POAC'25
St. John's, Newfoundland and Labrador, Canada

Proceedings of the 28th International Conference on Port and Ocean Engineering under Arctic Conditions
Jul 13-17, 2025
St. John's, Newfoundland and Labrador Canada

Study of ice prone waters in China as a potential experiment site for ice resisted structure design

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ABSTRACT

Natural formed ice during winter is important for the country in low latitudes for the potential application as a field work site. In China, the Bohai Sea and northern lakes are covered with ice for months. The hydrological and meteorological conditions in these areas are relatively complex and lead to various ice properties. Selecting a suitable filed work site requires comprehensive consideration of multiple environmental factors and their influences on the ice properties. Therefore, this study investigated the environmental conditions and physical and mechanical properties of the natural formed ice. Through satellite remote sensing images of the Bohai Sea from 2021 to 2023, the ice period and conditions in different icy waters were analyzed. Based on historical temperature data, the ice and air temperatures in different areas were analyzed. At the same time, experimental research was conducted on the physical properties of sea ice, such as compression and flexural strength. Also, the ice salinity, density and texture are also determined. It shows that the period of freshwater ice can reach four months which is longer than that from saline ice. However, the strength of freshwater ice is overall 3~4 times higher than the that of saline ice. There is no one dominating area based on current the survey data, the final decision may dependent on the prior demand.

KEY WORDS: Sea ice; Bohai Sea; strength; environment condition; fieldwork site

1 INTRODUCTION

With the global climate change, research in polar regions has increasingly received extensive attention from the international community (Comiso, et al., 2012; DeConto, et al., 2016). Researchers from the countries in high latitudes have done milestone experiments in the field, which provide important support for the Arctic engineering structure design. However, as a country located in mid-low latitude, it brings difficulties and challenges to perform sufficient field work for Chinese researchers, in both time and financial consuming.

Currently, research on sea ice in China primarily relies on indoor ice tank experiments and field measurements (Wang, et al., 2021). Due to the complex structure and composition of naturally occurring sea ice, accurately simulating real sea ice in the laboratory by freezing sea ice is challenging. Additionally, the limited size of ice tank chambers makes it difficult to conduct large-scale experiments involving significant thickness and structural dimensions. As a result, using naturally occurring sea ice for large-scale experiments is considered more reliable for studying polar sea ice. Polar sea ice typically forms in winter, with thicknesses ranging from a few meters to over ten meters. Its ice mass is dense and structurally stable, covering the ocean surface year-round. In contrast, the characteristics of sea ice in China's Bohai Sea are more diverse and complex. The formation of sea ice in the Bohai Sea is heavily influenced by climatic and hydrological conditions (Li, et al., 2021). It typically forms in winter, with thicknesses ranging from a few centimeters to one meter. The sea ice in the Bohai Sea is primarily driven by freshwater input, temperature fluctuations, and wind and wave actions. While its salinity and density are similar to those of polar sea ice, the formation and ablation periods are much shorter.

Lake ice, another significant natural ice body, is widely distributed in China. Compared to sea ice, lake ice is less influenced by wind, waves, and tides. In high-latitude regions, lake ice generally experiences a more stable and prolonged freezing cycle, which ensures the safety and integrity of the experimental process. Therefore, this paper selects a portion of domestic lake ice and an area along the eastern coast of the Bohai Sea as the preselected experimental sites. It analyzes the meteorological and hydrological conditions, as well as the physical and mechanical properties of the sea ice, and compares them with conditions in the Arctic and Antarctic regions to assess the feasibility of using these areas as polar experiment sites. This study thus provides a foundation for enhancing China's technological capabilities in polar scientific research and shipping. Additionally, it offers new research directions and technical support for addressing global climate change and advancing the development of polar resources.

2 LOCATION OVERVIEW

In this study, we primarily consider Hanzhang Lake, Moon Bay, Qinghai Lake, Inner Mongolia South Lake, and Wuliangsuhai Lake as the potential sites. Among them, Hanzhang Lake (41.118°N, 122.084°E) is located in Panjin City, Liaoning Province, China. Previous research (Xie, et al., 2023) identified it as a brackish water lake, however, a field experiment conducted in 2025 revealed that the ice salinity is almost 0, indicating it is freshwater ice. Moon Bay (40.2°N, 122.2°E), located in Yingkou, Liaoning Province, China, is situated near the Bohai Sea. Qinghai Lake (36.5°N-37.25°N, 99.5°E-100.75°E) is located at the junction of Hainan Tibetan Autonomous Prefecture and Haibei Tibetan Autonomous Prefecture in Qinghai Province, China. As the largest inland saltwater lake in China, it has a highland climate due to its location in the northeastern part of the Qinghai-Tibetan Plateau. Inner Mongolia South Lake (40.26°N, 111.15°E) is located in Hohhot, Inner Mongolia Autonomous Region, to the west of the Yellow River, and experiences a temperate continental monsoon climate. Wuliangsuhai Lake (40.97°N, 108.90°E) is situated in Ulatqian Banner, Bayannur City, Inner Mongolia Autonomous Region, and is one of the eight major freshwater lakes in China.

3 METEOROLOGICAL AND HYDROLOGICAL CONDITIONS

3.1 The water depths of potential sites

As one of the primary factors limiting the operation of navigational vehicles, water depth also impacts the relevant physical properties of sea ice. This study examines the water depths in the four regions described in Chapter 2, with the following results: the average water depth of Hanzhang Lake is 6 m, with the water level on its eastern side higher than that of other areas, averaging about 12.0 m. The deepest water depth along the eastern shore, near the middle road around the lake, can reach up to 16.0 m. The maximum high tide level in Moon Bay is 3.26 m, with an average maximum high tide level of 1.45 m. The average water depth of Qinghai Lake is 18.3 m, with a maximum depth of 26.6 m. The average water depth of Inner Mongolia South Lake is 2.60 m (Zhu, et al., 2025). In Wuliangsuhai Lake, the water depth ranges from 1.20 to

2.70 m, with an average depth of 1.60 m (Huo, et al., 2024).

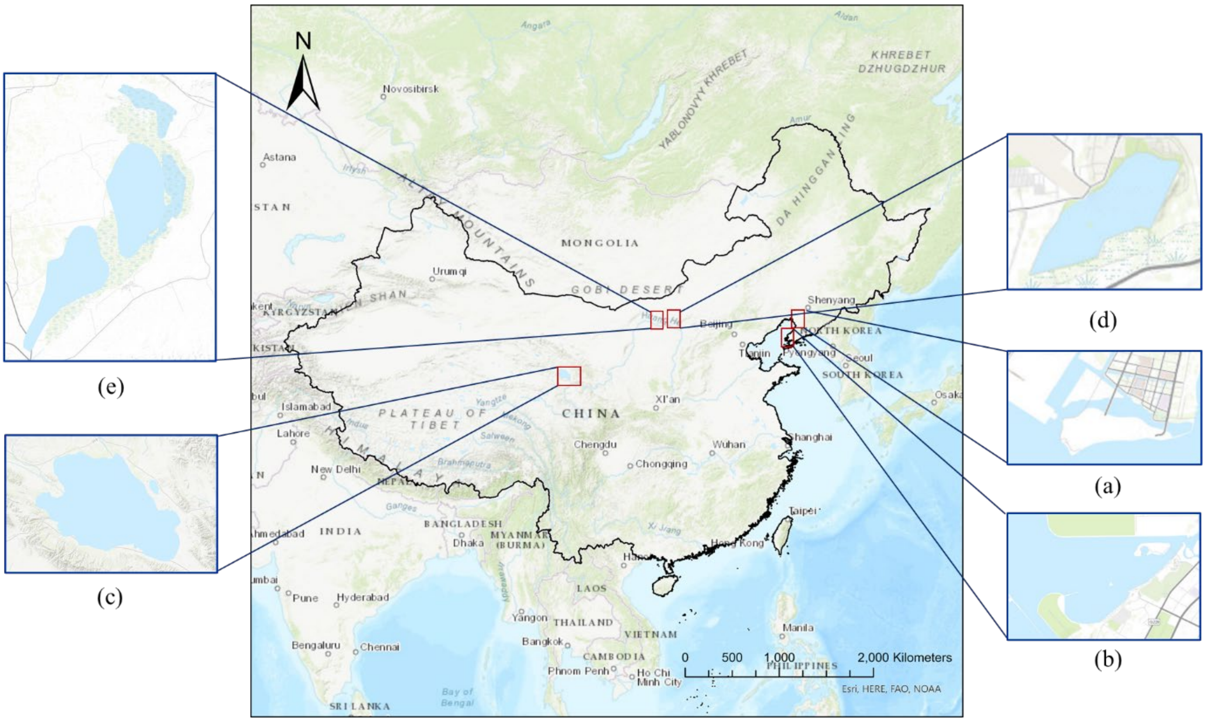


Figure 1. Distribution of five potential sites

(a. Hanzhang Lake; b. Moon Bay; c. Qinghai Lake; d. Inner Mongolia South Lake; e. Wuliangsuhai Lake)

3.2 The air temperatures of potential sites

The formation of sea ice is seasonal, and temperature plays an important role in the processes of ice formation, melting, and thickness variation. Higher temperatures increase the concentration of air bubbles and salts within the sea ice, which can reduce ice strength and its load-bearing capacity. Temperature fluctuations also affect the ductility and brittleness of sea ice, leading to changes in the break-up pattern and deformation behavior when subjected to stress. Additionally, temperature reflects seasonal variations in the region. Polar regions, which are covered by sea ice year-round, are prioritized as areas with lower temperatures for the selection of polar-like experiment sites. The air temperatures for the years 2021 to 2024 in the five potential sites described in Section 2 were obtained from the European Centre for Medium-Range Weather Forecasts, and the results are presented in Table 1.

Table 1 Winter temperatures at five potential sites, 2021-2023

Temperature(°C)	2021-2022			2022-2023			2023-2024		
	Min	Ave	Percentage below 0°C (%)	Min	Ave	Percentage below 0°C (%)	Min	Ave	Percentage below 0°C (%)
HanZhang Lake	-16.2	-14.2	81.9	-18.1	-15.1	79.7	-16.4	-14.4	82.2
Moon Bay	-17.2	-15.1	80.1	-18.5	-16.1	81.9	-16.7	-14.7	83.2
Qinghai Lake	-18.6	-14.7	86.6	-20.0	-16.7	83.6	-19.0	-15.5	81.3
Inner Mongolia South Lake	-20.6	-15.6	69.7	-25.0	-19.8	64.2	-26.6	-21.6	69.8
Wuliangsuhai Lake	-24.4	-19.4	75.7	-27.2	-21.4	70.7	-29.4	-23.8	75.9

A comparison of the average daily temperatures of the five potential sites revealed that Hanzhang Lake and Moon Bay recorded the highest temperatures, with a relatively small temperature difference between the two regions. The lowest average daily temperature was observed in Wuliangsuhai Lake, while the temperature in Inner Mongolia South Lake was slightly higher than that of Wuliangsuhai Lake. The temperature of Qinghai Lake, in contrast to the other four regions, exhibited smaller fluctuations, and the duration of low temperatures was longer.

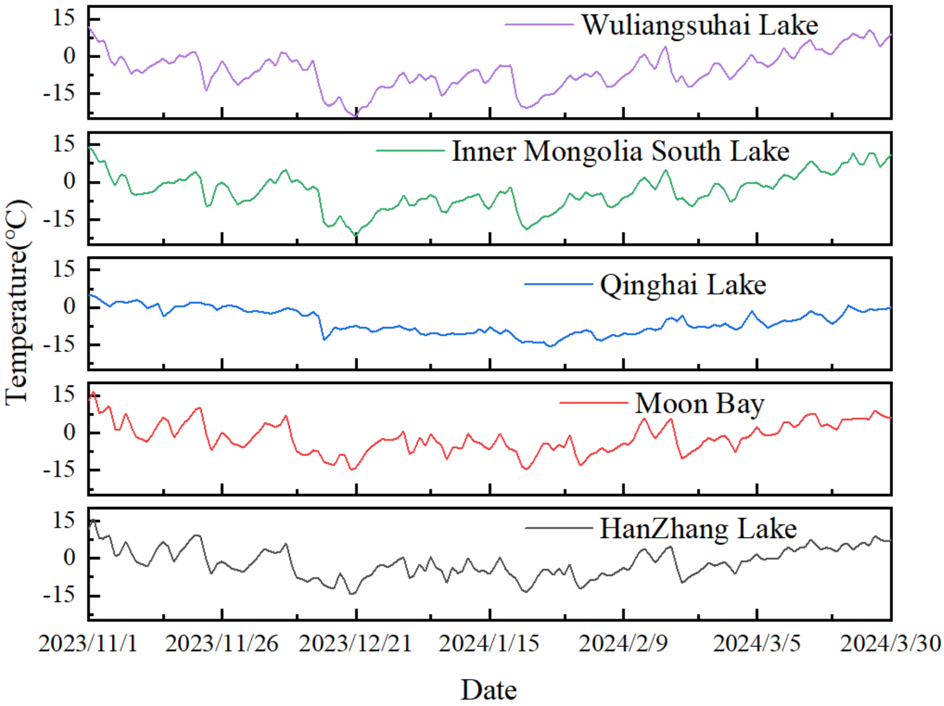


Figure 2. Changes in the average daily temperature from 2023 to 2024

3.3 The ice temperatures of potential sites

The surface ice temperature is strongly influenced by air temperature, which, in turn, governs the growth rate, morphology, and structural characteristics of ice crystals. Slow temperature changes result in the gradual growth of ice crystals, leading to the formation of large, single crystals with a more regular shape. In contrast, significant temperature variations promote the formation of polycrystals, resulting in more complex interfaces between crystals, with potential defects and irregularities. These profiles can be classified as linear, "C"-type, inverted "C"-type, and inverted "S"-type (Huo, et al., 2024). The average ice temperature in Hanzhang Lake is -7.2°C, with the highest ice temperature recorded in Moon Bay at -2.7°C, the lowest ice temperature at -30°C, and the average ice temperature at -13.8°C. The sea ice temperature in Qinghai Lake ranges between -2.3°C and -8.6°C.

3.4 The ice periods of potential sites

The icing period refers to the duration during which ice forms on the surface of an ocean or water body, typically including the freezing, growth, stabilization, melting, and break-up stages. A longer and more stable icing period can provide a suitable experimental window, and for large-scale prototype experiments, a prolonged icing period ensures the integrity of the experimental process. According to current domestic analyses of the lake ice formation and elimination processes, the icing period of Hanzhang Lake spans from early December to mid-March of the following year, with an icing cycle of approximately 3 to 4 months (Xie, et al., 2022). In Qinghai Lake, ice formation occurs from mid-December to the second half of March the following year, with an icing cycle ranging from 90 to 125 days, averaging 108 days (Qi, et al., 2019). Inner Mongolia's South Lake freezes from mid- to late-November and remains frozen until mid- to late March the following year, with an average icing cycle of 108 days, spanning approximately 3 to 4 months (Zhu, et al., 2025). Wuliangsuhai Lake experiences an icing period from late November to late March of the following year. For example, in the 2015-2016 season, remote sensing data show that the lake ice growing period lasted from November 21 to January 24 of the following year and become stable from January 25 to March 1, and the melting phase from March 2 to 25, with the total ice period duration of 126 days (Huo, et al., 2024). Currently, there are very few datasets on the sea ice growth in Moon Bay. Therefore, the ice period in Moon Bay is obtained from the analysis of aerial photographs and satellite imagery, which indicate an icing period from mid- to late December to the end of February the following year, with a period of 2 to 3 months.

4 PHYSICAL AND MECHANICAL PROPERTIES OF SEA ICE

4.1 The ice thickness of potential sites

For the potential sites examined in this study, ice thickness data are collected from reference and measurements. During the ice season of Hanzhang Lake, the ice growth rate can reach 0.44 cm/d while the average melting rate is 1.3 cm/d, and the maximum ice thickness reaches 30.7 cm in the winter of 2021-(Xie, et al., 2021). By the measurement in the winter of 2024-2025, the maximum sea ice thickness in the Moon Bay reached 25 cm. For Qinghai Lake, the sea ice thickness exhibits a decreasing trend. Based on the measurement from 1958 to 1983, the ice thickness remained around 50 cm, with a maximum thickness reaching 70 cm (Chen, et al., 1995).

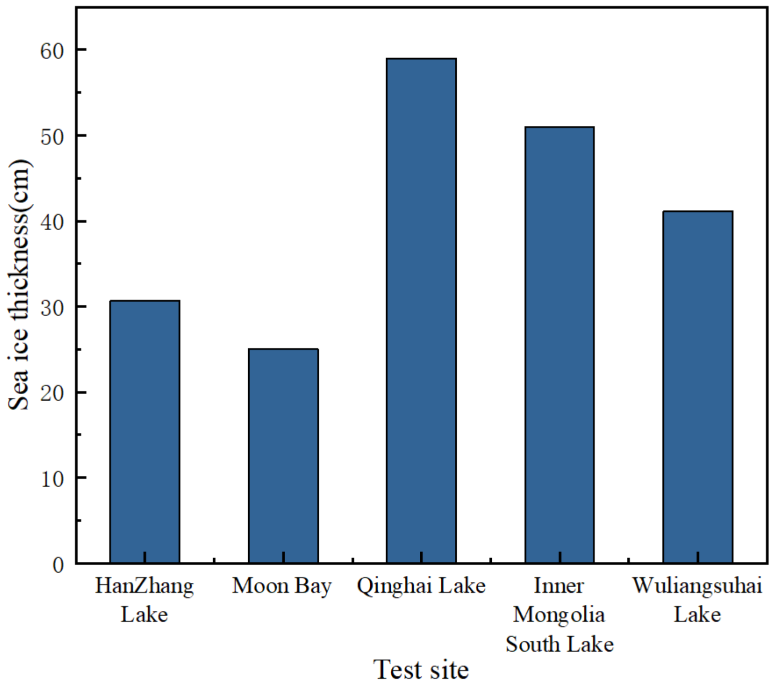


Figure 3 Maximum winter ice thickness at five potential sites

From 1983 to 2018, the average ice thickness in February reached 59 cm, marking the thickest stage of the lake ice formation and ablation process, while the minimum thickness recorded was 6 cm, and the overall average thickness was 29.4 cm (Wang, et al., 2021). Between 2003 and 2022, the maximum ice thickness of Inner Mongolia's South Lake, during the lake ice growth and elimination phases, occurred in February, ranging from 28 to 51 cm. The average ice thickness ranged from 14 to 30 cm and showed a decreasing trend (Zhu, et al., 2025). The ice thickness variation in Wuliangsuhai Lake,can be divided into three stages: growth, stabilization, and melting. In 2016, the average growth rates for these three stages were 0.33 cm/d, -0.11 cm/d, and -1.0 cm/d, respectively, with the maximum ice thickness reaching 41.1 cm (Yan, et al., 2017).

4.2 The ice salinity and density of potential sites

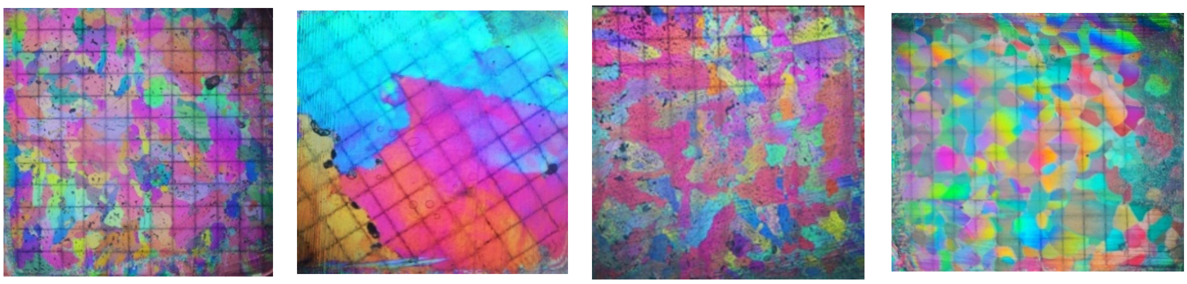
Sea ice salinity refers to the concentration of dissolved salts within sea ice, primarily derived from seawater, with sodium chloride (NaCl) being the most common. Due to the large molecular size of salts, they cannot integrate into the ice crystal structure. As a result, salts in sea ice exist as brine within the liquid inclusions inside the ice. The salinity of sea ice influences the porosity, which in turn affects the mechanical properties of the ice. Recent studies indicate that the salinity of lake ice in Hanzhang Lake ranges from 0.2‰ to 0.8‰ (Wang, et al., 2024). However, in 2025, it is measured to a range from 0‰ to 0.10‰. The density of the lake ice in Hanzhang Lake is 803 to 938 kg/m^3, with an average density is 883 kg/m^3. In Moon Bay, the salinity of sea ice ranges from 4.30‰ to 6.70‰, with an average of 5.00‰. The density of the ice in Moon Bay ranges from 766 to 917 kg/m^3, with an average density is 865 kg/m^3. For Qinghai Lake, the lake ice salinity is between 0.70‰ and 2.50‰, and the density of the lake ice ranges from 808 to 909 kg/m^3, with an average density is 858 kg/m^3. The ice density of Wuliangsuhai Lake ranges from 860 to 920 kg/m^3 (Yan, et al., 2017).

4.3 The ice strength of potential sites

The mechanical behavior of icebreaking and the resulting damage to sea ice are influenced by several key mechanical parameters, including the uniaxial compressive strength, flexural strength, and elastic modulus of the ice (Ji et al., 2011). To obtain reliable data on sea ice strength, strength experiments were conducted on samples collected from ice stations in the Arctic and Antarctic regions in recent years. For the regions discussed in Sec.2, sea ice strength data were obtained through on-site sampling and experiments. Uniaxial compressive and three-point flexural experiments were performed at Hanzhang Lake. The results showed that the uniaxial compressive strength ranged from 1.15 MPa to 7.32 MPa, with an average value of 3.52 MPa. The tough-brittle transition strain rate was between $10^{-3}s^{-1}$ to $10^{-2}s^{-1}$ (Wang, et al., 2024). The flexural strength ranged from 1.19 MPa to 5.39 MPa, while the modulus of elasticity varied from 1.71 GPa to 9.75 GPa. At Moon Bay, uniaxial compressive and three-point flexural experiments were carried out, with the loading direction in the uniaxial compressive tests perpendicular to the ice growth direction. The experimental results showed that the uniaxial compressive strength of the sea ice ranged from 0.61 MPa to 3.33 MPa, with an average value of 1.95 MPa. The flexural strength ranged from 0.21 MPa to 1.89 MPa, with an average of 0.70 MPa, and the modulus of elasticity ranged from 0.45 GPa to 2.49 GPa. At Qinghai Lake, uniaxial compressive and three-point flexural experiments revealed that the uniaxial compressive strength ranged from 0.5 MPa to 3.95 MPa, with the maximum flexural strength being 1.76 MPa and the minimum flexural strength being 0.80 MPa. The modulus of elasticity ranged from 0.58 GPa to 1.90 GPa. Lastly, cantilever beam flexural experiments were conducted at Wuliangsuhai Lake, where the maximum and minimum flexural strength of the sea ice were found to be 0.75 MPa and 0.44 MPa, respectively, and the modulus of elasticity ranged from 3.62 GPa to 6.71 GPa. (Wang, et al., 2024)

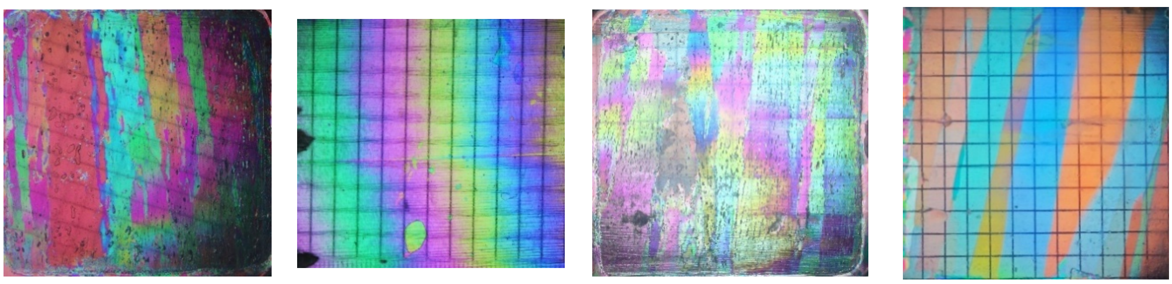
4.4 The ice texture of potential sites

Environmentally controlled changes in sea ice growth mechanisms can result in several distinct grain structures, with the most common being granular, columnar, and discontinuous columnar. The natural ice crystal structure of sea ice is typically columnar, with crystals along the vertical direction (thickness direction) being significantly larger than those in the horizontal direction (perpendicular to the thickness direction). Therefore, it is important to observe both directions of the ice crystal structure during sea ice crystal analysis. The following figure presents images of the ice crystal structures from different sampling sites (each grid is 5mm × 5mm). Upon examining the ice crystals, it is observed that the samples from Hanzhang Lake, Moon Bay, and Qinghai Lake all exhibit columnar ice. Notably, the ice crystal structure in Moon Bay and the central Bohai Sea is similar, characterized by smaller and irregularly shaped crystals. In contrast, the ice from Qinghai Lake shows more regular shapes, with crystal sizes comparable to those of sea ice. The ice crystals from Hanzhang Lake are much larger than those from the other sites, with a more regular shape, resembling the structure typically found in freshwater ice.



Sea ice | Hanzhang Lake | Moon Bay | Qinghai Lake

Figure. 4 Ice texture in the horizontal direction



Sea ice | Hanzhang Lake | Moon Bay | Qinghai Lake

Figure. 5 Ice texture in the vertical direction

5 DISCUSSIONS OF THE ICE PROPERTIES FROM THE POTENTIAL SITES

Currently, the Arctic sea ice research in China primarily focuses on Arctic summer sea ice during the melt season. This paper analyzes the meteorological and hydrological conditions of lake ice, along with the physical and mechanical properties of sea ice, and compares them to those in the Arctic. The main purpose is to identify a suitable experimental site in China that simulate polar conditions, addressing the limitations of indoor ice tanks for large-scale model experiments.

5.1 The Arctic sea ice

From 2008 to 2016, the Chinese scientific research team conducted studies in the Arctic, focusing on the temperature, salinity, density, and other related parameters of Arctic sea ice during the melting period. The results indicated that the temperature of the Arctic sea ice during the melting period ranged from -2.70°C to -0.30°C, the salinity of the ice layer varied between 0.40‰ and 3.00‰, and the density of the ice layer ranged from 606.6 to 903.2 kg/m^3 (Wang, et al., 2019) Additionally, during the Sixth Arctic Scientific Expedition, shipboard data on sea ice thickness were collected, which revealed that the average sea ice thickness in the dense ice region of the Arctic was 109.8 cm (Wang, et al., 2019). In 2016, during the Seventh Arctic Expedition, the Chinese research team conducted sea ice compressive strength experiments at a long-term ice station near the Arctic. The results showed that the columnar ice and the pelletized ice were in the range of $1.2\times 10^{-5}s^{-1}$ and $1.9\times 10^{-5}s^{-1}$, respectively. The ultimate uniaxial compressive strength in the vertical direction of the ice layer during the melting period was found to be 3.32 MPa (Wang, et al., 2018).

5.2 Comparison of ice properties

The analysis of meteorological and hydrological conditions, as well as the physical properties of ice at different locations, is summarized in Table 2, as discussed in Chapters 2 and 3. No sea ice field experiments were conducted at Inner Mongolia's South Lake, and therefore, fewer physical and mechanical properties were available for analysis. Field experiments were conducted in early 2025 at Hanzhang Lake, Moon Bay, and Qinghai Lake. Additionally, comparisons were made with sea ice characteristics from the Arctic (Kovacs, 1996; Timco et al., 2010).

Table 2 Summary of key factors at different potential sites

Influencing factor \ Site		Hanzhang Lake	Moon Bay	Qinghai Lake	Inner Mongolia South Lake	Wuliangsuhai Lake	Arctic
Water depth (m)	Max	16.0	3.26	26.6	—	2.70	—
	Ave	6.00	1.45	18.3	2.60	1.60	—
Temperature (°C)	Min	-18.5	-18.5	-20.0	-26.6	-29.4	—
	Ave	-15.1	-16.1	-16.7	-21.6	-23.8	—
below 0°C		82.2%	83.2%	86.6%	69.8%	75.9%	—
Ice temperature (°C)		-7.20	-13.8	-8.60	—	—	—
Ice period (day)		90-120	60-90	90~125	90-120	126	—
Ice thickness(cm)		30.7	25.0	59.0	50.9	41.1	200
Ice salinity (‰)		0-0.10	4.30-6.70	0.70-2.50	—	—	3.75-10.6

Ice density ($kg \cdot m^{-3}$)		803-938	766-917	808-909	—	860-920	607-903
Ice strength (MPa)	Compressive	1.15-7.32	0.61-3.33	0.5-3.95	—	—	0.4-5.1
	flexural	1.19-5.39	0.21-1.89	0.8-1.76	—	0.44-0.75	0.1-1.5
Modulus of elasticity (GPa)		1.71-9.75	0.45-2.49	0.58-1.90	—	3.62-6.71	1.7-9.1

6 CONCLUSIONS

The percentage of winter temperatures below 0°C in Hanzhang Lake, Moon Bay, and Qinghai Lake exceeds 80%. The lowest temperature recorded at Inner Mongolia's South Lake and Wuliangsuhai Lake can drop below -25°C, with average temperatures reaching below -20°C. The sea ice freezing period in all five potential sites lasts for at least three months, ensuring the integrity of the experimental process. The average water depth of Qinghai Lake is 18.3 meters. The maximum sea ice thickness in Moon Bay during the melting period is 25 cm, while in Hanzhang Lake, it exceeds 30 cm. In Wuliangsuhai Lake, the maximum sea ice thickness can reach 41.1 cm, and both Qinghai Lake and Inner Mongolia South Lake have sea ice thicknesses exceeding 50 cm. Notably, in recent years, the maximum sea ice thickness in Qinghai Lake has reached 59 cm. The salinity of the sea ice in Moon Bay and Qinghai Lake is similar to that found in polar regions. The sea ice density in Hanzhang Lake, Moon Bay, Qinghai Lake, and Wuliangsuhai Lake is also comparable to that of polar regions. Strength tests reveal that the ice strength in Hanzhang Lake exceeds that of polar regions, while the ice strength in Moon Bay and Qinghai Lake is similar to that found in the polar regions. The ice in Hanzhang Lake, Moon Bay, and Qinghai Lake is primarily columnar in structure, with the ice crystal structure in Moon Bay and Qinghai Lake resembling that of one-year-old ice in polar regions. This demonstrates that these sites in China can conduct polar-like experiments, addressing the limitations of ice tank experiments and contributing to advancements in China’s technological capabilities in polar scientific research and maritime operations.

ACKNOWLEDGEMENTS

This research was supported by the National key research and development program (Grant No. 2024YFC2816403), National Natural Science Foundation of China (Grant Nos. 52101300,52192693, 52192690, 42176241), High-Tech Ship Research and Development Program (Grant No. CBG2N21-2-3).

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