The Application of Multiple Regression Analysis in the Study of the Minimum Unfreezing Distance in the Downstream of Hydropower Station

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Abstract. Based on the analysis of the characteristics of thermal and ice regime in the lower reaches of the hydropower station, the multiple regression analysis of the measured data is carried out, and the calculation formula of the minimum unfreezing distance in the lower reaches of the hydropower station in the frigid region is established, which takes the average unit discharge per ten days of the coldest month of the hydropower station and the average discharge water temperature in the corresponding period as the independent variable. The minimum unfreezing distance in the lower reaches of the hydropower station in the frigid region is improved Method of calculation. Through the verification of the measured data, the calculation method of the minimum unfreezing distance in the downstream of the hydropower station proposed in this paper is closer to the objective reality than the traditional method.

1. Introduction
The climate in Northeast China is very cold in winter, and the natural river channels are generally formed into thick ice sheets. However, the downstream river channels of hydropower stations are not frozen for a certain distance, and the water flow is open flow. The length of the open flow section from the tail water of the power station to the downstream frozen ice edge is defined as the unfreezing distance \( L_f \). In the whole winter, the frozen ice margin is constantly changing. In the process of its growth and recession, there must be a location closest to the power station, at this time, \( L_f \) reaches the shortest. From the design point of view, it is of practical value to estimate the shortest distance. For example, under certain conditions, the backwater of ice jam in the downstream of hydropower station is more serious than that in the natural situation. The observation results of some power stations in the former Soviet Union show that serious backwater of ice jam will reduce the effective head of power station by 10% ~ 20%. It is possible to estimate the severity of ice jam by estimating \( L_f \). It also has a direct impact on the ice transportation downstream of the hydropower station.

Based on the investigation and observation data of the ice margin of Fengman, Yunfeng, Huanren, Huilongshan, Jingpohu, Baishan and Hongshi hydropower stations in Northeast China, this paper summarizes the general characteristics of the change of the thermal and ice regime in the downstream of the hydropower station, analyzes the main factors of \( L_f \), and on the basis of summarizing the previous research results [1-3], through multiple regression analysis of the measured data, establishes the calculation formula of the minimum unfreezing distance in the downstream of the hydropower station in the frigid region is based on the average discharge per unit width and the average water temperature in the corresponding period of the coldest month of the hydropower station.
calculation method of the minimum unfreezing distance in the downstream of the hydropower station in the frigid region is improved.

2. Characteristics of Ice Regime in the Downstream of Hydropower Station
The characteristics of ice regime in the downstream of hydropower station are as follows.

(1) The freezing date of the downstream channel was postponed and the freezing duration was shortened. The investigation and statistical data show that the freezing date of a certain range in the downstream of the hydropower station is later than the natural conditions, while the thawing is earlier, so the freezing duration is shortened.

(2) The development of frozen ice margin is unstable. Compared with the natural river, the process and shape of the downstream channel of the hydropower station are different. From the top to the bottom, it can be divided into ice free section, bank ice and ice flow section, unstable broken frozen section, stable broken frozen section and stable frozen section. Due to the different operation mode and meteorological factors of the power station, the length and surface morphology of each reach are also different.

3. Analysis and Estimation of the Minimum Unfreezing Distance in the Downstream of Hydropower Station
There are many factors that affect the minimum unfreezing distance in the downstream of hydropower station, i.e., $L_f$, but the main factors can be screened out, and the empirical relationship can be established based on the actual observation and investigation data to estimate $L_f$.

3.1. Traditional Calculation Method
Traditionally, the minimum unfreezing distance is calculated by the formula of the minimum unfreezing distance at the downstream of hydropower stations in Northeast China given in the Code for Hydrological Calculation of Hydropower and Water Conservancy Projects (DL / T5431-2009) [4].

$$L_f = 14.5(qt_s)^{1.228} + 8.5$$  \hspace{1cm} (1)

where $L_f$ is the minimum unfreezing distance at the downstream of the hydropower station, km; $q$ is the minimum ten day average outbound unit width flow in the coldest month, $\text{m}^3\cdot\text{s}^{-1}\cdot\text{m}^{-1}$; $t_s$ is the average outbound water temperature in the corresponding period with $q$, $\degree\text{C}$.

Formula (1) has the following aspects to be improved:

(1) In the formula, the power index of the minimum ten day average discharge $q$ in the coldest month is the same as that of the corresponding average discharge water temperature $t_s$ in the corresponding period (both are 1.228), indicating that the change of $q$ and $t_s$ has the same influence on the minimum unfreezing distance $L_f$ in the downstream of the hydropower station. The power index of $q$ and $t_s$ should be determined by multiple regression analysis based on the measured data, and the influence degree of the change of $q$ and $t_s$ on the minimum unfreezing distance $L_f$ downstream of the hydropower station should be analysed based on the analysis results.

(2) In the formula, the constant term is not zero, which is inconsistent with the actual situation. In fact, in the cold area of Northeast China where the minimum ten day average temperature is far less than 0 $\degree\text{C}$, $L_f$ should be 0 when $q = 0$ (corresponding to the condition that the power station does not discharge water for power generation) or $t_s = 0$.

3.2. Multiple Regression Analysis Results of this Study
Ice situation is the result of the cumulative effect of various factors, and it has hysteresis. Therefore, the average index of a certain period should be selected as the characteristic index to reflect the influence of the period. The data show that the shortest $L_f$ has a good relationship with the minimum value of the coldest ten days of each influencing factor. Therefore, the minimum value of the coldest ten days of the month is taken for each factor. Based on the observation and investigation data of seven power stations in Northeast China, the relationship between the minimum $L_f$ and each factor is analysed. Refer to the existing measured data results in the Code for Hydrological Calculation of
Water Conservancy and Hydropower Engineering (SL 278-2002) [5] and the measured data results in the investigation of the unfreezing distance downstream of Baishan and Hongshi hydropower stations, and table 1 is obtained after summary. In the table, $T$ represents the corresponding ten day average temperature, and other negative signs have the same meaning.

Table 1. Results of $L_f$ investigation and monitoring on the unfreezing distance of the downstream of 7 hydropower stations in Northeast China.

| Hydropower Station | Huanren | Huilongshan | Jingpohu | Yunfeng |
|--------------------|---------|-------------|----------|---------|
| Year               | 1976    | 1978        | 2012     | 2014    | 1976    | 1978    | 1978    | 1979    | 2013    | 2014    |
| $L_f$ (km)         | 24      | 12.5        | 12       | 11.5    | 12.5    | 9       | 21.6    | 17.3    | 105     | 100     | 110     |
| Date of occurrence | Early and middle January | Early and middle December | Early and middle January | Early January | Early and middle January | Middle January | Middle January | Middle January | Middle January | Middle January |
| $q$ ($\text{m}^3\text{s}^{-1}\text{m}^{-1}$) | 0.321   | 0.531       | 0.54     | 0.496   | 0.449   | 0.12    | 0.317   | 0.257   | 0.963   | 0.95    | 1.02    |
| $T$ (°C)           | -16.7   | -12.8       | -12      | -17     | -16.9   | -12.8   | -16.7   | -14     | -14.5   | -14.5   | -14.1   |
| $t_s$ (°C)         | 3.5     | 2.5         | 2.3      | 2.4     | 1.6     | 2       | 2.2     | 2.7     | 4.4     | 5.2     | 4.9     |

| Hydropower Station | Fengman | Baishan | Hongshi |
|--------------------|---------|---------|---------|
| Year               | 1959    | 1960    | 1961    | 2017    | 2018    | 2015    | 2017    | 2018    | 2014    | 2017    | 2018    |
| $L_f$ (km)         | 30      | 66      | 55      | 70      | 75      | 11.1    | 12      | 11.5    | 40      | 38      | 35      |
| Date of occurrence | Early January | Late January | Middle January | Middle January | Middle January | Middle January | Middle January | Middle January | Middle January | Middle January | Middle January |
| $q$ ($\text{m}^3\text{s}^{-1}\text{m}^{-1}$) | 0.362   | 1.03    | 0.862   | 1.08    | 0.95    | 0.385   | 0.366   | 0.351   | 0.764   | 0.821   | 0.75    |
| $T$ (°C)           | -20.2   | -18.4   | -16.9   | -16.8   | -16.5   | -15.9   | -16.1   | -16.5   | -15.2   | -15.3   | -15.1   |
| $t_s$ (°C)         | 2.9     | 3       | 2.9     | 3.8     | 4       | 3       | 3       | 2.5     | 2.5     | 2.5     |

Regression analysis was carried out for each variable and dependent variable $L_f$ respectively, and the results are shown in figure 1 to figure 3.

![Figure 1](image)
From figure 1 to figure 3, it can be seen that the minimum $L_f$ is closely related to the single wide flow rate $q$ and the outlet water temperature $t_s$, while the relationship with the temperature $T$ is poor. The reason is that the meteorological factors affecting the water body heat loss include not only the temperature, but also the solar radiation, cloud amount, wind speed, etc. A single temperature $T$ cannot reflect the comprehensive effect of the meteorological factors. According to this, the average unit discharge $q$ of the coldest month and the minimum ten day average outbound water temperature $t_s$ of the corresponding period are selected as independent variables and $L_f$ as dependent variables for multiple regression analysis, as shown in figure 4.
After the above multiple regression analysis, the following empirical formula can be obtained.

\[ L_f = 9.9598q^{0.7760}t_s^{1.4229} \]  

(2)

The range of data used in formula (2) is: the minimum unfreezing distance \( L_f \) is \( 9 \sim 105 \) km; the minimum ten day unit width flow \( q \) in the coldest month is \( 0.04 \sim 1.04 \) m\(^3\)\cdot s\(^{-1}\)\cdot m\(^{-1}\); the outlet water temperature \( t_s \) is \( 1.6 \sim 4.0 \)°C.

It can be seen from formula (2) that \( q \) and \( t_s \) have different indexes, which are 0.7760 and 1.4229, respectively, indicating that the influence of these two variables on \( L_f \) is different, that is, the influence degree of \( t_s \) on \( L_f \) is greater than that of \( q \) on \( L_f \).

3.3. **Comparison between \( L_f \) Calculation Method in This Paper and Traditional Method**

According to the measured data, the minimum unfreezing distance \( L_f \) is calculated by the calculation method proposed in this paper and the traditional calculation method, and the calculation results are listed in figure 5.
It can be seen from figure 5 that the point corresponding to the value of the minimum unfreezing distance $L_{f2}$ calculated by the method and the measured value of the minimum unfreezing distance $L_{f1}$ is located near the line $L_{f2} = L_{f1}$.

4. Conclusions
The conclusions are as follows:

(1) Taking $q$ and $t_s$ as two variables, we make multiple regression analysis on the dependent variable $L_f$. $q$ and $t_s$ have different indexes, which shows that the influence of $t_s$ on $L_f$ is greater than that of $q$ on $L_f$. The calculated value of the minimum unsealed distance is close to the measured value.

(2) For Hongshi hydropower station, in the winter of 2018-2019, in the coldest month (January 2019), the gate is closed for a long time, and the power station does not discharge water for power generation. In this case, the minimum ten day average single width flow $q = 0$. After investigation, the downstream of the power station has been completely frozen in winter of 2018-2019. The method of the invention is used to calculate the minimum unfreezing distance of the downstream is 0, while the minimum unfreezing distance of the traditional algorithm is 8.5km. Obviously, the constant term of 0 in the method of the invention is closer to the objective reality.

(3) It should be pointed out that due to the complexity of the influencing factors of $L_f$ and the fact that the data are only limited to a few large and medium-sized power stations in Northeast China, the empirical formula proposed in this paper has some limitations, which need to be further amended in the future.

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6. References
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