Effect of ice load and freeze-thaw environment on seawall

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Abstract: Some ports in cold regions are affected by ice load and freeze-thaw cycles, and the stability of structures and foundations is affected. In this paper, based on a seawall project, through laboratory tests, the various indexes of foundation soil freezing of sea dike are tested, including frost heaving rate, frost heaving force, thawing compression coefficient of frozen soil, uniaxial compression test, shear test and bending test of frozen soil. By using the parameters obtained from the test results, a three-dimensional numerical model of seawall engineering under ice load and freeze-thaw action is established. The stress and deformation of seawall structure and foundation are simulated, and the safety and stability of seawall are comprehensively analyzed.

1. Summary
Sea ice has a serious impact on the safe navigation and anchoring operation of ships. When the ice situation is serious, it will cause the ship maneuvering difficulties, hull damage, anchor removal and other accidents. If the density of drift ice in front of the wharf is large, it will bring difficulties to berthing operation. For ships moored in front of the wharf, the force of floating ice cannot be ignored. At present, some general mooring calculation software does not consider the force of floating ice on the ship. It is pointed out in the literature that ships of more than 5000t which can navigate normally in the drift ice area with ice thickness less than 10cm, can navigate in the drift ice area with ice thickness of 10-20cm, but it is difficult to navigate; if the ice thickness is more than 20cm, it cannot navigate. At present, in view of the ice situation in the northern sea area of China, some ports have given the principled countermeasures for safe navigation and anchoring of ships, but no unified standard has been formed.

Many countries in cold regions have carried out a lot of experimental and theoretical studies. Croasdale (1980) and Wessels (1988) respectively summarized the research on the interaction between
ice and inclined plane or cone, and demonstrated the effectiveness of installing cone. In the 1980s, it has been used in various structures, such as bridge piers and caissons. However, there are still great uncertainties in the research and application of ice loads on conical offshore structures.

In this paper, through the indoor freeze-thaw test of the foundation soil of sea dike engineering, the strength index changes of the foundation soil under the freeze-thaw cycle condition are summarized. On this basis, the ice load is simplified as static load, and the three-dimensional anti sliding stability calculation model of seawall engineering is established to evaluate the overall safety and stability risk of seawall engineering under ice load and soil freezing and thawing.

2. Experimental study on freezing thawing of foundation soil in seawall engineering

According to the freeze-thaw depth of the foundation soil in the engineering area, the soil samples of the seawall engineering foundation are selected to carry out the soil freeze-thaw test to study the change of the physical and mechanical properties of the foundation soil under the freeze-thaw cycle, so as to provide the basic data for the numerical simulation of the overall stability of the seawall project.

2.1. Test overview

The test is carried out based on the actual project. The soil samples are undisturbed soil samples, and the frozen soil conditions are simulated according to the seasonal frozen soil conditions in the project site. According to the actual data, the frozen depth of the seawall project area is 0.7m, the minimum temperature in winter and the frozen soil time are used to simulate the actual situation of frozen soil. There are two groups of soil samples, i.e. embankment and sea side soil samples, numbered as group A and group B respectively, and the temperature level is -20 °C. The required frozen soil test indexes are as follows: frozen soil density, freezing temperature, frost heaving test (test frost heaving rate), frozen soil thawing compression test (test thawing settlement coefficient of frozen soil and thawing compression coefficient), unconfined compressive strength test (test frozen soil and unconfined compressive strength after thawing), shear strength index test and flexural strength test of frozen soil.

The sampling and transportation process meet the requirements of engineering investigation. In order to facilitate comparison, the moisture content and density of the test soil layer were measured.

2.2. Test results

2.2.1. Frost heaving rate and frost heaving force of frozen soil

By fitting the curve of frost heaving rate and frost heaving force with time obtained in the process of soil frost heaving, the parameters a and B are shown in Table 1 respectively.

| No. | Property  | Frost heaving rate (%) | Frost heaving force (MPa) | Remarks                                                                 |
|-----|-----------|------------------------|--------------------------|-----------------------------------------------------------------------|
| A   | mucky soil| 3.43                   | 0.93                     | According to the classification method of frost heaving of frozen soil, the test samples are all weak frost heaving soil. |
| B   | mucky soil| 2.82                   | 0.86                     |                                                                       |

2.3. Strength test of frozen soil

The results are shown in Table 2. Uniaxial compression, shear and bending tests are carried out on frozen soil samples, and the corresponding strength indexes are obtained. Shown in Table 3-5.
### Tab 2 Thawing compression index of frozen soil

| No. | Property   | Freezing temperature /°C | Compressibility factor /MPa⁻¹ |
|-----|------------|--------------------------|-------------------------------|
|     |            | -10                      |                               |
| A   | mucky soil | -15                      | 0.21                          |
|     |            | -20                      | 0.26                          |
|     |            | -10                      | 0.18                          |
| B   | mucky soil | -15                      | 0.19                          |
|     |            | -20                      | 0.22                          |

### Tab 3 Relationship between uniaxial compressive strength and temperature of frozen soil

| No. | Property   | Temperature of frozen soil | Strength MPa | Average MPa |
|-----|------------|----------------------------|--------------|-------------|
|     |            | -10°C                      | -15°C        | -20°C       |
| A   | mucky soil | 1.66                       | 2.45         | 3.72        |
|     |            | 1.67                       | 2.63         | 3.96        |
|     |            | 1.47                       | 2.36         | 3.61        |
|     |            | 1.51                       | 2.14         | 3.16        |
| B   | mucky soil | 1.47                       | 2.29         | 3.71        |
|     |            | 1.44                       | 2.25         | 3.52        |
|     |            | 1.33                       | 2.32         | 3.68        |

### Tab 4 Test of shear strength index, internal friction angle and cohesion of frozen soil

| No. | Property   | Temperature (°C) | Confining pressure /MPa | Compressive strength (σ₁−σ₃)/MPa | C/MPa | φ     |
|-----|------------|------------------|--------------------------|-----------------------------------|-------|-------|
|     |            | -10              | 1.0                      | 2.23                              | 0.98  | 3.75  |
| A   | mucky soil | -20              | 2.0                      | 2.36                              |       |       |
|     |            |                  | 2.0                      | 4.45                              |       |       |
|     |            |                  | 3.0                      | 4.58                              | 2.01  | 2.99  |
|     |            | -10              | 1.0                      | 2.31                              | 0.96  | 4.85  |
| B   | mucky soil | -20              | 2.0                      | 2.37                              |       |       |
|     |            |                  | 2.0                      | 4.61                              | 1.89  | 5.57  |

### Tab 5 Test results of flexural strength of frozen soil

| No. | Property   | Temperature | Flexural strength /MPa | Average /MPa | Flexural strength /MPa | Average /MPa | Flexural strength /MPa | Average /MPa |
|-----|------------|-------------|------------------------|--------------|------------------------|--------------|------------------------|--------------|
|     |            | -10°C       |                        |              |                        |              | -15°C                  |              |
| A   | mucky soil | 0.548       | 0.858                  | 0.850        | 1.302                  |              | 0.468                  | 0.826        |
|     |            | 0.510       |                        |              |                        |              | 0.515                  |              |
3. Analysis of anti sliding stability of seawall under ice load and freezing thawing of foundation soil

Based on the large-scale finite element software, the overall anti sliding stability calculation model of seawall engineering considering ice load and freezing and thawing action of foundation soil is established. The safety and stability risk of seawall project is simulated and analyzed through numerical simulation using the parameters provided by laboratory tests above.

3.1. Finite element numerical simulation of seawall

3.1.1. Modeling

The standard section of seawall engineering is still taken as an example, and the simplified section diagram is shown as fig 1.

![Fig 1 Generalization of standard section of seawall engineering](image)

3.1.2. Parameter selection

The parameter selection of this numerical simulation is shown in Table 6, which is based on the actual engineering parameters and the above test results.

| Material                  | Density $\rho$/Kg/m$^3$ | Elastic modulus $E_0$/Pa | Poisson's ratio $\nu_s$ | Friction angle $\phi/\circ$ | Cohesion $C$/kPa |
|---------------------------|-------------------------|--------------------------|-------------------------|-----------------------------|------------------|
| Fence board               | 2450                    | 250000000                | 0.20                    | 50                          | 1                |
| Lump stone                | 1950                    | 800000000                | 0.25                    | 35                          | 0                |
| Sand filled pipe belt     | 1850                    | 100000000                | 0.30                    | 27                          | 30               |
| Muddy silty clay          | 1760                    | 24400000                 | 0.40                    | 2                           | 4                |
| Silt                      | 2050                    | 60900000                 | 0.35                    | 15.7                        | 7.2              |

3.2. Calculation results of anti sliding stability of seawall under ice load and soil freezing and thawing

The model can change the mechanical index of soil within the frozen thaw depth range of seawall engineering foundation, and then influence the anti sliding stability of seawall project. In the numerical simulation software, the change of soil freezing and thawing strength is simulated by setting field variables. The calculation results are shown in Fig. 2 ~ 3. As the strength index of foundation soil
gradually decreases under the action of freeze-thaw cycle, which affects the overall anti sliding stability of seawall engineering, the Mises yield stress of foundation soil layer of seawall engineering decreases after the freeze-thaw cycle, and the horizontal displacement and vertical displacement increase, but the change range is small, and the stress distribution in plastic zone is relatively uniform, and there is no obvious difference Sliding surface.

Fig 2 Nephogram of stress contour

Fig 3 Nephogram of displacement contour

4. Conclusion
The physical and mechanical parameters of soil under the action of freeze-thaw are obtained through the freeze-thaw test of sea dike foundation soil. Based on the parameters obtained from the test, the finite element numerical model is established to simulate the stress and deformation of the structure under the ice load and freeze-thaw cycles of the foundation soil, and the safety and stability of the seawall are analyzed.

(1) The compressibility coefficient of the thawed soil ranges from 0.18 to 0.26. With the decrease of freezing temperature, the thawing compression index increases.

(2) The uniaxial compressive strength of frozen soil has a good linear relationship with temperature. With the decrease of freezing temperature, the strength of frozen soil increases linearly, and the increase is obvious.

(3) From the frozen stress-strain curve of frozen soil, we can see that the curve can be expressed by an exponential function with strength limit. With the decrease of freezing temperature, the strength of frozen soil increases, but the strain of frozen soil decreases. In engineering, the strain of frozen soil should be controlled within 4 ~ 8% to ensure the frozen thaw is in elastic state.

(4) The triaxial shear test of frozen soil shows that the shear strength of frozen soil increases with
the decrease of freezing temperature and the increase of confining pressure. The stability of frozen wall can be improved by strengthening freezing in engineering.

(5) The flexural strength of frozen soil increases with the decrease of freezing temperature, but the increase range is small; the flexural strength of frozen soil is far less than the uniaxial unconfined compressive strength.

(6) Under the action of ice load and soil freezing and thawing, the stress field and displacement field of foundation soil layer of seawall engineering change, which is embodied in the increase of Mises yield stress, horizontal displacement and vertical displacement of foundation soil.

(7) Under ice load and soil freezing and thawing, there is no obvious plastic through zone in seawall structure, which indicates that ice load and soil freezing and thawing have little influence on the anti sliding stability of seawall.

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