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Research

China's Mariculture Net Cages in Typhoon and sea Ice Disasters: Challenges and Prevention Strategy

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Abstract:
In recent years, mariculture has been prominent in solving the problem of high-quality protein sources for human beings. As an essential mode of mariculture, cage culture has gradually entered a period of rapid development. However, extreme marine disasters such as typhoons and sea ice bring different degrees of damage to mariculture net cages and even jeopardize the lives and property safety of aquaculture practitioners. Strong winds and waves caused by typhoon disasters lead to cage overtopping, cage frame collapse, and structural damage. Sea ice disasters caused by net cage frozen and ice floes impingement lead to a decline in the structural stability of the net cage, deformation, shifting, and collapse. These problems cause the cultured fish to collide with each other, triggering fish injuries, fish diseases, and fish escapes. At the same time, drastic environmental changes have limited farmed fish growth, resulting in a significant decline in aquaculture production. In summary, typhoon and sea ice disasters have become essential factors restricting China's rapid development of mariculture net cages. This paper reviews the development of mariculture net cages in China, the damage of mariculture net cages in typhoons and sea ice disasters, and the hazards of typhoons and sea ice disasters on net cages. Moreover, put forward the routine maintenance of net cages and disaster prevention and mitigation strategies to provide references for the safety of mariculture net cages and the prevention and mitigation of marine disasters.

1. Introduction

China is a strong aquaculture country, accounting for about 59.71% of the world's total production (FAO, 2022). In 2021, China's marine aquaculture production was almost 2.21 × 10^7t, accounting for 40.99% of aquaculture production (FFABC, 2022), of which the total output of traditional net cages was 6.27 × 10^5t, and that of offshore net cages was 3.37 ×10^5t. The products of cage culture provide the population with large quantities of high-quality proteins and have become essential to guaranteeing food security in the country. However, with the rapid development of farmed net cages, the disaster of net cages is becoming more and more prominent. According to the statistics of China Marine Disaster Bulletin (2013-2022), the direct economic loss caused by marine disasters was 71.3 billion Yuan, with an average loss of 7.1 billion Yuan per year, and the one-year economic loss caused by the destruction of fishery facilities in 2021 was as high as 10.649 billion Yuan (FFABC, 2022). It can be seen that marine disasters cause severe damage to mariculture net cages and have a profound impact on the development of the marine netting industry.

Among the many marine disasters, typhoons and sea ice are the main disaster factors that damage marine net cages. Under the background of global warming and sea level rise, the frequency and intensity of typhoon disasters have escalated, and the losses caused to countries worldwide have been increasing yearly (Hou et al., 2020). China is no exception, with a vast coastline, complex coastal topography, seasonal changes in climate, and abundant marine resources, which provide a broad space for developing mariculture net cages. Nevertheless, the vast coastline and complex climate change have also led to frequent typhoon disasters in the mariculture industry of China. Extreme disasters such as typhoons are accompanied by strong winds and severe seawater fluctuations, resulting in damage to the floating collar, rupture of the netting, failure of the mooring system, and even lead to the cage's instantaneous submergence, losses, and overturning. During this process, the fish in the cages collide, leading to fish damage and disease, resulting in fish death (Jiang, 2021). In winter, there will be a long-term sea ice disaster in the sea area of northern China. The net cages in this sea area must withstand the pressure of frozen and the impact of ice floe. The impacts

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of frozen and floating ice on the cages lead to a decrease in the balance of the cage, resulting in deformation, displacement, and resupination, causing fish escape events. In addition, changes in environmental factors limit fish growth, resulting in a significant decrease in culture production.

In summary, the losses of aquaculture disasters are not optimistic, and typhoon and sea ice disasters have significantly restricted the development of Chinese mariculture. Therefore, this paper reviews the development and disaster situation of mariculture net cages. Furthermore, aiming at the harm of typhoon and sea ice disasters to net cages, this paper puts forward the daily maintenance of cages and the countermeasures of disaster prevention and mitigation to provide a reference for the safety of mariculture net cages and marine disaster prevention and mitigation.

2. Situation of cage culture in China

Cage culture is a vital mode of mariculture. There are three forms: traditional net cage, offshore cage, and deeper-offshore cage. Among them, traditional and offshore net cages are the most widely distributed and numerous, and they currently dominate the cage aquaculture industry. Deeper-offshore aquaculture is still in development; the number of the deeper-offshore cages is small, and this kind of cages have stronger capacity to withstand winds and waves and thus less affected by disasters. So, this study mainly explores the disaster problems of traditional net cages and offshore net cages.

2.1. The Traditional Net Cages

The traditional net cages are usually deployed in nearshore, inner bays, or around islands with the water depths up to 15 m (Dong et al., 2023). Usually, it has the shape of square or circle with a floating collar, netting, and mooring system. Common specifications include dimensions with lengths, widths, and heights each ranging from 3 to 8 meters. Until 2021, the number of net cages in China continued to grow, of which the number of traditional net cages with water depth not exceeding 15 m has developed to more than 2.3 million (the average aquaculture area of a single traditional net cage is projected to be 16 m^2), with a total culture output of 626,744 t. Compared with 2020, net cages increased by 91.45%, and the output increased by 10.91%. The cages are mainly distributed in Liaoning, Fujian, Guangdong, and Hainan provinces (Shi et al., 2021). *Larimichthys crocea*, *Epinephelus coioides*, *Lateolabrax japonicus*, *Stichopus japonicus*, and *Trachinotus ovatus* are the primary cultured species.

Table I The situation of the traditional net cage in 2021

Place	Aquaculture area (m^2)	Number of cages (-)	Production (t)
Liaoning	16,369,912	1,023,119	9,781
Fujian	12,831,288	801,956	308,953
Shandong	2,848,985	178,062	101,260
Guangdong	3,659,217	228,702	118,505
Hainan	935,893	58,493	9,005
Zhejiang	649,251	40,578	26,993
Guangxi	535,878	33,492	52,247
Total	37,830,424	2,364,402	626,744

Note: The average culture area of a single traditional net cage is 16 m^2, according to data from the China Fishery Statistical Yearbook (2022).

The traditional net cages are mostly quadrilateral structures with simple construction and poor wind and wave resistance (Fig. 1), which are not suitable to be placed in open sea areas with large wind and waves, so they are centralized in coastal shallow sea areas. The traditional net cages are numerous and densely distributed, often consisting of many small cages forming groups of cages. When cage groups are exposed to typhoons and sea ice disasters, strong winds, waves, and floating ice in the surrounding sea continuously strike them. Due to this, the net cage structure experiences excessive stress that exceeds its limit value, ultimately leading to frame fractures. Damage to individual net cages will reduce the structural stability of the group due to the dense distribution of traditional net cages. According to Table 1, 43.27% of all traditional net cages were recorded in Liaoning, while Fujian and Guangdong accounted for 33.92% and 9.67%, respectively. The majority of traditional net cages were found in these three regions, which represent almost 85% of all recorded cages. During 2015-2018, a total of 33 typhoons made landfall on China's coasts, with a total of 51 impacts on coastal areas. And the regions of Fujian and Guangdong are particularly susceptible to typhoon disasters. Between 2015 and 2018, the coast of China was hit by 33 typhoons that caused 51 instances of coastal impacts. Guangdong and Fujian Provinces were affected 14 and 8 times, respectively (Jiang et al., 2023). In the wake of such calamities, regular cage frames are extremely vulnerable to breaking, which ultimately impacts aquaculture zones.

2.2. Offshore Net Cage

The offshore net cages with water depth greater than 15 m and wind and wave resistance have also developed to nearly 40,000 (the average aquaculture water body of a single offshore net cage is estimated at 1,000 m^3). The total aquaculture production of the offshore net cages in 2021 is 337,193 t, an increase of 3.77 % in the quantity of cages and 15.04 % in production compared with 2020. The offshore net cages are mainly distributed in Zhejiang, Hainan, Guangdong, Guangxi, and Shandong province (FFABC, 2022; Shi et al., 2022). Larimichthys crocea, Trachinotus ovatus, Sebastes schlegelii, and Lateolabrax japonicus are the primary cultured species.

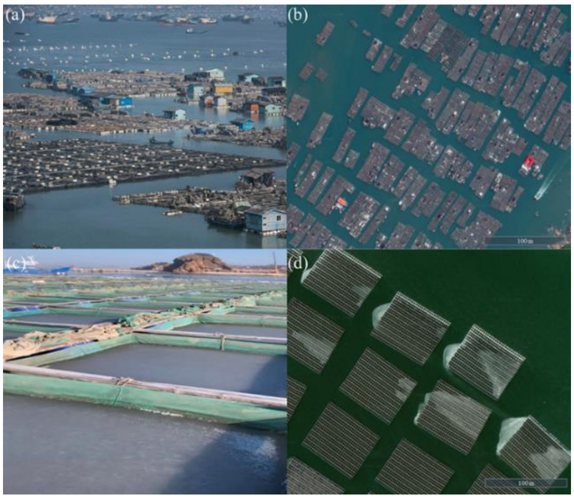

Fig. 1 The traditional net cages arrangement and remote sensing images: photos (a) and remote sensing images (b) of net cages in Ningde, Fujian Province (Google Earth: 2021/4/12); Frozen net cages (c) and remote sensing images (d) in Dalian, Liaoning Province (Google Earth: 2022/2/16).

Table II The situation of the offshore net cage in 2021

Place	Aquaculture area (m^2)	Number of cages (-)	Production (t)
Fujian	12,122,670	757,667	10,840
Hainan	7,614,785	475,924	53,571
Zhejiang	7,286,059	455,379	26,367
Guangxi	6,027,472	376,717	72,010
Shandong	3,439,473	214,967	33,332
Guangdong	2,829,330	176,833	45,841
Liaoning	333,440	20,840	2,232
Total	39,653,229	2,478,327	244,193

Note: The average culture area of a single offshore net cage is 1000 m^3, according to data from the China Fishery Statistical Yearbook (2022).

Now, China has successfully developed more than 10 kinds of offshore net cages, such as High-Density Polyethylene (HDPE) gravity net cages, floating rope cages, HDPE lifting cages, flounder special lifting cages, downstream net cages, multi-level structure cages, metal frame cages, and metal net cage (Shi et al., 2021). With the rapid development and application of anti-wave cage technology, China's offshore net cages, represented by HDPE gravity net cages, have formed a large-scale industrial development (Fig.2). While achieving rapid development, the damage caused by typhoon disasters to offshore net cages is also enormous. Especially in Fujian, Hainan, and Zhejiang, they have the most significant number of offshore net cages with dense distribution. When a typhoon occurs, the net cage mooring system can often not withstand the enormous wind and waves. Line breakage and anchor removal lead to mooring system failure, resulting in neighboring net cages squeezing each other, collisions, and even triggering multiple net cage continuous collisions. Continuous collisions between nets will lead to an exponential increase in disaster losses.

Fig.2 Offshore net cage arrangement and remote sensing images: Offshore net cage images (a) and remote sensing images (b) of Nanji Island, Zhejiang Province (Google Earth: 2021/8/8); Cage images (c) and remote sensing images (d) of offshore net cage in Ningde, Fujian Province (Google Earth: 2021/4/12)

3 Typhoon disaster

China is bordered by the western Pacific Ocean, where the world's largest typhoon originates, and is one of the countries with the most severe typhoon disaster (Deng, 2011; Niu, 2012; Han et al., 2016). Typhoon disasters occur in almost all of China's coastal provinces, with high incidences in Fujian, Hainan, Guangdong, and Zhejiang. These places account for 60% of the country's net cages, and typhoon disasters are the main disaster for these net cages. Typhoon landfalls are accompanied by strong winds and waves, resulting in different degrees of damage to the net cages (Table 3). This may even lead to the emergence of fish diseases, causing huge economic losses to aquaculture practitioners.

According to the statistics of China Fishery Statistical Yearbook 2012 and 2022, the loss of aquatic products and cages caused by typhoon disasters has been decreasing year by year (Fig.3). It shows that with the joint efforts of researchers, relevant departments and farmers, mariculture net cages' disaster prevention and mitigation have progressed. However, the economic loss of cages in 2021 is still as high as 1.01 billion Yuan (fish value and cage value), and more losses come from the death or escape of farmed fish. In the context of global warming and sea level rise, the frequency and intensity of typhoon disasters will continue to escalate, and the development of mariculture net cages will become more severe (Niu, 2012; Han et al., 2016).

Table III Hazards of typhoon disasters on net cages

Influence	Influence process	Consequences
Overtopping	The typhoon caused a severe atmospheric disturbance, resulting in the abnormal rise and fall of seawater, and then superimposed with the waves, causing more seawater over the top of the cage, that is, overtopping. Instantly, the overtopping causes fish to escape from the net cage.	Fish escape
Structural destroy	The structure of net cages under typhoon disasters can easily be seriously damaged. Under the joint action of strong wind, catastrophic waves, and storm surge, the net frame, guardrail, floating tube, anchor butt system, and netting are seriously damaged, which leads to decreased stability of the cage, and the cage drifting, capsizing, and loss.	The cage is completely or partially damaged, and fish escape.
Water environment damage	Rainfall and typhoon waves cause turbidity in aquaculture waters, leading to sediment and pollutant buildup from bottom sediments. In addition, the storm surge caused by the typhoon will cause changes in the environment of the affected waters, such as a decrease in salinity, temperatures, and dissolved oxygen, and drastic environmental changes that will kill fish.	Fish death (hypoxia or stress reaction)
Fish body damage	Storm surges, strong winds, and waves from typhoons can cause fish collisions, injuries, and diseases, leading to significant fish deaths in communities.	Fish death (disease)

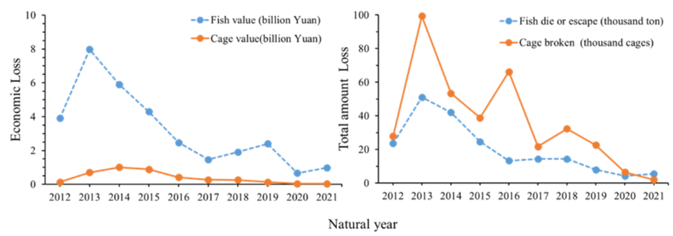

Fig. 3 Losses of cage culture caused by typhoon disaster in 2012-2021

In recent years, the loss of typhoon disasters to cage culture has been continuously reduced, but the strong typhoon Maria in 2018 still had a major impact on the cage culture. Nanji Island in Zhejiang Province is rich in natural resources, and it is necessary to carry out cage culture. Since 2017, it has been included in the national marine ranching demonstration area, but it has been attacked by strong typhoons in the following year, and the economic losses are serious. The research group analyzes and investigates the post-disaster situation of Nanji Island aquaculture cages as follows.

In 2018, the strong typhoon Maria was generated in the northwestern Pacific Ocean east of the Philippines. On July 11, Maria landed in Fuzhou, Fujian Province, with a maximum wind force of 14 at the center at the time of landing. Affected by Typhoon Maria, the economic losses in Jiangsu, Zhejiang, and Fujian amounted to 2 million Yuan, 0.435 billion Yuan, and 1.139 billion Yuan, respectively. The loss of maricultural net cages around Nanji Island was severe, with five companies losing 142 offshore net cages, 490 tons of fish, and a direct economic loss of 2.5 million Yuan. Post-disaster field investigations showed that all offshore net cages' three components of the floating frame, netting, and mooring systems were severely damaged and destroyed (Table 4). In addition, the typhoon storm surge of Maria caused drastic changes in the water environment. The waters of the mariculture area of Nanji Island were turbid, and the bottom sediment turned to the surface of the seawater, which seriously damaged the aquaculture environment and promoted the occurrence of suffocation death of fish and fish diseases, resulting in the organisms that survived in the disaster could not thrive.

Table IV Damage of offshore net cage in nanji island mariculture area

Damaged component	Damaged form (all cages)	Images
Floating collar	The floating collar comprises two thicker primary floating pipes and one thinner handrail pipe. The inner main floating pipe is connected with the handrail pipe through the column and connecting parts. The floating frame floats above the water surface and supports the overall structure of the cage. The main floating pipe of some net cages is broken or disconnected at the joint, seriously bent, and the floating frame is partially	 This cage's main floating pipe and column link are disconnected.

	submerged in the water. Large geometric deformation occurs due to external tension and compression, and the floating and supporting functions are seriously affected. The main floating pipe of the lighter disaster will also have slight local bending or creases. The handrail pipe or joint was broken, a large area collapsed, and a sizeable geometric deformation occurred. The column is often disconnected from the connection between the main floating pipe and the handrail pipe, the local column is toppled, and the auxiliary support function is affected. The damage to the main floating pipe, column, and handrail directly reduces the floating and supporting functions of the floating frame.	 This cage's handrail tube collapses.
Netting	The netting system of offshore net cages mainly plays the role of encircling a closed breeding space. The floating frame is disconnected, the force is uneven, and the external impact causes the net to be torn so that a closed breeding space cannot be formed; in severe cases, the rope connecting the net and the floating frame will be pulled off, and the net will fall off locally or wholly.	 The netting connection steel rope is pulled off.
Mooring systems	The mooring system is a critical component of the offshore net cage, mainly including anchor rope and plow-shaped anchor, which mainly plays the role of anchoring cage. The damage occurs if the anchor rope is lightly broken. The whole root is broken, or the anchor rope is not broken, and because it exceeds the bearing capacity of the anchor, the anchoring phenomenon occurs. The anchor system loses the mooring effect, which is easy to cause the cage to squeeze and collide with the adjacent cage. More seriously, the cage mooring system of the offshore cage is wholly destroyed, the netting is completely detached, the floating handrail pipe and the column are seriously damaged, and only the main floating pipe is still intact and pushed to the shore by the waves.	 Broken cable and anchor lead to cage extrusion collision.  Cage collision extrusion.  The cage was damaged entirely and pushed to shore by the waves.

4. Sea ice disaster

China is one of the countries seriously affected by sea ice. Because the Yellow Sea, the Bohai Sea, and the northern part of the Yellow Sea are semi-enclosed sea areas, the latitude is high, the foreshore area is large, the water is shallow, the salinity is low, and the temperature is significantly affected by land. These factors lead to different degrees of sea ice in Liaodong Bay, Bohai Bay, and Laizhou Bay in winter every year. Among them, the ice condition in Liaodong Bay is the heaviest (Fig.4), and a large area of fixed ice appears every year, among which the east coast is heavier than the west coast (Yuan et al., 2016; Zuo et al., 2019; Guo et al., 2023).

The coastal ice area has an essential impact on shallow sea and beach aquaculture. The coverage of the ice surface leads to a decrease in dissolved oxygen in the aquaculture area. When the temperature is too low, shellfish, fish, algae, and some benthic organisms die directly (Geng et al., 2023). Moreover, ice floe is constantly floating in the sea area. These ice floes are usually 5-10 cm thick, and the maximum ice floe range can reach 10-15 cm (Liu and Wu, 2017). These ice floes are incredibly harmful to the mariculture net cages in the sea area. Sea ice is the leading disaster factor of mariculture net cages in the Yellow Sea, Bohai Sea, and northern Yellow Sea. Net cage froze and ice floe problems hinder the average production of mariculture net cages (Table 5).

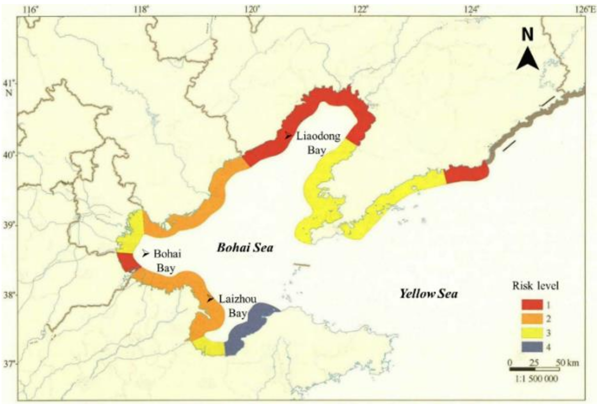

Fig.4 The distribution and risk level of sea ice disasters in the Bohai Sea and the northern coastal waters of the Yellow Sea (Yuan et al.2016).

Table V Damage of sea ice disaster to cages in winter

Influence	Influence process	Consequences
Net cage freezes	Sea ice in winter will lead to the freezing of net cages, and the ice layer increases the loading of the nets. It will lead to the deformation or rupture of the cages, damage to the floating frame, or even the rupture of the netting, resulting in fish escape.	The floating frame was damaged, and fish escaped.
Structural damage	Ice floes drift faster in winter and collide with net cages, causing wear and tear on facilities. In particular, the impact of large ice floes may lead to deformation or rupture of aquaculture facilities. Drifting ice floes can damage the mooring system of the net cages, cut mooring cables and floats, and lead to drifting and collision events with other cages.	The cage drifts, and fish escape.
Water environment damage	Sea ice and ice floes covering the surface of the nets will affect the circulation and mixing between water bodies, resulting in changes in dissolved oxygen and salinity. Ice prevents water exchange with the atmosphere, reducing oxygen supply and rapid changes in the water environment, causing fish stress mortality.	Fish death (hypoxia or stress).
Frostbitten fish	Ice floe covers the surface of the net cage, resulting in low water temperature. Under the influence of cold waves, the temperature of the aquaculture environment changes fast, resulting in decreased vitality, frostbite, or even death of fish or other aquaculture organisms.	Fish freezing death and foraging difficulties.
Restricting growth	As a result of sea ice and ice floes, the ice sheet restricts the abundance of zooplankton, resulting in a lack of adequate food sources for cultured animals, resulting in a decrease in their growth rate and, ultimately, a decrease in farmed yields.	Slow growth of fish and decline in aquaculture production.
Difficulty to maintain	Maintenance and management of net cages become more difficult under freezing conditions. For example, ice cover may make it difficult for staff to access net cages, hindering routine inspections and maintenance work.	The safety and stability of the cage are reduced.

The degree of damage and disaster loss of sea ice is lighter than that of typhoon disasters. Most of the direct economic losses caused by sea ice disasters in the Bohai Sea and the northern Yellow Sea in the past decade came from aquaculture losses (Table 6), with an average annual affected area of up to 58.3km2 and aquatic product losses of up to 12.2 thousand tons. In the winter of 2020, under the influence of the rapid development of sea ice in the waters of the Bohai Sea and the Yellow Sea, the culture of laver and bottom-seeding in Jiangsu was seriously damaged, and the direct economic loss was as high as 0.498 billion Yuan, which was the most severe loss in a decade.

Table VI Statistics on the occurrence of sea ice in the Bohai sea and northern yellow sea in winter 2012-2022

Year	Vessels damaged (-)	Aquaculture losses		Value (million Yuan)
		Affected area (km^2)	Amount (kt)	
2011/2012	0	380.80	-	155.00
2012/2013	2	229.20	19.60	321.88
2013/2014	-	86.70	2.20	23.99
2014/2015	18	6.70	-	6.05
2015/2016	2	16.70	3.70	20.04
2016/2017	-	20	-	0.80
2017/2018	-	0	0	1.00
2018/2019	-	0	0	0
2019/2020	-	0	0	0
2020/2021	-	241.80	71.80	498.11
2021/2022	-	0	0	0
Average	2	58.30	12.20	87.18

Data source: China Marine Disaster Bulletin (2012-2022).

5. Suggestions on disaster prevention and mitigation for mariculture cages

5.1. Suggestions for Typhoon Disaster

To mitigate the impact of typhoon disasters on net cages, meet the needs of disaster prevention and mitigation for net cages, and improve the disaster resistance of cage structures, a large number of researchers have focused on the hydrodynamics as well as the structural safety of net cages. Many scholars have used physical model tests (Pan, 2007; Bai et al., 2016) and numerical simulations (Mulyadi et al., 2018) to select the most suitable mooring system by evaluating the mooring mode and breaking strength of various net cages. For some structures of the net cage, such as the failure life of the floating collar, the failure probability of the mooring lines, and the mechanical properties of the cage guardrail (Liu et al., 2017).

Among these studies, Huang and Pan (2010) evaluated the failure risk of mooring ropes during a typhoon disaster based on the extended-period environmental loading of the single-point mooring (SPM) system and explored a suitable mooring breaking risk. Zhao et al. (2015) simulated a numerical model of the motions and elastic deformations of an HDPE floating collar in waves. They validate the optimal mooring system for floating cages. Kristiansen and Faltinsen (2012) and Kristiansen and Faltinsen (2014) proposed a screen-type force model for calculating the viscous hydrodynamic load on nets and simulating the net as a series of trusses. They investigated the mooring load on the net cage by experimental and numerical study. Bai and Wu (1998) analyzed the failure probability of a net mooring system by numerical simulation of a net cage under random wave action. The HDPE floating pipe fatigue lifetime was compared under different mooring cable arrangements. Mulyadi et al. (2018) conducted a mooring system selection analysis for mariculture net cages suitable for Indonesian waters, which resulted in the optimal mooring configuration.

In recent years, with the increase in the amount of mariculture net cages and the frequency of typhoon landfalls. More academics have begun to pay attention to the correlation study between typhoons and net cages, combined with disaster events, to assess the damage level of net cages and the failure rate of various components of the cages.

The most direct way to analyze the damage to the cages is to use wind and wave data during a typhoon disaster event. Such as Huang and Pan (2009) took Typhoon Mire as an example to analyze the damage characteristics of net cage material structure and mooring system. Shi et al. (2022) analyzed the effects of typhoon waves of different intensities on the structure of the mariculture net cages (floating collar, nets, and mooring lines) in the aquaculture area of Guishan Island and determined the failures of each part. Zhang et al. (2023) explore the structural vulnerability of sea cages to storm waves by theoretical analysis, hydro-elastic modeling, storm wave simulation, and post-disaster damage validation.

Since artificial neural networks (ANN) have performed well in hydrographic forecasting, active control of offshore structures, prediction of tidal surge inundation, and freak wave forecasting (Zhou and Zhao, 2023; French et al., 2017; Doong et al., 2018), some scholars have begun to try to analyze the damage of net structures by using neural network models to provide net damage prediction. For example, Zhao et al. (2019) evaluated the quantitative relationship between typhoons and the damage of circular gravity offshore cage structures by the BP neural network using the cage facilities and hydrological data around the Nanji Island in Zhejiang, China. Zhao et al. (2018) established an ANN model that can rapidly predict the structural stress and deformation of net cages in waves and provide disaster warnings before the sudden onset of typhoons. The rapid prediction of disasters is important for fisheries practitioners to implement appropriate disaster prevention measures. Bi et al. (2019) used an ANN model to predict the structural failure of HDPE offshore net cages near Nanji Island during Typhoon Maria. In the field investigation, the hydrodynamic characteristics data of the cage under different wave conditions are used as the training model, and it is found that the ANN model can accurately predict the damage level of the offshore net cage under the influence of typhoon waves.

These studies reveal net cages' stress and damage characteristics and laterally reflect the importance of typhoon and cage damage prediction in fishery disaster prevention. Due to the non-uniform specification of cages in different aquaculture areas, differences in geomorphological features, and differences in the water environment, the damage of net cages is also different. Therefore, the actual damage of nets varies widely for different aquaculture areas in China, and it is of great significance to study the impact of typhoon disasters on net cages from actual cases and provide a disaster warning program for disaster prevention in fishing culture. During typhoon disasters, it is essential to maintain the nets, reduce losses, and ensure the safety of facilities, cultured fish, and personnel. For this reason, this paper puts forward the following suggestions for disaster prevention and mitigation measures for net cages during typhoon disasters:

1) Net cage design

In the design and construction stage of the net cage, it is necessary to consider its wind, wave, and impact resistance and use strong and durable materials to increase the facility's stability.

2) Emergency plan

Before the cage is put into production, it is necessary to make a detailed emergency plan for the typhoon disaster, including evacuating the net cage and protecting the facilities and organisms. Moreover, train staff to ensure that they know the response.

3) Daily management

In daily management, it is necessary to regularly check the structure and equipment of aquaculture facilities and preventive measures should be taken in advance, such as strengthening facilities, checking equipment, and ensuring the stability of mariculture net cages to reduce possible damage. Check whether the parts of the cage structure are intact, and the parts with hidden dangers should be repaired and reinforced in time. Clean up the fouling organisms on the structure in time to avoid scraping the netting and causing the fish to escape. The necessary reinforcement of the mooring connection position of the cage structure is carried out, and the buffer device between the cage single structure is checked and fixed to improve the safety of the cage structure during the typhoon. Check and reinforce the mooring system, check whether the cable is broken or worn, and whether the attachment has affected the everyday use of the cable. If necessary, a relatively long anchor can be added on the possible windward side; check whether the rope buffer sinker or buoy is intact and firmly tied, and according to the wave height of extreme sea conditions, reinforce and lengthen all fixed anchor ropes at equal distances to avoid no buffer ' hard pull ' between the anchor rope and the cage structure; ensure that the cable is connected in different directions so that the net cage and the cable become whole, limit the deformation of the net cage, and avoid the net cage being hit by strong waves to deform or collapse or break.

4) Disaster-prone season

More frequent inspections and constant attention to meteorological and marine early warning systems are needed, especially before and after the disaster season. Know the possible typhoon disasters at any time in order to prepare for protection. According to the possible impact of typhoons, the weather station uses three forms of "news", "alarm", and "emergency alarm" to release to the society in the forecast. According to the possible impact of typhoons, the warning signals of blue, yellow, orange, and red typhoons are released to society from light to heavy. The anti-stress treatment of cultured fish was carried out by feeding immune polysaccharides, compound vitamins, and Chinese patent medicine preparation 7 days before the disaster. At the same time, hanging iodine and chlorine preparations were used to prevent the disease of net cages and cultured fish to reduce the damage and infection during typhoons.

5) During the disaster

If a typhoon warning occurs, the net cage should be transferred to a relatively safe place to avoid direct impact. Finally, after the disaster, timely check the damage to aquaculture facilities and fish, take measures to repair and restore, clean up disaster residues, and observe and restore water quality.

5.2. Suggestions for Sea Ice Disaster

1) Frozen Net Cage

If a typhoon warning occurs, the net cage should be transferred to a relatively safe place to avoid direct impact. Finally, after the disaster, timely check the damage to aquaculture facilities and fish, take measures to repair and restore, clean up disaster residues, and observe and restore water quality.

Compared with typhoon disasters, sea ice disasters have less impact on the scope, loss degree, and frequency of mariculture net cages. Therefore, at this stage, the decision-making on disaster prevention and mitigation of sea ice disasters are more inclined to prevention. The existing research focuses on the spatial and temporal distribution of sea ice disasters (Guo et al., 2023; Liang et al., 2016; Wu et al., 2016; Liu et al., 2019; Tao et al., 2018), sea ice prediction based on remote sensing and meteorological data (Li, 2017; Jiao et al., 2017; Pang et al., 2018), economic losses(Zuo et al., 2019; Guo et al., 2023; Pan et al., 2017), numerical simulation of sea ice (Wang et al., 2014; Bai and Wu, 1998; Liu et al., 2003; Su et al., 2005a; Su et al., 2005b; Lin et al., 2012; Zhao et al., 2014) With the deepening of research, China's sea ice short-term observation and forecasting system has been increasingly improved, which has played a positive role in ensuring the safety of production in the Yellow Sea and Bohai Sea in winter.

The ice conditions in the Yellow Sea, Bohai Sea, and the northern part of the Yellow Sea are complex. Some mariculture net cages have simple structures and poor ice and cold resistance. In order to ensure the safety of aquaculture facilities and the smooth progress of production, this paper proposes the following measures:

2) Net cage design

In designing and constructing mariculture net cages, it is necessary to consider ice resistance. In the selection of materials, materials with low-temperature resistance and high strength are used to ensure that the facilities have sufficient stability and can withstand the pressure and impact of ice.

3) Preventive measures

Before the sea ice season, it is necessary to take preventive measures, such as moving the net cage to a safe position, avoiding the high incidence of sea ice, replacing the mooring system and the floating frame structure with cold-resistant materials, painting anti-icing coating on the surface of the device to reduce sea ice adhesion, and using heating equipment to increase the temperature of the aquaculture water area.

4) Daily management

Before and after the sea ice season, it is necessary to regularly check the damage to the cages and repair them in time, and regularly monitor the water quality to ensure that the water temperature, oxygen content, and salinity are within the appropriate range. At the same time, winter sea ice cover will affect the feeding status of farmed animals. To provide adequate feed for animals to ensure the average growth of cultured fish.

5) Net cage freezes

When the cage structure is covered by sea ice, especially the important structure is covered by sea ice, it is necessary to break the ice layer and clean up the broken ice, check the safety of the facilities, and repair them in time to maintain the stability of the structure.

6) Ice Floe

An ice floe is a common disaster for mariculture net cages in cold regions. The primary damage forms come from the impact of ice floes and the accumulation pressure of ice floes. There are few studies on the impact of ice floes on mariculture net cages and more on the collision mechanics analysis of ice floes with structures and ships. Zhang et al. (2005) proposed using rubber pads and dampers as vibration isolation layers. They found that the method can effectively ensure the safety and comfort of the upper structure of the platform. Gagnon (2008) used the impact plate to simulate the collision force of the iceberg of the measuring ship and analyzed the pressure difference in the collision interval. Zhang et al. (2015) monitored the flexible anti-icing platform in Liaodong Bay of the Bohai Sea for many years. They found that the ice floe collision quickly caused the fatigue of the flexible structural pipe joints of the flexible anti-icing platform, which affected the regular operation of the upper facilities and the daily work of the personnel. They proposed the failure mode and evaluation index of the structure under ice-induced vibration, which provided a theoretical basis for the design and safety of the ice-resistant jacket platform. Wang and Zhou (2015) used LS-DYNA software to simulate the collision process between ship and sea ice, and the failure criterion of ice material was the von Mises failure criterion. The results show that during the collision process, the kinetic energy of the ship is mainly converted into the variable performance of the ship and ice; the more significant the initial speed of the ship and the thickness of the ice, the greater the final deformation of the ship; during the collision process, the unloading process accompanied by the failure of the ice material leads to the fluctuation of the ice force time history curve. The main damage area of the ship is where the water surface collides with the ice, and the method of improving the anti-collision performance of the ship is proposed. Dong and Li (2018) used the ice model of the von Mises failure criterion to simulate the collision damage between the semi-submersible offshore platform and sea ice. It was found that the damage in the center and outer area of the column of the platform was severe in the collision. Most of the kinetic energy of the ice floe is converted into the internal energy of the platform. The collision force between the platform and the ice floe increases and decreases with the initial kinetic energy of the ice floe. Xu (2021) studied the collision damage of ice floes on the outer plate of a semi-submersible offshore platform column. The collision response is analyzed mainly from damage, collision force, and energy perspectives. Then, the small iceberg's mass, velocity, and collision contact area are used as the influencing factors to study the effects of the three on the collision damage. It is found that with the increase of sea ice mass, the damage to the platform shows a rising trend. With the increase of sea ice speed, the damage to the platform increases first and then decreases. With the increase in collision area, the damage of the platform shows a decreasing trend.

Similarly, in order to solve the problem of ice floes in winter, marine platforms (Zhang et al., 2021; Qi et al., 2022), photovoltaic power generation (Li, 2023), beacon lights (Wang, 2017), detection buoys (Li, 2023), and mariculture net cages [60] have set up a variety of ice floe-resistant structures, which are supported by a sharp point or have the function of icebreaking knives and spikes, and these marine equipment rely on this unique structure to cut or punch the incoming ice floes so that they break into small pieces of ice floes. The marine equipment relies on this unique structure to cut or ram incoming ice floes, breaking them into smaller pieces. The small pieces of ice floes drift away with the ocean currents and eventually fail to collect around the equipment, reducing its load. Most domestic research on ice floe-resistant structures is still in the experimental stage, and some of the research results have been successfully applied to actual production (Zhang, 2018). The ice floe-resistant method for farmed nets remains conceptual, and further research is needed.

The disaster prevention and mitigation measures for ice floes at sea are generally the same as those for protective icing. However, the impact and coverage of ice floe need to be discussed. Therefore, the following protection suggestions are put forward: The disaster prevention and mitigation measures for ice floes at sea are generally the same as those for protective icing. However, the impact and coverage of ice floe need to be discussed. Therefore, the following protection suggestions are put forward:

1) Ice floe-resistant structure design

In the design and construction of mariculture net cages, ice floe-resistant structures are added, or other designs are adopted to strengthen the ice floe-resistant function of net cages, weaken the impact of ice floe and play a role in protecting net cages.

2) Preventive measures

Before the sea ice season, preventive measures need to be taken, such as moving the mariculture net cage to a safe position, avoiding the high incidence of ice floes, and using heating equipment to increase the temperature of the aquaculture environment.

3) Daily management

Before and after the sea ice season, it is necessary to regularly check the damage to the mariculture net cages and repair them in time. Always pay attention to the situation and movement trend of sea ice and ice floes. When it is found that the sea ice begins to close to the aquaculture area and may hit the mariculture net cages, it is necessary to add anti-icing nets in time or block the ice floes with ships to reduce the impact damage.

4) Ice floe accumulation

If it is found that ice floe begins to accumulate around the net cage, the ice layer should be smashed in time to clean up the broken ice and prevent the accumulation of ice to reduce the load on the net cage.

By taking these comprehensive measures, aquaculture practitioners can minimize the impact of winter sea ice and ice floes on mariculture net cages and ensure aquaculture's safe and stable operation.

6. SUMMARY

China has a long coastline and extensive seawater, providing convenient development conditions for mariculture net cages. In recent years, with the increasing attention of the state to mariculture and the continuous improvement of the level of science and technology, China's rapid development of mariculture net cages has increased. Under the influence of global warming and sea level rise, the frequency and intensity of marine disasters have escalated, and the hazards of typhoon and sea ice disasters on mariculture net cages are becoming increasingly evident. Typhoon disaster triggered solid winds and waves, leading net cages to flood, drift, tip, collapse, and rupture the netting. In sea ice disasters, the pressure of icing and the impact of ice floe lead net cages to deformation, displacement, and overturning. During disasters, drastic changes in the environment, fish diseases, and fish escapes cause significant losses in production. The onslaught of marine disasters continues to impede mariculture development, and disaster prevention and mitigation in the mariculture industry remains formidable. At this stage, China still lacks maintenance measures for net cages, disaster early warning and reporting services, comprehensive disaster risk assessment, and decision-making services for disaster prevention and mitigation. To ensure the security of net cage facilities and implement disaster prevention and mitigation strategies in China, the following prospects are presented:

1) Building a more complete emergency response system for aquaculture disasters is essential. According to the relevant requirements of the Marine Disaster Emergency Response Plan, the relevant departments of coastal cities have actively deployed disaster prevention and mitigation measures with "prevention-oriented" and accelerated the establishment of the working mechanism for early warning reports, information dissemination, emergency response, restoration, and reconstruction, as well as investigation and assessment of marine disasters. Relevant management departments and scientific researchers have strengthened close cooperation to improve the marine disaster detection system and realize data sharing.

2) Actively advocate the establishment of a database on farmed nets and marine disasters in coastal areas, including not only data on the characteristics of the disaster itself (typhoon: maximum wind force, wind speed, the radius of the wind circle; sea ice: icing area, thickness, ice floe flow rate and direction of the ice floe et al.) but also data on the disaster situation (damage site, affected area, economic loss et al.), forming an information sharing platform to provide scientific data support for the layout of the farmed nets, damage research and disaster prevention and mitigation measures. Establish an information-sharing platform to provide scientific data support for net cage layout, damage studies, and disaster prevention and mitigation measures.

3) Publicity, education, and skills training in marine disaster prevention and mitigation are essential to disaster prevention and mitigation. Increase the publicity of marine disaster warning and forecasting products to enhance the recognition of aquaculture practitioners. Regularly organize expert teams deep into coastal aquaculture enterprises to popularize and educate marine disaster prevention, mitigation knowledge, and net maintenance measures. Enhance aquaculture practitioners' awareness of disaster prevention and mitigation and their ability to avoid risks and save themselves.

Author contribution statement

Ming-Shan Sun: Writing-original draft, Investigation, Formal analysis, Data curation. **Chun-Wei Bi**: Conceptualization, Methodology, Supervision, Writing-review & editing, Funding acquisition. **Liu-Yi Huang**: Writing-review & editing.

Declaration of competing interest

The authors declare no known competing interests that could influence the work reported in this paper.

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