Scholar Publishing Group
International Journal of Engineering Technology and Construction
https://doi.org/10.38007/IJETC.2021.020302
ISSN 2789-7176 Vol. 2, Issue 3: 14-29

The Effect of Environmental Temperature Change on Stress Distribution in Reservoir Ice

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Keywords: Ambient Temperature, Reservoir Ice, Internal Stress, Reoxygenation Process

Abstract: In cold zones, cold and warm zones and high altitude areas, the surface fluidity decreases after the completion of the reservoir. When winter comes, the temperature decreases. Under natural conditions, part of the river reservoir area is not frozen or only bank ice may be covered by ice. The formation of ice layer hinders the heat exchange between cold atmosphere and reservoir water, and reduces the heat loss of water in winter. At this time, the water temperature of the reservoir is higher than that of the natural river, even higher than that of the ice-free reservoir. Water temperature is totally different from the hydrological and water temperature conditions of natural rivers and non-freezing reservoirs. At the same time, due to the formation of reservoir ice sheet, the reoxygenation process of the reservoir will be blocked. It may lead to the decline of reservoir water quality. Based on the above background, the purpose of this paper is to study the effect of environmental temperature changes on the stress distribution in ice reservoir. Therefore, firstly, the vertical variations of ice temperature along ice thickness and ice growth rate in different stages of ice growth are analyzed by using field data of reservoirs. Secondly, the numerical relationship between temperature and stress distribution in ice reservoir is established, and the effect of continuous temperature on ice stress is analyzed. A total of 140 groups of reservoir ice samples were tested at temperatures of - 2, - 5, - 10, - 15 and - 20 degree C. For the same temperature, the strain rate range is set to $10^{-8} \sim 10^{-2} s^{-1}$, the loading direction is perpendicular to the growth direction of ice crystals, and the relationship between the stress distribution in ice and the simple model of environmental temperature change is determined.

1. Introduction

China's North China, Northwest China, and Northeast China have higher latitudes. From October to April of each year, affected by the Mongolian airflow, the weather is cold. The main reason is that it is controlled by Mongolian high-pressure cold airflow, and its airflow direction and influence range: The area is in the central part of Mongolia's high-pressure cold air flow to the Aleutian low-pressure, controlled by the northwest; The eastern part is located in the high-pressure cold air of Mongolia, the airflow flows to the equatorial low pressure, controlled by the cold north or northeast airflow [1]; The cold wave of Baikal and western Heilongjiang is frequent Strong, it is the main condition for producing wind, cold, rain and snow. As a result, the climate in the northern region was cold in January, with an average temperature drop of 14 ℃ in high latitudes in January and 18 ℃ in some regions. As temperatures drop, from October, temperatures in most of the cold regions of the North began to fall below 0 ℃. In some areas, there are early ice in some areas and even frozen in some areas [2]. Due to the high pressure and cold wave of Lake Baikal and Mongolia, the temperature has dropped to varying degrees. Frozen water may appear in reservoirs, rivers, lakes and even seas and may form a certain area of ice [3-4]. Structures in these ice and water bodies, such as slope revetments in water, dam gates, docks in rivers, revetments of seaports, breakwaters, fixed structures in the ocean, and even ships frozen in ice contact, the latter being the border of the former And form a constraint on it [5]. When the ambient temperature (mainly temperature) changes, the temperature field inside the ice layer changes, causing strain on the ice. Due to the different constraints of hydraulic structures, the ice layer will generate temperature stress, which in turn will generate temperature expansion force for hydraulic structures [6-8].

Internationally, not only is there a fairly systematic study of ice plugs, but also a systematic study of ice problems in reservoir structures [9]. It is only because of the differences in environmental conditions in various places that these research results have both commonality and individuality [10-11]. In the ice problem of reservoir structures, the first is the assessment of freshwater ice growth. In this respect, regional numerical prediction models are developed, followed by emphasis on the differences in ice crystal structure in different environments, and systematic studies of ice mechanics are emphasized to ensure data [12-13]. The research on ice thermal expansion has been done in more detail. Now, even considering the change of water level in winter, the ice force on the structure around the reservoir is very meaningful for the operation of the reservoir in winter [14]. The excavation and erosion of slope soil by flowing ice in rivers and reservoirs is also a recent hot research. These results have direct guiding significance in the management and protection of reservoirs and rivers in the Kaifeng stage [15].

In order to understand the deformation and internal stress of the red blood flow pushing red blood cells into the slit, Young combined the fluid-cell interaction model based on the boundary integral equation with the multi-scale structural model of red blood cells for numerical study. The cell membrane takes into account the detailed molecular structure of the biological system. The results of Young confirm the presence of "folding" of the cells during which a portion of the film is curved inwardly to form a concave region. The time history and regional deformation, shear deformation and contact pressure distribution during and after displacement were investigated. Most interestingly, it was found that during the recovery phase after the trans location, significant dissociation pressure may occur between the cytoskeleton and the lipid bilayer. The magnitude of this pressure is closely related to the location of the dimple elements during transport. In some cases, greater dissociation pressure indicates the possibility of mechanically induced structural remodeling and structural damage such as vesicle formation. With quantitative knowledge of the stability of proteins, interproteins, and protein-lipid linkages under dynamic loading, it will be possible to achieve numerical predictions of these processes [16]. Wafer curvature has been applied to determine the internal stress of a film based on the Stoney equation. Fixing the wafer on the sample holder during film formation limits the deformation of the rectangular wafer, which may result in differences in stress data along the length and width directions. Salehyar discussed the effect of wafer size and wafer mounting on the internal stress of the TiN film as measured by the wafer curvature method. A rectangular wafer having different length/width ratios (L / W = 1:1, 2:1, 3:1, and 4:1) is fixed as a cantilever beam. After depositing the TiN film, the film/wafer profile was measured using a stylus profilometer and then the internal stress was calculated using the Stoney equation in the film. The Salehyar experiment found that the fixed end of the wafer limited the curvature of the wafer in the width direction to some extent. For the internal stress of the film measured by the wafer curvature method, the wafer profile should be scanned along the length direction, and the scanning distance should be greater than or equal to half the length of the wafer. When the length/width ratio of the wafer reaches 3:1, the curvature of the wafer and the calculated stress at different positions along the length direction are substantially the same. For the internal stress of the film measured by the wafer curvature method, it is recommended to consider the aspect ratio of the wafer to be greater than or equal to 3:1 and to scan the deformed profile along the length direction [17]. Microelectroforming technology is widely used in the manufacture of multilayer or movable metal microdevices. The fabrication of these devices typically suffers from high internal stresses in the microelectroformed layer, which severely limits the application and development of micro electroforming technology. Therefore, controlling internal stress is very important to improve the quality and performance of the micro-electroformed layer. However, published studies on the internal stress of electroformed layers are mostly based on additive-free solutions. Based on the additive solution, Du studied the effect of ultrasonic and current density on the compressive stress in the electroformed layer. The Du experiment found that the compressive stress increased with the current density in the range of 0.2 to 2 A / dm2. At the same time, compared with the non-ultrasound solution, the compressive stress in the ultrasonic solution is reduced by 73.4 MPa on average, and as the ultrasonic power of 200W decreases, the compressive stress also decreases with the decrease of the ultrasonic power. In addition, Du also discussed the mechanism of the compressive stress caused by the addition and the ultrasonic elimination of the compressive stress. This research work will complement the theory of ultrasonic stress reduction and may contribute to the development of micro electroforming technology [18-20].

This paper firstly uses the field observation data of the reservoir to analyze the vertical variation of ice temperature along the ice thickness and the ice growth rate at different stages of ice growth. Secondly, establish the numerical relationship between temperature and reservoir ice stress distribution, and analyze the continuous temperature change to the ice interior. For the influence of stress, 140 sets of reservoir ice samples were tested using -2, -5, -10, -15 and -20 ℃. For the same temperature, the strain rate range was set to the loading direction and ice crystal. The growth direction is vertical, and the relationship between the internal stress distribution of ice and the simple model of environmental temperature change is determined.

2. Proposed Method

2.1. Characteristics of Reservoir Ice

Ice is a complex natural substance. A large number of studies have shown that the structural properties, strength properties, thermodynamic properties and failure modes of ice itself are highly complex and subject to external conditions. Temperature is one of the important factors affecting the performance of ice materials. For example, the change in the modulus of elasticity of ice as a function of temperature can be considered as a function of ice temperature; the thermal properties of ice (ice density, heat transfer coefficient, specific heat and coefficient of thermal expansion) also vary with temperature. The strength of ice is usually defined as the maximum stress that the specimen can withstand. It is affected by the combination of experimental conditions and the properties of the ice material. Specifically, the strength of the ice is affected by temperature, ice crystal type, grain size, bubble density, and specimen loading. The direction, the size of the test piece, the strain rate and the stiffness of the test system are affected by many factors. In the ice strength test, the strength values measured by different researchers are different, sometimes even different, showing high dispersion. This problem has also been noted in the Bohai Ocean Test. In the same area of sea ice, different measurement methods can lead to large differences in test results. The intensity of ice is also related to its associated mode of failure. If the specimen undergoes ductile failure, the stress will increase with the increase of strain at the beginning. After increasing to a certain value, the stress will no longer increase with the increase of strain. This value can be defined as the yield strength of ductile failure; the brittle failure occurs in the test piece. At the beginning, the stress increases with the increase of the strain. When a certain value is reached, the instantaneous brittle fracture occurs, and the stress suddenly decreases. This value can be defined as the brittle strength.

2.2. Formation of Reservoir Ice

There are many factors that affect the internal pressure of reservoir ice. On the one hand, the natural conditions of the reservoir ice, such as the initial temperature of ice, the rate of temperature rise, the size of the ice, the shape, the state of the crack, the structural state of the ice, the thickness of the snow, the wind and the water depth. On the other hand, constraints, such as the shape of the slope protection, the material of the slope protection. Coupled with the rheology of ice and the randomness of ice pressure, the problem becomes complicated. The freezing period of the reservoir in Northeast China is about 180 days. It begins to freeze from late October to early November, and the average ice thickness can usually reach 1m. The formation of the ice cover can be divided into four stages: the micro-ice period, the shore ice period, the sealing period and the freezing period. The growth of reservoir ice is mainly controlled by heat. Compared with sea ice, there is no effect of brine phase change on ice growth; Compared with river ice, it is not necessary to consider the influence of ice flow. After the reservoir is frozen, as the temperature drops, the thickness of the ice layer will increase. The upper layer of ice is granular crystal, the middle and lower layers are columnar crystals, and the average particle size is proportional to the depth of ice. The C-axis of the surface grain is randomly distributed in space and belongs to the isotropic material; the C-axis of the middle and lower grain is randomly distributed in the plane and belongs to the in-plane isotropic material; But in the vertical direction, the nature of the ice shows the opposite sex.

The most important factor that usually affects the temperature change of the ice layer is the temperature. According to meteorological data, three typical types of winter temperature changes are summarized: general daily change types: the temperature rises from the morning, reaches the highest value at 14 or later, and then gradually decreases to a temperature lower than the temperature at which the temperature starts to rise. With the change of temperature, the value of static ice pressure at 8 o'clock and 1 S is small, and the value of static ice pressure at 14 o'clock is large, but the change is not large. Type of cooling over the next few days: as the temperature drops, the ice temperature also decreases, the ice layer shrinks, and the internal stress of the ice layer decreases. Therefore, the cooling weather produces large static ice pressure on the reservoir slope protection. The type of heating in the past few days: the rising temperature in the day refers to the temperature rise or continuous high temperature for more than two consecutive days. In the case of thicker ice layer, only the heating process for more than two consecutive days, in order to increase the temperature of the whole ice layer, the ice layer will be very large. Static ice pressure. Static ice pressures typically greater than 100 kn / m are almost always produced during this temperature change. However, when the ice temperature rises above -1.5 ℃, the increase in ice temperature does not increase the static ice pressure, but decreases. The effect of temperature changes on different depths of the ice layer is a heat transfer process. Therefore, the change in ice temperature tends to lag behind the temperature, and the lag time increases as the depth of the ice layer increases. The measured data show that the temperature rise process of one day has an effect on the ice layer above about 50 cm depth.

According to the analysis of domestic on-site ice pressure observation data, the law of the maximum static ice pressure in the reservoir is that there will be two climaxes each year, which are in the rapid warming period of the early winter and late winter. In the early winter, the ice thickness is small, the ice intensity is low, and a large ice pressure can be generated when the short-term temperature rises. In late winter or early spring, the temperature will rise sharply and warm, and the corresponding ice thickness will produce the maximum temperature expansion ice pressure. The daily variation of ice pressure is the lowest at 8 o'clock and the highest at 14 o'clock in the afternoon, mainly related to the change of ice temperature. Under the weather conditions where the temperature continues to rise, the ice pressure is the most extreme. The change of ice pressure along the depth of ice is generally larger and smaller, but the upper surface of the ice layer is slightly smaller. The depth of the maximum ice pressure depends on the number of days of continuous heating. The more the temperature rises, the more extreme ice pressure points. Deep, usually located between one-third and one-half of the thickness of the ice. This mainly reflects the cumulative effect of ice stress. As the saying goes, freezing three feet is not a cold day, and the production of extreme static ice pressure is not warm.

2.3. Calculation Method of Internal Stress of Reservoir Ice

In actual engineering, the reservoir ice in nature is heterogeneous. However, since the choice of the reservoir is ultimately based on the strength under uniform external extrusion load, the analysis of the problem under uniform internal stress conditions is also of great engineering significance. And it can lay a certain foundation for the study of problems under non-uniform internal stress conditions. For some old reservoirs, the difference between the maximum horizontal internal stress and the minimum horizontal internal stress will be reduced or even close with time due to the rheological properties of the reservoir and the changes of the times. As shown in Figure 1, the inner and outer boundaries are subjected to a uniformly loaded annular region, that is, an axisymmetric thick-walled cylinder problem, as shown in Figure 1.

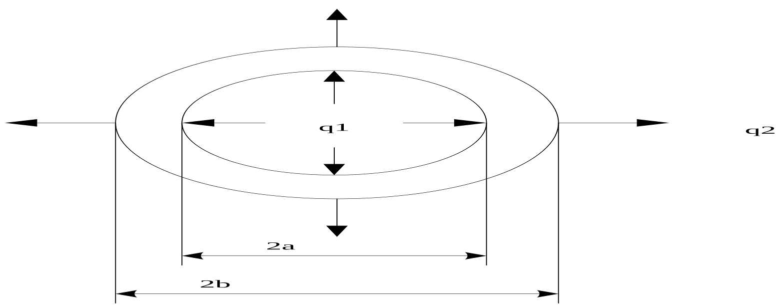


Figure 1. Lame's problem map

The empirical formula for calculating the ice pressure of ice caps according to the temperature data. The model comprehensively reflects the influencing factors of ice expansion pressure, and the formula is:

$$P = KK_s C_h \frac{(3 - t_a)^{1/2} \Delta t_a^{\ 1/3}}{-t_a^{3/4}} \left(T^{0.26} - 0.6\right) \tag{1}$$

Where: P represents the average expansion pressure of the ice layer (kg/cm ^{2});

t_a indicates the temperature at 8 o'clock in the morning (℃);

Δt_a means that the temperature rises between 8:00 and 14:00 (the first day is from 8:00 to 14:00, the temperature rises continuously) (℃);

T indicates the temperature rise duration (hours);

K_s indicates the influence coefficient of snow, generally taking no snow condition K_s =1;

K indicates the comprehensive impact coefficient, generally taking 4 ~ 5 (small reservoir can take 3.5 ~ 4);

C_h indicates the coefficient associated with the ice thickness h. When the thickness is 0.4, 0.6, 0.8, 1.0, and 1.2 m, the corresponding values are preferably 0.391, 0.311, 0.274, 0.252, and 0.237.

When the ice layer is thick, consider the ice pressure reduction factor of the following formula:

$$r = \frac{h}{h + h_s \cdot \lambda_l / \lambda_s} \tag{2}$$

Where: P represents the average expansion pressure of the ice layer (kg/cm ^{2});

h , h_s indicating the calculation of ice thickness and snow cover thickness (cm);

λ_l indicates the thermal conductivity of ice, which can be taken as 0.0055kg/cm ·degree ·hour;

λ_s means the thermal conductivity of snow, which can be 0.0006--0.0008 kg/cm ·degree ·hour. The short-term snow takes a small value and takes a large value for a long time.

In the case of solar radiation, the surrounding static pressure calculation formula under the condition of slope-type constraints, and point out the physical meaning of the formula: The static ice pressure should be composed of two parts; one is the temperature rise rate during the calculation period. The static ice pressure ΔP generated by the change of ΔT; the other is the initial static ice pressure P.

$$P = 0.097t \cdot \Delta T^{0.84} + 3.049^{\frac{23.071}{T_0}} \tag{3}$$

Another way to estimate the average ice pressure P of the ice layer:

$$P = kk_s C_h \frac{\Delta t_a^{\ 1/3}}{(-t_a)^{1/5}} \left(T^{2/5} - 1\right) \tag{4}$$

Where: P represents the average expansion pressure of the ice layer (kg/cm);

t_a indicates the initial temperature value, generally taking the temperature at 8 o'clock in the morning (℃);

Δt_a means that the temperature rises between 8:00 and 14:00 (the first day is from 8:00 to 14:00, the temperature rises continuously) (℃);

T represents the corresponding temperature rise duration (hours) corresponding to ΔT;

k_s indicates the influence coefficient of snow, which is 1.0 when there is no snow, and 0.5 when the ice thickness is 0.1-0.2m;

k indicates the comprehensive impact coefficient, which is generally 3.5-5 (3.5-4 for small reservoirs);

C_h indicates the coefficient associated with ice thickness h. When the thickness is 0.4, 0.6, 0.8, 1.0, and 1.2 m, the corresponding values are preferably 38.32, 30.48, 26.85, 24.70, and 23.13.

2.4. Analysis Principle of Internal Stress of Reservoir Ice

It is well known that the compressive stress of boundary-bound reservoir ice is primarily a result of temperature expansion from the top-to-bottom or bottom-up heat transfer from the outside to the ice. Sometimes the expansion pressure will also come from the freezing of new ice at the crack, and changes in wind, water flow and water level may also be important factors. However, these factors are mainly factors that produce ice loads. The most important concern in engineering applications is the extreme ice pressure, and the design of ice pressure only needs to consider some additional factors. The extreme ice pressure control mechanism usually includes the following:

(1) Limit temperature rise process control

The experimental measurements show that the temperature library ice pressure mainly depends on the temperature rise and temperature rise of the ice, and the temperature rise depends on the change of the ice cap heat budget and temperature parameters. Summarizing these factors, the final ice pressure will occur during the possible extreme temperature rise. The extreme temperature rise process can be predicted by statistical analysis or modeling of the observed data. This mechanism is primarily applicable to reflect the effects of different geographic and climatic conditions on ice stress.

(2) Ultimate driving force control

Under certain conditions, wind may become a major controlling factor in reservoir ice pressure, causing the windward surface structure to withstand large ice pressures. When considering the action of wind, the maximum wind speed becomes the control parameter of the ice pressure. In the case of power station reservoirs and the like, the slow water flow under the winter ice layer can also generate a large driving force for the ice sheet. At this point the flow rate becomes the corresponding control parameter.

(3) Loading area control mechanism

Some engineering problems need to predict the local ice pressure on the interface. The ice pressure on the unit area will decrease with the increase of the loading area. For the reservoir slope protection, it can be attributed to the relationship between ice pressure and its thickness. The ice pressure-area curve is an empirical equation derived from a large number of model tests and field measurements. Usually the ice pressure is expressed as a constant coefficient multiplied by a negative exponential power of the nominal contact area. Coefficients and indices are used to correct the effects of different latitudes or temperature zones, age of ice, and composition of ice materials. Although the ice pressure-area curve is purely empirical, this law implies a combined effect of the mechanical effects of the constraint effect and the size effect of the ice strength. The maximum ice pressure is associated with the local crush damage of the ice.

(4) Ultimate bearing capacity control

The above control mechanism does not involve the destruction of ice, so the actual upper limit of ice pressure cannot be determined. In fact, when the ice cap is stressed enough, it must be destroyed to release the excessively accumulated deformation energy, and the failure mode depends on the details of the force and deformation process. When the ice cap is destroyed, the ice pressure will quickly fall back from a peak and cause the end of the loading process. This load control mechanism confirms that the maximum ice pressure does not exceed the ultimate bearing capacity of the ice cap itself.

3. Experiments

3.1. Experimental Measurement Route

This study uses a combination of theoretical analysis, prototype observations, and mathematical models. In this paper, a numerical model of the temperature inside the reservoir ice is established, and the water temperature distribution law of the reservoir area is studied by using the three-dimensional water temperature model. The specific technical route is shown in Figure 2.

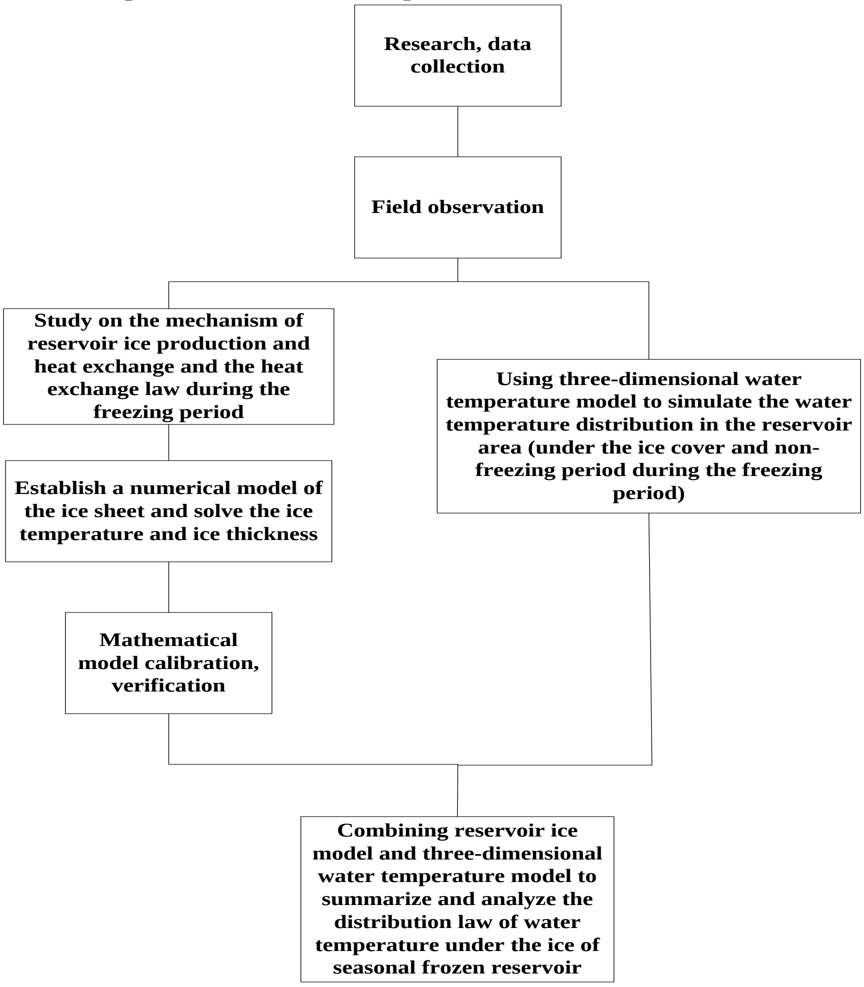


Figure 2. Technological route profile

3.2. Experimental Measurement Basic Engineering

MIKE series water environment software is a water environment simulation integrated software product launched by DHI; it can provide powerful functional support for river hydrodynamics and environmental simulation. Mainly used in water resources, water conservancy engineering, hydrodynamics, ecological and environmental chemistry, and water and environmental related fields. The MIKE3 model used in this simulation is a three-dimensional water environment simulation software. It is a professional engineering software for simulating hydrodynamics, water quality and sediment. It is mainly used in ports, rivers, lakes, estuaries and oceans, with advanced preparatory and post-processing. Functional and user friendly interface. MIKE3 model structure includes HD hydrodynamic module, convection diffusion module, Ecolab module, sediment module; mainly used in hydrodynamic simulation (estport, harbor, river, reservoir, hydraulic building optimization design); Convection diffusion simulation (saline intrusion, Warm drainage, pollutant transport, sewage deep sea discharge); Water quality simulation (dissolved oxygen balance, ammonia nitrogen, eutrophication, heavy metals, wetlands); Sediment transport simulation (viscous sediment, sediment load, riverbed evolution, channel back siltation, the channel dredging). This calculation is to use the reservoir module in the HD hydropower module to predict the water temperature.

3.3. Experimental Measurement Methods

This monitoring uses the WP type water temperature measuring instrument, and its structure includes three parts: instrument panel, sounding line, and induction probe. The instrument panel is used to display the water temperature: the sounding line is the length of the wire. Every lm is marked from the probe to determine the depth of the probe under water. The probe has a sensitive part at the top to sense the water temperature. temperature. After the probe is placed in the water, the water temperature is transmitted from the sensitive part of the front end of the probe to the instrument panel and the reading is displayed. 2. Measured point layout and monitoring method: The measuring points are arranged on the silt section of No.1-5 in the range of 6km in front of the dam, and the left, middle and right vertical lines are set on each section. The measurement results are given as a weighted average of three vertical lines of each section. A set of theodolites is arranged on the left bank of the 1# and 2# monitoring sections, and the 1# section is used as the known section. The theodolite is used to observe whether the measuring point is on the section line, and the guiding point is adjusted to the section line. The specific position of the measuring point on the section is determined by the angle of the measuring point on the 2# section of the theodolite. After the measuring point determines the position, the probe is placed down to the bottom of the reservoir for measurement, the thermometer is allowed to stand in the water for about 1 minute, and the water temperature data is read after the data has not changed. Then lift the sensor up and read it every 0.5m or lm. When reaching the surface of the reservoir, the measuring points are encrypted, and the temperature field in the reservoir area (winter includes ice thickness) is recorded and recorded.

Observe the ice temperature resistance strain gauge thermometer and use SBQ-2 hydraulic proportional bridge; observe the ice pressure steel string pressure gauge and use SS-II digital steel string frequency receiver. Three sets are arranged, each set is made of Φ12 steel bar, one of which is fixed with a wire and a thermometer, and the two are arranged in parallel. The thermometer is aligned with the center of the pressure surface of the pressure gauge, and the pressure surface is parallel to the dam axis and perpendicular to For the ice surface, if it is a single-sided pressure gauge, the pressure surface should face the reservoir area. The other two groups only have a fixed pressure gauge. The three sets of instruments are inserted into the reservoir when the ice thickness is 20cm. The height of the bracket should ensure that the instrument is in the measured ice layer and can be deep into the bottom of the reservoir to ensure stability. The cable drawn from the instrument is wrapped with plastic film and applied to the ice surface; after the cable bundle is pulled out, the ice is introduced into the observation room from the bottom of the ice, and the cable is buried in the instrument to leave enough relaxation to prevent the instrument from being pulled after freezing. Because the temperature ratio of the hydraulic bridge is required to be above 0 ℃, the temporary observation room is built by the gate building, and there is a fire pit and a stove inside. The cable from the instrument is introduced into the room.

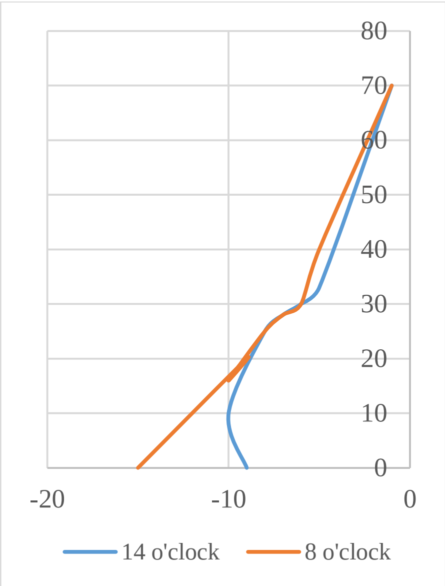
The observation time is from early December to late March. The ice layer gradually melted around March 5, the instrument response was not very sensitive, and the ice thickness was dangerous. Therefore, be careful when observing it. By the beginning of April, the ice was broken and the instrument could be taken out. The observation of ice temperature is the ratio of resistance measured by the hydraulic bridge, and then the temperature is calculated according to the given formula; the ice pressure is the vibration frequency of the pressure gauge measured by the frequency receiver, and the pressure value is found on the calibration curve provided by the manufacturer. It is usually observed 3 times a day, ie 8:00, 12:00 and 14:00.

4. Discussion

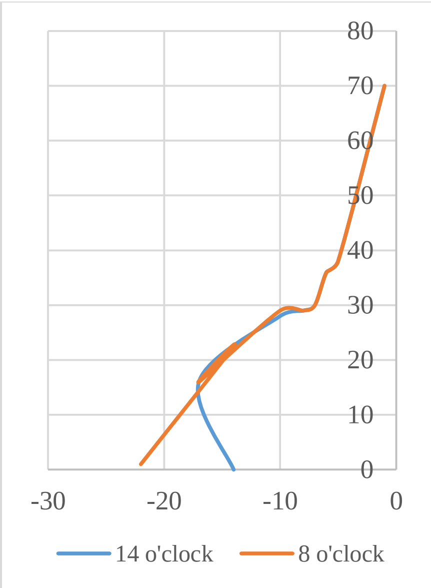
4.1. Analysis of Experimental Measurement Results

(1) Reservoir ice temperature measurement results

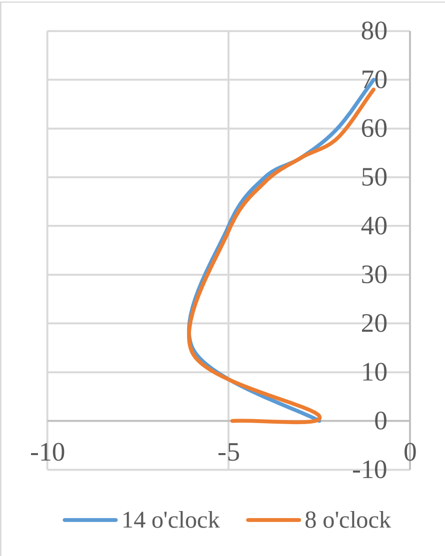
The ice temperature changes with the change of temperature, and increases with the depth of ice. The relationship between ice temperature and ice depth is shown in Figure. 3.



(a) General weather on January 20



(b) Temperature drop on January 23



(c)Temperature rise on January 31

Figure 3. Ice temperature to ice depth curve

Seen from the figure:

1) The curve at 8:00 in normal weather, when the temperature does not change much, the curve is close to a straight line, indicating that the ice temperature rises along the ice gradient with the same gradient.

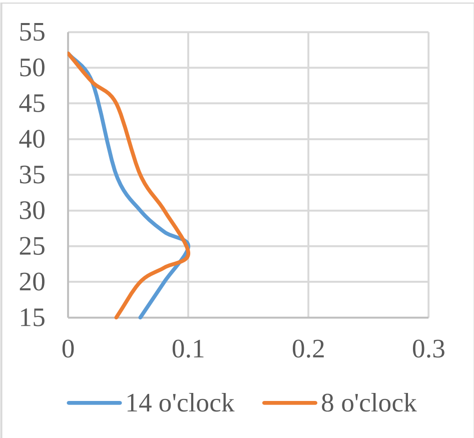
2) When the temperature is lowered, the curve at 8:00 is concave.

3) When the temperature rises, the curve at 8:00 is convex outward.

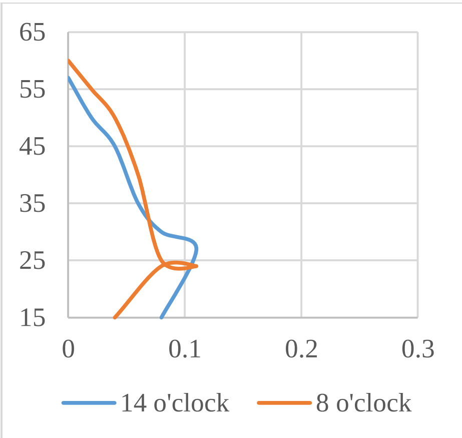
4) The curve at 14:00 is generally convex outward, indicating that the upper ice temperature rises sharply with increasing temperature. The temperature rise of the lower layer gradually decreases.

(2) Measurement and analysis of internal stress of reservoir ice

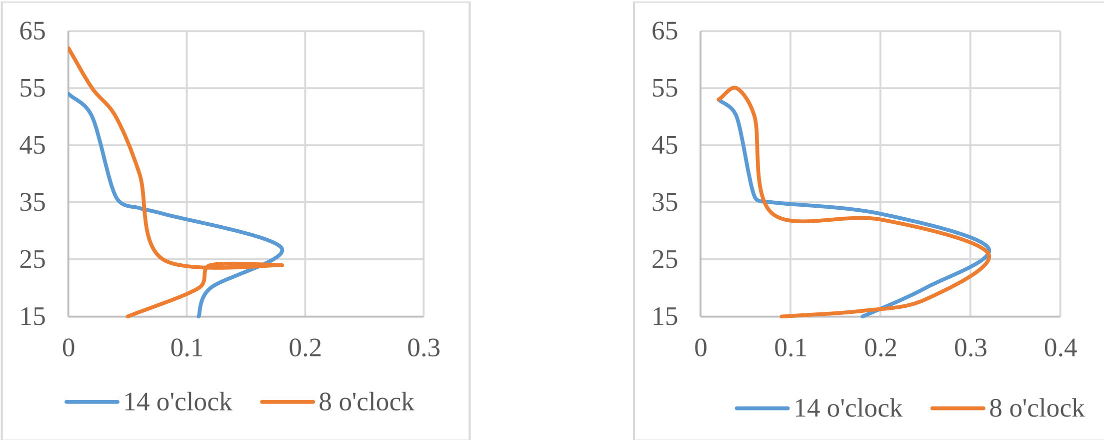
When the temperature of the reservoir ice layer rises, thermal expansion occurs, and the earth dam slope prevents it from expanding. The reservoir ice layer generates thrust for the slope protection, also called static ice pressure. The relationship between internal stress and ice depth of reservoir ice is shown in Figure 4:



(a)General weather on January 14



(b)Cooling on January 23



(c)Warming up on January 31 (d)February 5th

Figure 4. Reservoir ice stress-ice depth curve

1) The ice pressure has a large value in the continuous heating weather. For example, the temperature rises from -7 ℃ to -1 ℃ on February 5, 1993, and the maximum ice pressure is 0.35 MPa.

2) During continuous heating or continuous cooling, the ice pressure also has a small rise and fall, but the amplitude is not large.

3) When the average ice temperature is above -3 ℃, the increase in ice pressure is not obvious despite the large increase in temperature.

4) The stress value near the ice surface is the lowest, because the ice surface stress is released, and the maximum stress is 20 to 35 cm below the ice surface.

4.2. Analysis of Relationship between Temperature Change and Internal Stress of Ice

The indoor experiment of the ice sample was completed in an electronic universal testing machine and a cryogenic thermostatic test chamber device. The low temperature box is placed between the moving beam and the bottom platform of the testing machine, and the low temperature constant temperature circulating bath is used to form the low temperature test environment. In order to ensure the temperature inside the test box, the access precision in the box can reach the secondary temperature control of 0.1 ℃. The device has a resolution of up to 0.01 ℃. Before the experiment, the low temperature constant temperature circulating bath was turned on to cool the low temperature constant temperature test chamber to the set temperature, and then the sample was placed in a low temperature box for more than 12 hours, so that the sample fully reached the heat balance. During the test, the sample should be placed away from the sensor as much as possible to ensure that the sensor axis, the test machine center line and the ice sample geometric axis coincide with each other to ensure uniformity and linearity of loading. A total of 140 ice samples were tested using the temperatures of -2, -5, -10, -15 and -20 ℃. For the strain rate range at the same temperature, $10^{-8} \sim 10^{-2} s^{-1}$ was set to be perpendicular to the direction of ice crystal growth.

At the same test temperature, each sample showed a peak in the stress-strain curve, and the corresponding intensity was called the peak intensity. The same set of samples at the same temperature were obtained for each peak intensity value-strain rate plotted as a double logarithmic curve, and Figure 5 is a curve at -20 ℃. It can be seen from the figure that in the ductile zone, the peak intensity increases with the increase of the strain rate; in the brittle zone, the peak intensity decreases with the increase of the strain rate; at the strain rate of $10^{-5} \sim 10^{-3} s^{-1}$ there exists a transition zone, and the peak intensity is approximately Maximizes at a strain rate of $10^{-4} s^{-1}$. At the five temperatures used in the test, the ultimate compressive strength and strain rate of freshwater ice decreased with temperature, and the strain rate in the transition zone gradually decreased.

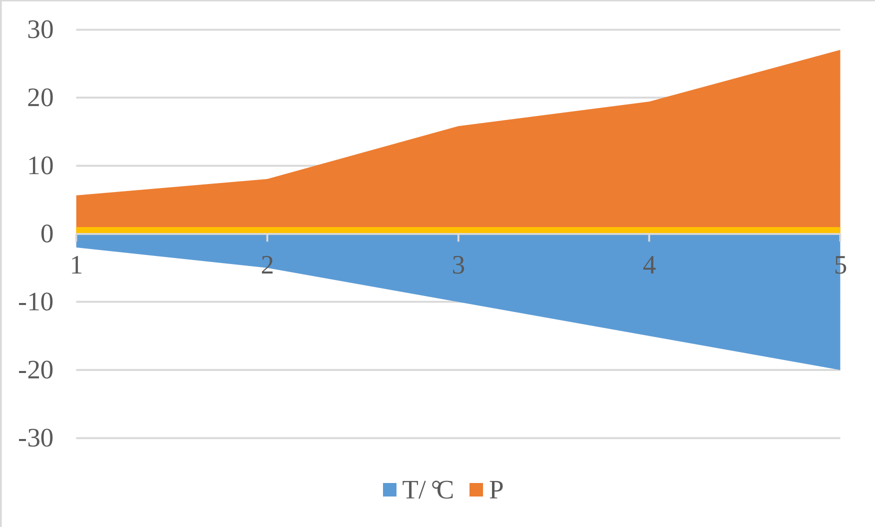


Figure 5. Temperature and internal stress diagram

Table 1. Values of A and B under different temperature

T/ ℃	A	B	Correlation coefficient r
-2	5.653	0.168	0.9990
-5	8.059	0.174	0.9995
-10	15.825	0.204	0.9983
-15	19.432	0.208	0.9990
-20	27.029	0.206	0.9980

Relationship between internal stress and strain rate of reservoir ice under different temperature conditions in ductile zone:

$$\sigma = A\varepsilon^{B} \tag{4}$$

Where σ is the internal stress, MPa;

ε is the strain rate, s^{-1};

A, B are coefficients related to stress, temperature, and ice crystal structure.

Analysis of the above relationship in the range of -2 to -20 °C, can be found that the values of A, B are as shown in Table 1. It can be seen from the table that the correlation coefficient obtained by the regression analysis is higher, close to 1, and the peak intensity is a power function relationship with the strain rate.

5. Conclusion

On the basis of summarizing the work of the predecessors, this paper studies the numerical simulation of the reservoirs at different frequencies and studies the environmental temperature changes of the reservoir under the freezing and non-freezing periods. The influence of stress distribution on the internal stress distribution of reservoir ice is analyzed. The mathematical model of the internal stress and ambient temperature of the reservoir ice was established. The finite element method was used to solve the model based on the local meteorological data. The variation of the temperature inside the ice sheet during the icing period of the reservoir was analyzed. Through the analysis and research of the reservoir, this paper not only has obtained some scientific research results, but also has certain engineering significance.

Based on the collected hydrological data and water temperature observation data of the same area, this paper uses a three-dimensional mathematical model to numerically simulate the internal stress distribution of the reservoir ice. Through the calibration and verification of the environmental temperature model, it shows that the model meets the accuracy requirements when performing long-term large-flow simulation calculation, and can obtain satisfactory results and provide scientific basis for reservoir dispatching. From the simulation results of the internal stress distribution of the ice in each month, the reservoir is layered in summer and winter, and the water discharge temperature of the reservoir is higher than the original natural water temperature. The summer discharge water temperature is lower than the original natural river water temperature. The temperature of the effluent water in winter is higher than that of the natural river channel, and the maximum temperature difference does not exceed 4 ℃, which will not have a major impact on the downstream ecological environment.

This study combines local meteorological data to simulate the internal stresses of a reservoir during ice coating. Through the verification of typical examples, it is determined that the finite element method can be used for the calculation of the heat conduction equation. The calculation method is effective and reliable, and an internal ice model is established. Mathematical models of stress distribution and ambient temperature changes are feasible. The calculation results show that the internal stress of ice changes with the change of ambient temperature during the thickening process of ice. The temperature of the ice on the upper surface of the ice cover is the temperature-dependent temperature value and then rises to the lowest value of the upper surface. At the ice-water interface around 0 ℃, the internal stress of ice is densely distributed on the upper surface of the ice sheet and sparsely distributed at the ice-water interface. The calculation results are consistent with the actual situation and can be applied to the calculation of the internal stress distribution of ice in other seasonal frozen reservoirs.

Funding

This article is not supported by any foundation.

Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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