



The effects of ice-water discharge ratio and flow Froude number on local scour around tandem double piers and ice jam thickness in an S-shaped channel

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Abstract: In cold regions, bridge piers in rivers can alter flow characteristics and influence the formation and evolution of ice jams, complicating the local scour around the piers and the distribution of ice jam thickness. This study, based on experiments conducted in an S-shaped flume, examines how the flow Froude number and the ice-water discharge ratio affect the local scour depth around tandem double piers and the ice jam thickness. The results reveal that, while a positive correlation exists between the flow Froude number and the scour depth under both open flow and ice-covered flow conditions, the relationship between the scour depth and the flow Froude number under ice-jammed flow conditions is considerably more complex. Due to the influence of the ice jam on scour depth, there exists a critical Froude number at which the relationship between the flow Froude number and scour depth changes. The results indicate that when the flow Froude number is below the critical value, the ice jam thickness decreases slightly, while the scour depth shows a positive correlation with the flow Froude number. When the flow Froude number reaches the critical Froude number, the scour depth peaks. When the flow Froude number exceeds the critical value, the ice jam thickness decreases significantly, and the scour depth becomes negatively correlated with the flow Froude number. Additionally, when the flow Froude number remains constant, an increase in the ice-water discharge ratio leads to a rise in ice jam thickness, which in turn causes the scour depth to increase.

Keywords: Ice jam; S-shaped channel; Tandem double piers; Ice-water discharge ratio; Local scour.

1 INTRODUCTION

The formation and evolution of river ice in winter can be divided into four periods: the floes floating period, the freeze-up period, the ice-covered period, and the river break-up period (Beltaos, 2012). Ice jams occur during the transitional periods of freeze-up and break-up, and may also occur in mid-winter in temperate regions (Beltaos, 2008). The freezing and breakup of rivers are influenced by thermal, hydraulic, and topographic factors (Hou et al., 2023). Ice jam formation is primarily caused by ice covers obstructing the downstream movement of ice blocks, while factors such as bridge piers, reduced riverbed slopes, and channel constriction further facilitate ice jam formation (Beltaos et al., 2000).

Ice jams lead to a significant rise in water levels, potentially triggering extreme ice-jam flood events that threaten human life and property (Rokaya et al., 2018). For example, in China's Ningxia-Inner Mongolia reach of the Yellow River, statistics show that ice-jam flood events occurred in 30 years between 1951 and 2010, causing substantial property damage to residents along the riverbanks (Liu et al., 2018). The Red River in Canada frequently experiences ice-jam flood disasters (Lindenschmidt et al., 2012). The losses from ice-jam floods on the Saint John River account for 70% of total flood losses in New Brunswick (Humes et al., 1988). Additionally, approximately 50% of bridge failures in the province are associated with winter ice processes (Beltaos et al., 2003). In the United States, ice jams cause average annual damages exceeding 100 million dollars (White et al., 2007). The presence of ice cover or ice jams has been demonstrated to

significantly influence sediment transport dynamics in rivers (Beltaos, 1983; Knack and Shen, 2015). A representative case occurred on the Grasse River in 2003, where spring snowmelt and rainfall led to downstream ice jam accumulation. The ice jam caused both 3 meters of backwater rise and ice jam toe induced flow constriction, exacerbating localized bed erosion beneath the ice (Kolarski and Shen, 2023). Zhao et al. (2023) investigated suspended-sediment transport during cold and warm winters in the Toudaoguai reach of the Yellow River and demonstrated that variations in ice-cover extent and thermal regime significantly affect sediment transport processes. Additionally, ice jams intensify local scour around bridge piers (Wang et al., 2015). As bridge foundations are subjected to local scour, this can potentially cause bridge failure (Akhlaghi et al., 2020). Extensive research has been conducted on local scour around bridge piers under open-flow conditions (Shen et al., 1969; Chiew et al., 1987; Dey et al., 1995; Aataie-Ashtiani et al., 2006; Liu et al., 2018). Based on the two main forms of river ice: ice cover and ice jam, the research on local scour around bridge piers in cold regions can be categorized into studies under ice-covered and ice-jammed flow conditions.

The presence of the ice cover shifts the maximum velocity closer to the bed, increasing the shear stress on the bed (Sui et al., 2010). Ackerman et al. (2002) explored local scour at cylindrical piers under open flow and ice-covered flow conditions, finding that the local scour depth was 25% to 35% greater under ice-covered flow conditions. Wu et al. (2014) investigated local scour at semicircular abutments by varying the roughness of the ice cover, observing that the local scour depth

increased by 35% under rough ice compared to smooth ice. Namaee et al. (2019) investigated local scour at side-by-side double piers under both open and ice-covered flow conditions. Their results indicated that increasing the pier spacing-to-diameter ratio reduced both the intensity of the horseshoe vortex and the local scour depth. They also proposed an equation to calculate the local scour depth under these conditions. Valela et al. (2021) studied local scour around piers under ice-covered flow conditions by varying the submergence depth of the ice cover. They found that as the submergence depth of the ice cover increased, the flow velocity increased, leading to a rise in the local scour depth around the pier. Sirianni et al. (2022) experimentally studied the effect of different upstream ice cover lengths on the local scour depth around a pier. They found that the local scour depth did not increase with the length of the ice cover. When the upstream ice cover length was 2.66 m (half of the maximum ice cover length in the experiment), both the local scour depth and the scour hole volume reached their peak. As the ice cover length continued to increase, both the local scour depth and scour hole volume decreased. Wang et al. (2021a) conducted experimental studies on local scour around a single pier under both open flow and ice-covered flow conditions. They found that the local scour depth under ice-covered flow conditions was 20% to 30% greater than under open flow conditions, and the scour hole area and volume increased by 40% to 50%. They also developed formulas to calculate the local scour depth, scour hole area, and scour hole volume. Sang et al. (2022) investigated local scour around tandem double piers. By altering hydraulic conditions, the L/D ratio (where L is the pier spacing and D is the pier diameter), and median particle size, they found that at $L/D = 9$, the rear pier experiences the smallest local scour depth. As L/D increases, the influence of the front pier on the rear pier diminishes. When L/D exceeds 17, the effect of sediment deposition around the front pier on the rear pier's local scour depth becomes negligible. Natural rivers are predominantly sinuous and meandering, and their flow dynamics differ from those in straight channels. In curved channels, the centrifugal force induces a secondary flow, which is a key hydrodynamic feature. This secondary flow drives surface water toward the concave bank and bottom water toward the convex bank, resulting in an asymmetric velocity distribution and bed shear stress (Lotsari et al., 2017; Naghavi et al., 2023). Such alterations in the hydrodynamic structure can significantly influence the local scour process around bridge piers. Li et al. (2023) analyzed local scour around tandem double piers in an S-shaped flume. Under consistent hydraulic conditions, the scour depth pattern near tandem piers in the curved flume mirrored that in the straight flume: the deepest scour holes occurred at the upstream curve apex, with diminishing inter-pier interaction as pier spacing increased. When L/D exceeds 15, the rear pier's scour depth approximates 90% of the front pier's, with negligible influence of the rear pier on the front pier. Song et al. (2023) examined local scour around side-by-side double piers in an S-shaped channel. Under identical conditions, piers on convex banks exhibit significantly more severe scour compared to those on concave banks, with the densimetric Froude number exerting a greater influence on scouring at convex bank piers, demonstrating a pattern distinctly different from that observed in straight channels. As the L/D ratio increases, the local scour depth at piers on convex banks increases, while it decreases at piers on concave banks.

Compared to sheet ice-covered flow conditions, local scour around piers and the thickness distribution under ice-jammed flow conditions are significantly more complex. Wang et al. (2021b) experimentally investigated local scour around piers in

a straight flume under ice-jammed flow conditions. They observed that both the scour depth and length around the pier exceeded those under ice-covered flow conditions and increased with flow velocity. Additionally, the scouring dynamics were significantly influenced by variations in ice jam thickness. Hu et al. (2022) examined how variations in pier shape affected local scour in the straight flume as ice jams evolved. Their findings indicated that scour formed more rapidly around the pier when the initial ice jams were primarily due to mechanical thickening. In contrast, when hydraulic thickening dominated the formation of initial ice jams, the scouring process resembled that under ice-covered conditions, with the local scour depth increasing with the flow Froude number, ice discharge rate, and pier shape coefficient. Dong et al. (2024) investigated the effects of various factors, such as flow Froude number, ice-water discharge ratio, pier spacing, and median particle size, on the local scour depth around tandem double piers and ice jam thickness in an S-shaped flume. They found that the relationship between the flow Froude number and the local scour depth around the piers exhibited a critical value. When the flow Froude number reached this critical value, the local scour depth around the tandem double piers peaked. However, their study was limited in scope, as they only examined the relationship between the flow Froude number and the local scour depth at a single ice-water discharge ratio. Different ice-water discharge ratios can influence the peak value of the local scour depth around the piers. Wang et al. (2016a) compared the critical conditions for ice jam formation in S-shaped and straight flumes. They found that the critical flow Froude number for ice jam formation in the curved flume exceeded that in the straight flume, with a thicker ice jam on the convex bank and a thinner ice jam on the concave bank. The equilibrium ice jam thickness decreased with increasing initial flow velocity, while it increased with greater initial flow depth and ice discharge rate.

In summary, in cold regions during winter, the ice covers or ice jams can intensify the local scour around bridge piers. Research under ice-covered and ice-jammed flow conditions has primarily focused on local scour around single pier in straight flumes. However, natural rivers are often meandering, and tandem double piers are commonly found in rivers (Figure 1). Therefore, this study experimentally investigates the effects of various flow Froude numbers and ice-water discharge ratios on local scour around tandem double piers and ice jam thickness in an S-shaped flume. The research findings can provide a reference for bridge construction and ice jam thickness determination in cold region rivers.



Fig. 1. Photograph of tandem double piers under ice-jammed conditions.

2 MATERIALS AND METHODS

2.1 Experimental setup

The laboratory experiments were conducted in an S-shaped flume measuring 25.17 m in length and 0.60 m in width. The flume was divided into 27 cross-sections (CS) from upstream to downstream. From CS-2 to CS-27, the sand layer in the flume had a thickness of 15 cm. In natural rivers, pier scour primarily involves non-cohesive sediment. To avoid the interference of cohesive forces on sediment incipient motion and scour development, sediment with a median particle size $d_{50} \geq 0.32$ mm was selected, which is larger than the particle size of cohesive sediment (Van Rijn, 2007). The sediment used in the experiments was collected from natural river channels, with median particle sizes (d_{50}) of 0.71 mm, 0.61 mm, 0.44 mm, and 0.32 mm. The primary sediment size employed in the experiments was 0.71 mm, with a nonuniformity coefficient (η) of 1.61. The bulk density (ρ_b) of the sediment was 1.43 g/cm³, and the particle density (ρ_s) was 2.61 g/cm³. A median particle size of $d_{50} = 0.71$ mm was primarily used in the experiments. The critical velocity for incipient motion V_c was calculated according to Melville et al. (1988), yielding a flow intensity $V_0/V_c \approx 0.40$ –0.49, which satisfies the clear-water scour condition. The distribution curve of the sediment particles is shown in Figure 2. Styrofoam panels were used between CS-25 and CS-26 to simulate the ice cover, where ice particles accumulated to form ice jams (Figure 3a). Oblate ellipsoid particles made from polyethylene plastic, measuring 3.5 mm in length and with a mass density of $\rho_i = 0.918$ g/cm³ which is similar to the density of river ice at 0.92 g/cm³ (Leppäranta, 2015), were used to simulate ice particles (Figure 3b). Ice discharge rate represents the volume of ice added per second (in units of m³/s). To maintain a stable ice discharge rate, adjustments were made

using an ice hopper located between CS-2 and CS-3. During the experiments, the ice discharge rate (Q_i) was maintained constant, as predetermined by the experimental design. For example, to achieve $Q_i = 2.9 \times 10^{-5}$ m³/s, 15.97 kg of model ice particles were added to the ice hopper every 10 minutes. The ice discharge rates for each experiment are summarized in Table 1. Acrylic tubes with a pier diameter of 2 cm were used to simulate bridge piers. According to Chiew (1984), sidewall effects are negligible when the ratio of flume width to pier diameter (B/D) exceeds 10. In this experiment, the B/D ratio was 30 (60/2), confirming that sidewall effects had minimal influence on the results. The experiments were conducted in the third curved top section (CS-18), where the front pier was positioned at the center of this section and the rear pier was placed along the center line of the bend according to the pier spacing. The plan view of the S-shaped flume is shown in Figure 4.

The flow Froude number is defined as $Fr = V_0 / \sqrt{gH_0}$, where V_0 is the mean flow velocity at the upstream control cross-section (m/s), H_0 is the initial water depth (m), and g is the gravitational acceleration. The Reynolds number is defined as $Re = V_0 H_0 / \nu$, where ν is the kinematic viscosity of water. Regarding the similarity criterion, because ice jam evolution and the local scour process are predominantly gravity-driven, the experiments maintained Froude number similarity. The flow Froude number range in the experiments, ranging approximately from 0.10 to 0.13, is generally consistent with that observed in ice-jam-prone reaches of natural rivers (Beltaos, 2008). Meanwhile, the Reynolds number Re ranges approximately from 2×10^4 to 3×10^4 , indicating fully developed turbulent flow in which the effects of viscous forces are negligible. Therefore, strict Reynolds number equality was not pursued, which is a common practice in hydraulic model studies (Barahimi and Sui, 2024).

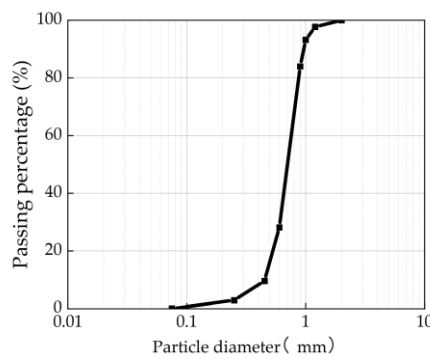


Fig. 2. Distribution curve of sediment particles in the bed.

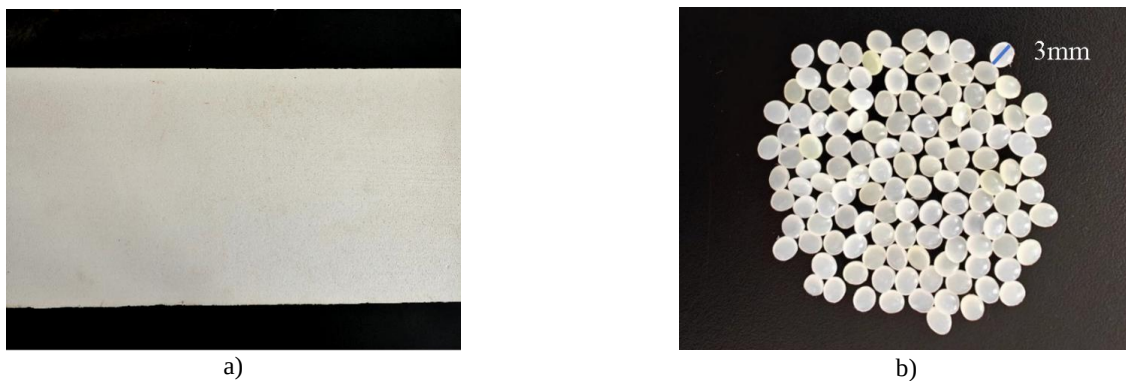


Fig. 3. Simulation of (a) ice cover and (b) frazil ice particles.

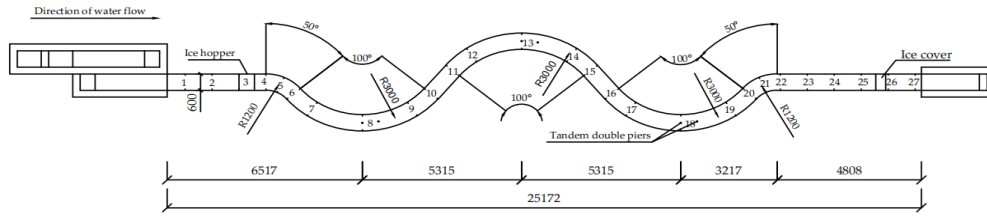


Fig. 4. The plan view of the S-shaped flume in this study (unit: mm).

Table 1. Experiment settings under ice-jammed flow conditions.

Number	H_0 (m)	V_0 (m/s)	L (m)	d_{50} (mm)	Fr -	Q_i/Q_w -
1	0.20	0.150	0.30	0.32	0.107	1.6×10^{-3}
2	0.20	0.150	0.30	0.44	0.107	1.6×10^{-3}
3	0.20	0.150	0.30	0.61	0.107	1.6×10^{-3}
4	0.20	0.150	0.30	0.71	0.107	1.6×10^{-3}
5	0.20	0.150	0.20	0.71	0.107	1.6×10^{-3}
6	0.20	0.150	0.10	0.71	0.107	1.6×10^{-3}
7	0.20	0.150	0.09	0.71	0.107	1.6×10^{-3}
8	0.20	0.150	0.08	0.71	0.107	1.6×10^{-3}
9	0.20	0.150	0.06	0.71	0.107	1.6×10^{-3}
10	0.20	0.150	0.04	0.71	0.107	1.6×10^{-3}
11	0.20	0.140	0.30	0.71	0.100	1.6×10^{-3}
12	0.20	0.160	0.30	0.71	0.114	1.6×10^{-3}
13	0.20	0.161	0.30	0.71	0.115	1.6×10^{-3}
14	0.20	0.167	0.30	0.71	0.119	1.6×10^{-3}
15	0.20	0.170	0.30	0.71	0.121	1.6×10^{-3}
16	0.20	0.172	0.30	0.71	0.123	1.6×10^{-3}
17	0.20	0.140	0.30	0.71	0.100	1.4×10^{-3}
18	0.20	0.150	0.30	0.71	0.107	1.4×10^{-3}
19	0.20	0.160	0.30	0.71	0.114	1.4×10^{-3}
20	0.20	0.162	0.30	0.71	0.116	1.4×10^{-3}
21	0.20	0.170	0.30	0.71	0.121	1.4×10^{-3}
22	0.20	0.140	0.30	0.71	0.100	1.2×10^{-3}
23	0.20	0.150	0.30	0.71	0.107	1.2×10^{-3}
24	0.20	0.160	0.30	0.71	0.114	1.2×10^{-3}
25	0.15	0.140	0.30	0.71	0.115	1.2×10^{-3}
26	0.20	0.165	0.30	0.71	0.118	1.2×10^{-3}
27	0.20	0.170	0.30	0.71	0.121	1.2×10^{-3}
28	0.20	0.140	0.30	0.71	0.100	1.0×10^{-3}
29	0.20	0.150	0.30	0.71	0.107	1.0×10^{-3}
30	0.20	0.160	0.30	0.71	0.114	1.0×10^{-3}
31	0.20	0.163	0.30	0.71	0.116	1.0×10^{-3}
32	0.15	0.144	0.30	0.71	0.119	1.0×10^{-3}
33	0.20	0.170	0.30	0.71	0.121	1.0×10^{-3}
34	0.15	0.140	0.30	0.71	0.115	0.8×10^{-3}
35	0.15	0.150	0.30	0.71	0.124	0.8×10^{-3}
36	0.15	0.160	0.30	0.71	0.132	0.8×10^{-3}
37	0.20	0.164	0.30	0.71	0.117	0.8×10^{-3}
38	0.20	0.165	0.30	0.71	0.118	0.8×10^{-3}
39	0.20	0.167	0.30	0.71	0.119	0.8×10^{-3}
40	0.20	0.170	0.30	0.71	0.121	0.8×10^{-3}
41	0.15	0.146	0.30	0.71	0.120	1.0×10^{-3}
42	0.15	0.150	0.30	0.71	0.124	1.4×10^{-3}

2.2 Experimental Procedure

A total of 42 experiments were conducted in the S-shaped flume, and all experiments were conducted in a stepwise manner, detailed in Table 1.

1) At the beginning of each experiment, the piers were placed in designated positions in the flume. Then, the sand bed in the flume was leveled using a sand scraper to ensure an even surface. Flow stability was maintained by controlling the weir head at the

upstream rectangular weir through precise adjustments to the pipe valve.

2) The flow depth in the flume was gradually increased by slowly rotating the pipe valve to avoid rapid rises that could cause riverbed scour. In the experiment, the weir was used to regulate the flow rate. The corresponding water head over the weir crest was calculated using weir flow formulas, and the pump valve was adjusted to match this calculated head value, thereby achieving the desired flow rate in the flume. Once the

flow depth stabilized, the valve was adjusted to achieve the desired experimental conditions, as monitored by the upstream CS-3 piezometer tube. The experiment proceeded only after the flow depth remained constant for 10 minutes.

3) In the experiments, we simulated the ice jams formed by frazil ice accumulating against the fixed ice cover between CS-25 and CS-26. The ice hopper was then activated to discharge ice particles at a designated rate, initiating ice-covered flow with incoming ice particles in the channel.

4) The local scour depth around the pier (d_s) is the vertical distance from the original bed surface in front of the pier to the deepest point of the scour hole. Measurements were taken using a point gauge with an accuracy of ± 0.1 mm. The measurement frequency was every 5 minutes for the first 30 minutes, every 10 minutes for the subsequent 30 minutes, and every 30 minutes thereafter until the scour reached an equilibrium state. Three repeated tests were conducted for the equilibrium scour depth, and the relative error of the scour depth measurements was within $\pm 5\%$. Flow velocity was measured using a propeller-type current meter with an accuracy of $\pm 5\%$, with a sampling duration of 15 seconds at each measurement point, and the time-averaged value was taken as the velocity at that point.

5) In the curved flume, the ice jam thickness at each cross-section reaches a state of dynamic equilibrium, meaning it

fluctuates only within a limited range. At this point, the ice jam development is considered to have reached equilibrium. When the crest of an ice wave passes downstream through the cross-section where the pier is located, the sediment in the scour hole circulates with the flow inside the hole without being transported out, and the rate of change in scour depth is less than 1 mm/h. Under these conditions, the pier scour is regarded as having attained equilibrium (Mia and Nago, 2003). When both ice jam development and pier scour meet their respective equilibrium criteria, the entire experiment is considered to have reached an overall equilibrium state. Each experiment lasted between 10 and 12 hours. After equilibrium was attained, a point gauge was employed to measure the depth and extent of the scour hole.

3 RESULTS

3.1 Ice Jam Accumulation and Evolution Process

It was observed in the experiments that, for cases with a relatively high ice-water discharge ratio ($Q_i/Q_w \geq 0.0012$), the influence of ice jam formation and evolution on local scour around the bridge piers can be divided into four stages. The ice jam development process at different stages is illustrated in Figure 5, corresponding to Test Number 4.

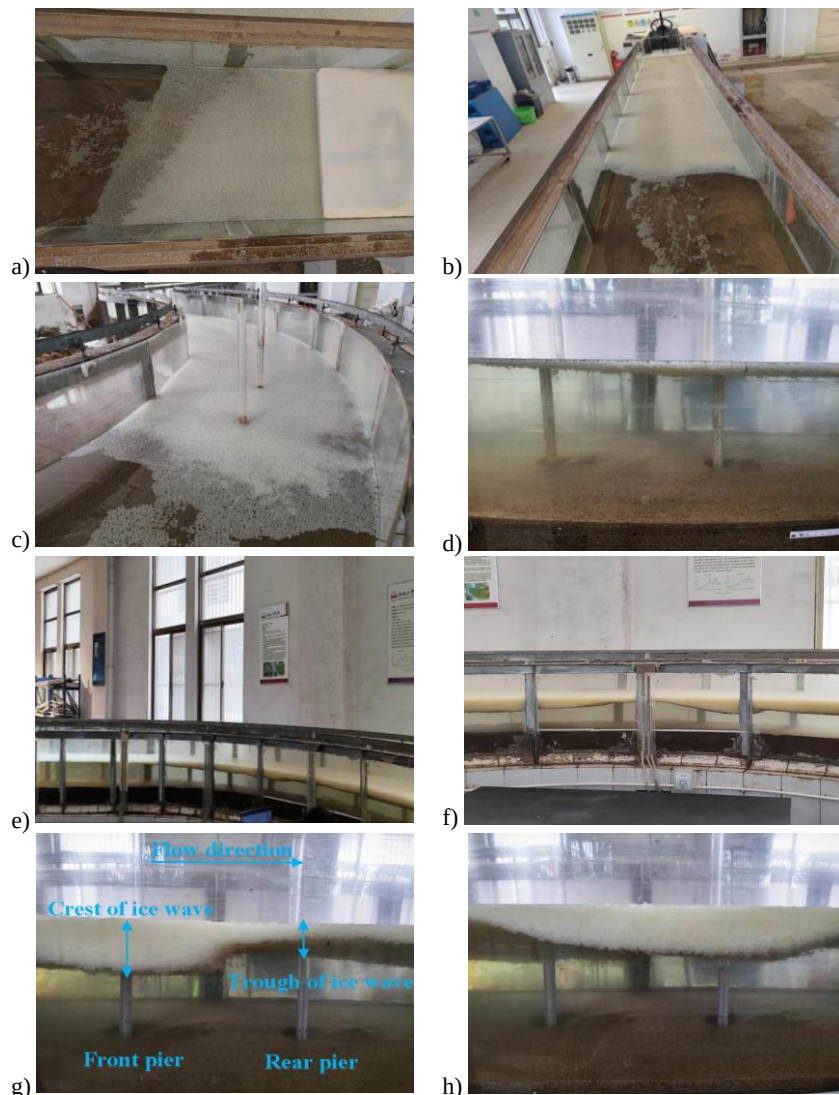


Fig. 5. Ice jam development process: a) ice jam at the lodging position; b) ice jam advancing upstream; c) leading edge of the ice jam passing the bridge piers; d) ice particles submerging at the bridge piers; e) ice jam accumulating and thickening; f) generation of ice waves; g) ice wave passing the front pier; h) ice wave passing the rear pier.

1) Initial ice jam formation stage (Figures 5a and 5b): Ice particles moved from upstream to downstream and began to accumulate at the simulated ice cover lodging position (Cross-Sections 25-26). The ice jam developed upstream in parallel, approximately perpendicular to the cross-section, along the straight flume segment. At this stage, the leading edge of the ice jam had not yet reached the cross-section where the piers were located (Cross-Section 18). The piers were approximately under open flow scour conditions, and both the scour depth and the height of the downstream sediment deposition were relatively small.

2) Ice jam development stage (Figures 5c and 5d): The leading edge of the ice jam continued to advance upstream and passed through the pier cross-section. At this point, the pier scour condition transitioned from open flow scour to scour under ice-jammed conditions. A large amount of ice particles submerged, driven by the wake vortices around the piers. The ice jam thickness near the piers began to increase, and the scour intensity started to intensify.

3) Ice jam thickening stage (Figures 5e and 5f): After the initial ice jam had formed, the leading edge of the ice jam no longer advanced further upstream. The ice jam thickness at each cross-section continued to increase as a result of the continuous ice supply from upstream. Once the ice jam thickness reached a certain level, the ice wave phenomenon occurred. During ice wave propagation, the highest point of the ice surface is referred to as the wave crest, and the lowest depression as the wave trough. The ice wave crests and troughs migrated from upstream to downstream along with the flow. When the ice wave crest passed through the pier cross-section, the ice jam thickness abruptly increased, the pier scour rate rose rapidly, and the scour intensity reached its peak (Figures 5g and 5h).

4) Equilibrium ice jam stage: The ice jam thickness at each cross-section fluctuated only within a limited range, the average thickness tended to stabilize, and the upstream ice supply was essentially balanced by the downstream ice outflow. The local scour depth around the piers reached its maximum value, the morphology of the sediment deposition no longer changed, and the ice jam and scour process attained a dynamic equilibrium.

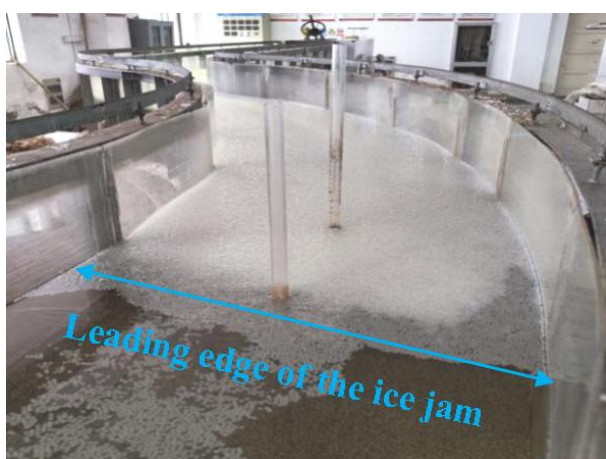
For cases with a relatively low ice-water discharge ratio ($Q_i/Q_w < 0.0012$), no ice waves have been observed in the flume, the leading edge of the ice jam could not reach the upstream ice supply cross-section, and the ice jam did not exhibit a distinct thickening stage. The pier scour intensity was relatively low, and only Stages (1), (2), and (4) were present.

3.2 Condition for Ice Jam Passage Past the Pier

Figure 6 presents photographs of the ice jam front passing and not passing the bridge piers: (a) taken from Test Number 38, and (b) taken from Test Number 40. The influence of different flow Froude number and ice-water discharge ratio on the position of the ice jam front in the curved flume under ice-jammed conditions is shown in Figure 7. Figure 7(a) shows that as the flow Froude number increases, the leading edge of the ice jam progressively moves downstream. This observation aligns with the findings of Wang et al. (2016), who reported that higher flow Froude numbers enhance river ice transport capacity. As the leading edge of the ice jam advances downstream toward tandem piers, a large amount of ice particles submerges near the piers and are transported downstream. This process is primarily driven by the influence of horseshoe vortices around the piers. If the ice particle transport rate exceeds the upstream ice supply, the ice jam cannot progress past the upstream side of the pier. Figure 7(b) illustrates the critical condition for determining whether the ice jam can pass the tandem piers. The dividing line follows the equation:

$$Q_i/Q_w = 0.2714 Fr - 0.0239 \quad (1)$$

When the ice-water discharge ratio $Q_i/Q_w > 0.2714 Fr - 0.0239$ (left side of the line), the ice jam front can develop past the tandem piers, as shown in Figure 6(a). Conversely, when the ice-water discharge ratio $Q_i/Q_w < 0.2714 Fr - 0.0239$ (right side of the line), the ice jam front cannot progress past the tandem piers. As shown in Figure 6(b), the pier scour in this case approximates the condition under open flow.



a)



b)

Fig. 6. Experimental field photos: a) ice jam front passing the pier; b) ice jam front arrested upstream of the pier.

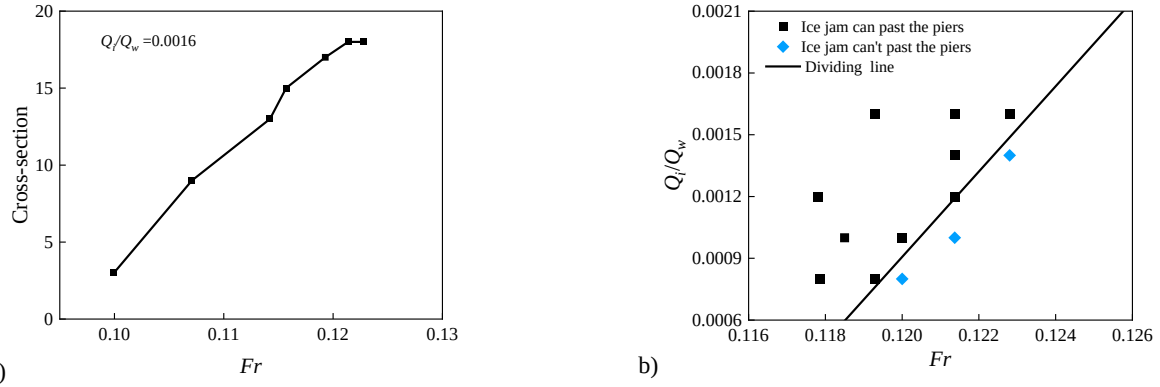


Fig. 7. Progression of the ice-jam front in the curved flume: a) Cross-sectional location of the ice jam front; b) Conditions for ice jam front passing the piers.

3.3 Variation in Vertical Velocity Profiles under Different Ice Jam Thicknesses

Under ice-jammed flow conditions, varying ice jam thicknesses significantly alter the flow structure. This alteration introduces complexity into the local scour process around the piers. To compare the influence of different ice jam thicknesses on the velocity distribution, the measured velocity data were normalized by the flow depth beneath the ice jam. Figure 8 presents the vertical velocity distributions for different ice jam thicknesses. As shown in Figure 8, the position of the maximum velocity point shifts toward the riverbed as the ice jam thickness increases. This shift occurs because a thicker ice jam generally exhibits greater bottom roughness, which causes the maximum velocity point to migrate toward the surface with lower flow resistance (Zabilansky et al., 2005). The roughness of ice jam can be determined by fitting the logarithmic law of the wall to the velocity data adjacent to the ice cover (Sirianni et al., 2022):

$$V_a = \left(\frac{u_*}{\kappa}\right) \ln y + \left(\frac{u_*}{\kappa}\right) \ln\left(\frac{30}{k_s}\right) \quad (2)$$

$$n_i = 0.039 k_s^{\frac{1}{6}} \quad (3)$$

V_a is the mean flow velocity at a distance y from the underside of the ice jam, u_* is the shear velocity, and κ is the von Kármán constant ($\kappa = 0.41$). By performing regression fitting on the velocity profile that follows the logarithmic law (from the water surface to the position of maximum velocity), as shown in Figure 9. The slope and intercept obtained from the fitting are substituted into Equation (2) to calculate the roughness k_s for different ice jam thicknesses. The derived roughness k_s is then substituted into Equation (3) to determine the Manning coefficient for varying ice jam thicknesses (Li, 2012).

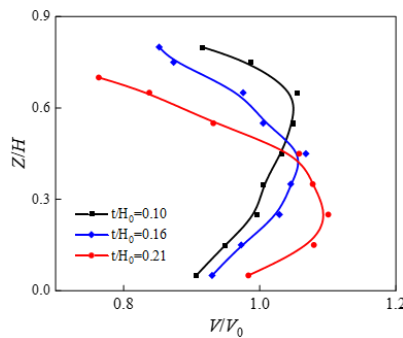


Fig. 8. Vertical velocity profiles under different ice jam thicknesses.

The Manning roughness coefficient of the riverbed was calculated using Equation (4) of Hager (2010). From Figure 10, it can be observed that the Manning coefficient of the ice jam increases with increasing ice jam thickness. This finding is consistent with the linear relationship reported by Beltaos (2008) based on field measurements, where ice jam roughness was found to increase proportionally with ice jam thickness.

$$n_b = 0.039 d_{50}^{\frac{1}{6}} \quad (4)$$

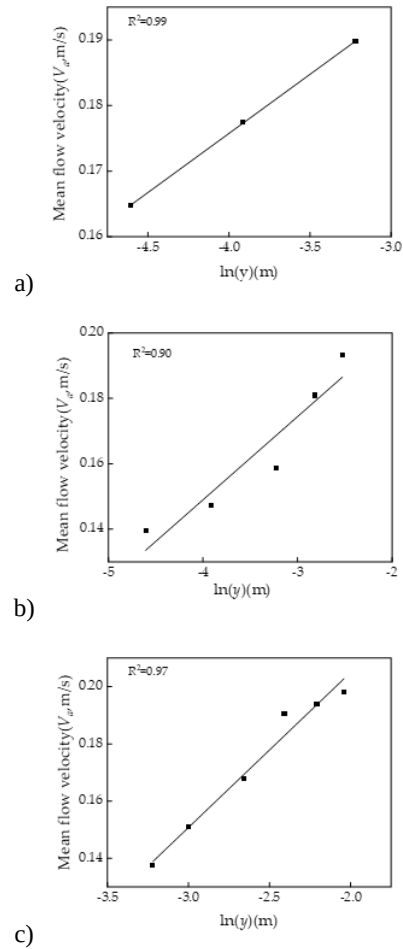


Fig. 9. Linear regression for the ice jam using the law of the wall approximation: a) $t/H_0=0.10$; b) $t/H_0=0.16$; c) $t/H_0=0.21$.

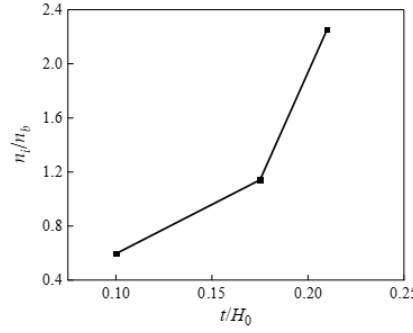


Fig. 10. Manning coefficients under varying ice jam thicknesses.

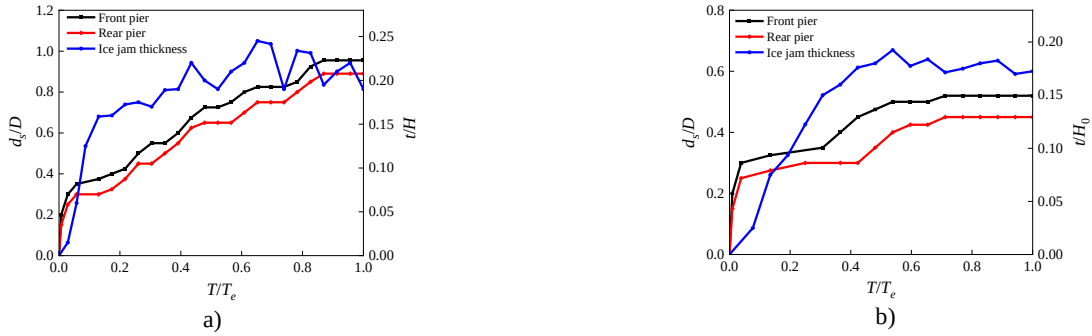


Fig. 11. Variation in scour depth and average ice jam thickness with time: a) With the presence of ice waves; b) Without presence of ice wave.

3.4 Variation in Scour Depth and Ice Jam Thickness with Time

Figure 11 illustrates the temporal variations of the local scour depth around tandem double piers and the ice jam thickness under ice-jammed flow conditions. Given the limited spacing between tandem piers, the ice jam thickness variation between the front and rear pier cross-sections is negligible. Therefore, we adopted the average ice jam thickness across the tandem pier section as the representative parameter for scour analysis, enabling systematic investigation of the relationship between scour evolution duration and ice jam thickness. The trends of the local scour depth and ice jam thickness over time vary under different conditions. When the ice-water discharge ratio $Q_i/Q_w = 0.0016$, with the approaching flow depth of $H_0 = 0.2$ m, and approaching flow velocity of $V_0 = 0.15$ m/s, we observed a wavy migration process of ice particles at the bottom of the ice jam, which closely resembles the movement of sediment particles on riverbeds. This bed-load transport of sediment has been widely referred to as “sand waves”. Given the similarity in the dynamic behavior between this ice particle migration and sand waves, we have defined this phenomenon as “ice waves” (Wang et al., 2019). Ice waves form in the flume as the ice jam develops. Initially, when the leading edge of the ice jam has not yet reached the pier, the scour hole develops slowly. As the leading edge of the ice jam passes the pier, the ice jam thickness increases continuously, and the constricting effect of the ice jam on the flow’s cross-section intensifies, leading to more severe scouring of the riverbed. As the ice jam continues to develop and ice waves form, the local scour depth around the pier increases rapidly when the crest of the ice wave passes the pier due to the increase in the ice jam thickness. In contrast, when the trough of the ice wave passes the pier, the local scour depth increases slowly as the ice jam thickness decreases. Once the ice jam reaches a dynamic equilibrium and the crest of the ice wave passes the pier, the sand particles in the scour hole oscillate with

the flow without exiting. At this point, the local scour depth around the piers reaches its maximum. When $Q_i/Q_w = 0.0008$, $H_0 = 0.2$ m, $V_0 = 0.15$ m/s, due to the relatively low Q_i/Q_w , ice waves do not form within the flume as the ice jam develops. Before the leading edge of the ice jam reaches the pier, the local scour depth increases slowly. When the leading edge of the initial ice jam reaches the piers, the local scour around the piers intensifies as the ice jam thickness increases. As the ice jam thickness gradually stabilizes, the local scour depth around the piers reaches its maximum. The observed difference in scour evolution between the two experimental conditions primarily resulted from insufficient ice discharge to generate ice waves, leading to predominantly horizontal ice jam progression.

3.5 Influence of Ice-water discharge ratio on scour depth and ice jam thickness

Figure 12 shows the influence of different ice-water discharge ratios on the local scour depth around the piers and the ice jam thickness. As seen in Figures 12(a) and 12(b), within the experimental range and with a constant flow Froude number, the local scour depth around the piers increases with the ice-water discharge ratio. This is because a higher ice-water discharge ratio leads to an increase in ice jam thickness, which reduces the flow cross-sectional area at the pier. The consequent increase in flow velocity and bed shear stress around the pier results in greater scour depth (Wang et al., 2016b). Meanwhile, Figure 12(c) shows that under a fixed ice-water discharge ratio, the ice jam thickness decreases as the flow Froude number increases. This occurs because a higher Froude number enhances the river’s ice-transport capacity, leading to a reduction in ice jam thickness.

3.6 Influence of flow Froude number on scour depth and ice jam thickness

Figure 13 illustrates the various flow Froude numbers affecting the local scour depth around piers in the straight flume

under open flow and ice-covered flow conditions. The data are sourced from Wang et al. (2016) and Sang et al. (2022). For both the front and rear piers, d_s/D increases with increasing Fr under both open flow and ice-covered flow conditions, and the scour depth under ice-covered flow conditions is generally greater than that under open flow conditions. This trend occurs because an increase in the flow Froude number leads to higher flow intensity, resulting in a greater local scour depth. This trend aligns with the classical scour theory, which states that under clear-water scour conditions, the scour depth increases monotonically with flow intensity (Melville et al., 1988). Furthermore, the ice cover acts as a fixed upper boundary, which alters the vertical velocity profile and enhances the turbulent kinetic energy and shear stress near the riverbed (Namaee and Sui, 2020). As a result, the local scour depth under ice-covered flow conditions is greater than that under open flow conditions.

3.7 Influence of Flow Froude Number on Scour Depth and Ice Jam Thickness

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kinetic energy and shear stress near the riverbed (Namaee and Sui, 2020). As a result, the local scour depth under ice-covered flow conditions is greater than that under open flow conditions.

The various flow Froude numbers affect the ice jam thickness in an S-shaped flume under ice-jammed flow conditions (Figure 14). As can be seen from Figure 14, for each fixed Q_i/Q_w condition, the relative ice jam thickness t/H_0 generally exhibits a decreasing trend with increasing Fr . This trend is consistent with existing studies, namely, that an increase in Fr enhances the ice transport capacity of the flow, leading to a reduction in ice jam thickness (Wang, 1999). Although Q_i/Q_w varies simultaneously in the figure, the curves under all conditions essentially display the same monotonic decreasing trend, indicating that the influence of Fr on ice jam thickness is not altered by the specific value of the upstream ice discharge.

The influence of different Fr on the local scour depth around the piers in the curved flume under ice-jammed conditions is shown in Figure 15, and the comparison of pier scour depths between ice-jammed and open flow conditions is presented in Figure 16. As shown in Figure 15, unlike the monotonic positive correlation between the local scour depth around the piers and the flow Froude number under open flow and ice-covered flow conditions, the scour depth under ice-jammed flow conditions exhibits a non-monotonic trend (first increasing then decreasing) due to variations in ice jam thickness. This behavior indicates the existence of a critical Froude number. Within the experimental parameters and with a constant ice-water discharge ratio, when the Froude number is less than the critical Froude number, the local scour depth is positively correlated with the flow Froude number. This is because, within this range, although ice jam thickness decreases with increasing the flow Froude number, the rate of decrease is relatively low. The ice jam continues to enhance turbulent kinetic energy and shear stress near the riverbed (Aghaji Zare et al., 2016).

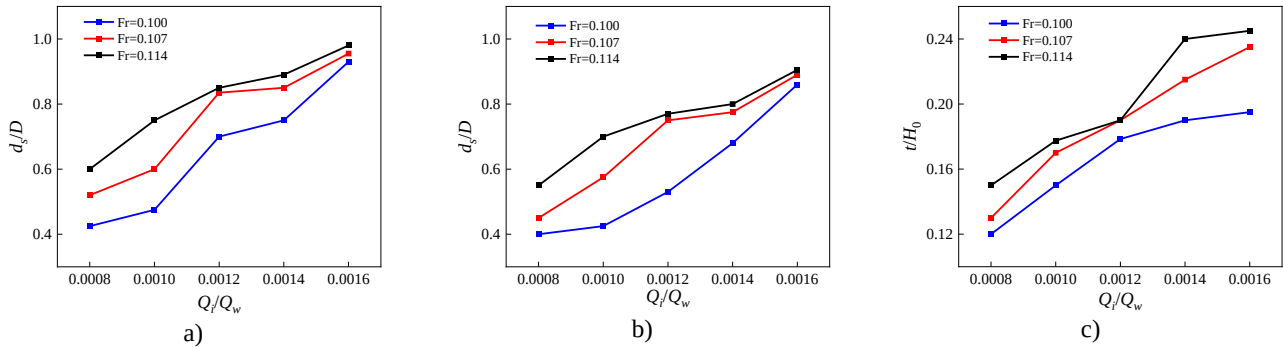


Fig. 12. The scour depth and ice jam thickness under different ice–water discharge ratio: a) local scour depth around the front pier; b) local scour depth around the rear pier; c) ice jam thickness.



Fig. 13. Influence of flow Froude numbers on the scour depth: a) front pier; b) rear pier.

Concurrently, the increase in flow intensity leads to higher near-bed shear stress. When the flow Froude number equals the critical Froude number, the scour depth reaches its peak, and the correlation between the flow Froude number and scour depth changes. When the flow Froude number exceeds the critical Froude number, the local scour depth becomes negatively correlated with the flow Froude number. This is because, with increasing Fr , the ice jam undergoes an overall downstream shift (Figure 7), and t decreases considerably. Consequently, the constriction effect of the ice jam on the flow cross-section at the pier is reduced, and the scour conditions gradually transition toward those of open flow. The pier scour depth approaches that under open flow conditions (Figure 16), resulting in a decrease in scour depth with increasing Fr .

3.8 Influence of Pier Spacing and Median Sediment Size on Local Scour Depth

Figure 17 illustrates the influence of different L/D ratios on the local scour depth around bridge piers. Under ice-jammed flow conditions, the scour depth for tandem piers reaches its peak

at $L/D = 3$. According to Sumer et al. (2002), when the L/D ratio of tandem piers is less than 3, the presence of the rear pier causes flow blockage, which intensifies the horseshoe vortex upstream of the front pier and consequently increases the local scour depth. For tandem piers with $3 < L/D < 5$, this blocking effect diminishes, resulting in reduced scour depths. When L/D exceeds 5, the local scour depth increases again with increasing L/D ratios. This occurs because larger L/D ratios enhance flow disturbance around the piers, reduce the river's ice transport capacity. The ice jam thickness increases, thereby exacerbating the local scour depth.

Figure 18 illustrates the influence of median sediment particle size on the local scour depth around tandem piers. As shown in the figure, within the experimental range, a negative correlation exists between the median sediment particle size and the local scour depth around tandem piers under ice jam flow conditions. This phenomenon occurs because, under identical flow conditions, larger sediment particles require higher critical velocities for initiation of motion, consequently reducing the local scour depth (Melville et al., 1988).

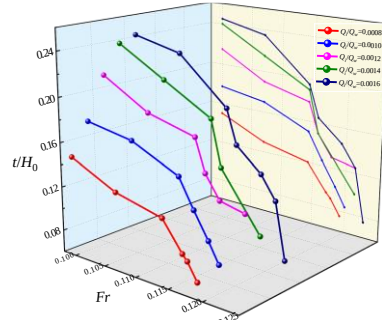


Fig. 14. Influence of different flow Froude numbers (Fr) on relative ice jam thickness (t/H_0).

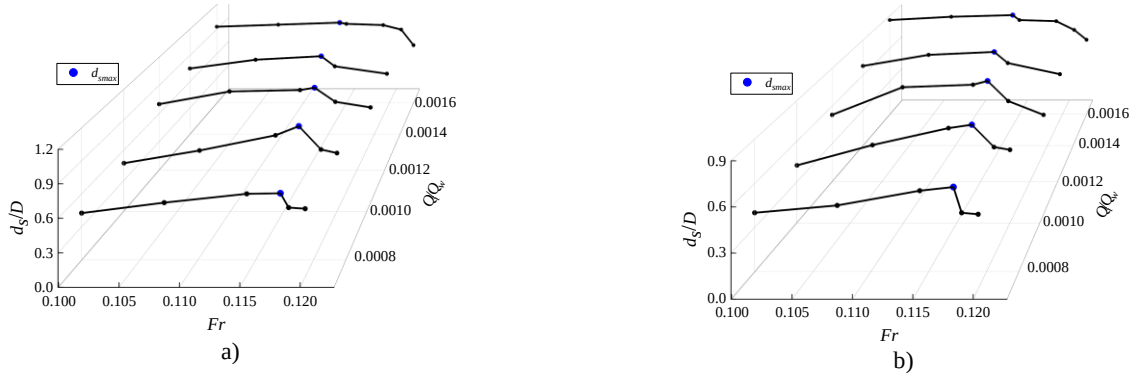


Fig. 15. Influence of different flow Froude numbers on local scour depth: (a) Front pier, (b) Rear pier.

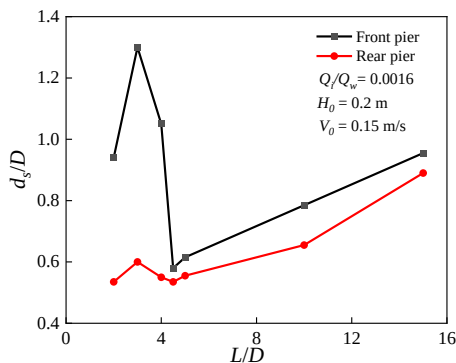


Fig. 17. Local scour depth around piers under different L/D ratios.

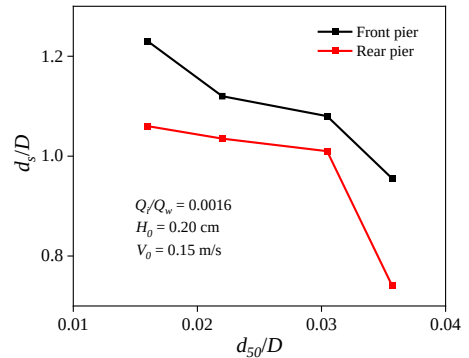


Fig. 18. Local scour depth around piers different median sediment particle sizes.

3.9 Formula for Calculating the Peak Scour Depth Around Piers

Local scour around bridge piers under ice-jammed conditions is a process involving ice jam thickness, changes in flow conditions, and sediment scour. To identify the dominant parameters governing this process, a dimensional analysis based on the Pi-Buckingham theorem was conducted.

For the critical flow Froude number Fr_c , the primary physical quantities affecting its magnitude include: the mean approach flow velocity V_0 , the gravitational acceleration g , the approach flow depth H_0 , the ice discharge Q_i , and the water discharge Q_w . Selecting V_0 , H_0 , and ρ (water density) as the basic physical quantities, the dimensional analysis yields the following dimensionless relationship:

$$Frc = f_1(Q_i/Q_w) \quad (5)$$

For the local scour depth around piers, the relevant physical quantities include: flow parameters (V_0 , H_0 , g , Q_w), ice jam parameters (ice jam thickness t , ice discharge Q_i), geometric parameters (pier diameter D), and sediment parameters (median particle size d_{50} , sediment density ρ_s). Since the sediment parameters varied within a limited range in this experiment and are not the focus of the present study, they are incorporated into the empirical constants here. Selecting V_0 , H_0 , and ρ as the basic quantities, the dimensional analysis gives:

$$d_s/D = f_2(Fr, t/H_0, Q_i/Q_w) \quad (6)$$

where Fr is the flow Froude number, representing the ratio of inertial forces to gravitational forces, and serves as the core parameter for characterizing the flow's ice transport capacity and scour intensity; Q_i/Q_w is the ice-water discharge ratio, reflecting the relative magnitude of ice supply to the flow transport capacity and directly influencing the ice jam thickness and its constriction effect on the flow cross-section; and t/H_0 is the relative ice jam thickness, reflecting the degree of vertical compression of the flow cross-section by the ice jam.

By setting the dependent variable as $\ln(Fr)$ and the independent variable as $\ln(Q_i/Q_w)$, we derived Equation (7). By setting the dependent variable as $\ln(d_s/D)$ and the independent variables as $\ln(Fr)$, $\ln(t/H_0)$, and $\ln(Q_i/Q_w)$, we derived Equation (8).

$$\ln(Fr) = k + c \ln\left(\frac{Q_i}{Q_w}\right) \quad (7)$$

$$\ln\left(\frac{d_s}{D}\right) = e + a \ln(Fr) + b \ln\left(\frac{t}{H_0}\right) + d \ln\left(\frac{Q_i}{Q_w}\right) \quad (8)$$

By reformulating in exponential form, Equation (7) can be expressed as Equation (9), and Equation (8) can be rewritten as Equation (10).

$$Fr_c = k_1 \left(\frac{Q_i}{Q_w}\right)^{c_1} \quad (9)$$

$$\frac{d_s}{D} = e_1 (Fr)^{a_1} \left(\frac{t}{H_0}\right)^{b_1} \left(\frac{Q_i}{Q_w}\right)^{d_1} \quad (10)$$

In the equation, the coefficients are denoted as a , a_1 , b_1 , c , c_1 , d , d_1 , e , e_1 , k and k_1 .

Based on the experimental data at the critical points, the following dimensionless regression equation for the critical Froude number under ice-jammed flow conditions was derived:

$$Fr_c = 8.81 \times 10^{-2} \left(\frac{Q_i}{Q_w}\right)^{-0.004} \quad (11)$$

When the flow Froude number is less than the critical flow Froude number, the following equation can be used to determine the local scour depth around the front pier under ice-jammed flow conditions:

$$\frac{d_s}{D} = 3.65 \times 10^{-4} (Fr)^{2.29} \left(\frac{t}{H_0}\right)^{0.12} \left(\frac{Q_i}{Q_w}\right)^{0.81} \quad (12)$$

The following equation has been derived to calculate the local scour depth around the rear pier under ice-jammed flow conditions:

$$\frac{d_s}{D} = 5.13 \times 10^{-4} (Fr)^{2.42} \left(\frac{t}{H_0}\right)^{0.08} \left(\frac{Q_i}{Q_w}\right)^{0.84} \quad (13)$$

When the flow Froude number (Fr) is more than the critical flow Froude number (Fr_c), the following equation has been derived for calculating the local scour depth around the front pier under ice-jammed flow conditions:

$$\frac{d_s}{D} = 84.78 (Fr)^{-0.24} \left(\frac{t}{H_0}\right)^{0.36} \left(\frac{Q_i}{Q_w}\right)^{0.68} \quad (14)$$

The following equation has been derived to calculate the local scour depth around the rear pier under ice-jammed flow conditions:

$$\frac{d_s}{D} = 19.89 (Fr)^{-1.25} \left(\frac{t}{H_0}\right)^{0.21} \left(\frac{Q_i}{Q_w}\right)^{0.85} \quad (15)$$

Under ice-jammed flow conditions with a constant ice-water discharge ratio, equations (12–13) show that when the Froude number is less than the critical flow Froude number, the scour depth exhibits a positive correlation with flow Froude number. When the flow Froude number equals the critical flow Froude number, the scour depth reaches its peak value. When the flow Froude number exceeds the critical flow Froude number, the scour depth decreases as flow Froude number increases (Equations 14–15). This finding contrasts with the results of the formula proposed by Dong et al. (2024), which suggests a positive correlation between the scour depth and the flow Froude number. Therefore, under ice-jammed flow conditions, when the flow Froude number exceeds the critical flow Froude number, it is more appropriate to use Equations (14–15) to calculate the scour depth. As the flow Froude number continues to increase, the ability of the ice jam in the flume to develop past the tandem piers depends on both the Froude number and the ice-water discharge ratio, as defined by Equation (1). The error analysis of the formulas is presented in Table 2. Figure 19 illustrates a comparison between the calculated local scour depths around the piers and the measured results. The results in Figures 19(a)–(d) were calculated using Equations (12)–(15), respectively. The results presented in these figures demonstrate a close agreement between the calculated and measured values for both piers.

The formulas proposed in this study are semi-empirical and semi-theoretical equations derived based on experimental conditions, rather than universal physical models. By means of

controlled variable experiments, this study investigated the quantitative relationships between the scour depth and the primary influencing factors under ice-jammed conditions, providing a preliminary reference for bridge design in cold regions. Due to the complexity of the coupled ice jam–flow–sediment process, no mature physical model is currently available to accurately predict this process; therefore, research based on experimental data remains the primary approach at present.

To examine the similarities and differences between pier scour under ice-jammed flow conditions and that under pressurized flow (Umbrel et al., 1998; Carnacina et al., 2019; Koushki et al., 2025), the measured local scour depth was compared with values calculated using Equation (16) proposed

by Koçyigit et al. (2024) for pressurized flow beneath a fixed bridge deck. Equation (16) comprehensively accounts for the influence of parameters including the particle densimetric Froude number (Fr_d), bridge deck thickness (a), the weir overflow depth (h_w), and deck alignment coefficient (K_a), where $Fr_d = V_0 / \sqrt{\Delta g d_{s0}}$. To adapt the formula to the ice-jammed flow conditions in this study, equivalent parameter substitutions were made as follows: the bridge deck thickness was replaced by the average ice thickness; the deck alignment coefficient was set to 0 since the pier was perpendicular to the flow direction; and the weir overflow depth was assigned a value of 0. To avoid the influence of wake vortex from the upstream pier, the front pier was selected for comparison.

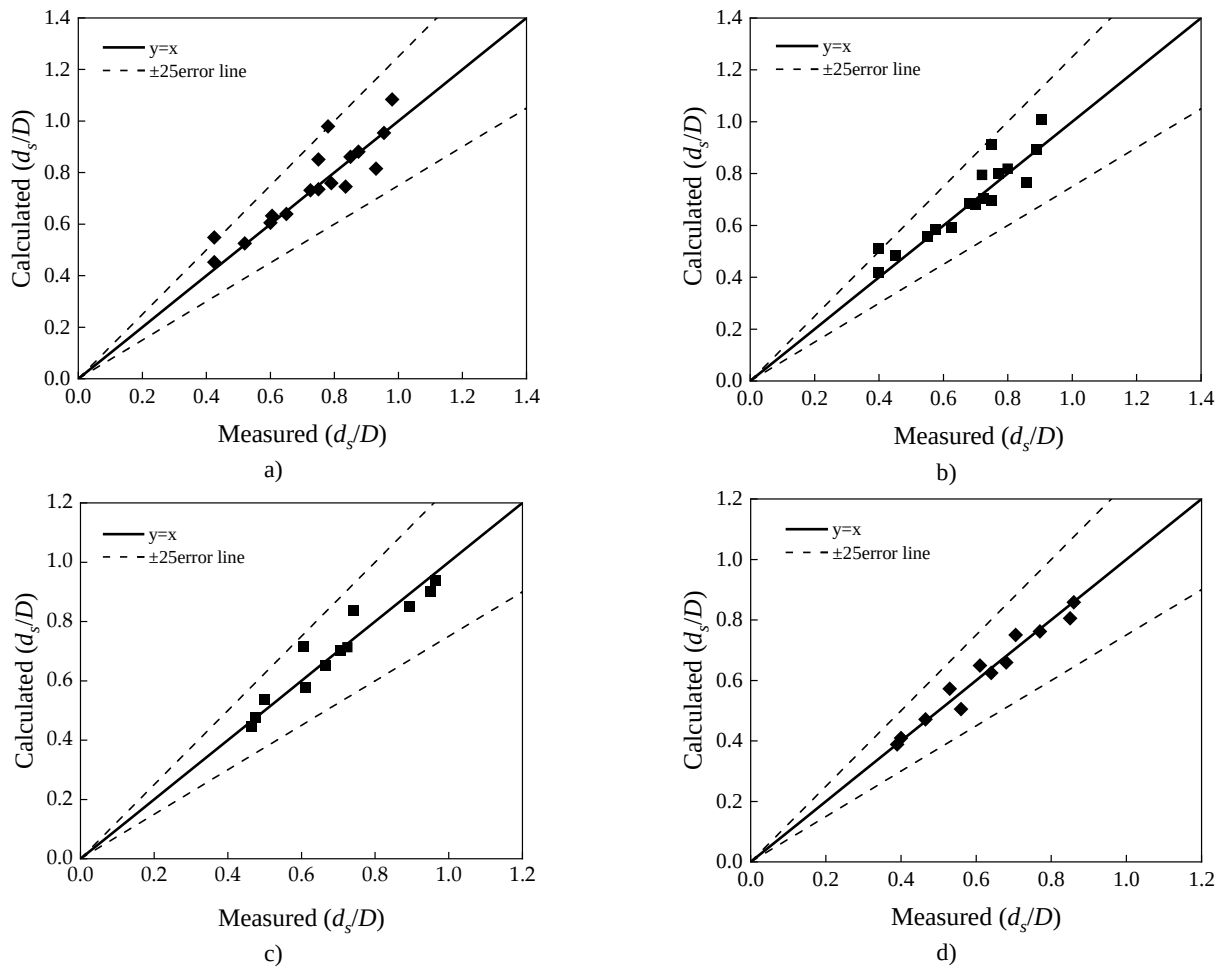


Fig. 19. When $Fr \leq Fr_c$, relationship between regression-predicted and measured scour depth of tandem double piers: (a) Front pier, (b) Rear pier. When $Fr > Fr_c$, relationship between regression-predicted and measured scour depth of tandem double piers: (c) Front pier, (d) Rear pier.

Table 2. Error statistics table.

Equation Number	Coefficient of Determination (R^2)	Mean Absolute Percentage Error (MAPE)	Root-mean-square Error (RMSE)	Mean Absolute Error (MAE)
11	0.943	0.522 %	0.001	0.001
12	0.814	7.362 %	0.077	0.052
13	0.849	7.234 %	0.065	0.047
14	0.910	5.492 %	0.050	0.037
15	0.960	3.889 %	0.030	0.024

The comparison results are shown in Figure 20. Overall, the calculated values from the formula are higher than the measured scour depths under ice-jammed flow conditions. This discrepancy is primarily attributed to the fact that the rough, porous, and unstable bottom of an ice jam generates greater flow resistance and energy dissipation (She et al., 2006) compared to a smooth, fixed bridge deck. Consequently, directly applying the bridge deck thickness value derived from fixed-boundary conditions may lead to an overestimation of the vertical contraction intensity. Furthermore, since the formula from the literature is established for steady flow conditions, the complex temporal evolution of an ice jam could also influence the local scour depth at the pier.

$$\frac{d_s}{H_0} = -0.043 + 0.169Fr_d - 0.052\left(\frac{a}{H_0}\right) - 0.411\left(\frac{h_w}{H_0}\right) + 0.060K_a \quad (16)$$

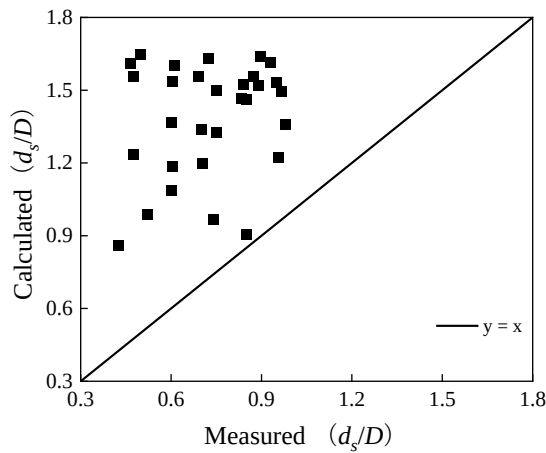


Fig. 20. Comparison of measured scour depths under ice-jammed flow conditions with values calculated using the pressurized flow formula.

4 DISCUSSION

1) Under open flow and ice-covered flow conditions, the local scour depth around the pier increases monotonically with flow intensity. In contrast, under ice cover, the vertical velocity profile is altered, enhancing the turbulent kinetic energy and bed shear stress, which in turn leads to greater local scour depths. The ice jams not only act as a porous boundary but also participate in the flow dynamics. Its thickness varies dynamically with time and flow conditions, influencing the flow constriction effect. This results in a non-monotonic relationship between the flow Froude number and the local scour depth. Due to the limitations of the experimental setup, variations in turbulence intensity under ice-jammed flow conditions could not be measured, warranting further investigation.

2) The sinuosity of natural rivers varies widely. The S-shaped flume used in this experiment has a relatively low sinuosity, representing a common scenario in natural rivers (Keshavarzi et al., 2016). Circular piers arranged in tandem are prevalent in rivers; therefore, circular tandem piers were adopted in the tests. It is evident that variations in channel sinuosity, pier shape, and transverse pier spacing can influence local scour and ice-jam thickness distribution. These issues warrant further investigation.

3) Ice jam thickness in curved channels varies transversely, being thicker at convex banks and thinner at concave banks. During ice jam progression, its thickness around piers shows complex and dynamic changes. The average ice jam thickness is calculated from measurements taken at the channel centerline of each pier's cross-section. The average ice jam thickness at the channel centerline of the tandem pier section was adopted to facilitate qualitative analysis.

The ice jam thickness varies slightly across the tandem pier cross-section, but these differences have minimal qualitative impact.

4) This experimental study is a conceptual investigation. Its primary objective is to examine the qualitative influence of the flow Froude number and the ice-water discharge ratio on the local scour depth around bridge piers and the ice jam thickness under ice-jammed conditions, rather than to predict pier scour in a specific prototype river. Therefore, strict geometric scaling based on a particular prototype was not applied.

5) In natural cold-region rivers, air temperature is a key factor influencing the formation, evolution, and ablation of ice jams, determining processes such as the production rate of frazil ice and the ablation of the ice cover (Łukaszewicz and Graf, 2020). In the present experiments, the water temperature in the flume was approximately 20 °C, and the model ice was made of polyethylene plastic particles with a density similar to that of natural ice. No melting or freezing occurred during the experiments. Over the relatively short experimental duration of 10–14 hours, the accumulation and evolution of the ice jam were dominated by hydrodynamic processes. Current studies on pier scour under ice-covered and ice-jammed conditions have primarily focused on hydrodynamic factors, without considering thermal effects (Wang et al., 2021; Dong et al., 2026). Variations in water temperature can affect the kinematic viscosity ν of water, thereby influencing the Reynolds number and the viscous effects in the flow field. However, in the cold-region rivers on which this study focuses, the winter water temperature typically ranges from 0 to 4 °C, and the corresponding variation in kinematic viscosity over this range is relatively small (Turcotte and Morse, 2017). The slight change in viscosity induced by water temperature variations has a negligible impact on the local scour process around bridge piers.

5 CONCLUSION

Experiments conducted in an S-shaped flume investigated the effects of the flow Froude number and ice-water discharge ratio on local scour around tandem double piers and ice jam thickness under ice-jammed flow conditions. The main findings are as follows:

1) Unlike the monotonic increase in the scour depth with the Froude number (Fr) observed under open flow and ice-covered flow conditions, a critical Froude number (Fr_c) exists for ice-jammed flow conditions due to the influence of ice jam thickness variations on the scour depth. Within the experimental range and under a constant ice-water discharge ratio (Q_i/Q_w), the scour depth increases with Fr when $Fr < Fr_c$, primarily because the enhanced flow intensity leads to greater near-bed shear stress. The scour depth reaches its peak when Fr equals Fr_c . When $Fr > Fr_c$, the scour depth decreases with increasing Fr , mainly due to a significant reduction in ice jam thickness and downstream migration of the ice front, which weakens the flow constriction effect at the cross-section where the pier is located.

2) Changes in ice jam thickness significantly influence the local scour process around the pier. Experiments show that increasing ice jam thickness raises its Manning's coefficient, altering the vertical velocity profile. This causes the point of maximum velocity to shift toward the riverbed, enhancing near-bed shear. These results align with the field observations of Beltaos (2008), which indicate a linear increase in ice jam roughness with thickness.

3) Whether ice jams can develop upstream of the piers is jointly influenced by Fr and Q_i/Q_w . The critical condition for the ice front to pass the piers is $Q_i/Q_w = 0.2714Fr - 0.0239$. If the Q_i/Q_w exceeds this threshold, the ice front advances past the pier. Otherwise, it stalls downstream, and pier scour conditions approximate those of open flow. This critical relationship provides a basis for predicting the type of local scour around the piers.

4) Under ice-jammed flow conditions, when the ice-water discharge ratio is held constant and the flow Froude number equals the critical flow Froude number, the scour depth reaches the peak

scour depth. From a bridge design perspective, using the peak scour depth as the design criterion ensures enhanced safety for foundation integrity. From a flood control operation perspective, it is advisable to avoid operating under flow conditions near the critical Froude number.

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NOMENCLATURE

a	- bridge deck thickness
B	- flume width
D	- pier diameter
d_{50}	- median particle diameter
d_s	- local scour depth
Fr	- flow Froude number
Fr_c	- critical Froude number
Fr_d	- particle densimetric Froude number
g	- acceleration of gravity
H_0	- approaching flow depth
h_w	- weir overflow depth
k_s	- roughness coefficient
κ	- Von Kármán constant
K_d	- deck alignment factor
L	- pier spacing
L/D	- relative pier spacing
n_i	- Manning roughness coefficient of the ice jam
n_b	- Manning roughness coefficient of the riverbed
Q_i	- ice discharge rate
Q_w	- flow rate
Q_i/Q_w	- ice-water discharge ratio
t	- ice jam thickness
T_e	- time to equilibrium
V_0	- approaching flow velocity
u_*	- shear velocity

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