

Channel deformation around non-submerged spur dikes with different alignment angles under ice cover

Rahim Jafari, Jueyi Sui*

School of Engineering, University of Northern British Columbia, 3333 University Way, Prince George, BC, Canada.

* Corresponding author. E-mail: jueyi.sui@unbc.ca

Abstract: This study explores how the ice cover on water surfaces affects the deformation of the channel bed around non-submerged spur dikes. Laboratory experiments have been conducted by using two types of model ice cover with different roughness coefficients and three sands with different median grain sizes. The effects of various layout angles of non-submerged spur dikes on the maximum scour depth and scour patterns around spur dikes have been evaluated. Results showed that the dike orientation angle is the critical factor influencing the maximum scour depth. The presence of an ice cover and its roughness coefficient dramatically affect the channel bed deformation around spur dikes. The combined effect of the dike orientation angle, ice cover roughness, and flow Froude number resulted in different scour patterns. For instance, the upstream length of scour holes decreases by approximately 60% when the dike angle changes from 90° to 60°, while an increase in flow rate by about 50% leads to a 20% increase in the downstream length of scour holes. Equations have been derived to determine the maximum scour depth around spur dikes, considering the effects of ice cover, bed material and the dike layout angles.

Keywords: Non-submerged spur dikes; Ice cover; Dike layout angles; Scour depth; Non-uniform natural sand.

1 INTRODUCTION

The flowing water in rivers and streams plays a pivotal role in sustaining human life while serving as a habitat for various forms of aquatic vegetation and animals. Human activities have modified river flows by constructing various channels and structures (Giglou et al., 2018). The in-stream infrastructures such as spur dikes, and bridge piers significantly affect flow characteristics and riverbed deformation. The flow characteristics in the presence of in-stream infrastructures have been investigated by many researchers (Namaee et al., 2021; Wu et al., 2014b).

Spur dikes are one of the in-stream infrastructures widely used in river engineering and water ecological restoration projects for various purposes such as bank protection, the maintenance of navigation channels, flood control, improvement of the habitat zone, and ecosystem rehabilitation. Spur dikes are hydraulic structures extending to the river flow from the channel bank and can be built from various materials such as riprap, concrete, and steel structures. A spur dike is described as permeable if river flow can pass through it, and it is impermeable if it completely blocks the flow (Pandey et al., 2018). A permeable spur dike usually slows down the sediment transportation by reducing the velocity on its upstream side, and thus reduces the scour process (Gu et al., 2011). In contrast, an impermeable spur dike can benefit riverbank protection and flood control. By repelling a turbulent flow in some parts of the river, an impermeable spur dike protects the riverbank from erosion. In the event of a flood, by reducing the flow energy, an impermeable spur dike redirects and controls the rapid flows (Teraguchi et al., 2008; Zhang and Nakagawa, 2008). Spur dikes significantly change the flow patterns and bed morphology due to the decrease in the channel width and formation of a contraction section. An obvious flow separation and recirculation are generated in the vicinity of a spur dike, which raises the turbulence kinetic energy and shear velocity surrounding the spur dike, and thus cause the extreme scouring process of the river bed (Yazdi et al., 2010).

The erosion process around a spur dike is one of the most critical issues in fluvial hydraulics and has been investigated for predicting the geometry of the scour holes (Giglou et al., 2018). Derrick et al. (1989) studied spur dikes and pile dikes that are widely used in large river development projects. Some research works are focused on the sediment deposition pattern and velocity structures behind the permeable spur dike (Tominaga et al., 2000). Ishigaki et al. (2000) claimed that the vortex development occurs aside from the dike, and the deepest hole is created at some distance from the obstacle. Also, either by means of laboratory experiments or computational simulations, some research works have been conducted to investigate flow structures, and sediment transport in the presence of different obstacles in channels such as spur dikes, bridge piers and abutments (Wu et al., 2016).

As pointed out by Kuhnle et al. (2002) that the flow depth and orientation angle of a dike affect the maximum erosion depth and the scour hole volume. Results showed that the ratio of the scour volume to the maximum erosion depth is variable and rises with the decrease in flow depth in shallow rivers and demonstrated that the blockage ratio significantly affected the geometric characteristics of the scour hole (Zhang et al., 2018). Ishigaki and Baba (2004) found that the downward-angled spur dike (oriented at a downstream angle) was less effective than the deflecting one (intended to deflect the flow rather than completely block it) in protecting channel banks from erosion. To date, most reported research works are about the calculation of the maximum scouring depth, instead of the scour hole geometry (Kuhnle et al., 2002). Based on the morphological dimensions of scour holes, Haltigin et al. (2007) predicted the geometric features of scour holes.

In cold regions, such as northern Canada, it is pervasive for rivers to be covered by ice in winter. The presence of an ice cover emerges as an important factor that significantly influences the morphology and scouring patterns around spur dikes (Namaee and Sui, 2019a; Wu et al., 2015a). The appearance of an ice cover on the water surface enforces different geomorphological

situations to flow characteristics, sediment transportation, and velocity distribution (Wu et al., 2014b). Ackermann et al. (2002) stated that the presence of an ice cover on the water surface could increase the scour hole depth up to 35%. Sui et al. (2010) pointed out that the location of the maximum streamwise velocity depends on the ratio of roughness coefficients of the ice cover to that of channel bed and will be shifted toward the smoother boundary. This change in the streamwise velocity contributes more kinetic energy to the riverbed and increases the bed shear stress (Wang et al., 2008). Therefore, the roughness coefficients of the ice cover and channel bed play an essential role in the scour morphology under an ice-covered flow condition (Smith and Ettema, 1995). Zabilansky et al. (2006) claimed that the roughness of an ice cover is significant for the deformation of the channel bed. Hains (2004) concluded that the roughness of an ice cover considerably affects the bed shear stress, and the increase in the bed shear stress will result in amplified bed erosion and scour depth.

Numerous numerical simulations and laboratory experiments have been carried out to study the bed morphology and local scour around spur dikes. However, to the authors' knowledge, no research work has been reported to investigate the effect of an ice cover on the geometrical features of channel bed deformation around non-submerged spur dikes with different alignment angles. The current research is based on laboratory experiments to investigate the geometric characteristics of channel bed deformation around spur dikes considering different alignment angles under both smooth and rough ice-covered flow conditions.

2 METHODOLOGY AND MATERIALS

2.1 Experimental setup and equipment for measurements

Experimental investigations typically take place in compact indoor hydraulic flumes due to the higher costs associated with constructing larger outdoor flumes. Smaller-scale flumes often have limitations in flow depths and discharge ranges, and considerations must be made regarding the impact of sidewalls within the flume. On the other hand, larger flumes offer a wider range of options for selecting hydraulic parameters and can be considered as approximations of small natural rivers. Conducting simulations of scour phenomena in larger hydraulic flumes is expected to yield more accurate results (Wu et al., 2015a).

This experimental investigation was carried out in a large-scale outdoor flume located at the Quesnel River Research Center in Canada. As showed in Figure 1, this flume is 38.2 m long length, 2.0 m wide, and 1.3 m deep. The longitudinal slope of the flume bed is 0.2%. A water holding tank with a capacity of 90 m³ and dimension of 40.0 m × 2.0 m × 1.3 m is located upstream of the flume and used to maintain a designated discharge for each experimental run. The tank is supplied by three standpipes, facilitating a maximum flow rate of 0.12 m³/s. Notably, along the flume section from upstream to downstream, a gradual change in water level was observed, attributed to the flume's slope. Consequently, the flow was classified as non-uniform. A roof covers the entire flume section was built to mitigate the influence of environmental factors, including precipitation, wind, and tree leaves.

Two sandboxes were meticulously constructed within the flume, with a spacing distance of 10.2 meters. The upstream sandbox is 5.6 m long, 2.0 m wide, and 0.3 m deep, while the downstream one spans 5.8 meters in length, 2.0 meters in width, and 0.3 meters in depth. Notably, one sidewall of each sandbox section is made of plexiglass, facilitating precise observation of the scouring process. In this study, three types of non-uniform natural sediments with median diameters (D_{50}) of 0.48 mm, 0.60

mm, and 0.90 mm, with the standard deviations 1.97 mm, 2.39 mm, and 1.41 mm, respectively, were selected as the bed material. Moreover, the average sediment density of these three types of sediments was 1.7 g/cm³.

A staff gauge was installed in the middle of each sandbox to monitor the flow depth. The tailgate located at the downstream end of the flume was used to control the flow depth and, consequently, the flow velocity within the channel. The mean approaching flow velocity ranged from 15 cm/s to 30 cm/s. The model spur dike is made of impermeable marine plywood, standing at a total height of 80 cm, with a width of 5 cm and a length of 50 cm. Positioned centrally within each sandbox, the dike was partially submerged, with 30 cm of its height buried beneath the sand bed while the remaining 50 cm protruded above the initial bed surface (Figure 1). For each inflow and cover condition, the model spur dike was placed at three alignment angles (inclined to the downstream sidewall), 90°, 60°, and 45°, respectively. Consequently, the dike positioned perpendicular to the flume sidewall exhibited the highest blockage ratio at 25%, and the blockage ratio for the dike alignment angles of 60° and 45° reduced to 20% and 15%, respectively.

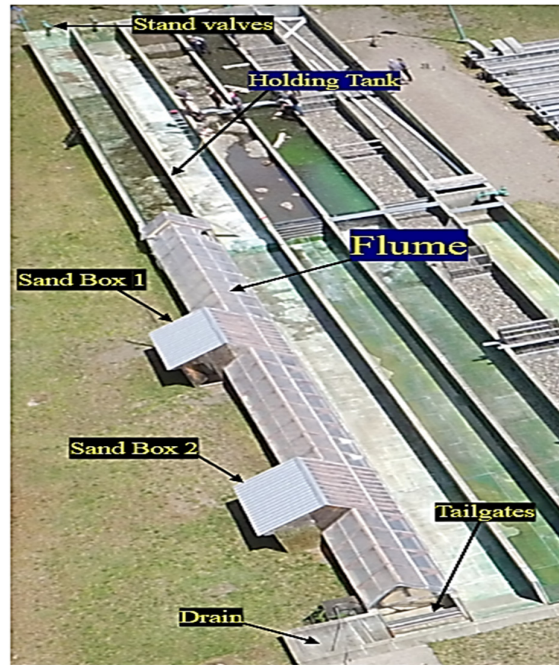
Styrofoam panels which are 1.99 m wide and 2.4 m in long were utilized to replicate the ice cover floating on water surface. Two distinct types of model ice covers were used to assess the impact of the ice cover roughness coefficient on channel bed deformation, namely smooth and rough ice covers. The model smooth ice cover mimics the sheet ice typical of natural rivers, while the model rough ice cover replicates an ice jam formed by accumulated ice floes. The smooth ice cover was modelled using untreated Styrofoam panels. To create the model rough ice cover, numerous Styrofoam cubes with the dimension of 2.5 cm × 2.5 cm × 2.5 cm were affixed to the bottom surface of the Styrofoam panels in a staggered arrangement, with a spacing distance of 35mm between the adjacent cubes. For experiments conducted under ice-covered flow conditions, the entire flow surface in the flume was covered by the model ice cover (Figure 2).

A SonTek-IQ Plus which is an optimum apparatus for flow measurement in natural rivers was used to measure the approaching flow velocity, water depth, and incoming discharge into the flume. The data collection process of the IQ Plus is exposed to an error of 1% in the range of measurement scale (Manual, 2017). An IQ Plus was fixed to the flume bed in front of each sandbox.

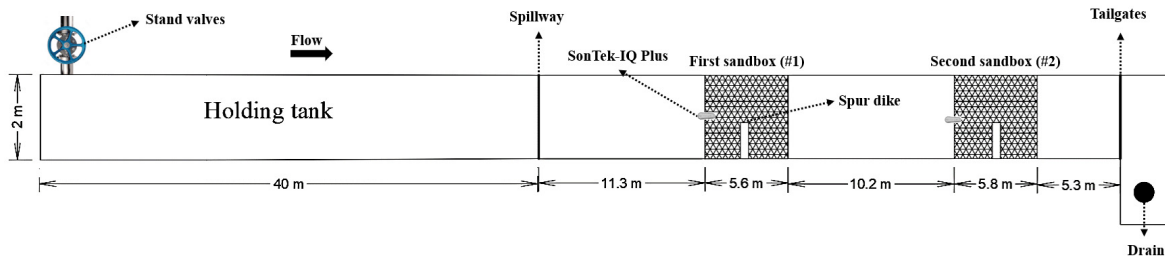
An Acoustic Doppler velocimeter (ADV) was used to measure the flow velocities. To ensure reliable measurement data using the ADV, it is imperative to assess both the signal-to-noise ratio (SNR) and the correlation (COR). According to the user manual for ADV, to achieve the most accurate data in this experimental study, these two parameters were set as follows: SNR > 15 and COR > 70%. The software program known as WinADV was used to filter the ADV data files such as SNR and COR. To obtain the most accurate data at each measuring location, the data sampling rate of ADV was set with the highest frequency (25 Hz) for 120 to 150 seconds. After configuring the ADV appropriately and implementing data spike filtering, velocity measurements in the current study were reliable within the range of 0.25 cm/s, with an error margin of ±1.5% of the measurement scale.

2.2 Data acquisition procedures

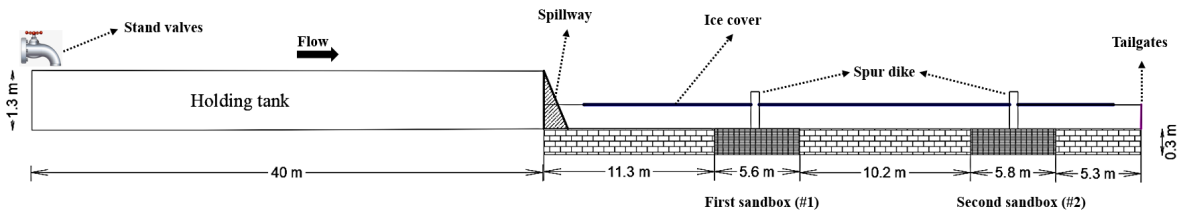
Experimental runs have been carried out in the same flume on local scour around bridge piers and abutments under ice-covered flow conditions (Namaee and Sui, 2020; Namaee et al., 2021; Wu et al., 2014a, 2014b, 2015a, 2015b). Time is one of



(a) Overview of the flume



(b) Plan view



(c) Vertical view

Fig. 1. Flume for experiments: (a) Overview of the flume, (b) Plan view; (c) Vertical view.

the important factors in studying channel bed deformation around the in-stream infrastructures such as spur dikes. The scouring process is complete when the scour hole reaches its equilibrium condition, such that the dimensions of scour holes and deposition dunes remain constant over time. It is found that the quasi-equilibrium scour process can happen within the first 6 hours of the experiment, and there was hardly in the scour hole pattern after 12 hours (Namaee and Sui, 2019b). Thus, the duration for all experimental runs in this study lasted 24 hours to ensure an equilibrium scour condition can be achieved. In this study, the following procedures for data acquisition were followed:

1) Before initiating each experimental run, verification of the fullness of the upstream water holding tank is essential. Subsequently, the initial step involves in levelling the entire

surface of each sandbox. Following this, all Styrofoam panels (or model ice cover) are systematically and carefully arranged side by side on the flume bed to facilitate experiments under ice-covered flow conditions.

2) Then, the valves were slowly opened to allow the gradual inflow of water from the upstream holding tank into the flume, preventing initial erosion at the spur dikes. The flow depth in the flume increased gradually, and concurrently, the model ice cover began to float on the water surface. Once the flow attained the desired depth, the valves were fully opened to achieve the required flow rate. Throughout each experimental run, monitoring and calculating water level, flow rate, and approaching velocity were conducted using the IQ Plus. In the meantime, the flow depth was also monitored using a staff gauge located at the midpoint of the sandboxes.

3) The experiment was completed after 24 hours. Then, then ADV was carefully positioned within the flow to measure the velocity field around the spur dikes at diverse locations.

4) After all required measurements for flow velocity were completed, all valves were turned off. Then, the model ice cover was carefully removed from the water surface. The flume slowly drained by lowering the tailgate to avoid disturbance of the deformation patterns of the sand bed. The geometry of scour holes and deposition dunes around spur dikes was carefully measured using a calliper. The Surfer Golden Software was used to process all measured data for the geometry of scour holes and deposition dunes to generate 3D plotting of the profile and contour lines for scour hole and deposition dunes. The data collected from all experiments and results are summarized in Table 1.



Fig. 2. A cover condition experiment under smooth ice cover with a 45° inclination angle.

3 RESULTS

Channel bed scour initiates when shear stresses around an obstacle, such as a spur dike, exceed the critical shear stress of riverbed material. In the early stages, intense scouring predominantly occurs at the dike toe, leading to rapid development and deepening of the scour hole. However, as time progresses, typically after approximately 2 hours, the scouring process gradually slows down as bed shear stresses diminish. Eventually, when shear stresses become insufficient to displace significant bed material, the scouring process reaches an equilibrium state, indicating the maximum scour depth (Richardson and Davis, 1995). It has been noted that in channels with finer bed material, smaller flow depths and higher flow velocities tend to result in larger maximum depths of scour holes. This phenomenon occurs because higher velocities generate stronger downflow on the upstream side of the dike, leading to intensified horseshoe vortex activity, a primary mechanism of scouring. Moreover, as flow depths decrease while maintaining a constant flow velocity, downflow and vortex activity within the scour hole are enhanced. This relationship is further amplified by an increase in the flow Froude number, which elevates turbulence kinetic energy within the scour hole, consequently expanding the erosion process (Jafari and Sui, 2021). Consequently, the maximum depth of scour holes tends to be lesser in deeper flows with lower flow Froude numbers.

Notably, during the evolution of a scour hole, the quantity of coarse particles within the scour hole progressively augmented.

These larger sediment particles settled on the scour hole's surface, forming what is commonly known as an armor layer, which impedes further scouring. The presence of an armour layer indicates that the scouring process is approaching an equilibrium state. Additionally, the formation of an ice cover on the water surface and variations in the alignment angle of the dike were found to influence the maximum depth of a scour hole around the dike.

The presence of a spur dike in a river modifies the flow dynamics by obstructing the streamflow and redirecting the incoming flow in a different direction. As a result of the contraction caused by the presence of a spur dike, the flow velocity at the dike tip increases significantly. Additionally, the flow is separated into two segments. One portion of the flow experienced acceleration and displacement towards the flume's central region. The velocity can be increased by up to 60% of the approaching flow velocity to the dike, depending on the dike alignment angle and the flow surface cover condition (Jafari and Sui, 2021). The other part of the flow goes toward the channel bed, creating a strong downflow at the dike's upstream side, eroding around the dike toe and forming a scour hole. There are three crucial factors for assessing the scour: the location of the initial scour hole, the development of the scour pattern, and the maximum depth of scour holes after reaching the equilibrium state (Namaee and Sui, 2020; Valela et al., 2021; Zhang et al., 2018).

3.1. Vortex system at the dike

It was observed that the local scour was initiated at the upstream side of the dike toe once an experiment starts. Due to the local flow acceleration around the dike and strong vertical downward flow, a primary vortex was formed within the initial scour hole. The two most important factors influencing the primary vortex are the dike orientation angle and the approaching velocity. For the dike with an alignment angle of 90°, the primary vortices were more substantial and lasted longer. By reducing the dike alignment angle, the primary vortex became less noticeable. As the approaching velocity increased, the downflow interaction became strong and these vortices exhibited greater intensity. Additionally, an adverse pressure gradient formed within the scour hole, leading to the development of a secondary vortex system known as a horseshoe vortex. These vortices were visible within the scoured zone and developed clockwise inside the scour hole around a spur dike. The horseshoe vortex's strength depends on flow rate, blockage ratio, and flow surface condition. By increasing the flow rate and blockage ratio (i.e., increase the dike alignment angle from 30° to 90°), the scour hole around the spur dike became deeper, implying that the intensity of the horseshoe vortex was increased. Under an ice-covered flow condition, flow circulations are intensified, leading to strong vortices inside the scour hole at a spur dike. With the increase in the roughness coefficient of an ice cover, the scour hole around a spur dike became wider and deeper, indicating a more powerful horseshoe vortex inside the scour hole. Thus, the bed shear stress under an ice-covered flow condition was raised above the critical shear stress for the incipient motion of bed materials under an open flow condition. Consequently, an increased sediment movement was observed, leading to the further development of the scour hole under an ice-covered flow condition. After a couple of hours, the primary vortex faded and was no longer visible. The horseshoe vortex system continued to be the major cause for the expansion of the scour hole. Sediment particles in the scour hole were transported downstream by the vortex system and deposited in the low-velocity zone behind the spur dike. In this low-velocity zone, the

Table 1. Experimental data and results.

Sand size (mm)	Dike angle	Surface condition	Water depth (cm)	Approach velocity (cm/s)	F_r	Le/B	D_{50}/H	n_i/n_b	$\sin \theta$	Scour max (cm)
0.9	90°	Open	11	29.08633	0.28	0.25	0.009	—	1	11.6
			21	30.1414	0.21	0.25	0.0045	—	1	12.0
			29	21.92688	0.13	0.25	0.003	—	1	8.2
		Smooth	12	28.2097	0.26	0.25	0.009	1.068	1	14.0
			23	27.03777	0.18	0.25	0.0045	1.068	1	14.8
			32	24.8049	0.14	0.25	0.003	1.068	1	10.0
		Rough	10	29.71363	0.3	0.25	0.009	2.46	1	16.3
			22	29.38163	0.2	0.25	0.0045	2.46	1	16.0
			32	26.57668	0.15	0.25	0.003	2.46	1	12.2
	60°	Open	11	25.96993	0.25	0.22	0.009	—	0.86	9.6
			23	33.04617	0.22	0.22	0.0045	—	0.86	13.5
			34	29.22092	0.16	0.22	0.003	—	0.86	8.8
		Smooth	9	21.61143	0.23	0.22	0.009	1.068	0.86	11.5
			21	24.40018	0.17	0.22	0.0045	1.068	0.86	14.5
			32	21.26135	0.12	0.22	0.003	1.068	0.86	10.6
		Rough	11	28.04753	0.27	0.22	0.009	2.46	0.86	14.5
			22	27.91255	0.19	0.22	0.0045	2.46	0.86	15.8
			33	19.79175	0.11	0.22	0.003	2.46	0.86	12.8
	45°	Open	13	27.103	0.24	0.18	0.009	—	0.7	8.3
			24	30.68811	0.2	0.18	0.0045	—	0.7	8.9
			33	23.39025	0.13	0.18	0.003	—	0.7	6.3
		Smooth	11	25.96993	0.25	0.18	0.009	1.068	0.7	10.2
			24	30.68811	0.2	0.18	0.0045	1.068	0.7	11.1
			34	21.91569	0.12	0.18	0.003	1.068	0.7	8.0
		Rough	9	26.30957	0.28	0.18	0.009	2.46	0.7	12.4
			18	29.23435	0.22	0.18	0.0045	2.46	0.7	12.7
			33	23.39025	0.13	0.18	0.003	2.46	0.7	10.2
0.6	90°	Open	12	20.61478	0.19	0.25	0.006	—	1	9.5
			26	23.9559	0.15	0.25	0.003	—	1	12.0
			32	17.71779	0.1	0.25	0.002	—	1	7.2
		Smooth	8	15.06012	0.17	0.25	0.006	1.142	1	11.3
			21	18.65896	0.13	0.25	0.003	1.142	1	14.2
			33	16.19325	0.09	0.25	0.002	1.142	1	9.4
		Rough	12	22.78476	0.21	0.25	0.006	2.636	1	13.5
			24	21.48168	0.14	0.25	0.003	2.636	1	16.7
			36	20.67181	0.11	0.25	0.002	2.636	1	11.7
	60°	Open	11	20.77595	0.2	0.22	0.006	—	0.86	8.0
			22	23.5053	0.16	0.22	0.003	—	0.86	9.3
			32	17.71779	0.1	0.22	0.002	—	0.86	6.2
		Smooth	12	16.27483	0.15	0.22	0.006	1.142	0.86	9.8
			23	21.02938	0.14	0.22	0.003	1.142	0.86	11.4
			35	16.67674	0.09	0.22	0.002	1.142	0.86	8.3
		Rough	10	16.83773	0.17	0.22	0.006	2.636	0.86	11.5
			21	21.52957	0.15	0.22	0.003	2.636	0.86	13.8
			34	12.78415	0.07	0.22	0.002	2.636	0.86	10.7
	45°	Open	9	16.9133	0.18	0.18	0.006	—	0.7	7.2
			23	24.03358	0.16	0.18	0.003	—	0.7	10.8
			29	16.86683	0.1	0.18	0.002	—	0.7	5.4
		Smooth	11	17.65956	0.17	0.18	0.006	1.142	0.7	8.9
			20	19.61	0.14	0.18	0.003	1.142	0.7	12.6
			32	14.17423	0.08	0.18	0.002	1.142	0.7	7.2
		Rough	11	18.69835	0.18	0.18	0.006	2.636	0.7	10.6
			21	18.65896	0.13	0.18	0.003	2.636	0.7	14.4
			32	14.17423	0.08	0.18	0.002	2.636	0.7	9.6
0.9	90°	Open	11	28.04753	0.27	0.25	0.009	—	1	12.7
			22	27.91255	0.19	0.25	0.0045	—	1	11.5
			36	26.30957	0.14	0.25	0.003	—	1	8.2
		Smooth	12	27.12471	0.25	0.25	0.009	1.068	1	14.8
			22	29.38163	0.2	0.25	0.0045	1.068	1	13.3
			34	21.91569	0.12	0.25	0.003	1.068	1	10.3
		Rough	7	19.88817	0.24	0.25	0.009	2.46	1	16.5
			17	23.2451	0.18	0.25	0.0045	2.46	1	15.6
			28	18.23082	0.11	0.25	0.003	2.46	1	12.0

0.6	90°	Open	10	16.83773	0.17	0.25	0.006	—	1	7.5
			20	21.01071	0.15	0.25	0.003	—	1	11.0
			30	17.15517	0.1	0.25	0.002	—	1	7.2
		Smooth	12	16.27483	0.15	0.25	0.006	1.142	1	9.6
			21	20.09427	0.14	0.25	0.003	1.142	1	13.2
			32	15.94601	0.09	0.25	0.002	1.142	1	9.0
		Rough	11	18.69835	0.18	0.25	0.006	2.636	1	11.8
			22	24.97438	0.17	0.25	0.003	2.636	1	15.7
			31	13.951	0.08	0.25	0.002	2.636	1	11.3
0.48	90°	Open	12	20.61478	0.19	0.25	0.0048	—	1	13.5
			21	20.09427	0.14	0.25	0.0024	—	1	13.8
			30	18.87069	0.11	0.25	0.0016	—	1	14.0
		Smooth	13	22.58584	0.2	0.25	0.0048	1.186	1	14.8
			22	23.5053	0.16	0.25	0.0024	1.186	1	15.4
			34	23.742	0.13	0.25	0.0016	1.186	1	15.7
		Rough	9	19.73218	0.21	0.25	0.0048	2.737	1	16.7
			22	22.03622	0.15	0.25	0.0024	2.737	1	17.5
			31	19.18262	0.11	0.25	0.0016	2.737	1	17.2
	90°	Open	8	15.94601	0.18	0.25	0.0048	—	1	11.2
			18	15.94601	0.12	0.25	0.0024	—	1	8.2
			29	16.86683	0.1	0.25	0.0016	—	1	9.1
		Smooth	12	18.4448	0.17	0.25	0.0048	1.186	1	13.1
			22	19.09806	0.13	0.25	0.0024	1.186	1	10.8
			31	15.69487	0.09	0.25	0.0016	1.186	1	10.9
		Rough	25	32.88697	0.21	0.25	0.0048	2.737	1	15.2
			24	23.01608	0.15	0.25	0.0024	2.737	1	12.5
			33	14.394	0.08	0.25	0.0016	2.737	1	12.7
	60°	Open	13	25.97371	0.23	0.22	0.0048	—	0.86	14.8
			24	24.55049	0.16	0.22	0.0024	—	0.86	14.2
			36	18.79255	0.1	0.22	0.0016	—	0.86	12.1
		Smooth	11	20.77595	0.2	0.22	0.0048	1.186	0.86	16.4
			22	20.56714	0.14	0.22	0.0024	1.186	0.86	16.2
			32	21.26135	0.12	0.22	0.0016	1.186	0.86	14.5
		Rough	11	24.93114	0.24	0.22	0.0048	2.737	0.86	18.5
			21	24.40018	0.17	0.22	0.0024	2.737	0.86	18.0
			33	25.1895	0.14	0.22	0.0016	2.737	0.86	15.8
	45°	Open	12	17.35982	0.16	0.18	0.0048	—	0.7	9.0
			19	17.74821	0.13	0.18	0.0024	—	0.7	7.7
			27	16.27483	0.1	0.18	0.0016	—	0.7	6.0
		Smooth	11	18.69835	0.18	0.18	0.0048	1.186	0.7	11.1
			21	15.78835	0.11	0.18	0.0024	1.186	0.7	9.2
			33	12.59475	0.07	0.18	0.0016	1.186	0.7	8.3
		Rough	11	20.77595	0.2	0.18	0.0048	2.737	0.7	13.4
			21	21.52957	0.15	0.18	0.0024	2.737	0.7	11.0
			32	14.17423	0.08	0.18	0.0016	2.737	0.7	10.5

streamflow mixed with the separated flow downstream of the dike generated another vortex system called the wake vortex. Following the dispersal of the primary vortex, the final scour process was resulted from these two remaining vortex systems, namely, horseshoe and wake vortex. The scour hole surrounding the dike progressively increases in width and depth over time, expanding in the upstream, downstream, and lateral directions toward the middle of the channel. Due to the difference in strength and rotation direction of the vortices, the shape and slope of scour holes located upstream of a spur dike differ significantly from those downstream of a spur dike.

3.2 Scour morphology

3.2.1 Features of scour holes

The process of channel bed deformation around a spur dike is influenced by various factors including flow characteristics, grain size of bed material, water surface cover condition, spur dike layout and alignment angle. The configurations of scour holes and deposition dunes can be effectively depicted using contour maps, which provide two-dimensional representations of three-dimensional data, as depicted in Figure 3. Lines of equal

"Z" values in contour maps portray channel bed deformation around the dike. The shape of scour holes and deposition dunes can be clearly comprehended by analysing a contour map.

The results showed that the presence of an ice cover on the water surface leads to a wider scour hole in the lateral direction compared to that under an open channel flow condition. One can see from Figure 3 that the scour hole around a dike under an open flow condition exhibited a circular shape, while the scour hole extended toward another side of the channel wall under an ice-covered condition. This effect was accentuated under a rough covered flow condition, implying that an increase in the ice cover roughness corresponds to an enlargement in the size of the scour hole around a dike. This finding aligns with Sui et al. (2009), who investigated the local scour caused by submerged jets under ice-covered flow conditions.

In addition to the cover roughness, the dike alignment angle also significantly influences the local scour process around a dike. As depicted in Figure 4, reducing the dike alignment angle from 90° to 45° resulted in an elongated shape of scour hole in the streamwise direction. The quasi-semicircular scour hole associated with the 90° alignment angle was changed to an elliptical shape.

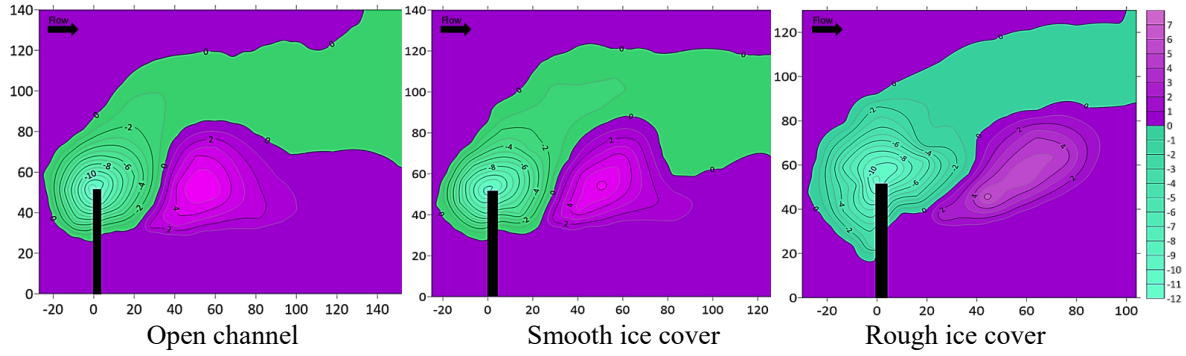


Fig. 3. Scour holes under various water surface conditions ($F_r = 0.19$, and 90° -dike alignment).

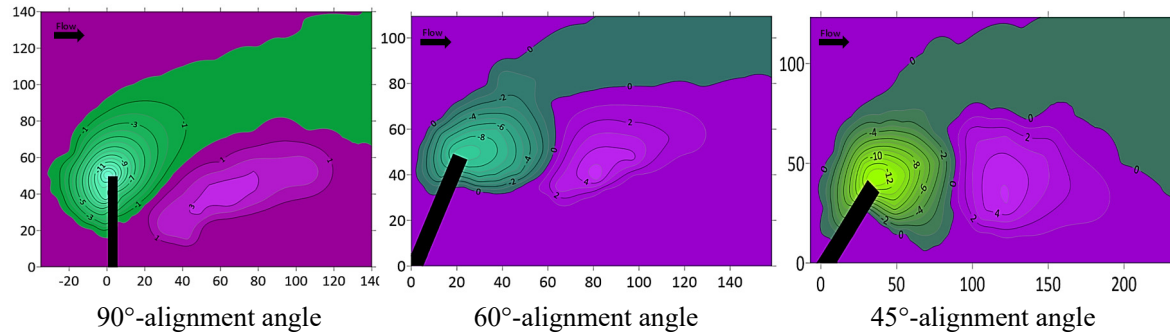


Fig. 4. Plan diagram of scour holes for different dike alignment angles under an open flow condition ($F_r = 0.19$).

3.2.2 Scour hole geometry

The scour hole pattern around a spur dike is another essential factor for studying the scouring process. To offer a more comprehensive portrayal of experimental results and enhance the applicability of these results to real-world scenarios, this study employed the following dimensionless variables to assess the development of scour holes and deposition dunes around spur dikes. In this context, the dimensions of scour holes in all direction were normalized by the spur dike length (Figure 5).

1) The upstream and downstream lengths (a/L and b/L) of a scour hole are used to examine the extent of a scour hole in the streamwise direction. Their combination, $(a+b)/L$, represents the maximum scour hole length in the streamwise direction.

2) The maximum outward width, measured from the dike tip to the outer boundary of a scour hole (w/L), is used to express the maximum outward scour width in the transverse direction. By utilizing this variable, one can evaluate whether the maximum outward width of a scour hole can be extended to the opposite channel sidewall.

3) The maximum inward width of a scour hole along the front side of a spur dike (c/L) is the distance measured from the dike tip to the inner boundary of the scour hole in the transverse direction. Along the rear side of a spur dike, the maximum inward width of a scour hole in the transverse direction is expressed as (d/L). These two ratios (c/L and d/L) can be used as indicators for assessing the extension of a scour hole toward the channel bank where the dike is attached. By examining these maximum inward scour widths, one can evaluate whether the scouring process around the dike has the potential to induce channel bank erosion and thereby carrying the risk of detrimental consequences such as landslides and spur dike failure.

These ratios are influenced by various factors including flow surface conditions (open channel, smooth ice-covered, and rough

ice-covered flow), hydraulic parameters (flow depth and velocity), dike alignment angles and dimensions, as well as the grain size of bed materials. In the following section, by assessing these ratios, the influence of the distinct experimental setups on the scour hole geometry has been evaluated.

a). Upstream length of a scour hole (a/L)

The experimental results demonstrate that hydraulic conditions substantially impact the upstream length of a scour hole (a/L). As the approaching flow depth decreases, the upstream length of a scour hole (a/L) increases. With every 10-cm increase in the flow depth, there is an approximately 20% reduction in the upstream length of a scour hole (a/L). The finer the bed material (D_{50}), the larger the upstream length of a scour hole (a/L). Moreover, the upstream length of a scour hole (a/L) was expanded by elevating the approaching flow velocity. This means that the experimental scenario with the largest flow Froude number and finest bed material will generate the largest upstream length of a scour hole (a/L).

As depicted in Figure 6, the upstream length of a scour hole (a/L) exhibited marginal expansion under a smooth covered condition compared to that of an open flow condition. However, the presence of a rough ice cover led to a pronounced increase in the upstream length of a scour hole (a/L) by 25%. Hence, the roughness coefficient of an ice cover plays a crucial role in the initiation and development of a scour hole toward the upstream zone of a spur dike. Under the same covered flow condition, an elevation in the flow depth diminishes the influence of the ice cover on the scouring process toward the upstream of the spur dike.

The findings indicate that a reduction in the dike alignment angle led to an immense decrease in the upstream length of a scour hole (a/L), as shown in Figure 6. A decrease of the dike alignment angle from 90° to 60° results in a reduction of approximately 60% in the upstream length of a scour hole (a/L). A marginal reduction of the dike alignment from 60° to 45°

exhibited a less noticeable impact on the upstream length of a scour hole (a/L). By increasing the approaching flow velocity, the impact of the dike alignment angle on the upstream length of a scour hole (a/L) will become strong and intensified.

b). Downstream length of a scour hole (b/L)

Results showed that the influences of pertinent factors on the downstream length of a scour hole (b/L) differ from those on the upstream length of a scour hole (a/L). In particular, the water surface cover condition has a much less impact on the downstream length of a scour hole (b/L), namely, just caused a slight increase in the downstream length of a scour hole (b/L) compared to that under an open flow condition. Also, the impact of a rough ice cover on the downstream length of a scour hole (b/L) is not clearly different from that of a smooth ice cover. Furthermore, by increasing the flow depth, the downstream length of a scour hole (b/L) decreases slightly but is observable.

Results also showed that the downstream side of a scour hole expanded as the approaching velocity increases, but it is less noticeable compared to the impact of the flow rate. With an increase of about 50% in the flow rate (from 55 L/s to 120 L/s), the downstream length of a scour hole (b/L) increased by about 20%.

By changing the dike alignment angle, the shape of scour holes changes substantially. With the decrease in the dike alignment angle, the downstream length of a scour hole (b/L) expanded. As shown in Figure 7, the reduction of the dike alignment angle from 90° to 60° resulted in a major change in the downstream length of a scour hole (b/L). However, a further

decrease in the dike alignment angle from 60° to 45° had a less conspicuous effect on the downstream length of a scour hole (b/L). In summary, as the flow rate increases and the dike alignment angle decreases simultaneously, the downstream length of a scour hole (b/L) will substantially increase in both streamwise and lateral directions under an ice-covered flow condition.

c). Maximum outward width of a scour hole (w/L)

The flow velocity considerably impacts the width of the scour hole around a spur dike. By increasing the flow velocity from 0.15 m/s to 0.30 m/s, the maximum outward scour width (w/L) increases about 8%. The depth of the approaching flow is another factor significantly influences the maximum outward scour width (w/L). As the approaching flow depth increases, a noticeable decrease in the maximum outward scour width (w/L) is resulted. An increase of each 10-cm in the water depth leads to about decrease of 15% in the maximum outward width of a scour hole (w/L). Given that the maximum outward width of a scour hole (w/L) increases with the approaching flow velocity but decreases with the flow depth, the flow Froude number (Fr) can be employed to represent the influences of flow velocity and water depth on the maximum outward scour width (w/L). Results showed that, with an increase of each 30% in the Froude number, the maximum outward scour width (w/L) increases by 15%~20%. The findings reveal that the presence of an ice cover on the water surface amplifies the influence of the flow Froude number on the maximum outward scour width (w/L). A higher flow Froude number under the rough ice-covered flow condition led to a larger maximum outward scour width (w/L).

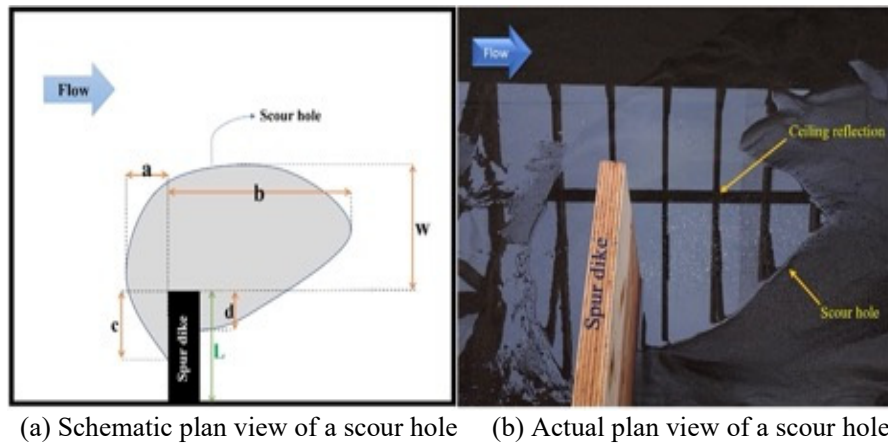


Fig. 5. Plan view of the scour hole.

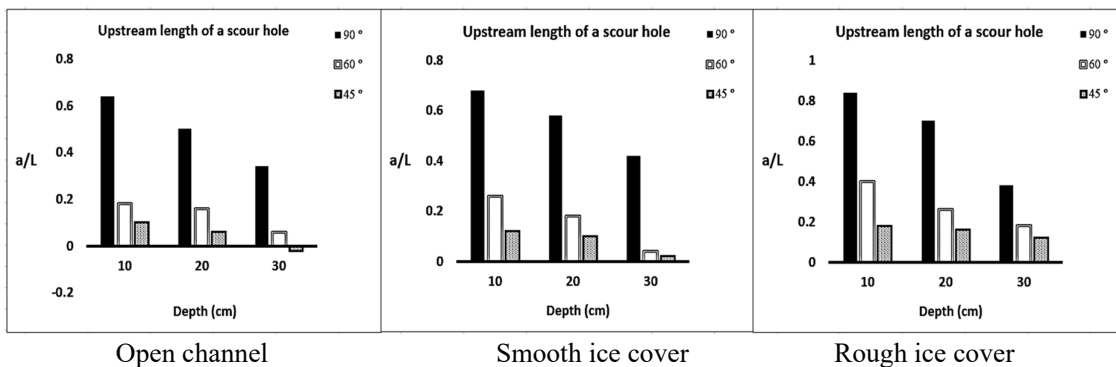


Fig. 6. Effect of experimental conditions on the upstream length of a scour hole (a/L).

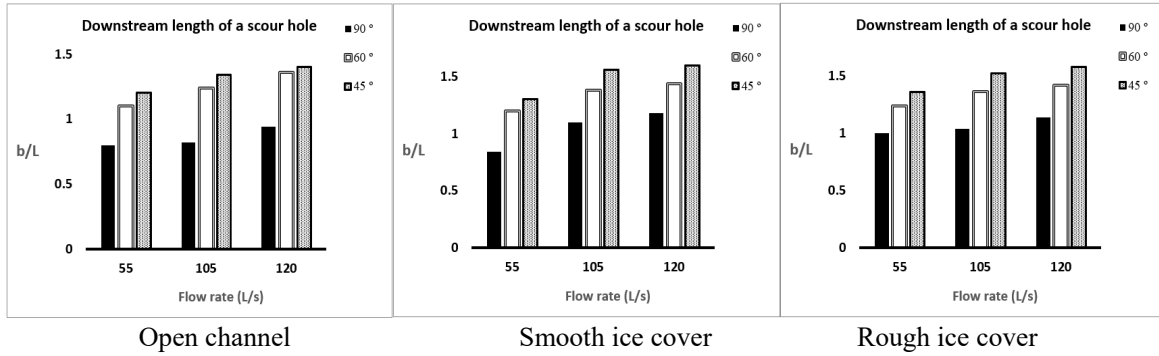


Fig. 7. Effect of experimental conditions on the downstream length of a scour hole (b/L).

As illustrated in Figure 8, the maximum outward scour width (w/L) also depends on the dike alignment angle. A decrease in the dike alignment angle leads to the change of the scour hole shape from a semi-circular shape to an elliptical shape. Hence, the maximum outward scour width (w/L) decreased with the decrease in the dike alignment angle. Depending on the cover condition and flow Froude number (F_r), a decrease in the dike alignment angle from 90° to 60° results in a reduction of 20%~30% in the maximum outward scour width (w/L). A further reduction in the dike angle from 60° to 45° had a marginal effect on the maximum outward scour width (w/L). In this study, the maximum outward scour width (w/L) reached the smallest when the dike was placed at an alignment angle of 45°.

It has been observed that the maximum outward scour width (w/L) increases by adding an ice cover on the water surface. Also, the rougher the ice cover, the larger the maximum outward scour width (w/L). As the water depth increases, the effects of the ice cover on the maximum outward scour width (w/L) became mitigated. Furthermore, an increase in flow velocity amplifies the impact of an ice cover on the development of a scour hole. Throughout all experimental runs, the maximum outward scour width never extended to the opposite side wall of the flume, reaching a maximum of 62 cm (from the tip of the dike to the outside boundary of the scour hole). Consequently, the far sidewall does not influence the development of the scour hole and the maximum outward scour width.

d). *Maximum frontal inward width of a scour hole (c/L)*

If the inside boundary of a scour hole extends to the channel bank to which the dike is attached, it can induce bank erosion, landslides, and dike failure. Thus, the assessment of the maximum frontal inward scour width of a scour hole is necessary for the spur dike design. Results indicate that an increase in the flow depth leads to a decrease in the maximum frontal inward scour width (c/L). The higher the approaching flow velocity, the larger the maximum frontal inward scour width (c/L). Combining the impact of flow depth and velocity on the maximum frontal inward scour width (c/L), it can be concluded that an increase in the Froude number caused an increase in the maximum frontal inward scour width (c/L). Notably, as the particle size of the bed material decreases and the Froude number increases, a substantial increase in the maximum frontal inward scour width of a scour hole (c/L) will be resulted. Based on all experimental runs conducted under different conditions, it has been found that the maximum frontal inward scour width (c/L) is hardly close to one, namely, $c/L < 1$. This result indicates that the likelihood of bank erosion and landslides is extremely low when the criteria of $c/L < 1$ is ensured in the spur dike design. As

shown in Figure 9, the presence of an ice cover on the water surface is another factor that significantly affects the maximum frontal inward scour width (c/L). The appearance of an ice cover on the water surface leads to an increase in the maximum frontal inward scour width (c/L) by 40~50% comparing to that under an open flow condition. Nevertheless, an increase in the roughness coefficient of an ice cover has little impact on the maximum frontal inward scour width (c/L).

The dike alignment angle considerably influences the maximum frontal inward scour width (c/L). As the dike alignment angle decreases, the maximum frontal inward scour width (c/L) decreases accordingly. This finding suggests that the maximum frontal inward scour width (c/L) with the 90° alignment angle clearly differs from that around a dike with the 60° alignment angle. This effect becomes less prominent by further reducing the dike alignment angle.

e). *Maximum rear inward width of a scour hole (d/L)*

The maximum rear inward width of a scour hole (d/L) is as crucial as the maximum frontal inward scour width (c/L). However, as illustrated in Figure 10, the maximum rear inward scour width (d/L) was consistently less than the maximum frontal inward scour width (c/L) in all experimental runs and never reached one. Results showed that the maximum rear inward scour width (d/L) increases with the increase in the Froude number. However, the Froude number had a minor impact on the maximum rear inward scour width (d/L) compared to the maximum frontal inward scour width (c/L).

Similarly, the presence of an ice cover on water surface causes a larger maximum rear inward scour width (d/L) than that under an open flow condition. Results showed that the maximum rear inward scour width (d/L) slightly increases as the cover roughness increases. In addition, under an ice-covered flow condition, the maximum rear inward scour width (d/L) increases with the decrease in flow depth and particle size of the bed material. The impact of the ice cover is more pronounced for the case of shallow flow depth and finer bed material ($D_{50} = 0.48$ mm).

The dike alignment angle has an entirely reverse impact on the maximum rear inward scour width (d/L) compared to that on the maximum frontal inward scour width (c/L). The maximum rear inward scour width (d/L) exhibits a noticeable increase with the decrease in the dike alignment angle. Furthermore, an increase in the flow velocity under an ice-covered condition magnifies the impact of the dike alignment angle on the maximum rear inward scour width (d/L). Under the same flow and cover conditions, the maximum rear inward scour width (d/L) with an alignment angle of 45° is more than that with the larger alignment angles of 60° and 90° (Figure 10).

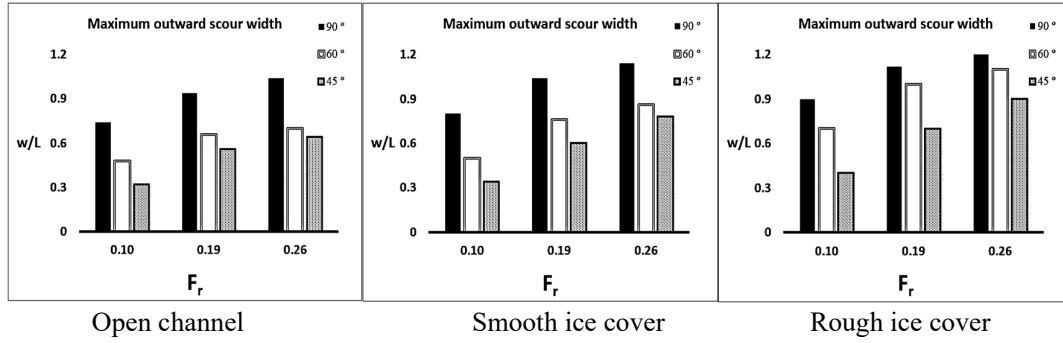


Fig. 8. Effect of experimental conditions on the maximum outward scour width (w/L).

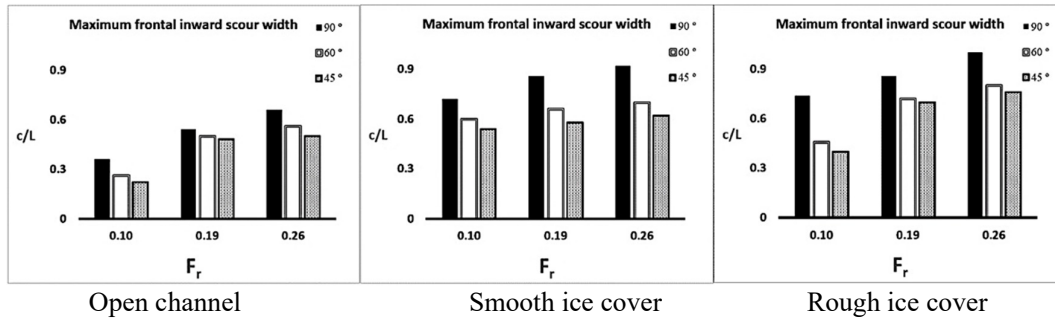


Fig. 9. Effect of experimental conditions on the maximum frontal inward scour width (c/L).

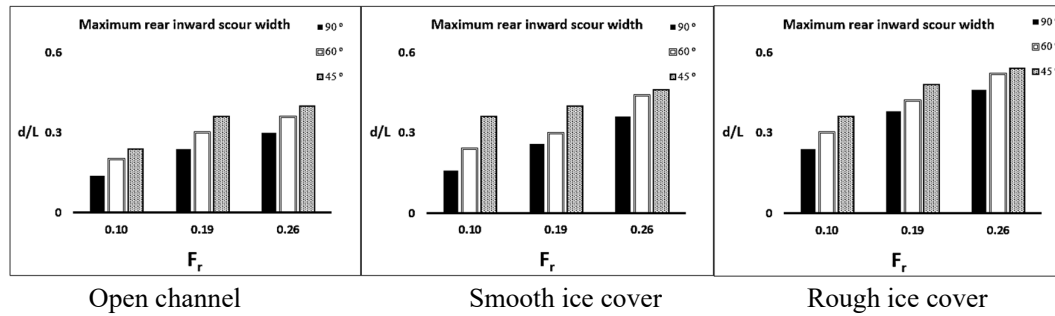


Fig. 10. Effect of experimental conditions on the maximum rear inward scour width (d/L).

3.3 Maximum scour depth

Understanding the maximum depth of a scour hole and its location is crucial for designing in-stream infrastructures like spur dikes, bridge piers, and abutments. To ensure structural integrity and longevity, foundations must be situated at a certain depth below the riverbed to mitigate the detrimental effects of hydraulic forces induced by flowing water and river ice. Understanding the influence of hydraulic factors and channel conditions, particularly in the presence of ice cover and ice jam, is essential for accurately predicting scour holes' maximum depth and locations around in-stream infrastructures.

Experimental observations revealed no discernible impact of different flow conditions (flow velocity and depth) on the time required for the development of a scour hole to reach an equilibrium condition. Notably, under rough ice-covered flow conditions, the local scour around a dike with a 90° alignment angle took the longest time to reach an equilibrium state. A significant difference in the maximum scour depth was clearly noticed among a wide range of the flow Froude numbers from 0.10 to

0.26. With the increase of each 15% in the Froude number, the maximum depth of a scour hole increased by 5%~10%. For most experimental runs, the maximum scour depth was located near the toe of the dike with an alignment angle of 90° . With the decrease in the flow Froude number, the location of the maximum depth of a scour hole was observed to shift a marginal amount toward downstream. As illustrated in Figure 11, the cross-section profile of the scour hole was transformed from a narrow "V" shape to a broader "V" shape. Additionally, a substantial reduction in the scour hole volume was observed as the Froude number decreases. For an increase of each 30% in the Froude number, the volume of a scour hole increased approximately 12%.

The most prominent effect induced by an ice cover on the development of scour holes around the dikes was the augmentation of the scour area. The presence of an ice cover on water surface resulted in a broader scour hole in both streamwise and transverse directions, particularly in the case of a rough ice cover. This implies that the maximum depth of scour holes is mainly influenced by the water surface cover conditions. The outcomes indicate that, under a smooth ice-covered condition,

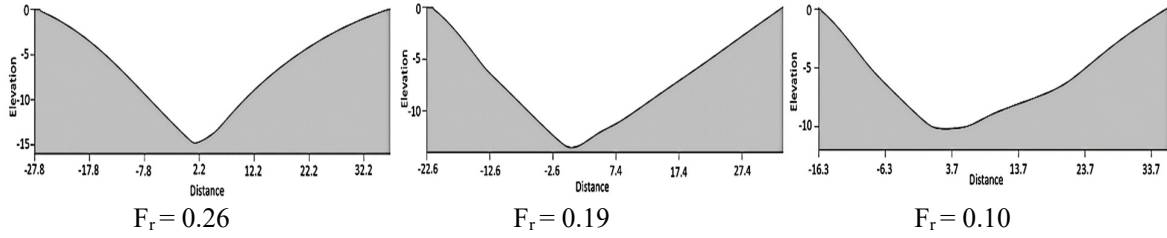


Fig. 11. Cross-section profile of scour holes around a dike with the alignment angle of 90° for different Froude numbers under an open flow condition.

the maximum depth of a scour hole increases about 10% compared to that under an open flow condition, and the increases about 15% under the rough ice-covered condition. The effect of an ice cover on the location of the maximum depth of scour holes does not demonstrate a consistent trend. As the scour hole enlarged, the slopes of both the entrance and exit sections of the hole become steeper, but with a milder slope of the exit section compared to that of the entrance section, regardless of water surface cover conditions. Under a rough ice-covered flow condition, the slope of the entrance section of a scour hole is much steeper than that of exit section compared to that under an open flow condition.

The dike alignment angles significantly influence the size and shape of the scour holes. By reducing the dike alignment angle, the geometric patterns of scour holes were different. One significant impact is the scouring depth. Under the same flow and cover conditions, the maximum depth of scour holes is observed at the dike with an alignment angle of 90° . The depth of scour hole decreases significantly as the dike alignment angle reduces. In general, regardless of the dike alignment angle, the position of the maximum depth of scour holes appears proximate to the dike toe. As the dike alignment angle decreases, the location of the maximum scour depth is shifted away from the dike toe, and the scouring process is progressed from upstream to downstream.

The key parameters that affect the depth of scour holes around an in-stream infrastructure should include flow velocity, turbulence intensity, water depth, sediment characteristics (such as grain size), structure geometry, roughness coefficients of riverbed and ice cover. The following important parameters influencing the maximum depth of scour holes (Y_{max}) should be considered in this experimental study:

$$Y_{max} = f(H, V, L_e, B, D_{50}, n_i, n_b, \sin \theta) \quad (1)$$

where, H is the approaching water depth, V is the approaching flow velocity, L_e is the dike effective length which is defined as the vertical distance from the dike tip to the sidewall to which the dike is attached, B is the channel width, D_{50} is the median particle size of the bed material, n_i is the roughness coefficient of an ice cover, n_b is the roughness coefficient of the riverbed, θ is the dike alignment angle.

To precisely assess the impact of each parameter on the maximum depth of scour holes and obtain a more detailed depiction of the laboratory results, the essential parameters mentioned in Equation (1) are represented as dimensionless variables as follows:

$$\frac{Y_{max}}{H} = f\left(F_r, \frac{L_e}{B}, \frac{D_{50}}{H}, \frac{n_i}{n_b}, \sin \theta\right) \quad (2)$$

This experimental study regarding local scour around non-submerged dikes with different alignment angles has been conducted under ice-covered flow conditions compared to that

under open flow conditions. As discussed above, the influence of an ice cover on the maximum depth of scour holes around the angled dike is substantial, since the distribution profiles of flow velocity and the composite roughness coefficient of the channel under an ice-covered flow condition differ significantly from those in an open flow. Thus, it is necessary to derive distinct equations for describing the maximum depth of scour holes under ice-covered and open flow conditions, respectively. Based on data obtained from laboratory experiments, following two equations have been derived to estimate the maximum depth of scour holes for ice-covered and open flow conditions, respectively.

Ice-covered flow condition:

$$\frac{Y_{max}}{H} = 17.07(F_r)^{0.63} \left(\frac{L_e}{B}\right)^{0.43} \left(\frac{D_{50}}{H}\right)^{-0.26} \left(\frac{n_i}{n_b}\right)^{0.153} (\sin \theta)^{0.40} \quad (3)$$

$$R^2 = 0.97$$

Open channel flow condition:

$$\frac{Y_{max}}{H} = 12.66(F_r)^{1.04} \left(\frac{L_e}{B}\right)^{0.174} \left(\frac{D_{50}}{H}\right)^{-0.33} (\sin \theta)^{0.57} \quad (4)$$

$$R^2 = 0.963$$

Results of estimations using Equations (3) and (4) reveals that, under both open channel and ice-covered flow conditions, a larger flow Froude number (F_r) corresponds to a deeper maximum depth of scour holes. However, under ice-covered flow conditions, the exponent of the Froude number in Equation (3) is approximately 60% of that under open flow conditions. This suggests that the impact of the flow Froude number on the maximum depth of scour holes under ice-covered flow conditions is less pronounced than that under open channel conditions.

Under both open channel and ice-covered flow conditions, the negative exponent of the ratio of the median particle size of bed material to the flow depth (or relative particle size) indicates that the maximum depth of scour holes increases as the relative particle size decreases. This negative exponent of the relative grain size means the finer the bed material, the deeper the maximum depth of scour holes. One can also see from Equations (3) and (4) that there is no significant difference in the exponents of the relative grain size between the ice-covered flow and open channel flow.

Equations (3) and (4) demonstrate that the blockage ratio (L_e/B), representing the ratio of the effective dike length to the channel width, is a crucial factor influencing the maximum depth of scour holes. This influence is more pronounced under ice-covered flow than that under open flow conditions, as indicated by the positive exponents of the blockage ratio. In this study, three dike alignment angles (90° , 60° , and 45°) resulted in the blockage ratios of 25%, 20%, and 15%, respectively. As the blockage ratio increases, with the same approaching flow rate, the flow velocity around the dike rises, suggesting higher kinetic

energy and turbulence intensity. Results showed that the dike alignment angle of 90° resulted in the most substantial downward vertical velocity, which created a negative velocity gradient and increased vertical momentum transport around the dike and inside the scour hole. With the decrease in the blockage ratio, a negative velocity gradient gradually reduced, and thus the turbulence kinetic energy decreased. Under ice-covered flow conditions, this contributed to the development of a stronger horseshoe vortex, ultimately leading to a much deeper scour hole compared to that under open flow conditions. The proposed equations under both open channel and ice-covered flow conditions suggested that the dike alignment angle has a notable influence on the maximum depth of scour holes. As indicated by the positive exponents of the sin-function of the dike alignment angle, the smaller the dike alignment angle, the less the maximum depth of scour holes.

Under an ice-covered flow condition, the positive exponent of the ratio of the ice-cover roughness coefficient to the bed roughness coefficient (or relative roughness coefficient) signifies a direct relationship between the maximum depth of scour holes and the relative roughness coefficient. In other words, a deeper maximum depth of scour holes will be resulted from an increase in the relative roughness coefficient, whether through an increase in the cover roughness coefficient (from smooth ice cover to rough ice cover) or a reduction in the bed roughness coefficient (from coarse bed particles to fine bed material).

The comparison between the calculated maximum depth of scour holes using the proposed equations and the results from laboratory experiments under both open channel and ice-covered flow conditions is presented in Figure 12. The substantial agreement between the calculated results and experimental data indicates the reliability and accuracy of Equations (3) and (4).

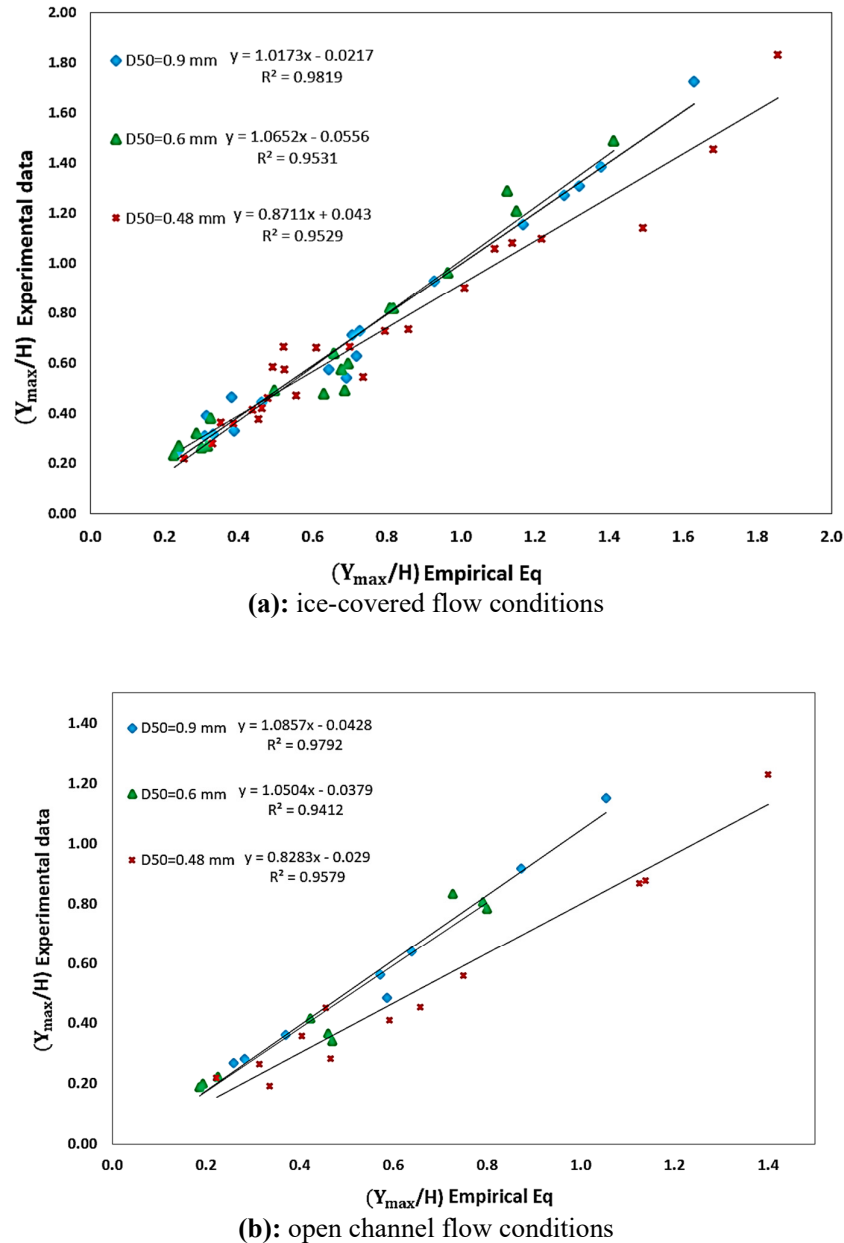


Fig. 12. Calculated maximum depth of scour holes using proposed equations compared to results of laboratory experiments: (a) ice-covered flow conditions, (b) open channel flow conditions.

4 CONCLUSIONS

In the present study, laboratory experiments have been carried out to examine the effect of ice cover with different roughness and non-submerged spur dikes with different alignment angles on the morphological features of scour holes around spur dikes by changing bed materials and hydraulic conditions. The following results have been drawn from this study:

1) The scouring was initiated with the primary vortex, and the channel bed deformation around a dike continued with the horseshow vortex and wake vortex. The horseshoe vortices last the longest among different vortex systems. The orientation of spur dikes and flow Froude number emerged as the primary determinants of the vortex system. Notably, the most robust downflow and vertical velocity within the system was generated in the flow with a higher Froude number around the spur dike with the 90° alignment angle.

2) The upstream length of the scour hole (a/L) is significantly affected by the dike alignment angles, flow Froude number and the presence of an ice cover. Among them, the dike alignment angle is the controlling factor for both the upstream length (a/L) and downstream length (b/L) of the scour hole. Averagely, the upstream length of scour holes (a/L) decreased by 60% when the dike angle was changed by about 90° to 60°. The presence of a rough ice cover on the water surface led to an increase in the upstream length of a scour hole (a/L). For flow with high flow Froude number under the rough ice cover, the upstream length of scour holes (a/L) and the frontal inward scour width (c/L) around the 90°-angled dike reached the largest values. With an increase of about 50% in the flow rate, the downstream length of a scour hole (b/L) increased by about 20%. The change of the dike alignment angle from 90° to 60° resulted in a significant change in the downstream length of a scour hole (b/L). However, a further decrease in the dike angle from 60° to 45° had a less effect on the downstream length of a scour hole (b/L).

3) An increased flow Froude number corresponds to greater scour hole depths around a dike in both open channel and ice-covered flow scenarios. A finer bed material contributes to deeper scour holes regardless of flow surface cover conditions. The impact of flow Froude number on the maximum scour depth under ice-covered conditions is less pronounced than that under open channel conditions. Under an ice-covered flow condition, a larger relative roughness coefficient leads to a larger maximum depth of scour holes.

4) The proposed equations under both open channel and ice-covered flow conditions are derived to compute the maximum depth of scour holes around angled non-submerged spur dikes. These equations take into account factors such as dike alignment angle, flow Froude number, dike blockage ratio, particle size of bed material, and relative roughness coefficient (for covered flow conditions). The calculated maximum depths of scour holes using the proposed formula agrees well with those of laboratory experiments, indicating that the performance of the proposed equations is reliable.

Funding. The Natural Sciences and Engineering Research Council of Canada (NSERC) under the Discovery Grant Program RGPIN-2019-04278.

Conflicts of interest. The authors declare no conflict of interest.

REFERENCES

Ackermann, N., Shen, H.T., Olsson, P., 2002. Local scour around circular piers under ice covers. In: Proc. International

- Symposium on Ice: 02/12/2002-06/12/2002. Dep. of Physic, Univ. of Otago, pp. 149–155.
- Derrick, D.L., Gernand, H.W., Crutchfield, J.P., 1989. Inventory of river training structures in shallow-draft waterways. Army Engineer Waterways Experiment Station Vicksburg MS Hydraulics Lab.
- Giglou, A.N., Mccorquodale, J.A., Solari, L., 2018. Numerical study on the effect of the spur dikes on sedimentation pattern. *Ain Shams Engineering Journal*, 9, 4, 2057–2066.
- Gu, Z.-P., Akahori, R., Ikeda, S., 2011. Study on the transport of suspended sediment in an open channel flow with permeable spur dikes. *International Journal of Sediment Research*, 26, 1, 96–111.
- Hains, D.B., 2004. An experimental study of ice effects on scour at bridge piers. Dissertation, Lehigh University, Bethlehem, USA.
- Haltigin, T.W., Biron, P.M., Lapointe, M.F., 2007. Predicting equilibrium scour-hole geometry near angled stream deflectors using a three-dimensional numerical flow model. *Journal of Hydraulic Engineering*, 133, 8, 983–988.
- Ishigaki, T., Baba, Y., 2004. Local scour induced by 3D flow around attracting and deflecting groins, *Proceedings 2nd International Conference on Scour and Erosion (ICSE-2)*. November 14–17., 2004, Singapore.
- Ishigaki, T., Baba, Y., Muto, Y., 2000. Vortex motion around a plate with footing in open channel flow and its effect on local scouring. *Advances in Hydro Science and-Engineering*, 4, 169–176.
- Jafari, R., Sui, J., 2021. Velocity field and turbulence structure around spur dikes with different angles of orientation under ice covered flow conditions. *Water*, 13, 13, 1844.
- Kuhnle, R.A., Alonso, C.V., Shields Jr, F.D., 2002. Local scour associated with angled spur dikes. *Journal of Hydraulic Engineering*, 128, 12, 1087–1093.
- Manual, S.-I.S.U.s., 2017. SonTek-IQ Series Intelligent Flow Featuring Smart Pulse HD User's Manual. Xylem brand, SmartPulse HD.
- Namaee, M., Sui, J., 2019a. Local scour around two side-by-side cylindrical bridge piers under ice-covered conditions. *International Journal of Sediment Research*, 34, 4, 355–367.
- Namaee, M.R., Sui, J., 2019b. Effects of ice cover on the incipient motion of bed material and shear stress around side-by-side bridge piers. *Cold Regions Science and Technology*, 165, 102811.
- Namaee, M.R., Sui, J., 2020. Velocity profiles and turbulence intensities around side-by-side bridge piers under ice-covered flow condition. *Journal of Hydrology and Hydromechanics*, 68, 1, 70–82.
- Namaee, M.R., Sui, J., Wu, Y., Linklater, N., 2021. Three-dimensional numerical simulation of local scour around circular side-by-side bridge piers with ice cover. *Canadian Journal of Civil Engineering*, 48, 10, 1335–1353.
- Pandey, M., Ahmad, Z., Sharma, P., 2018. Scour around impermeable spur dikes: a review. *ISH Journal of Hydraulic Engineering*, 24, 1, 25–44.
- Richardson, E., Davis, S., 1995. Evaluating scour at bridges: Federal highway administration hydraulic engineering circular no. 18, Publication FHWA-IP-90-017.
- Smith, B.T., Ettema, R., 1995. Ice-cover influence on flow and bedload transport in dune-bed channels. Research Report, Iowa Institute of Hydraulic Research, the University of Iowa, Iowa city, United States.
- Sui, J., Faruque, M., Balachandar, R., 2009. Local scour caused by submerged square jets under model ice cover. *Journal of Hydraulic Engineering*, 135, 4, 316–319.
- Sui, J., Wang, J., He, Y., Krol, F., 2010. Velocity profiles and

- incipient motion of frazil particles under ice cover. *International Journal of Sediment Research*, 25, 1, 39–51.
- Teraguchi, H., Nakagawa, H., Muto, Y., Baba, Y., Zhang, H., 2008. Flow and sediment transport around impermeable or permeable groins. *Proceedings of Hydraulic Engineering*, 52, 175–180.
- Tominaga, A., Nakano, Y., Fujita, T., 2000. Visualization analysis of flow structures in submerged spur dikes. *Proceedings of Hydraulic Engineering*, 44, 1041–1046.
- Valela, C., Sirianni, D.A., Nistor, I., Rennie, C.D., Almansour, H., 2021. Bridge pier scour under ice cover. *Water*, 13, 4, 536.
- Wang, h., Zhao, J., Chen, Z., 2008. Experimental investigation of ice and snow melting process on pavement utilizing geothermal tail water. *Energy Conversion and Management*, 49, 6, 1538–1546.
- Wu, P., Balachandar, R., Sui, J., 2016. Local scour around bridge piers under ice-covered conditions. *Journal of Hydraulic Engineering*, 142, 1, 04015038.
- Wu, P., Hirshfield, F., Sui, J., 2014a. Further studies of incipient motion and shear stress on local scour around bridge abutment under ice cover. *Canadian Journal of Civil Engineering*, 41, 10, 892–899.
- Wu, P., Hirshfield, F., Sui, J., 2015a. Local scour around bridge abutments under ice covered condition—an experimental study. *International Journal of Sediment Research*, 30, 1, 39–47.
- Wu, P., Hirshfield, F., Sui, J., 2015b. Armour layer analysis of local scour around bridge abutments under ice cover. *River Research and Applications*, 31, 6, 736–746.
- Wu, P., Hirshfield, F., Sui, J., Wang, J., Chen, P., 2014b. Impacts of ice cover on local scour around semi-circular bridge abutment. *Journal of Hydrodynamics*, 26, 1, 10–18.
- Yazdi, J., Sarkardeh, H., Azamathulla, H.M., Ghani, A.A., 2010. 3D simulation of flow around a single spur dike with free-surface flow. *Intl. J. River Basin Management*, 8, 1, 55–62.
- Zabilansky, L.J., Hains, D.B., Remus, J.I., 2006. Increased bed erosion due to ice, *Current Practices in Cold Regions Engineering*, pp. 1–12.
- Zhang, H., Nakagawa, H., 2008. Scour around spur dyke: recent advances and future researches. *Kyoto University Disaster Prevention Research Institute Annual Report*. 51(B): 633–652.
- Zhang, L., Wang, P., Yang, W., Zuo, W., Gu, X., Yang, X., 2018. Geometric characteristics of spur dike scour under clear-water scour conditions. *Water*, 10, 6, 680.

Received 8 January 2024

Accepted 31 May 2024