Frazil jam risk assessment for water diversion projects

Mengkai Liu, Jia Yang and Guanghua Guan

ABSTRACT

Frazil jams are common ice phenomena in rivers in winter and also threaten the safe operation and limit the water conveyancing efficiency of long-distance canal systems in cold regions. In this paper, based on the canal pool conditions from the Fenzhuanghe sluice to the Beijumahe sluice of the Middle Route of the South-to-North Water Diversion Project, the analytic hierarchy process (AHP) and the fault tree principle (FTP) for frazil jam risk assessment are proposed. The risk factors of frazil jams are then identified based on the AHP. Then the probability and consequence severity of frazil jams induced by each risk factor are scored by experts, and the weights of each risk factor are proposed. Finally, risk level and prevention measures are proposed. The results show that there are 20 risk factors for canal frazil jams and the possibility of risk factors is positively correlated with the consequence severity. As yet, experts have not formed a unified view on the frazil jam mechanism of water diversion projects, and the scoring results are highly dependent on expert positions. This paper recommends the FTP as the frazil jam risk evaluation method, and the corresponding frazil jam level of the project is level III.

Key words | analytic hierarchy process, canal system, fault tree principle, frazil jam, risk assessment, risk factor

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INTRODUCTION

In China, water resources have the characteristic of nonuniform spatiotemporal distribution. Some water diversion projects have been constructed to solve this problem, resulting in rational allocation of water resources and promoting social development.

The Middle Route of the South-to-North Water Diversion Project (MRSNWDP) is an important project to alleviate the water resource shortage in North China by utilizing the water resources in the Yangtze River. It provides water for domestic use, industry and agriculture to 19 large-sized and medium-sized cities and more than 100 counties (county-level cities) in the North China plain, including Beijing and Tianjin. The average annual water diversion is 9.5 billion m^3/year. The total length of the main canal is 1,432 km, spanning latitudes 33°N - 40°N from north to south, and the water flows from a warm temperate region to a semicold region (Yang *et al.* 2011). Different degrees of ice form every year in the canal section 500 km north of Anyang. The project is under remote automatic control by 63 sluices. Due to the complexity of ice evolution interactions, the automatic control of the canal systems in winter faces difficulties and risks, among which frazil jams are one of the most significant risks. At present, the project adopts a low flow rate and high water level in winter to prevent the formation of ice hazards. During the winters of 2014–2016, serious frazil jams occurred in this project (Wen *et al.* 2015; Huang *et al.* 2019). Among them, the most serious one was in 2015–2016. The canal section 120 km north of the PuYanghe inverted siphon had a total frazil jam length of approximately 26.5 km and a thickness between 1.5 m and 2.3 m (Huang *et al.* 2019), which seriously threatened the canal system operation safety and water supply security.

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Significant progress has been made in river ice research in the last three decades (Shen 2010), which has provided support for solving the problem of water diversion of the MRSNWDP during the ice formation period. In terms of numerical simulation, Lal & Shen (1991) developed a computer model called RICE for simulating river ice processes based on the concept of two-layer ice transport. In 2008, Shen *et al.* (2008) refined and validated the DynaRICE model proposed in 2000 (Shen *et al.* 2000) and applied it to the study of the formation and release of ice jams. Beltaos (2008) discussed advances in numerical modeling and mitigation techniques.

Understanding the formation mechanism of frazil jams is of great significance to the design and operation of a canal system. Yang (2018) reviewed the advances in ice hydraulics theory, model experiments and prototype observations, and elaborated on the formation and various coefficients of frazil jams. Fu *et al.* (2015) studied different diversion discharge and operation water levels of inverted siphons and provided references for frazil jam prevention of inverted siphons during the ice formation period. Fan *et al.* (2019) examined the validity of existing formulations of frazil jam resistance by including the seepage flow effect and showed that the seepage flow resistance is a dominant part of the jam resistance, except for the portion of the jam that is very thin.

Based on the limitations of numerical simulations and predictions, a geographical model is used in winter risk research. Munck *et al.* (2017) constructed a geographic model to predict the location of ice dam formation by quantifying the influence of different geographical factors on ice accumulation. Li *et al.* (2017) adopted the concept of the geographic model and used the fuzzy evaluation method to predict the locations of frazil jams in the Jingshi canal portion of the MRSNWDP. In addition to the geographic model, Guo *et al.* (2018) forecast a frazil jam during river breakup based on the neural network.

However, the ice conditions in a canal system have similarities with river ice conditions, but also have particularities mainly reflected in the following aspects (as shown in Figure 1): a relatively short channel length; a different range of ice sources; a channel divided into segments by sluice gates; ice-block cables placed before the entrance of the inverted siphon and sluice; upstream ice masses that are prevented from crossing through the sluice gate into the downstream channel; the ice production in the pool is related to the water heat loss in the pool; and the canal pool can adjust the water level and flow velocity, which can control the formation mode of the ice cover.

Very little work has been performed to assess the risk induced by ice-related floods because most risk assessments are limited to open-water floods (Lindenschmidt *et al.* 2016). Frazil jams and breakup jams are common ice phenomena in rivers in winter, but the occurrence phases and ice formation are different. Frazil jams mainly occur during the initial freezing-up period while breakup jams mainly occur during the breakup period especially during the mechanical breakup period. Frazil jams are mainly formed by large undercover accumulations of frazil ice, while breakup jams are mainly formed by broken ice covers. To ensure the safety of water conveyance in canal systems, it is necessary to evaluate the risk level and determine the main risk factors for canal systems through a comprehensive understanding of frazil jam mechanisms, and provide support for targeted prevention and control of frazil jams. In this paper, through analyzing the frazil jam mechanism, the frazil jam risk factors are identified by the analytic hierarchy process (AHP), and questionnaires scored by peer experts are used to evaluate the probability and consequence severity of

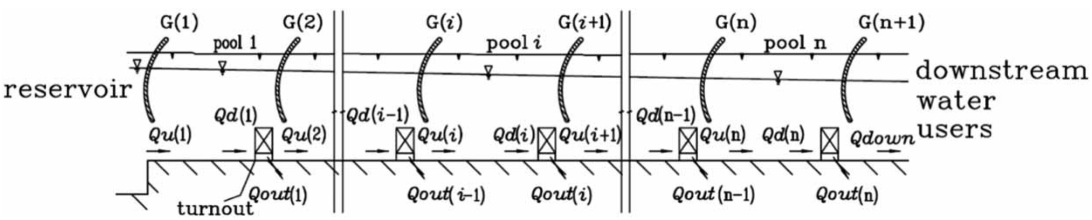

Figure 1 | Schematic diagram of a canal system (G is the sluice gate, *i* refers to the serial number of the pool, *Qu* is the flow through the upstream gate of the pool, *Qd* is the flow through the downstream gate of the pool, *Qdown* is the water demand of downstream users, and *Qout* is the flow transferred from the main canal to the submain canal through the outlet).

frazil jams induced by each risk factor, and to achieve the frazil jam risk assessment for a typical pool.

FRAZIL JAM RISK ASSESSMENT METHODS FOR A CANAL SYSTEM

Risk assessment process

In this study, the AHP and the fault tree principle (FTP) are used to evaluate the frazil jam risk. FTP refers to whether the relation of the same layer factor to the upper layer event is an 'and' or 'or' relation in the assessment process. An 'and' relation means that all factors occur simultaneously to cause a risk event, and an 'or' relation means that any risk factor occurrence can cause a risk event. In the calculations of this paper, if it is an 'and' relation, the weight of each factor should be considered; if it is an 'or' relation, the maximum value among the risk factors under each criterion layer is selected as the score of this criterion layer. The risk level of the frazil jam is calculated from the bottom layer to the top layer, which is determined by the following two methods: (1) directly calculating the risk degree of the risk factor (possibility multiplied by consequence severity) to the top layer and obtaining the risk value of the frazil jam; (2) the probability and consequence severity of each factor are calculated to the top layer, and then the frazil jam risk value is obtained by multiplication. The calculation process is shown in Table 1.

Assessment criteria

Assessment criterion and level for the probability of a frazil jam

According to the risk occurrence possibility level criterion in GB/T 50927-2013, the criterion for the probability of a frazil jam is shown in Table 2.

Assessment criterion for the consequence severity of a frazil jam

According to the evaluation criterion for the risk impact degree on targets in GT/B 27921-2011, the criterion for the consequence severity of a frazil jam is shown in Table 3.

Table 1 | Risk assessment method calculation process

Calculation process \ Assessment method	Based on AHP		Based on FTP	
	Method (1): Calculated by risk degree of risk factor	Method (2): Calculated by possibility and consequence severity	Method (3): Calculated by risk degree of risk factor	Method (4): Calculated by possibility and consequence severity
Weight of risk factor layer	$W_i = P_iS_i / \sum_{i=1}^{m} P_iS_i$	$W_{pi} = P_i / \sum_{i=1}^{m} P_i$ $W_{si} = S_i / \sum_{i=1}^{m} S_i$	/	/
Corresponding risk value of each factor	$R_i = P_iS_iW_i$	$R_{pi} = P_iW_{pi}$ $R_{si} = S_iW_{si}$	/	/
Weight of criterion layer	$W_j = \sum_{i=1}^{m} P_iS_i / \sum_{i=1}^{n}\sum_{i=1}^{m} P_iS_i$	$W_{pj} = \sum_{i=1}^{m} P_i / \sum_{i=1}^{n}\sum_{i=1}^{m} P_i$ $W_{sj} = \sum_{i=1}^{m} S_i / \sum_{i=1}^{n}\sum_{i=1}^{m} S_i$	$W_j = max(P_iS_i) / \sum_{j=1}^{n} max\ (P_iS_i)$	$W_{pj} = max(P_i) / \sum_{j=1}^{n} max(P_i)$ $W_{sj} = max(S_i) / \sum_{j=1}^{n} max(S_i)$
Corresponding risk value of each criterion	$R_j = \sum_{i=1}^{m} P_iS_iW_i$	$R_{pj} = \sum_{i=1}^{m} P_iW_{pi}$ $R_{sj} = \sum_{i=1}^{m} P_iW_{si}$	$R_j = \max(P_iS_i) * W_j$	$R_{pj} = \max(P_i)*W_{pj}$ $R_{sj} = \max(S_i)*W_{sj}$
Risk value of frazil jam	$R = \sum_{i=1}^{n} R_j$	$R = \sum_{i=1}^{n} R_{pj} * \sum_{i=1}^{n} R_{sj}$	$R = \sum_{i=1}^{n} R_j$	$R = \sum_{i=1}^{n} R_{pj} * \sum_{i=1}^{n} R_{sj}$

Where, R_j is the risk value of the jth criterion in the criterion layer; n is the criterion number; m is the risk factor number under each criterion; P_i and S_i are the possibility and consequence severity of the frazil jam induced by the ith risk factor in the jth criterion respectively; W_j is the weight of the jth criterion in the criterion layer; W_{pj} and W_{sj} are the possibility weight and consequence severity weight of the jth criterion respectively; and R_{pj} and R_{sj} are the possibility risk value and consequence severity risk value of the jth criterion respectively.

Table 2 | Assessment criterion and level for the probability of a frazil jam

Level	Qualitative judgment standard: Value for risk probability level	Qualitative judgment standard: Qualitative description	Quantitative judgment standard: Probability interval
1	(0, 1]	Extremely low probability	<0.0001
2	(1, 2]	Low probability	0.0001–0.001
3	(2, 3]	Intermediate probability	0.001–0.01
4	(3, 4]	High probability	0.01–0.1
5	(4, 5]	Extremely high probability	>0.1

Table 3 | Assessment criterion for the consequence severity of a frazil jam

Influence degree	Evaluation value	Description
Extremely slight	(0, 1]	Basically does not affect the daily operation, causing minor losses
Slight	(1, 2]	Slight impact on daily operation, causing lower losses
Moderate	(2, 3]	Moderate impact on daily operation, causing moderate losses
Severe	(3, 4]	Serious impact on daily operation, causing considerable losses
Disastrous	(4, 5]	Significant impact on daily operation, causing significant losses

Assessment criteria and level for a frazil jam

According to the risk assessment level criterion in GB/T 50927-2013, the frazil jam risk level is determined by the probability, consequence severity and weight. It is divided into four levels and shown in Table 4.

RISK FACTOR IDENTIFICATION OF A FRAZIL JAM

Analysis of the frazil jam formation process

Frazil jams are formed from large undercover accumulations of frazil ice produced in fast-flowing open water, blocking the water cross-section and resulting in a large increase in the amount of upstream water. Therefore, factors affecting frazil jam formation should include: excessive ice production, high flow velocity in some channels, and insufficient downstream ice transport capacity in the channels. Ice

Table 4 | Assessment criterion and level for a frazil jam

Risk classification	Risk level	Assessment value	Description
Negligible risk	I	(0,4]	Risk monitoring should be conducted
Acceptable risk	II	(4,9]	Risk monitoring should be strengthened
Conditional acceptable risk	III	(9,15]	Risk management should be implemented to reduce risks, and the costs of risk reduction should be less than the losses after the risk occurrence
Unacceptable risk	IV	(15,25]	Risk control measures should be taken to reduce the risk, at least reduce to an acceptable or conditionally acceptable level

production is the upper limit of the frazil jam volume; flow rate provides conditions for the frazil jam formation; and the difference between the ice transport capacity and the submerged ice is the actual volume of the frazil jam.

The amount of ice production is the primary factor in determining the formation and volume of the frazil jam. Ice production is determined by the length of the open channel and the strength of the cold wave in the pool. The longer the open channel length and the more freezing the cold wave, the greater the ice production. The upstream water temperature is also a factor that influences ice production (Guo *et al.* 2017).

Frazil ice submergence is controlled by the flow rate, while the rate is affected by channel operation scheduling, structural characteristics and accidents. A low water level target before a sluice, a hydraulic gradient increase caused by ice cover and a large water transfer plan will result in an increase in the rate. Structural characteristics refer to irregular geometries in the project, such as a narrow cross-section and steep bed slope. Li *et al.* (2017) showed that the reason for the accumulation of frazil ice is the change in the cross-section width from upstream to downstream. In this study, the narrow cross-section ratio and bed slope change ratio are used to describe the influence of the channel structure characteristics on the frazil jam risk. In cold regions, there are also accidents in which data acquisition errors cause an increase in the flow rate, such as erroneous scheduling judgments caused by serious distortions in the readings of the hydraulic parameters (Huang *et al.* 2019). Other accident factors causing an increase in the flow rate are sluice faults, canal leakage, high precipitation, and operational mistakes.

A decrease in the ice transport capacity of a channel is a vital condition for the undercover accumulations of submerged frazil ice. A frazil jam can be initiated by the congestion of a large surface ice discharge at natural or man-made channel obstructions or constrictions, which may consist of the leading edge of a stationary ice cover, a reduced top width due to border ice growth, a change in the channel alignment or cross-section, a reduction in the channel slope, or a reduction in the channel velocity (Shen & Liu 2003). The experiment conducted by Wang *et al.* (2016) shows that a curved channel is more likely to form frazil jams. The canal system operation mode is also a critical factor in ice transport capacity (Wang & Chen 2011). Taking the MRSNWDP as an example, this project adopts the mode of constant water-level operation before downstream sluices, complying with the regulation that the upstream velocity is higher than the downstream velocity in the channel. During the freezing period, the ice transport capacity downstream is lower than that upstream, but the downstream ice concentration is higher than that upstream. In the cross-section with high frazil ice concentration, the ice transport capacity is insufficient, providing favorable conditions for frazil jam formation and overtopping.

Hierarchical structure of the frazil jam risk

According to the above identification, the hierarchical analysis diagram of frazil jam formation is obtained, as shown in Figure 2. There are 20 risk factors identified in

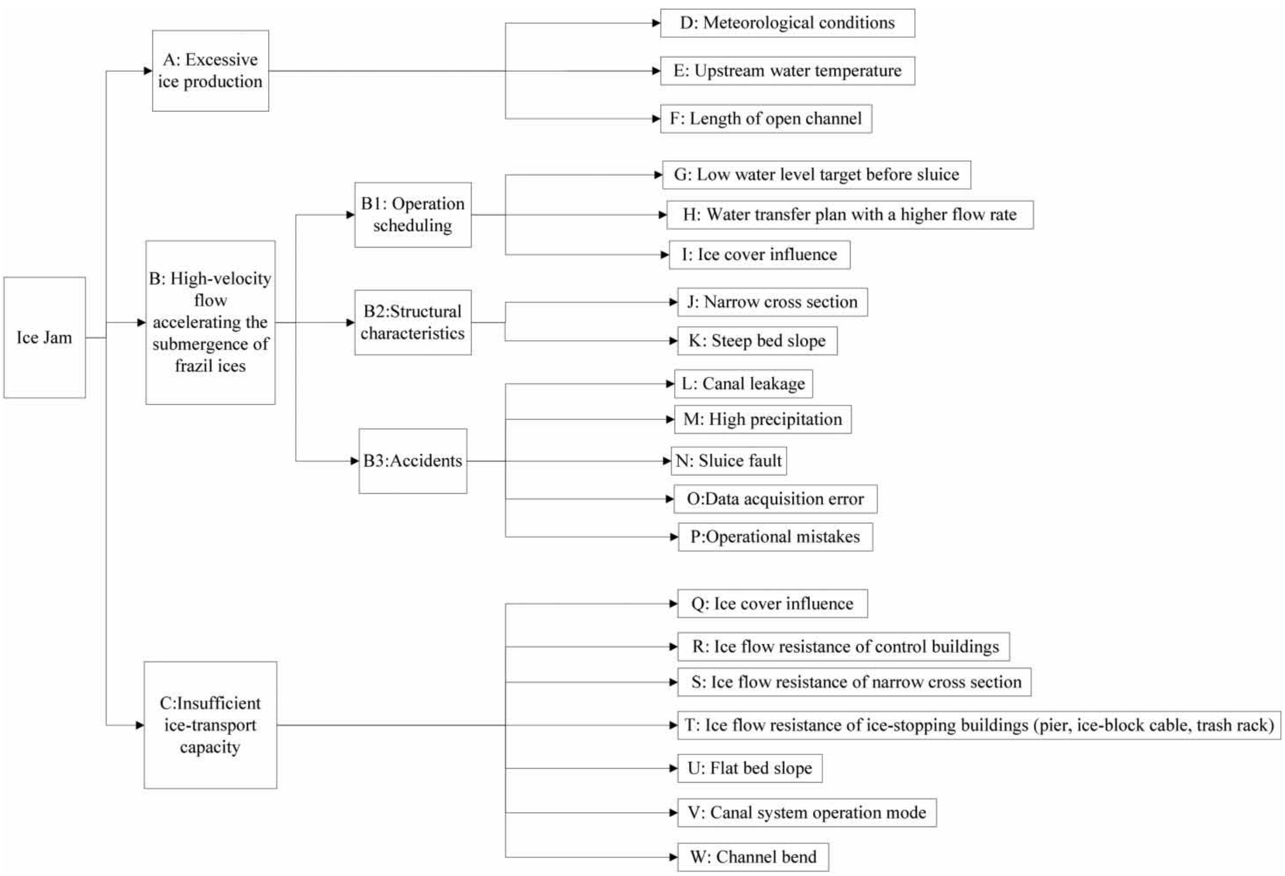

Figure 2 | Risk factors of frazil jams.

this paper, in which the calculation of the narrow cross-section ratio I_n and the bed slope change ratio I_s are shown in Equation (1).

$$I_n = A_{down}/A_{up}, \quad I_s = g_{down}/g_u \tag{1}$$

where, A_{down} is the downstream cross-sectional area, a_{up} is the upstream cross-sectional area, g_{down} is the downstream bed slope, and g_u is the upstream bed slope.

PROJECT BACKGROUND

In this study, the canal section from the Fenzhuanghe sluice to the Beijumahe sluice of the MRSNWDP is selected as a typical pool, located at Baoding Management Station. According to meteorological data statistics, Baoding City has a long-term average temperature of −1.5 °C in winter, and ice conditions occur annually. During the winter of 2015–2016, serious frazil jams 5 km long and 0.5–1.0 m thick occurred in this pool (Huang *et al.* 2019). The specific parameters included in the expert questionnaire are shown in Table 5.

Table 5 | Structure parameters in a typical pool

Structure	Specific parameters
Typical channel section	25.314 km long and 7.5 m wide
Narrow cross-section	I_n: 0.83 (upstream), 0.83 (downstream)
Steep bed slope	I_s: 9.60 (aqueduct, midstream), 5.03 (tunnel, upstream), 3.31 (midstream)
Flat bed slope	I_s: −4.07 (midstream), 0.10 (midstream), 0.20 (upstream), −0.70 (midstream) (a negative value is caused by the slope changing from a positive slope to a negative slope)
Channel bend	Bending degree: 90° (upstream), 100° (midstream), 95° (downstream)
Others	2 inverted siphons (South Jumahe inverted siphon, North Jumahe inverted siphon), 1 aqueduct (Shuibeigou aqueduct), 1 tunnel (Xiacheting tunnel), 15 bridges

Note: The information in parentheses indicates the location of structures in the pool.

EXPERT QUESTIONNAIRE ANALYSES AND RISK ASSESSMENT

The frazil jam risk factor assessment questionnaire is designed according to the characteristics of a typical pool. The scoring content is the possibilities and consequence severities of frazil jams induced by the risk factors, and the scoring criteria are implemented according to the relevant criteria previously mentioned. The overall questionnaire reliability value analyzed by SPSS (Statistical Product and Service Solutions) is 0.916, indicating that the questionnaire results are reliable and can be used for subsequent analyses.

Expert questionnaire analyses

Questionnaire respondents analysis

The questionnaire was specifically targeted at relevant experts in water conservancy design institutions, research institutions and universities, and 20 copies were collected. The composition of the questionnaire respondents is shown in Figure 3. It can be seen that the number of questionnaires collected from each job position is basically the same, which is conducive to position scoring analysis, and the advanced professional titles account for 90%, which reflects the reliability of the questionnaire results to a certain extent. The respondents are experts with different professional titles engaged in channel design, scientific research and teaching. The scope of the experts consulted is relatively comprehensive, and they have been exposed to frazil jam research in their respective positions. The questionnaire results can be considered reliable and representative.

Linear relationship between risk factor possibility and consequence severity

Figure 4 shows the scoring relationships between the probabilities and consequence severities of frazil jams induced by various risk factors scored by experts. It can be seen that there is an obvious positive correlation between them; that is, the greater the possibility of disaster caused by a risk factor, the more serious the consequence will be. This indicates that the main risk factors should be identified to carry out prevention and control of frazil jam risk, but the consequences caused by the failure of prevention and control are also unfavorable.

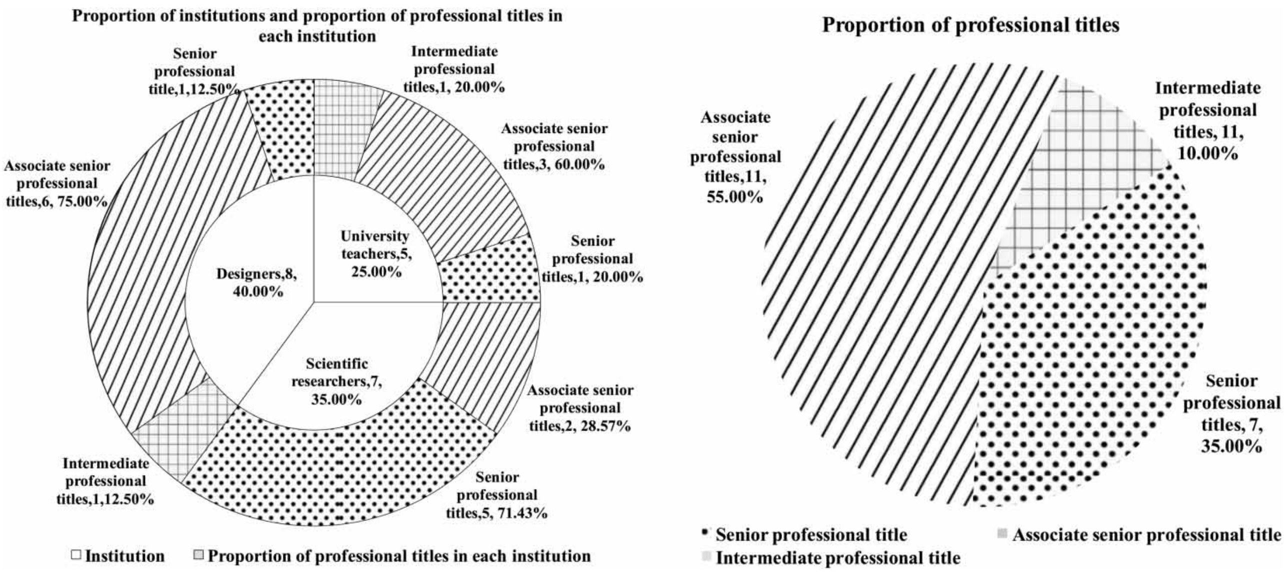

Figure 3 | Characteristics of questionnaire respondents.

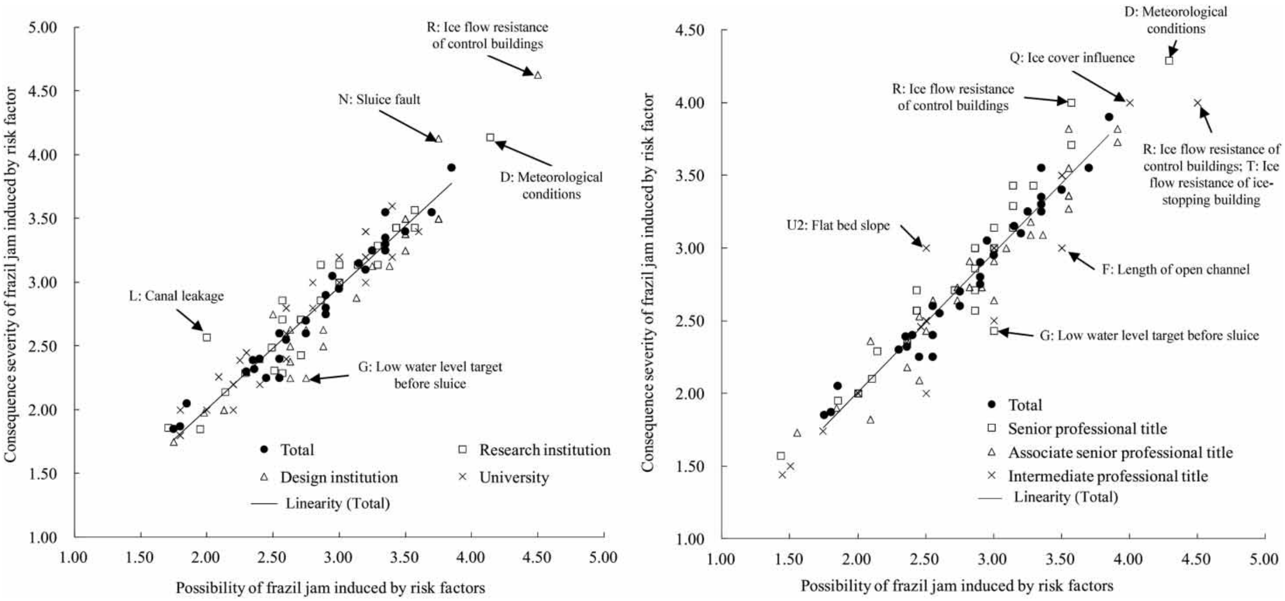

Figure 4 | Linear relationship between the risk factor possibility and consequence severity.

Cognitive differences of risk factors in questionnaire respondents

Different experts have different scores for the same factor, and the standard deviation of each factor in the total questionnaire results is obtained by SPSS. If there are multiple situations for the same factor, the maximum value of these standard deviations is taken as the standard deviation of this risk factor. According to Equation (2), the deviation percentage of the probability and

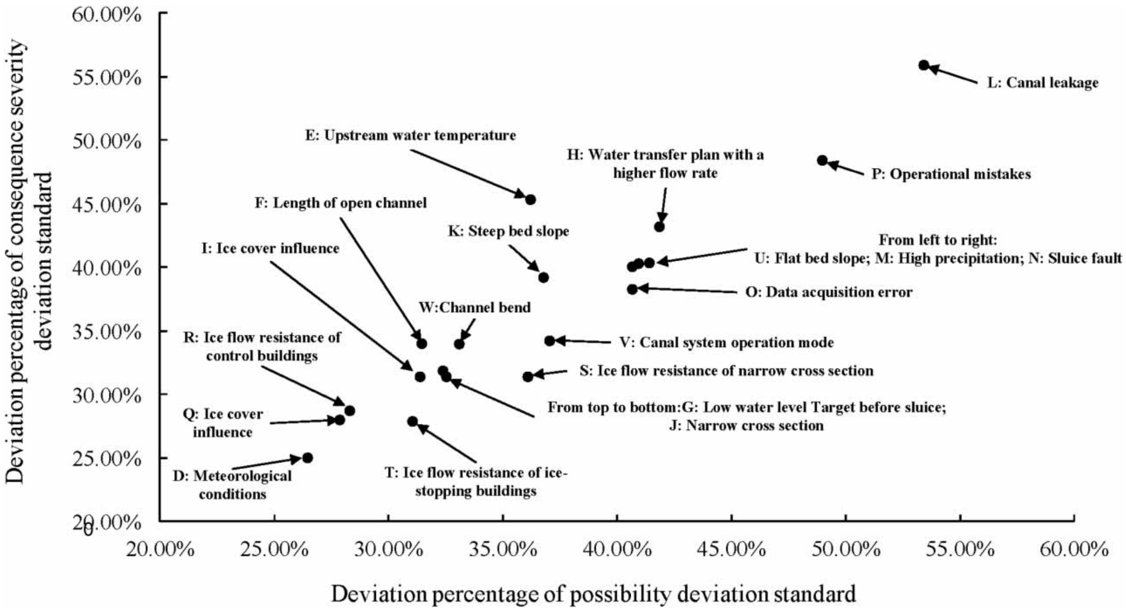

Figure 5 | Deviation percentage of risk factor.

consequence severity of each risk factor was obtained, and was divided by 5% as a counting unit, as shown in Figure 5.

$$\text{Risk factor deviation percentage} = \text{standard deviation of each factor}/\text{average scored value of each factor}*100\% \quad (2)$$

It can be seen from Figure 5 that the deviation percentages of the possibilities and consequence severities are concentrated in [20%, 60%], among which 70% of the factors are in [30%, 45%]. Experts have the largest deviation in risk recognition of canal leakage accidents and operational mistakes, and have the most unified recognition of meteorological conditions. In addition, the factors with a large risk degree in the scoring results are R: ice flow resistance of control buildings, D: meteorological conditions, U: flat bed slope, N: sluice fault, T: ice flow resistance of ice-stopping buildings, W: channel bend, Q: ice cover influence, and J: narrow cross-section. By analyzing the scoring deviations of these factors, it is found that they are all, with the exception of the bed slope and sluice fault, in the [25–35%] interval, which indicates that the experts have a relatively consistent opinion of the main risk factors. Through standard deviation analysis, it also shows that experts in the industry have different opinions on frazil jam mechanisms and the control of water diversion projects. It is necessary to undertake more research into canal frazil jam hazard mechanisms, narrow the differences in opinion among experts, and promote the standardization and safety of water diversion projects from design to operation management in cold regions.

The influence of questionnaire respondent groups on the survey results

Due to the different job characteristics and experience backgrounds of the experts, there are differences in the cognition of risk factors. The risk degree of the risk factors in the total results is sorted from large to small, as shown in Figure 6. The scores divided by professional titles fluctuate more than the scores divided by institutions, indicating that the scores of each factor by experts in institutions are relatively similar. However, experts with different professional titles have different emphases on different risk factors, in which the scores of intermediate titles fluctuate greatly due to the limitation of the number of samples (only accounting for 10% of the total samples).

Project designers are the most concerned about the possibility of frazil jam formation due to control buildings and sluice faults; while university teachers believe that

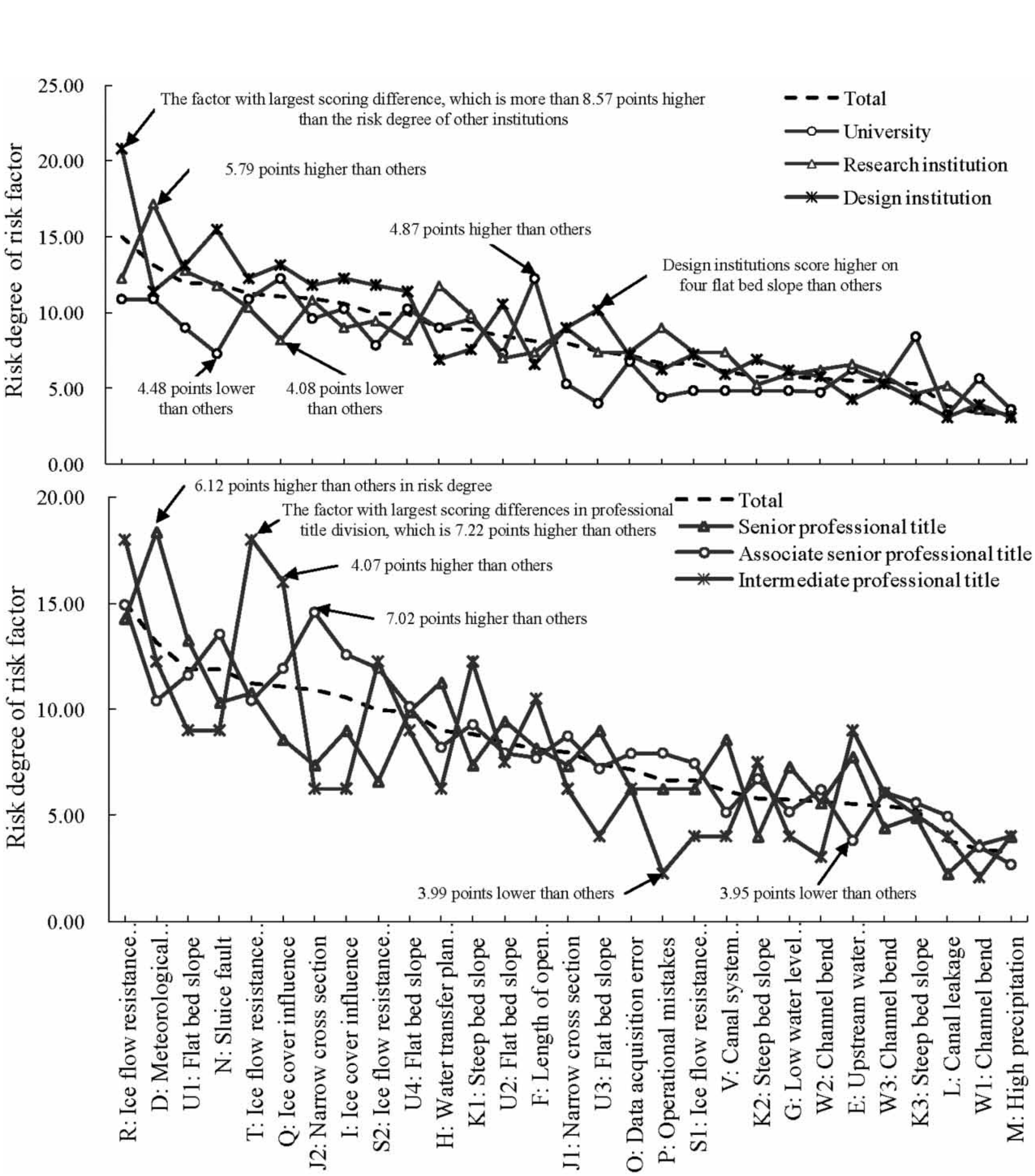

Figure 6 | Risk degree sorting divided by institution and professional title.

sluice faults have little influence on jam formation and pay more attention to channel length. Scientific researchers have focused more on the effect of meteorological conditions on jam formation. Experts with senior professional titles are most concerned about factors affecting ice production, such as meteorological conditions; experts with associate senior professional titles focus more on the flow conditions of frazil jam formation, such as the effect of narrow cross-sections on the increase in flow velocity; experts with intermediate professional titles pay more attention to ice transport capacity in channels, such as the ice flow resistance capacity of ice cover and ice-stopping buildings. This indicates that different object groups have a fixed cognitive pattern for frazil jam risk based on their own job characteristics and experience, and there are limitations in that they take into account their own job characteristics too much and do not fully consider the frazil jam risk.

RISK ASSESSMENT AND ANALYSES

Results and analysis of frazil jam risk assessment

According to the calculation process previously mentioned, the risk assessment results of each institution/professional title are shown in Figure 7. After comparison, it can be seen that: (1) the risk value of frazil jam calculated by the FTP is larger than that of the AHP; (2) using the same method, the top-layer risk value calculated by the risk factor risk degree is larger than that of the other calculation method; (3) design institutions think the project has the largest risk, with the risk level of III–IV; (4) universities think the ice hazard of the project is the smallest, with the risk level of II–III; (5) the difference in the frazil jam risk considered respondents with different professional titles is smaller than that of different institutions, indicating that the recognition of frazil jam risk is more dependent on the jobs of the respondents.

Compared with the AHP, the FTP considers the relationship between each factor occurrence and the criterion layer. The FTP distinguishes whether all the factors occur at the same time to cause the occurrence of upper layer risk events or whether any risk factor can cause disasters. However, the AHP has no relevant distinction. The weights of all the factors are taken into account when calculating the upper layer risk level. When a factor has multiple situations (such as multiple narrow cross-sections), it takes the weighted average value of this factor. The weighted average value reduces the impact of the maximum value of the factor on the risk-causing, sometimes resulting in a lower risk level. Therefore, the FTP is recommended for the assessment of frazil jam risk level. This paper recommends a frazil jam risk value of the assessment pool of 13.29 and a risk level of III.

Prevention and control of frazil jam risks

According to the total results, all risk factor weights were calculated by using the overall hierarchy of the AHP, and the results are shown in Table 6. The risk factor with the largest weight is the ice flow resistance of control buildings, with a weight of approximately 9%. It is also found that the weight difference between factors is small, with a weight interval length of approximately 7%. It can be considered that there is no absolute risk factor for controlling the frazil jam risk, which suggests higher requirements for risk prevention and control. That is, all risk factors should be covered in the prevention and control measures.

Ice flow resistance of control buildings is a phenomenon that cannot be avoided in water diversion projects, which is an important manifestation of the difference between river ice and the channel ice. The frazil jam risk can be reduced by optimizing the channel design length. In addition, in

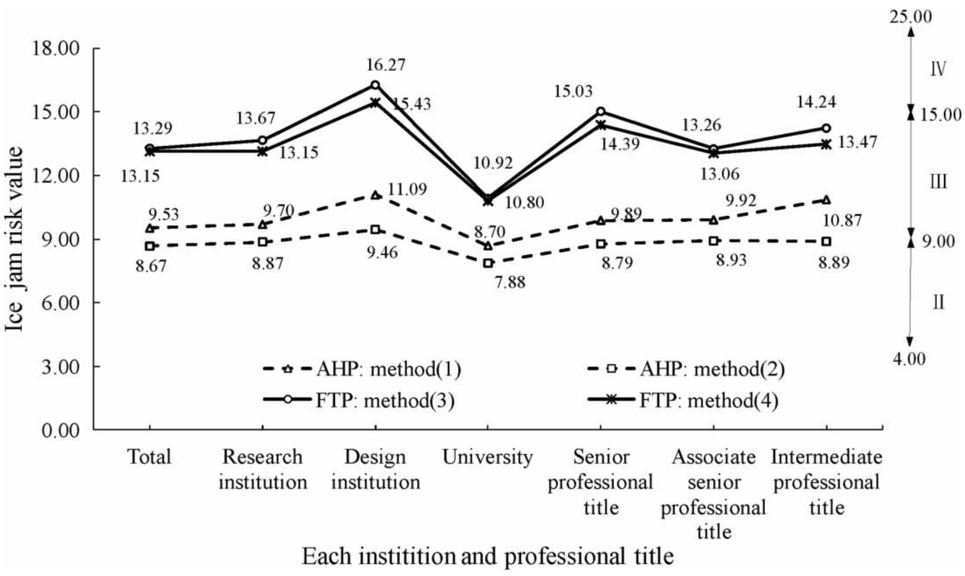

Figure 7 | Risk levels of each institution and professional title.

Table 6 | Overall hierarchy of risk factors weights

Ordinal	Risk factor	Weight	Ordinal	Risk factor	Weight
1	R: Ice flow resistance of control buildings	8.93%	11	F: Length of open channel	4.83%
2	D: Meteorological conditions	7.81%	12	O: Data acquisition error	4.25%
3	N: Sluice fault	7.07%	13	K: Steep bed slope	4.17%
4	T: Ice flow resistance of ice-stopping buildings	6.67%	14	P: Operational mistakes	3.94%
5	Q: Ice cover influence	6.57%	15	V: Canal system operation mode	3.64%
6	I: Ice cover influence	6.28%	16	G: Low water level target before sluice	3.41%
7	U: Flat bed slope	5.78%	17	E: Upstream water temperature	3.28%
8	J: Narrow cross-section	5.74%	18	W: Channel bend	3.00%
9	H: Water transfer plan with a higher flow rate	5.35%	19	L: Canal leakage	2.25%
10	S: Ice flow resistance of narrow cross-section	5.12%	20	M: High precipitation	1.92%

the design stage, it is also necessary to optimize the water conveyance route to reduce the geometrical changes in the channel and avoid the situations of narrow cross-sections, flat bed slope and ice flow resistance of bridge piers. In the operational stage, the main ways to reduce the frazil jam risk include implementing forecasting of freezing periods, predicting the jam events, optimizing the dispatching operation mode, changing the environment of frazil jam risk, and balancing frazil jam risk and water delivery efficiency; sluice maintenance and anti-freezing measures should be implemented before and during the ice period; segmental ice blocking and ice removal measures should be taken to reduce the ice pressure downstream; and frazil jam risk response mechanisms should be established.

CONCLUSIONS

In this study, a hierarchical structure of risk factors for frazil jams in a water diversion project is proposed, which mainly included three major factors: excessive ice production, high-velocity flow and insufficient ice transport capacity, and a total of 20 risk factors.

The research results show: that there is a positive correlation between the possibility and consequence severity of risk factors; the maximum weight risk factor is ice flow resistance of control buildings, but the weight differences between each factor are small, and all the risk factors identified in this paper should be fully considered in the risk prevention and control; the FTP is recommended for the frazil jam risk assessment; the risk value of the typical channel is 13.29, and the risk level is III.

The questionnaire analysis shows that experts in the industry have different opinions on the frazil jam mechanism of water diversion projects, and there are limitations of high dependence on their own positions and an incomplete understanding of the frazil jam risk. Design institutions think the project has the largest risk. If the frazil jam risk prevention and control can be considered in the engineering design stage, the pressure during the operational stage can be reduced.

The shortcoming of this paper is that expert scores have subjective experience, and the results are influenced by the sample distribution and sample number. In subsequent research, the number of samples will be continuously increased and more attention should be paid to the real ice hazard of the project to enhance the reliability and the applicability of the assessment results.

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