j.cnki.42-1395/u.2020.05.024.

4.4 RCOs in the decommissioning phase of OWF

The actual decommissioning of most OWFs in China is at present a decade away, and there are no fixed set of rules and procedures available so far. In order to make sure that the decommissioning of an OWF will be conducted in due time, a decommissioning fund should be set aside in advance, and a planning of decommissioning should be drawn up as early as possible.

As depicted in chapter 2, the decommissioning phase is simply the reverse procedure of the construction phase. In this regard, most of the RCOs in the construction phase are conceivably applicable to the decommissioning phase. First, the maritime authorities have to check and issue the marine license for permitting the decommissioning operation in the designated site. Second, a specialized maritime regulatory framework should be developed and implemented by the maritime authorities, including seaworthiness of working vessels, competency of crew members, dissemination of MSI, deployment of guardship, traffic control, contingency planning and emergency response, and most importantly the dismantling requirements of substructures and marine cables. The key factor to be considered removing substructures and cables is whether it's to be removed entirely or if any parts are to be left behind. In cases where there are no environmental and economic concerns, the complete removal can be implemented. Nonetheless in a majority of cases the concerns over the safety, environmental and economic aspects co-exist, which therefore should be handled on a case by case basis. The substructures could be cut bellow seabed level where safety of navigation is guaranteed and the costs reduced. They could be cut bellow the LAT level where the marine wild-lives are preserved, but additional safety measures have to be established such as the marking of the marine habitats and establishment of prohibited area to enhance safety of navigation and habitats. The marine cables could be left in situ avoiding major disruptions to marine environment, or they could be recovered from the seabed if no disruptions induced. Ultimately the decisions are left for the national maritime authorities to make taking into account the safety, environmental and economic factors. In all cases, any remaining parts of substructures and marine cables must not endanger safety of navigation. Third, the establishment of Special Marks (light buoys displaying Morse "O" Yellow light characteristic) in accordance with GB 4696-2016 for marking the marine operation boundary is necessary. Last but not least, after completion of decommissioning of the OWF, the nautical charts and publications should be duly corrected and the AtoNs not in use should be removed.

Additionally, the navigation environment in this phase will probably evolve along with the development of shipping industry, offshore wind industry, fishery industry, etc. Therefore, a NRA prior to the actual decommissioning of an OWF should be carried out in order to prescribe pragmatic safety mitigating measures that are commensurate to the degree of risk.

Chapter 5 Conclusions and Prospects

5.1 Research outputs

Although the first commercial OWF of China was established in 2010, lagging behind twenty years compared with European countries, the offshore wind industry has been developing very fast for the past decade. The rapid development of OWFs is accompanied with negative impacts on navigation environment in different phases of an OWF, among which three outstanding risk factors have been identified and analysed.

(1) The siting of OWF. The national energy and oceanic authorities had jointly established relevant rules regulating the development and construction process of OWFs, nonetheless unfeasible siting of OWFs still occurred in some cases. The immediate cause can be summarized as an irreconcilable conflict of the use of marine spaces between safety of navigation of ships and OWFs. The root cause and hidden reason however is the lack of voice and early participation of the maritime authorities.

(2) The minimum safety distance. Generally three kinds of minimum safety distance calculation models had been presented from different perspectives of vessel drift induced collision, collision probability, collision avoidance regulations and

electromagnetic radiation.

(3) The marking of OWF. In accordance with international and national provisions, the OWFs shall be properly marked to enhance safe and expeditious navigation of ships. However, judging from the statistics of the markings of some representative OWFs in China, different marking techniques had been utilized due to the application of different national and international regulations on the marking of offshore structures including GB 4696-2016, GB 17380-1998 and IALA R0139. The inconsistency in the adoption of marking regulations may impair the effectiveness of AtoNs and confuse the mariners.

Navigational risk assessment has been widely used in the risk management of OWFs. Plenty of NRA models have been developed so far, but the use of models by the eight countries in question is quite diversified. OWF developers are responsible for carrying out NRA in most countries except the Netherlands. All countries have guidelines on NRA, but none of them require specific NRA model except German. The diversification use of various NRA models needs to be addressed in that different models used on the same area may obtain diverse outcomes. The NRA of Binhai OWF has been successfully conducted using OpenCPN and the novel mathematical model developed by the author. Based on the actual navigation environment, risk analyses and practical NRA achievements of Binhai OWF, risk control options have been proposed in different phases of OWF from the perspectives of maritime safety supervision and navigation service.

(1) RCOs in the design phase of OWF. The maritime authorities should get actively involved as early as possible in the siting of OWF to raise attention of the energy authorities and the developers on maritime safety concerns. The MSP perhaps is a desirable tool in harmonizing the use of marine spaces by different stakeholders, and the maritime authorities should be involved by providing accessible maritime data.

Moreover, the maritime authorities should develop specific OWF siting criteria instead of vague and ambiguous wordings, and the diversification use of NRA models should be harmonized to achieve relatively accurate result and remove the bureaucratic burden.

(2) RCOs in the construction phase of OWF. A designated maritime safety supervision regulation consisting a wide range of matters should be formulated to enhance safety of navigation during the construction phase of OWF. The marking of the construction area should be harmonized using Morse “O” lighting rhythm to indicate the marine operation area of an OWF.

(3) RCOs in the operating phase of OWF. The marking of OWFs in the operating phase should also be harmonized according to international and national recognized regulations. Generally speaking, the OWFs comprised of an array of wind turbines should be fitted with Morse “C” lighting rhythm, and the isolated structures such as the meteorological mast or substation should be fitted with Morse “U” lighting rhythm. Based on the existing RCOs of the Binhai OWF, additional RCOs have been prescribed including establishment of Safety Zone, Safe Passing Distance and Recommended Route, the marking of Recommended Route and adjustment of light characteristics of light beacons, elimination of the blind spots of maritime safety supervision and establishment of an Electronic Fencing System.

(4) RCOs in the decommissioning phase of OWF. Most of RCOs in the construction phase of OWF are applicable to the decommissioning phase given that one is the reverse process of the other. Nonetheless, the decommissioning process should be somehow treated differently due to the uncertainties and complexity. A planning procedure should be carried out as early as possible to minimise the uncertainties and complexity. A decommissioning fund should also be arranged in advance to ensure the scheduled decommissioning procedure. In order to facilitate safety of navigation,

the maritime authorities should put forward the specific regulatory framework concerning the dismantling requirements, etc. Additionally, A NRA procedure should be implemented prior to the decommissioning operation to assess risks and come up with risk mitigation measures accordingly.

5.2 Shortcomings and prospects

Comparatively speaking, the maritime safety supervision and navigation service for OWFs are emerging new topics, at least in China. There are few existing mature supervision and service practices for the time being. The risk mitigation measures for each phase of an OWF that the author has proposed remain to be reviewed and validated. Some measures perhaps will be proved to be insufficient and inadequate, and should be further improved. Some measures may be considered as over-designed, excessive and non cost-effective. The existing measures are not proportionate to the degree of risk in that the maritime industry and offshore wind industry focusing on the specialized knowledge in their respective fields aren’t aware of the necessity to understand the technical details that their counterpart requires. Relying upon the ocean, the maritime industry and offshore wind industry are becoming a community of shared interests. Therefore, it’s highly necessary for both parties to learn from each other as a start particularly with the advent of more intricate systems such as maritime autonomous surface ships and floating wind turbines, and then work out pragmatic risk control options as they see fit that are both sufficient and cost-effective. Only by doing so can we enhance the cooperation on efficient use of marine spaces and promote the harmonious co-existence between safety of navigation and OWFs.

References

Beinke, T., Ait Alla, A., & Freitag, M. (2018). Decommissioning of Offshore Wind Farms- A Simulation-Based Study of Economic Aspects. Dynamics in Logistics, 2018. 216-222. https://doi.org/10.1007/978-3-319-74225-0_30

CHEN, Z.C (2020). Mechanisms of Offshore Wind Power Development in Four European Countries—A Comparative Analysis in Technological Innovation System Approach.Journal of Hebei University of Geo-sciences,43(04).91-101. https://DOI:10.13937/j.cnki.hbdzdxxb.2020.04.014

CHEN, J.J. (2017). Discussion on the Placement Scheme of Aids to Navigation for Offshore Wind Farm. Pearl River Water Transport, (21).83-84. https://DOI:10.14125/j.cnki.zjsy.2017.21.031

CHEN, X.L. (2017). Research on Optimization of the Offshore Wind Farm Considering Navigation Safety Factors. [Master's thesis, Dalian Maritime University].https://kns.cnki.net/kcms/detail/detail.aspx?FileName=1017196163.nh&DbNam e=CMFD2017

Douvere, F., Maes, F., Vanhulle, A. & Schrijvers, J. (2007). The role of marine spatial planning in sea use management: The Belgian case. Marine Policy, (31). 182-191. https://doi.org/10.1016/j.marpol.2006.07.003

Ellis, J., Forsman, B., Huffmeier, J. et al. (2008). Methodology for assessing risks to ship traffific from offshore wind farms. In: Vattenfall reports. Available via Vattenfall.https://corporate.vattenfall.se/globalassets/sverige/om-vattenfall/om-oss/var-verksamhet/vindkraft/kriegers-flflak/5-kriegers-flflak-risk-assessment_11335732.pdf.

Eva, T., Elena, G., David, M. & Elsa, J. (2019). Challenges of decommissioning offshore wind farms: Overview of the European experience. Journal of Physics: Conference Series, 1222. https://doi:10.1088/1742-6596/1222/1/012035

GU, E.K. (2015). Research on the Impact of Zhoushan Ocean Energy Development on Navigation Environment and Associated Maritime Supervision Countermeasures. Workshop on Maritime Control, (04).56-59. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=HSZG201504025&DbName=CJFQ2015

Gimpel, A., Stelzenmüller, V., Grote, B., Buck, B.H., Floeter, J., Núñez-Riboni, I., Pogoda, B. & Temming, A. (2015). A GIS modelling framework to evaluate marine spatial planning scenarios: Co-location of offshore wind farms and aquaculture in the German EEZ. Marine Policy, (55).102-115. https://doi.org/10.1016/j.marpol.2015.01.012

Gjødvad, J.F. & Ibsen, M.D. (2016). ODIN-WIND: An Overview of the Decommissioning Process for Offshore Wind Turbines. MARE-WINT, 403-419. https://doi.org/10.1007/978-3-319-39095-6_22

HE, J.Y. (2016). Development Status of Offshore Wind Turbines in China. Wind Energy, (06).40-42. https://DOI:10.3969/j.issn.1674-9219.2016.06.010

International Maritime Organization. (2018). SOLAS 2018 Consolidated Edition.

JIANG, A.W & LI, Q. (2019). The Study on Offshore Wind Farm Aids to Navigation Placement Scheme. Transportation Science & Technology of Fu Jian, (02),131-133.https://DOI:CNKI:SUN:FJJT.0.2019-02-035

JIANG, T. (2012). Discussion on the Navigation Impact Evaluation Method of Offshore Wind Farm Project. China Water Transport, (05). 5-6+8. https://kns-cnki-net-s.svpn.dlmu.edu.cn:8118/kns8/defaultresult/index

JIANG, F. C., GUO, Y. B., & MA, Q. D. (2014). Comprehensive Evaluation of the Offshore Wind Power Project Navigation Safety. Advanced Materials Research,3294.259-262.https://DOI: 10.4028/www.scientific.net/AMR.986-987.259

Stephen, J. (2010). Planners to the rescue: Spatial planning facilitating the development of offshore wind energy. Marine Pollution Bulletin, 60(4).493-499. https://doi.org/10.1016/j.marpolbul.2009.11.010

Kim, T., Park, J.& Maeng, J. (2016). Offshore Wind Farm Site Selection Study Around Jeju Island, South Korea. Renewable Energy, (94). 619-628. https://doi-org-s.svpn.dlmu.edu.cn:8118/10.1016/j.renene.2016.03.083

Kerkvliet, H. & Polatidis, H. (2016). Offshore wind farms' decommissioning: a semi quantitative Multi-Criteria Decision Aid framework. Sustainable Energy Technologies and Assessments,18.69–79. https://doi.org/10.1016/j.seta.2016.

09.008.

LIU, J.L. (2020). The Study on the Construction and Vessel Navigation Safety of Offshore Wind Farms. China Water Transport, 20(07). 27-28. http://kns.cnki.net/kcms/detail/detail.aspx?FileName=ZSUX202007013&DbName=CJFQ2020

LIANG, S. (2018). Navigation Risk Analysis and Safety Precautions for Zhejiang Offshore Wind Farms. [Master’s thesis, Dalian Maritime University]. https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201901&filename=1019028960.nh

LI, J., XIE, Z.Z. & CHEN, X.B. (2013). Risk Assessment of Offshore Wind Farm project during Construction and Operation Phases Based on SVM. Journal of Engineering Management, (04). 51-55. http://www.cqvip.com/QK/92079A/201304/47086042.html

LI, D.K., TANG, H.Q., LIN, M.Q., HUANG, L.F. & DONG, B. (2014). Risk Assessment and Analysis of Vessel Navigation Safety of Fujian Offshore Wind Farm Sites. Proceedings of Navigation of China, 2014.181-187. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=PJJY201509001023&DbName=CPFD2017

LIU, K.Z., ZHANG, J.F., YAN, X.P. & YANG.X. (2010). Study on the Influence of Offshore Wind Farm on the Detection Performance of Marine Radar. Journal of Wuhan University of Technology, (03). 561-564. http://www.cnki.com.cn/article/cjfdtotal-jtkj201003034.htm

LIU, B.Q., XU, M. & LIU, Q. (2015). Main problems and countermeasures of offshore wind power development in China. Ocean Development and Management, (03).7-12. https://kns.cnki.net/kcms/detail/detail.aspx?FileName=HKGL201503002&DbName=CJFQ2015

Lian Yungang Maritime Safety Administration. (2020). Statistics of water traffic accidents of Lian Yungang MSA in 2019. http://www.lyg.msa.gov.cn/ssjtaq/49360.jhtml

Lian Yungang Maritime Safety Administration. (2019). Accident investigation report of the collision between Su Lian Yungang 8866 and No. 38 Wind turbine of Binhai H2 OWF. http://www.lyg.msa.gov.cn/html/ssaqsgxx/20191210/

48300.html

MCA. (2016). MGN 543 (M+F) Safety of Navigation: Offshore Renewable Energy Installations(OREIs) - Guidance on UK Navigational Practice, Safety and Emergency Response. Marine guidance note, Maritime and Coastguard Agency (MCA).

Moulas, D., Shafiee, M. & Mehmanparast, A. (2017). Damage Analysis of Ship Collisions with Offshore Wind Turbine Foundations. Ocean Engineering, (143). 149-162. https://DOI: 10.1016/j.oceaneng.2017.04.050

Mehdi, R. A., Baldauf, M., & Deeb, H. (2020). A Dynamic Risk Assessment Method to Address Safety of Navigation Concerns Around Offshore Renewable Energy Installations. Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 234(1), 231–244. https://doi.org/10.1177/1475090219837409

Mehdi R.A. & Schröder-Hinrichs JU. (2016). A Theoretical Risk Management Framework for Vessels Operating Near Offshore Wind Farms. MARE-WINT, 359-400. https://doi.org/10.1007/978-3-319-39095-6_21

Mehdi, R.A., Schröder-Hinrichs, JU., Van-Overloop, J. & Pålsson, J. (2018). Improving the coexistence of offshore wind farms and shipping: an international comparison of navigational risk assessment processes. WMU J Marit Affairs, (17).397-434. https://doi.org/10.1007/s13437-018-0149-0

Ministry of Transport, China. (2016). GB 4696-2016, Maritime buoyage system, China. http://www.gb688.cn/bzgk/gb/

Ministry of Transport, China. (1998). GB 17380-1998, The regulation for the marking of offshore structures in China. http://www.gb688.cn/bzgk/gb/

Merpanda. (2020). Diving strategy of a meteorological mast in Huizhou, Guangdong. https://mp.weixin.qq.com/s/RHaESJtRN3GAD3B8B6Wx1g

NIE, Y.Y., LIU, K.Z., YANG, X., CHEN, S.Z. & MA, J. (2019).Safety Distance Between Offshore Wind Farms and Ship Routes. Navigation of China, 42.12-17. https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CJFD&filename=ZGHH201904003

REN, H.H., ZHANG, L.L & LI, X.B. (2010). Analysis of the Impact of Offshore Wind Farm Project Construction on Navigation Safety and Countermeasures. Journal of Transport Information and Safety, (06). 30-32+36. http://www.cnki.com.cn/Article/CJFDTotal-JTJS201006011.htm

Rawson, A. & Rogers, E. (2015). Assessing the Impacts to Vessel Traffic from Offshore Wind Farms in the Thames Estuary. Scientific Journals of the Maritime University of Szczecin, 43(115). 99–107.

Rodríguez-Rodríguez, D., Malak, D.A., Soukissian, T. & Sánchez-Espinosa, A. (2016). Achieving Blue Growth through maritime spatial planning: Offshore wind energy optimization and biodiversity conservation in Spain. Marine Policy, (73). 8-14. https://doi.org/10.1016/j.marpol.2016.07.022

Spyridonidou, S., Vagiona, D.G. (2020). Spatial Energy Planning of Offshore Wind Farms in Greece Using GIS and a Hybrid MCDM Methodological Approach. Euro-Mediterranean Journal for Environmental Integration, 5. 24. https://doi.org/10.1007/s41207-020-00161-3

Schröder-Hinrichs,J. (2019). Core concepts of Risk, Safety & Reliability. [PowerPoint slides].

Schröder-Hinrichs, J.U. (2020). Risk Management and Accident Investigation. [PowerPoint slides].

Smythe, T.C. & McCann, J. (2019). Achieving integration in marine governance through marine spatial planning: Findings from practice in the United States. Ocean & Coastal Management, (167). 197-207. https://doi.org/10.1016/j.ocecoaman.2018.10.006.

SUN, J.D., ZHONG, Q.Y. & DENG, W. (2020). Safety Assurance Method of Offshore Wind Farm Based on Electronic Fencing and Acousto-optic Early Warning System. China Water Transport, (05),60-63. http://doi:10.13646/j.cnki.42-1395/u.2020.05.024.

Torres, F. S., Kulev, N., Skobiej, B. Meyer, M., Eichhorn, O. & Schäfer-Frey, J. (2020). Indicator-based Safety and Security Assessment of Offshore Wind Farms. 2020 Resilience Week (RWS), 26-33. https://doi: 10.1109/RWS50334.2020.9241287

Thousand Wind Turbine Project. (2021). Directions of Zone Application for Planning. https://www.twtpo.org.tw/eng/offshore/directions.aspx

Tercan, E., Tapkın, S., Latinopoulos, D., Dereli, M.A., Tsiropoulos, A & Ak, M.F. (2020). A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea. Environ Monit Assess, 192:652. https://doi.org/10.1007/s10661-020-08603-9

The World Association for Waterborne Transport Infrastructure. (2018). INTERACTION BETWEEN OFFSHORE WIND FARMS AND MARITIME NAVIGATION.

The International Association of Marine Aids to Navigation and Lighthouse Authorities. (2017). R1010 THE INVOLVEMENT OF MARITIME AUTHORITIES IN MARINE SPATIAL PLANNING (MSP). https://www.iala-aism.org/product/r1010-involvement-maritime-authorities-marine-spatial-planning-msp/

The International Association of Marine Aids to Navigation and Lighthouse Authorities. (2017). R1001 the IALA Maritime Buoyage System. https://www.iala-aism.org/product/r1001-iala-maritime-buoyage-system/

The International Association of Marine Aids to Navigation and Lighthouse Authorities. (2013). R0139 THE MARKING OF MAN-MADE OFFSHORE STRUCTURES(O-139). https://www.iala-aism.org/product/marking-of-man-made-offshore -structures-o-139/

World Forum Offshore Wind. (2021). Global Offshore Wind Report 2020. https://www.wfo-global.org

WANG, G.P, ZHONG, Q.Y. & ZHU, C.B. (2020) .Study on the determination of safe distance between offshore wind farm and Shipping route. China Water Transport, (12).35-38. https://doi:10.13646/j.cnki.42-1395/u.2020.12.012

Wright, G., Mehdi, R. A., & Baldauf, M. (2016). 3-dimensional Forward Looking Sonar: Offshore wind farm applications improving the safety & reliability of offshore wind farms. European Navigation Conference (ENC), 2016, 1-8. https://ieeexplore.ieee.org/abstract/document/7530563/

XIE, Z.Z. (2013). Risk Evaluation Study of Offshore Wind Power Project at

Operating Period. [Master's thesis, Dalian University of Science and Technology]. https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201302&filename=1013198446.nh

YU, Q., LIU, K.Z., Teixeira, A.P. & Soares, C.G. (2019). Assessment of the Influence of Offshore Wind Farms on Ship Traffic Flow Based on AIS Data. Journal of Navigation, 73(1). 131-148. https://DOI: 10.1017/S0373463319000444

YU, Q., LIU, K.Z., CHANG, C.H. & YANG, Z.L. (2020). Realizing Advanced Risk Assessment of Vessel Traffic Flows Near Offshore Wind Farms. Reliability Engineering & System Safety, 203. https://doi.org/10.1016/j.ress.2020.107086

YI, Y.C. (2004).Present Situation, Future Prospect and Market Analysis of Wind Power Worldwide. International Wind Power for China. 2004(05),18-22. https://www.doc88.com/p-6292952193420.html

ZHANG, G.C. & LIU, L. (2014). Constraints on Offshore Wind Farm Construction in Ru Dong, Nan Tong City. China Water Transport, 2014(11).40-41. https://DOI:10.13646/j.cnki.42-1395/u.2014.11.016

ZHANG, M. (2014). Research on the Influence of Offshore Wind Power Construction on Ship Navigation Safety. Tian Jin Maritime, (04). 58-60. http://www.cnki.com.cn/Article/CJFDTOTAL-TJHH201404025.htm