

Turbulent flow structure around a single submerged angled spur dike under ice cover

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Abstract: This experimental study examines the velocity fields around the single submerged spur dike in a large-scale flume under three flow conditions: open channel, smooth ice-covered, and rough ice-covered. The effects of dike orientation were investigated for alignment angles of 90°, 120°, and 135°. Instantaneous three-dimensional velocity components were recorded using an acoustic Doppler velocimeter. Results show that the spur dikes generate distinct transverse flow regions in the streamwise, lateral, and vertical directions. Alignment angles greater than 90° reduced streamwise velocity near the dikes, while the frontal surface of the dike tip exhibited increased velocity magnitudes. Downstream, significant variations in Reynolds shear stress were observed, driven by flow separation and the formation of a recirculation wake zone. Quadrant analysis revealed that under ice-covered conditions, turbulent interactions near the dike tip were dominated by ejection and sweep events, whereas sweep events were more prevalent in open channel flows, influencing overall flow dynamics.

Keywords: Flow field; Ice cover; Orientation angle; Quadrant analysis; Spur dike.

1 INTRODUCTION

The installation of spur dikes is a common engineering practice to enhance channel functionality and mitigate flood risks. These structures, which extend from riverbanks into the flow, disrupt water and sediment transport to prevent erosion and stabilize the banks. By altering flow patterns, spur dikes trap sediment and modify local hydrodynamics, generating vortices and eddies that influence sediment transport, erosion, and deposition. The flow dynamics around spur dikes are complex, influenced by factors such as dike geometry, flow velocity, and sediment characteristics, necessitating site-specific studies and hydraulic modeling to optimize design and minimize adverse effects (Akbari et al., 2021; Fang et al., 2006; Li et al., 2023). Spur dikes can be categorized based on submergence levels (submerged or non-submerged) and alignment angles, with repelling-type spur dikes (obtuse angles) preferred for submerged conditions to direct sediment toward riverbanks and protect the dike foundations (Patel and Kumar, 2024; Zhang et al., 2018).

In cold regions, ice cover significantly impacts channel bed morphology and flow fields (Wang et al., 2021; Wu et al., 2014, 2015). Hydraulic structures such as spur dikes and bridge piers create complex flow interactions under ice-covered conditions. Hydraulic structures in rivers, such as spur dikes and bridge piers/abutments, result in complex flow fields under ice-covered flow conditions. Hu et al. (2022) found increased turbulence intensities in scour holes around piers under ice cover. In narrow rivers, ice cover can induce pressurized flow conditions, shifting the maximum flow velocity toward the channel bed (Zabilansky and White, 2005). Ice cover also increases the wetted perimeter and alters velocity distributions, pushing the maximum velocity toward smoother boundaries (Smith et al., 2023; Sui et al., 2010).

Predominant research focuses on turbulent flow characteristics around non-submerged spur dikes, with three-dimensional velocity measurements obtained using an acoustic Doppler velocimeter (ADV). Previous studies, such as Barbhuiya and

Dey (2004), observed vortex formation around vertical structures in channels, while Hei et al. (2009) identified flow regions around spur dikes using laser-based techniques. Turbulent flow structures, including the burst phenomenon, have been extensively studied, with quadrant analysis providing insights into coherent structures responsible for turbulent momentum transport (Huai et al., 2019; Kline et al., 1967; Lu and Willmarth, 1973).

Given the variability in hydraulic conditions due to extreme weather events and ice cover, spur dikes designed as non-submerged may become fully submerged, significantly altering flow fields (Sui et al., 2002, 2005). To the authors' knowledge, flow behavior around submerged angled spur dikes under ice-covered conditions has not been extensively studied. This research investigates turbulent flow dynamics near submerged spur dikes in a laboratory flume using ADV to measure instantaneous velocities under both open-channel and ice-covered conditions. The study examines how spur dike geometry affects turbulent flow through quadrant analysis of velocity fluctuations, quantifying the contribution of each quadrant and analyzing changes in dominant burst processes. Specifically, the study aims to assess the effects of different dike alignment angles on turbulent flow structures, using Reynolds shear stress and quadrant analysis to identify velocity field patterns and interactions between dike geometry and flow conditions. Although real-world applications often involve groups of spur dikes, this study isolates single structures to provide fundamental insights into hydrodynamic behavior under ice-covered conditions.

2 MATERIAL AND METHODS

2.1 Facilities for experiments

Experiments took place in a large concrete outdoor flume at the Quesnel River Research Center (QRRR) in Likely, British Columbia, measuring 38.20 m in length, 2.00 m in width, and 1.30 m in depth. A staff gauge, accurate to 1 mm, recorded the approaching flow depth upstream of the leveled sandbox surface,

ensuring flow uniformity during each experimental run. At the flume exit, a tailgate ensured the flow reached the desired depths along the flume. The current study utilized two sandboxes. As shown in Figure 1a, the upstream sandbox measures 5.60 m in length, 2.00 m in width, and 0.30 m in depth, while the downstream sandbox is 5.80 m long, 2.00 m wide, and 0.30 m deep. The distance from the downstream sandbox's exit to the tailgate measures 5.30 m. The flume bed features a 0.20% slope. Due to the backwater effect, water levels at the two sandboxes slightly vary.

The aspect ratio B/h , where B is the channel width, and h is the approaching flow depth, is a key hydraulic parameter used to classify channels as narrow or wide. This study considers channels wide when $B/h > 5$, consistent with laboratory conditions where sidewalls are assumed smooth. In natural settings, however, lateral roughness elements such as vegetation along riverbanks can increase flow resistance and reduce effective channel width. As a result, a higher aspect ratio threshold may be required to account for these roughness effects (Knight and Macdonald, 1979). A Cartesian coordinate system was established for three-dimensional velocity measurements, with the x-axis aligned with the streamwise flow, the y-axis perpendicular to the flow towards the opposite side of the observation station, and the z-axis vertically upward towards the water surface. The coordinate system's origin was positioned at the center of the spur dike surface attached to the sidewall. The plane $z = 0$ corresponds to the initial sandbox surface, with velocity fluctuations in the x-, y-, and z-directions represented as u' , v' , and w' , respectively. The placement of the submerged spur dike model was guided by Kuhnle et al. (2002), who found that the scour region's tail length around a spur dike is typically less

than 20 times the dike's length, regardless of alignment angle. The model spur dike had a thickness of 5 cm and was embedded in the sandbox bottom, with heights T of 20 cm and 25 cm above the initial channel bed. The submergence level was quantified using the overtopping ratio S , defined as the ratio of flow depth h to spur dike height T ($S = h/T$), in accordance with Li et al. (2023) and McCoy et al. (2007). For this study, "minor submergence" corresponds to $S = 1$, where the flow depth approximately equals the dike height. "Moderate submergence" occurs when $S = 1.25$, where a larger portion of the dike is submerged. To minimize downstream interference, the model submerged spur dikes were placed at one-third of the length of each sandbox, as shown in Figures 1a and 1b, which also illustrate the adopted coordinate system.

Velocity data were collected with a SonTek Acoustic Doppler Velocimeter (ADV). The SonTek ADV, featuring a high-resolution current meter, includes a downward-looking probe and three receivers. It monitors flow velocity through the Doppler effect, identifying changes in frequency (Doppler shift) reflected by moving solid particles in the water. Velocity data was analyzed with WinADV to preclude aliasing. WinADV analyzes signal quality through a correlation coefficient (COR) and signal-to-noise ratio (SNR). Following SonTek/YSI's guidance, the study applied criteria of SNRs above 15 dB and CORs exceeding 70% at 25 Hz, rendering 85% of the data suitable. A definitive strategy and standard for determining suitable ADV sampling times for turbulent flow are still lacking. Previous methods lack universal applicability, heavily dependent on researchers' judgments. Proposed criteria, rooted in statistical methods, have drawbacks related to experiment scale and flow conditions. Park and Hwang (2021) suggested a sampling

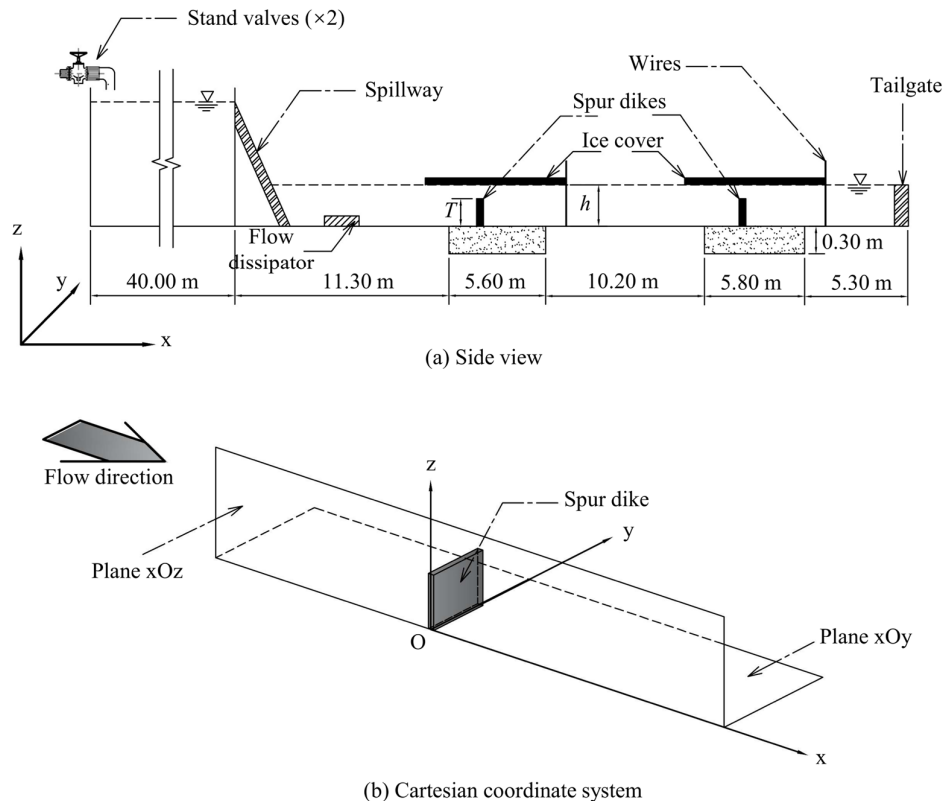


Fig. 1. Schematic diagram of the experimental flume: (a) Side view; (b) Cartesian coordinate system.

time based on the integral time scale (T_i), calculated using Equation (1), with a recommended range from $150T_i$ to $200T_i$:

$$T_i \equiv \int_0^{t_0} \frac{\langle u_i(t)u_i(t+\tau) \rangle}{\langle u_i(t) \rangle^2} d\tau \quad (1)$$

where τ denotes the lag between two points, t_0 represents the first zero-crossing time in the normalized autocorrelation function, $u_i(t)$ denotes the velocity component, and the subscript i specifies the x, y, and z direction (O'Neill et al., 2004).

The laboratory experiments in this study yielded integral time scales ranging from 0.21 to 0.74 seconds. Park and Hwang (2021) recommended the sampling period should range from 31.5 to 148 seconds. In this study, each measurement event's sampling period was 120 seconds, considered adequate for accurate turbulence statistics determination (Jafari and Sui, 2021, 2024; Namaee and Sui, 2019a, 2019b, 2020). Experiments showed that the open-channel flow condition produced the shallowest scour depth (Li et al., 2023), which was used as a reference point for the timing of positioning the ADV during instantaneous velocity measurements. Specifically, the ADV was deployed when the scour depth approached the equilibrium depth observed under open-channel conditions. Velocity measurements were restricted to the area near the dike head to further reduce potential interferences of varied terrain elevations under ice-covered flow conditions. The velocity profiles were measured starting 3 mm above the channel bed, spanning three cross-sections: 10 cm upstream of the dike, at the dike tip, and 10 cm downstream. Seven measurement points were selected for each spur dike layout. Vertical velocity measurements were taken from the bed to the water surface at each location, covering 8–10 different flow depths. A total of 1500 instantaneous velocity measurements in three dimensions were recorded at each point. Figure 2 illustrates the locations of the measurement points, and Table 1 details the flume setup and spur dike configurations for both open-channel and ice-covered conditions.

2.2 Ice cover and sediment setups

The available materials for modeling ice cover fall into three categories: rigid, synthetic, and natural. When strength is not a priority, researchers often use rigid, unbreakable substitutes for ice cover, including wood, paraffin, polyethylene, polypropylene plastic, and styrofoam (Jafari and Sui, 2021, 2024). styrofoam panels modeled smooth ice cover, while rough ice cover was

created by affixing styrofoam cubes (with a 2.5 cm edge length) to the panel bottoms. The Manning's coefficient for smooth styrofoam panels is estimated at 0.013 (Jafari and Sui, 2021, 2024). Using Li's equation to calculate Manning's coefficient (n_i) for rough model ice cover, with a roughness height of 0.025 m, n_i is calculated as 0.021 (Li, 2012). These values align with calculated results for surveyed ice-covered channels, either through average roughness height estimation (0.0075 to 0.029) or the logarithmic law (0.0088 to 0.033) (Li, 2012). Equation (2) expresses the calculation for n_i :

$$n_i = 0.039 k_s^{1/6} \quad (2)$$

where k_s denotes the average roughness height at the ice cover's bottom. Field observations indicated that most rivers form smooth, floating ice covers (Turcotte et al., 2011). This study modeled the ice cover using a horizontally fixed, slightly buoyant Styrofoam layer anchored at both ends with wires. The attached Styrofoam cubes were submerged for rough ice conditions by placing weighted plywood on top. Although floating ice in natural rivers can exhibit lateral movement and minor vertical adjustments due to flow forces and variations in ice thickness, the experimental setup ensured horizontal stability, maintaining controlled conditions for consistent measurement. This design facilitated the analysis of key flow dynamics beneath the ice while minimizing the complexity introduced by vertical fluctuations. Furthermore, the local scour processes observed under fixed and floating ice covers were comparable, with increased ice cover roughness correlating with greater local scour depths (Hains and Zabilansky, 2004).

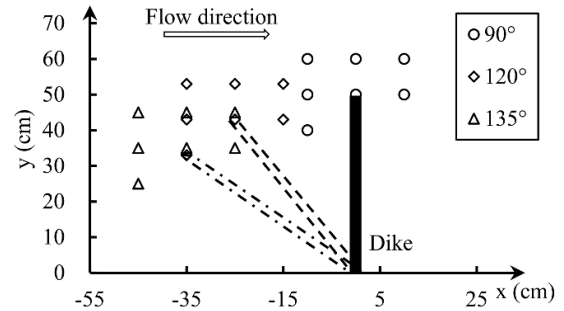


Fig. 2. Schematic plot of measuring positions (dike length = 50 cm).

Table 1. Summary of experimental conditions and features of the flume and spur dikes under the open channel condition.

Run #.	Sandbox position	Discharge, Q (L/s)	Spur dike height, T (m)	Alignment angle, α (°)
1	Upstream	148	0.15	90
2	Upstream	148	0.15	120
3	Upstream	160	0.15	135
4	Upstream	156	0.20	90
5	Upstream	152	0.20	120
6	Upstream	140	0.20	135
7	Downstream	112	0.20	90
8	Downstream	124	0.20	120
9	Downstream	108	0.20	135
10	Downstream	128	0.25	90
11	Downstream	132	0.25	120
12	Downstream	124	0.25	135

The entrance length for fully developed flow (l_e) can be estimated using the following equation (Çengel and Cimbala, 2014):

$$l_e = 1.359 L_c Re^{1/4} \quad (3)$$

where Re represents the flow Reynolds number, and L_c represents the characteristic length. The model floating ice cover, consisting of styrofoam panels, measures 9.60 m long and 2.00 m wide for the upstream sandbox and 9.80 m long and 2.00 m wide for the downstream sandbox, extending 2.00 m before and after each sandbox (Figure 1a). This configuration ensured the model ice cover spanned sufficient space for the flow to fully develop.

Non-uniform bed materials have been utilized in flume studies to comprehensively understand the differences between clear-water and live-bed scour processes. In laboratory flume investigations, sediment sizes must match or exceed 10% of the natural channel bed sediment sizes in the field (Ettema et al., 1998). This study used non-uniform sediments with a median particle size (d_{50}) of 0.90 mm were used in this study to imitate the natural riverbed. The channel bed Manning roughness coefficient (n_b) for the sand used as bed material was calculated as 0.020 using Equation (4) (Julien, 2018).

$$n_b = 0.064 d_{50}^{1/6} \quad (4)$$

2.3 Quadrant analysis

Huai et al. (2019) note that turbulent flow structures are frequently assessed through the conditional statistics of streamwise and vertical velocity variations (u' and w') via quadrant analysis. This study employed quadrant analysis to investigate how spur dike parameters influence sweep, ejection, outward, and inward movements. The submergence level and alignment angle of a spur dike significantly impact turbulence structure under consistent approaching flow conditions (Jafari and Sui, 2021, 2024; Vaghefi et al., 2016). In quadrant analysis, the $u'-w'$ plane is divided into four quadrants: Q₁, Q₂, Q₃, and Q₄.

The hole parameter H_t (threshold level) is introduced through filtration using a hyperbolic area for calculating the frequency of each bursting event, focusing on the predominant contributions to $-u'w'$. This approach allows for the extraction of significant Reynolds shear stress values in each quadrant while filtering out minor background events (Huai et al., 2019). The hole parameter, H_t , differentiates between background disturbances from large-magnitude burst events, the latter of which could significantly affect sedimentation processes. H_t is defined as:

$$H_t = \frac{|u'w'|}{u'w'} \quad (5)$$

The fluctuation of H_t enables the computation of the fractional contributions to total Reynolds stress from events of varying magnitudes within each quadrant, excluding the hole area, expressed as:

$$\overline{u'w'_s} = \frac{1}{n} \sum_{j=1}^n I(u'_j w'_j) \quad (6)$$

where $\overline{u'w'_s}$ represents the proportion of turbulent bursts exceeding the threshold, $u'_j w'_j$ denotes the conditional Reynolds stresses, n signifies the number of events, and the indicator function I is defined to complete the conditional averaging technique:

$$I = \begin{cases} 1, & \text{if } |u'w'| \geq H_t (\overline{u'u'})^{0.5} (\overline{w'w'})^{0.5} \\ 0, & \text{if } |u'w'| < H_t (\overline{u'u'})^{0.5} (\overline{w'w'})^{0.5} \end{cases} \quad (7)$$

The stress proportion, S_i , for quadrant i is defined as the flux contribution to u' and w' from that quadrant using:

$$S_i = \frac{\langle u'w' \rangle_i}{|u'w'|} \quad (8)$$

where

$$\langle u'w' \rangle_i = \lim_{t \rightarrow \infty} \frac{1}{T_t} \int_0^{T_t} u'(t) w'(t) I dt \quad (9)$$

where T_t denotes the total time. S_1 and S_3 are positive (> 0), while S_2 and S_4 are negative (< 0). A computer program in RStudio was developed to analyze the bursting phenomena and ascertain each quadrant's contribution to the Reynolds shear stress.

3 RESULTS AND DISCUSSION

3.1 Distributions of velocity around angled spur dikes

Although the flow is fully developed before reaching the spur dike, the dike's presence induces a new boundary layer. This study's laboratory setup consists of two isolated, non-interacting spur dikes, with hydrodynamics analyzed individually around each. Despite the presence of two dikes, no interaction effects are considered. Velocity fields around a single spur dike were measured at three cross-sections: 10 cm upstream, at the tip of the dike, and 10 cm downstream. For each dike alignment angle, velocity measurements were taken at seven positions along these cross-sections (CSs, Figure 2). Due to limitations of the ADV, measurements were taken at least 0.10 m from the probe head, restricting full depth (z -axis) coverage (Namace and Sui, 2020). While channel confinement in flume experiments can cause sidewall effects, altering flow patterns and creating velocity dips, these effects were minimal in this study's wide channel, where the flow was largely two-dimensional in the center, reducing the impact of secondary currents (Khanarmuei et al., 2020).

The streamwise velocity (u) is the most critical 3D velocity component for characterizing turbulence structure, demonstrating the highest value and variability compared to the other two velocity components (v , w). Distortion in the streamwise velocity profiles decreases as the dike orientation angle exceeds 90° , leading to more uniformly distributed measured velocities, evidenced by u/u_{avg} values fluctuating less around 1.0. As Figure 3 illustrates, increasing the dike orientation angle from 90° to 135° results in lower streamwise velocities under any water surface condition. Of note, u_{avg} represents the depth-averaged value of u .

Figure 4 illustrates the impact of the alignment angle on velocity vectors in the X-Y plane ($z/h = 0.45$, with dike height $T = 25$ cm). The origin (0,0,0) is positioned at the center of the spur dike surface attached to the sidewall. The vortex magnitude at the dike tip increases with the alignment angle, as indicated by denser and longer velocity vectors. Due to ADV limitations, only time-averaged velocity fields near the dike tip are presented, which do not fully capture the vortex structure. For deflecting dikes (angles $> 90^\circ$), the X-Y plane velocity field near the tip shows minimal sensitivity to water surface conditions. Unlike the altered vertical velocity profiles (Figure 3), the presence of ice cover has little effect on X-Y plane velocity vectors. Subsequent analysis explores velocity distributions in the Y-Z plane at various cross-sections around the spur dike.

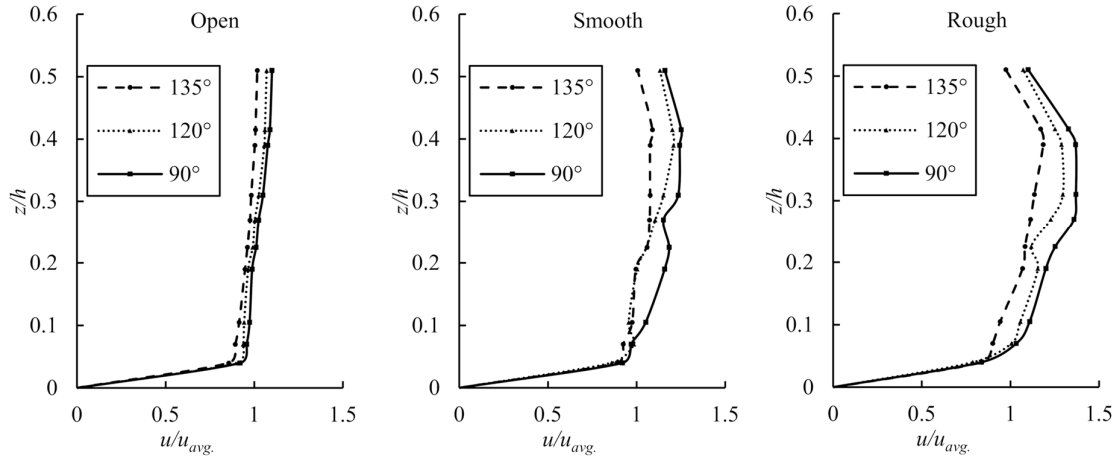


Fig. 3. The non-dimensional streamwise velocities ($u/u_{avg.}$) in front of the spur dike tip (minor submergence of spur dikes, $T = 25$ cm).

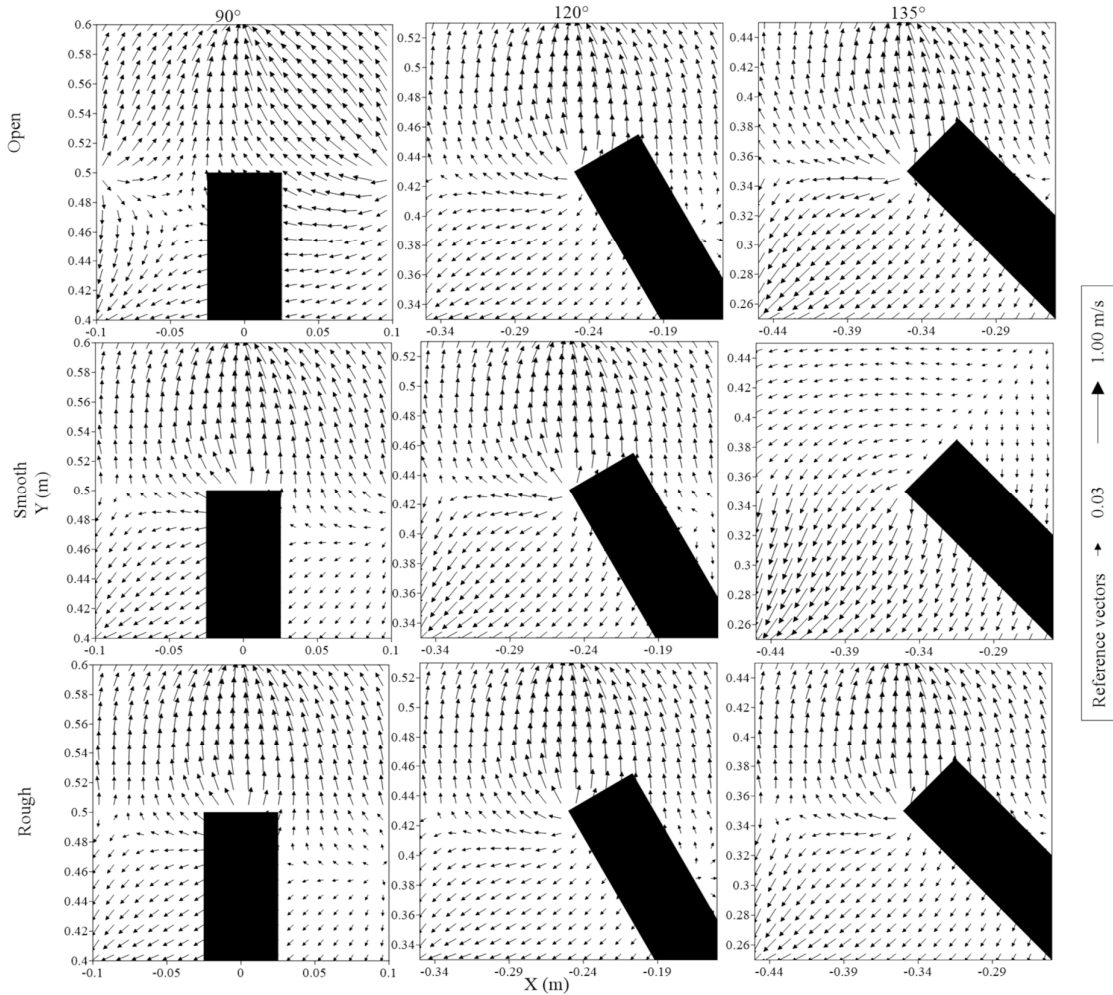


Fig. 4. Flow velocity vectors generated from measured data in the X-Y plane close to the dike tip for different alignment angles ($z/h = 0.45$). Note: water flows from left to right.

Figure 5 presents the distribution of the dimensionless time-averaged streamwise velocity (u/U) at the rear of the spur dike, where U is the average flow velocity, and L' is the projected normal length of the dike, calculated as $L_d \sin \alpha$. The data show a recirculation zone with reverse flow ($u/U < 0$) caused by the dike's obstruction. Under minor submergence, reverse flow

velocities are higher. In contrast, with moderate submergence, the flow over the dike reduces the reverse flow magnitude, indicated by lighter shading.

Figure 6 shows the dimensionless time-averaged lateral velocity (v/U). Similar to the u/U patterns, negative v/U values are observed near the bed behind the dike ($x = 0.025$ m). More

lateral flow occurs above the dike with lower submergence in open flow conditions. However, assessing the submergence effects on v/U at the dike's rear side under ice-covered conditions was difficult due to ADV limitations. Regardless of ice cover roughness, the impact of submergence on v/U becomes less pronounced, as reflected in the contour patterns.

Figure 7 shows the distribution of the dimensionless time-averaged vertical velocity (w/U). Unlike the u/U and v/U distributions, no significant downward flow is observed near the bed. Under ice-covered conditions and moderate dike submergence, downward flow is evident near the dike tip, passing through the gap between the dike and the ice cover.

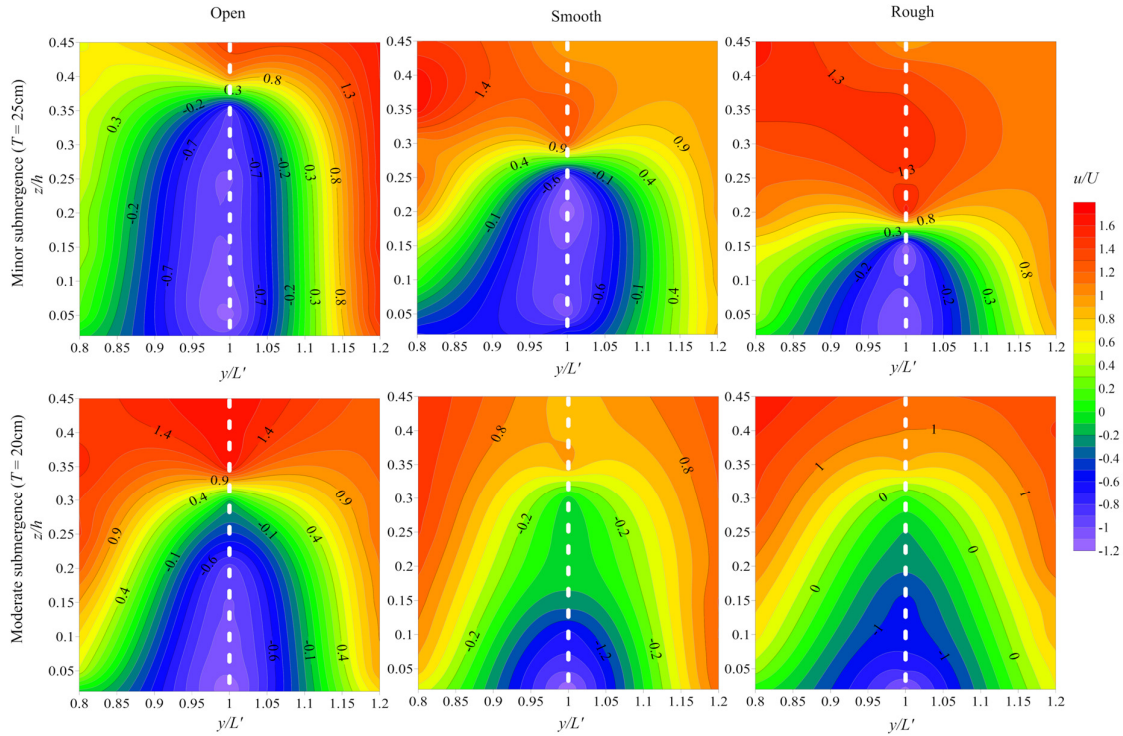


Fig. 5. Time-averaged streamwise velocity contours at the rear side of the spur dike ($x = 0.025$ m, $\alpha = 90^\circ$). The outline of the spur dike is denoted in dash lines, and the flow is oriented towards the viewer and perpendicular to the paper's plane.

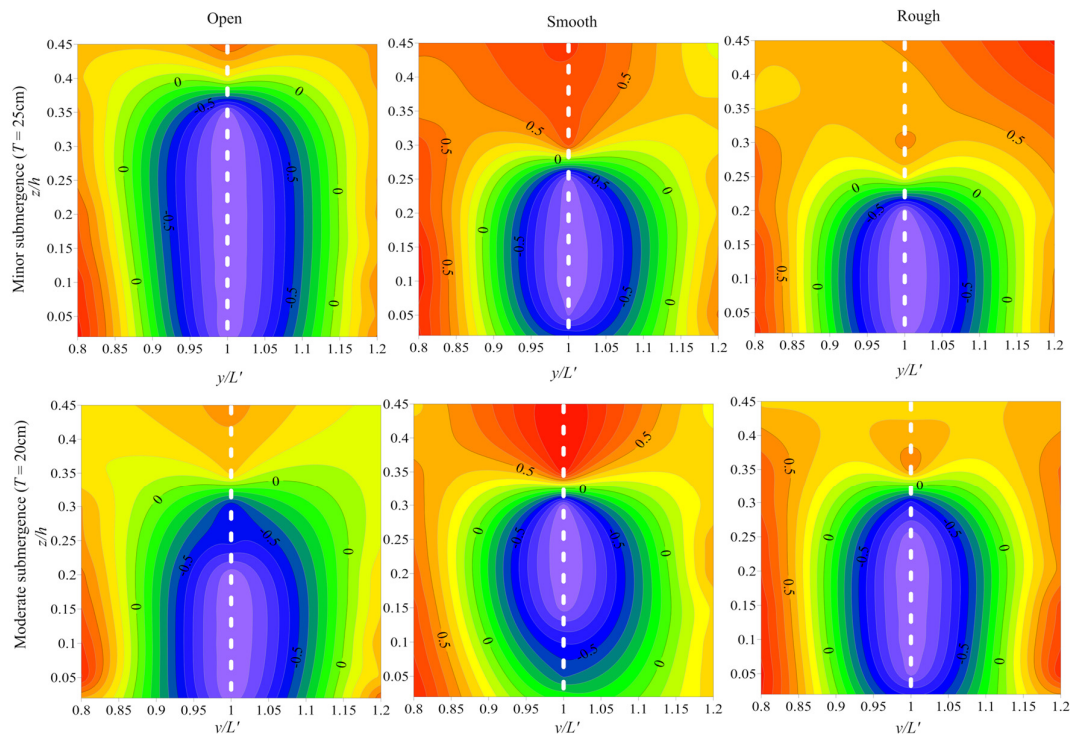


Fig. 6. Time-averaged lateral velocity contours at the rear side of the spur dike ($x = 0.025$ m, $\alpha = 90^\circ$). The outline of the spur dike is denoted in dash lines, and the flow is oriented towards the viewer and perpendicular to the paper's plane.

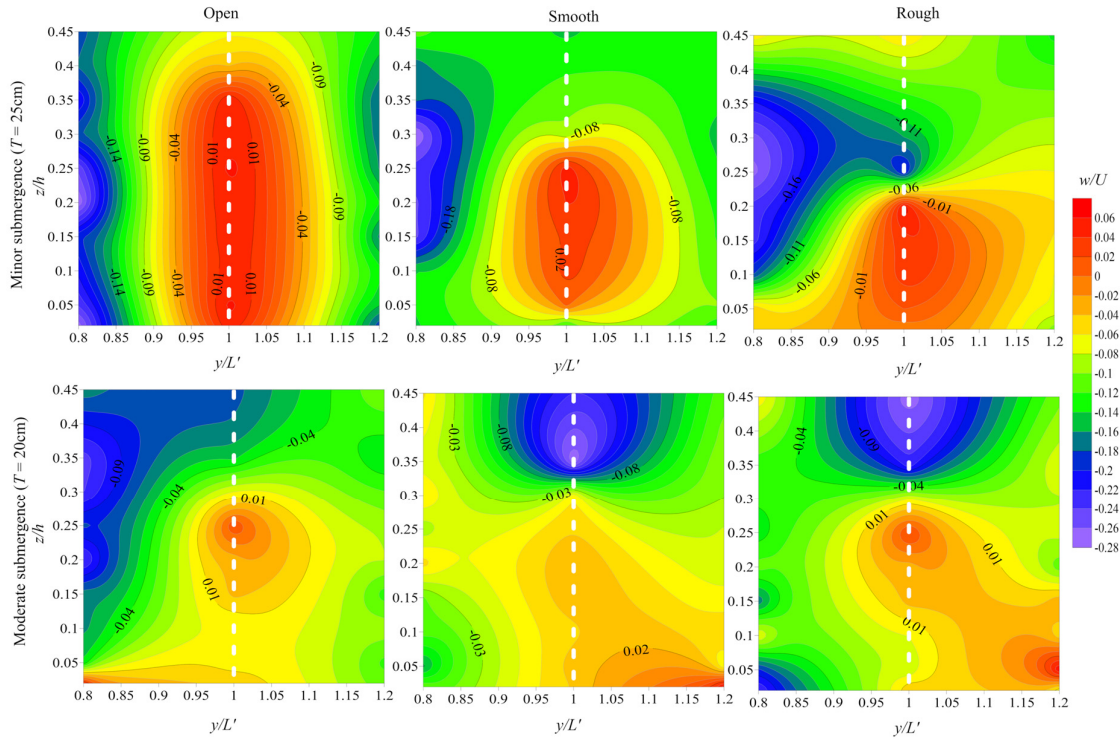


Fig. 7. Time-averaged vertical velocity contours at the rear side of the spur dike ($x = 0.025$ m, $\alpha = 90^\circ$). The outline of the spur dike is denoted in dash lines, and the flow is oriented towards the viewer and perpendicular to the paper's plane.

Negative vertical velocities also occur in open flow conditions but are less concentrated. These negative velocities suggest the presence of a horseshoe vortex, which wraps around the dike's rear and directs vertical flow toward the bed (Koken and Constantinescu, 2008). However, the precise profile of this vortex is difficult to capture due to the limitations of ADV measurements.

Figure 8 presents vector graphs of velocity data in the X-Z plane, 10 cm upstream of the dike tip ($y = 60$ cm, $T = 25$ cm, $\alpha = 90^\circ$) under various cover conditions. Due to limitations of the down-looking ADV, the top 10 cm of the flow velocity field cannot be recorded (Namaee and Sui, 2019b). The results show that, under ice-covered conditions, the downward flow extends closer to the bed, with rough ice further intensifying this effect. Despite the ADV's high-frequency sampling capability, data noise was above 50 Hz. The ADV's sampling volume, located 10 cm below the probe, had a diameter of approximately 0.6 cm, which limited accurate capture of the recirculation zone and vortices. Additionally, using a single ADV restricted the study's ability to fully capture the temporal and spatial complexities of recirculation and vortex dynamics in the flume.

The following analysis focuses on the streamwise velocity component, which has the highest magnitude of the three velocity components. Under ice-covered conditions, the maximum velocity occurs between the ice cover and the bed, influenced by their roughness coefficients, regardless of dike orientation and submergence levels. The maximum velocity shifts closer to the bed as ice cover roughness increases. For instance, with a 90° spur dike and minor submergence, $u_{\max}$ occurs at a depth of $z/h = 0.31$ under smooth cover and $z/h = 0.27$ under rough cover. Ice cover conditions affect both the location and magnitude of $u_{\max}$ (Figure 3). A smooth ice cover increases streamwise velocity by up to 20%, while a rough ice cover results in a 24% increase compared to open channel flow at the same depth.

These findings align with experimental studies and analytical simulations (Namaee and Sui, 2020). The results show that the influence of ice cover on velocity distribution increases with larger dike alignment angles, and this effect becomes more pronounced as ice cover roughness increases. Negative velocity values indicate flow separation, forming a recirculating region. The impermeable spur dike alters the streamwise flow, causing the boundary layer to detach from the dike's frontal surface.

According to the law of the wall (also known as the logarithmic law), turbulent flow's average velocity at a given depth is proportional to the logarithm of the distance from that point to the boundary. The log-law (Equation 10) serves as a general expression for velocity distribution across depth in alluvial channels:

$$u_{avg}(t) = \frac{u_*}{\kappa} \ln \left(\frac{z + Wk_e}{k_e} \right) + C \quad (10)$$

where $u_{avg}(t)$ is the time-averaged streamwise velocity, u_* is the shear velocity, κ is the von Karman constant, W is a coefficient of adjustment of the origin below the top roughness elements, C is an empirical constant, and k_e is the equivalent sand grain roughness (or Nikuradse roughness), approximated by d_{50} . W is estimated through trial and error, aiming to maximize the coefficient of determination (R^2) between u and $\ln[(z + Wk_e)/k_e]$. When W equals 0, experiments indicate that κ is approximately 0.41 and C approximately 5.20 for a smooth wall (Afzalimehr and Rennie, 2009). This study analyzed experimental data under open channel flow conditions to determine the best-fit values for W and C using $\kappa = 0.41$. Figure 9 displays a sample logarithmic law fitting for measured velocity data under open channel flow conditions. The origin adjustment coefficient W is estimated to be 0. Table 2 lists the constants in the sample curve-fitting process.

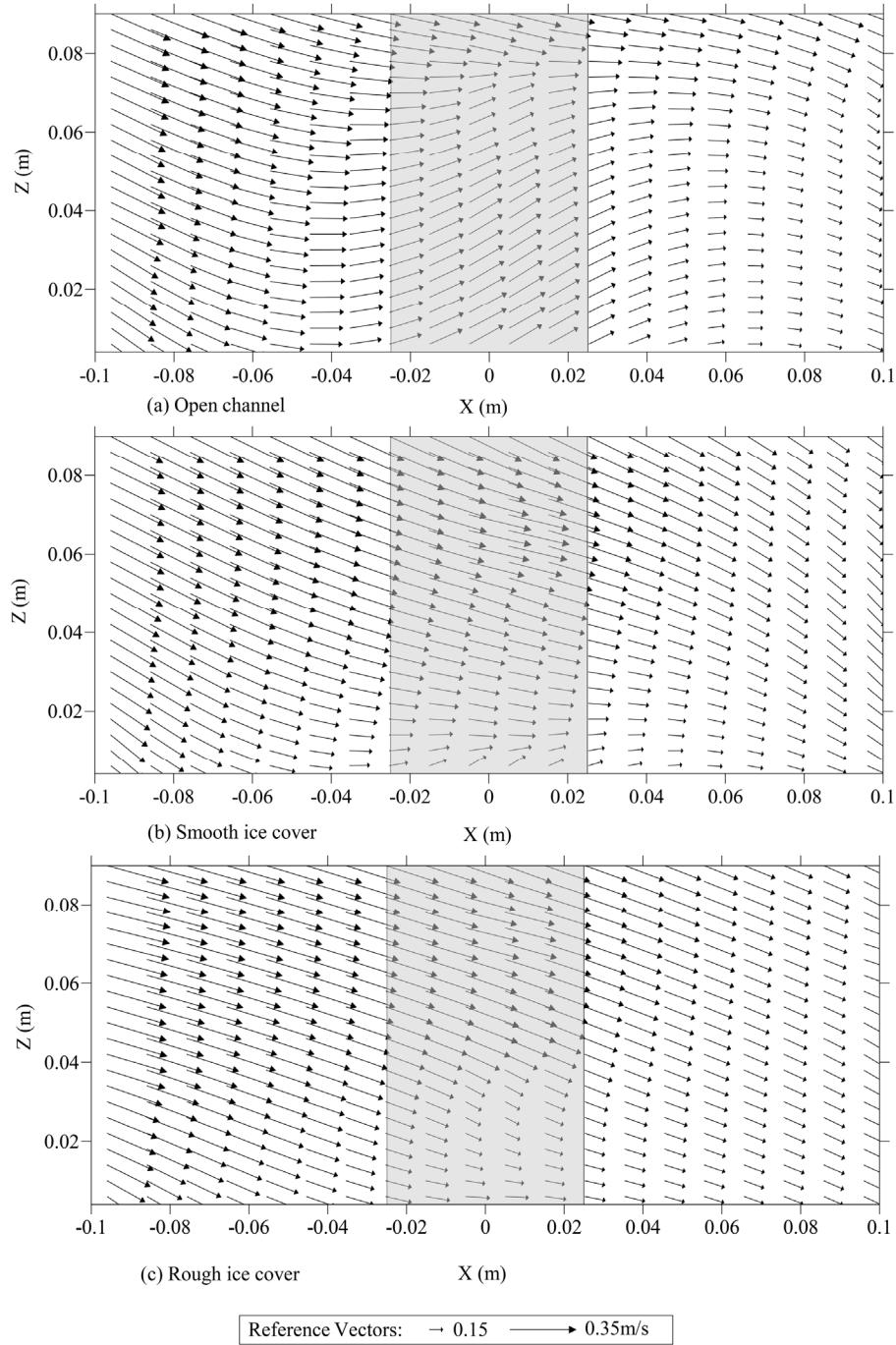


Fig. 8. Flow vectors in the X - Z plane at the dike tip ($y = 60$ cm, $T = 25$ cm, $\alpha = 90^\circ$). (a) Open channel, (b) Smooth ice cover, (c) Rough ice cover. The spur dike outline is shaded in light grey, and the flow direction is from left to right.

Kuhnle et al. (2008) applied the logarithmic law to simulate mean velocity near the boundary, setting k_e to 0 on the submerged dike surface and 1.0 mm on the sand channel bed. For minor submergence, the logarithmic equation was modified using empirical coefficients and adjusted k_e for moderate submergence to simulate the streamwise velocity profile under open channel flow conditions.

Under ice-covered flow conditions, the vertical streamwise velocity profile is divided into two layers: the lower bed layer and the upper ice layer. The logarithmic law approach applies

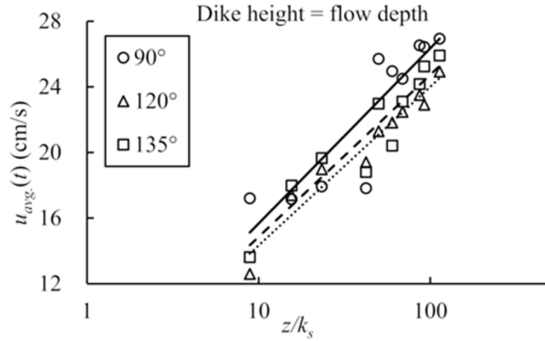
separately to each layer under ice-covered conditions (Zhang et al., 2021), as expressed in the following equation:

$$\begin{cases} u_b = \frac{u_{*b}}{\kappa} \ln \left(30 \frac{z}{k_{eb}} \right) \\ u_i = \frac{u_{*i}}{\kappa} \ln \left(30 \frac{h-z}{k_{ei}} \right) \end{cases} \quad (11)$$

where subscripts b and i represent the corresponding variables in the lower bed layer and upper ice cover layer, respectively, with

Table 2. Examples of curve-fitting constants in the logarithmic law equation for $L_d = 50$ cm spur dike.

Submergence level	Alignment angle α (°)	u^*/κ	C	Root mean square R^2
Minor	90	4.64	4.99	0.89
Minor	120	4.20	4.66	0.95
Minor	135	4.29	4.98	0.88

**Fig. 9.** Fitting logarithmic law distribution on measured data under the open channel flow condition.

z denoting the distance to the channel bed. The bed layer shear velocity (u_{*b}) is determined through regression analysis of the data before the decrease in streamwise velocity (u). Given that the two-layer theory posits that both layers share the same maximum velocity, Equation (11) is iteratively solved using the Microsoft Math Solver.

Figure 10 shows the estimated velocity profiles under open channel (using Equation 9) and ice-covered flow conditions (using Equation 10) for minor submergence cases of spur dikes. Dots with different shapes represent the measured data. Figure 10 demonstrates that laboratory-measured velocity profile trends apply across the entire flow depth. Additionally, Figure 10 confirms that an ice cover shifts the maximum velocity location to a certain depth beneath it, with the maximum velocity closer to the channel bed under rough ice conditions than under smooth ice conditions (Namace and Sui, 2019a). Note that the flow

velocities and depths in Figure 10 are not normalized, reflecting the parabolic relationship between instantaneous flow velocity and distance to the channel bed, as shown by the equations.

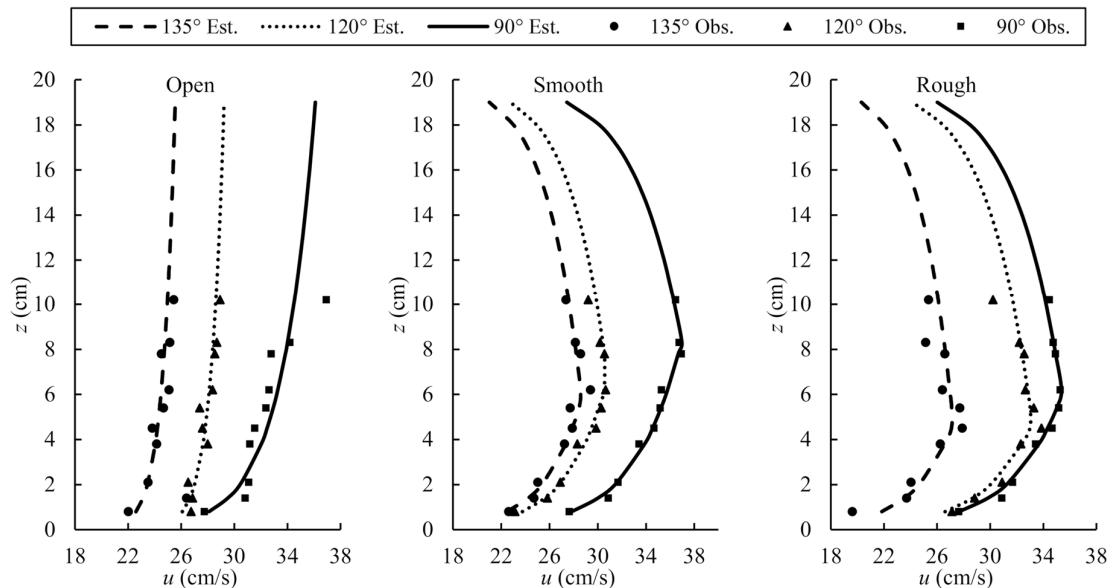
3.2 Variation of Reynolds shear stress at different measurement positions

Reynolds stress (τ_{ij}) accounts for turbulent variations in fluid momentum. It leads to vertical mixing and longitudinal and vertical momentum exchange (Feddersen and Williams, 2007). Theoretically, Reynolds stress distribution is linear along the flow depth and follows an exponential function for turbulence intensity. Shan et al. (2016) proposed a method for estimating bed shear stress in smooth and vegetated compound channels. For a single channel like the experimental flume, the direct covariance method (COV) (Equation 12) provides an unbiased estimation of channel bed stress, considered optimal by Kim et al. (2000):

$$\tau_{ij} = -\rho \overline{u'w'} \quad (12)$$

where ρ represents the fluid's mass density, u' and w' are instantaneous longitudinal and vertical velocity variations. Given the water temperature around 8 °C (± 2 °C), mass density is approximated at 1 g/cm³. The COV method calculates Reynolds shear stress (RSS) using fluctuating velocity components measured by ADV, efficiently applied amidst sediment movement (Shahmohammadi et al., 2021). The RSS component is normalized by dividing it by the square of the shear velocity.

Normalizing RSS to critical shear stress ($-\overline{u'w'}/u_*^2$) aids in comparing flows with varying Reynolds numbers and eliminates density variation effects from water temperature changes. Results for the 90° dike alignment case were selected to analyze RSS variation, as velocity profiles with this alignment show the most significant magnitude and variation. Figures 11 and 12 display the vertical profiles of the RSS at measuring points 10 cm upstream of the dike tip CS (C-10), 10 cm downstream of the dike tip CS (C10), and the dike tip CS (C0) in the X - Z plane for the 90° alignment dike under minor and moderate submergences, respectively.

**Fig. 10.** Comparison of the measured (Obs.) and equation-estimated (Est.) velocities.

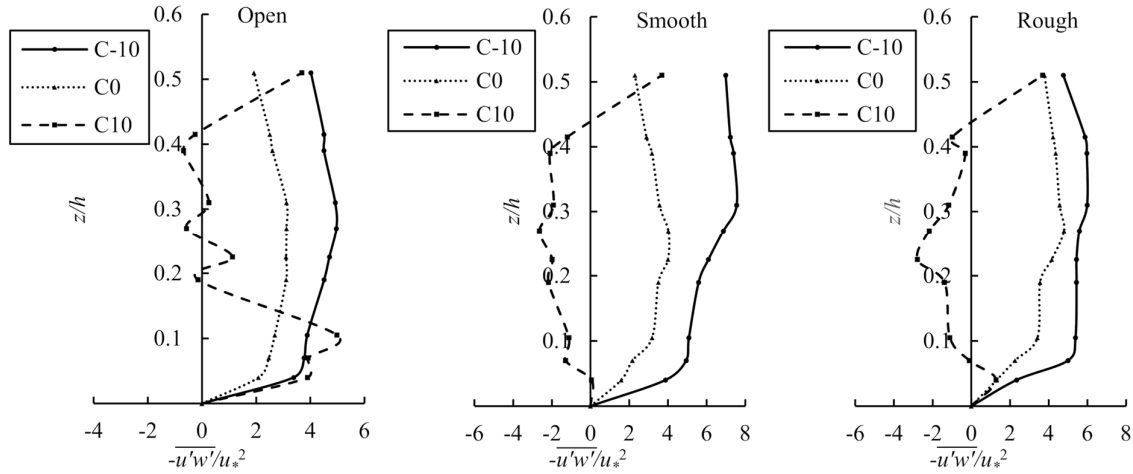


Fig. 11. Vertical RSS profiles in the X - Z plane ($-u'w'/u_*^2$) for the minor submergence case of the spur dike.

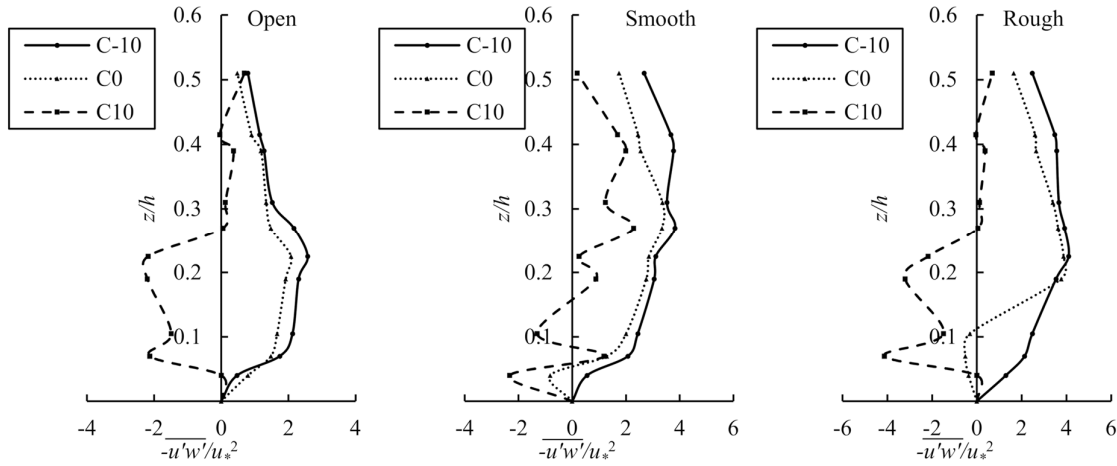


Fig. 12. Vertical RSS profiles in the X - Z plane ($-u'w'/u_*^2$) for moderate submergence case of the spur dike.

Figures 11 and 12 show that the Reynolds shear stress (RSS) downstream of the spur dike (C10) exhibits significant variation due to the recirculation wake zone formed by flow separation, where the flow reverses direction. RSS values steadily decrease in the streamwise direction, with a more pronounced decline in the case of moderate submergence due to the larger separation zone above the dike tip. A negative RSS was observed at the dike tip (C0), where local scour occurs, indicating upward vertical momentum transfer driven by a negative streamwise velocity gradient ($du/dz < 0$) (Jafari and Sui, 2021). RSS is more pronounced under ice-covered conditions compared to open-channel flow. For minor dike submergence, RSS values under smooth and rough ice covers are, on average, 5% and 12% higher than in open-channel flow, respectively. For moderate submergence, RSS values are 7% higher under smooth ice and 15% higher under rough ice compared to open-channel conditions.

In both minor and moderate dike submergence cases, RSS increases in the near-bed zone ($z/H = 0.2-0.3$) before rapidly declining. The decrease in RSS above the near-bed zone is more pronounced for moderate submergence due to the larger separation zone above the dike tip. This variability in RSS around the moderately submerged spur dike is directly linked to

the expanded separation zone with increased submergence. Given the local scour at the dike tip, vertical RSS distribution at C0 was selected for detailed analysis.

Shahmohammadi et al. (2022) identified three distinct zones in the vertical distribution of Reynolds stress in shallow flows: increasing, damping, and decreasing. Figure 13 illustrates these zones, extending the linear regression line in the decreasing zone to zero at the water surface. In the moderate submergence case, irregularities in the RSS profile may be attributed to limitations in ADV measurements near the separation zone, prompting a focused analysis on the minor submergence case, where the dike height nearly matches the flow depth.

With increasing ice cover roughness, both the RSS-increasing and RSS-decreasing zones expand, while the RSS-damping zone contracts by 37.5% and 81.25% for smooth and rough ice cover, respectively, compared to open channel flow. The maximum normalized RSS for minor submergence occurs at $z/H = 0.1, 0.2$, and 0.2 for open channel, smooth, and rough ice-covered flows, respectively. Table 3 summarizes the normalized depths of the three zones: RSS-increasing, RSS-damping, and RSS-decreasing zones at the dike tip under various cover conditions in the minor submergence case.

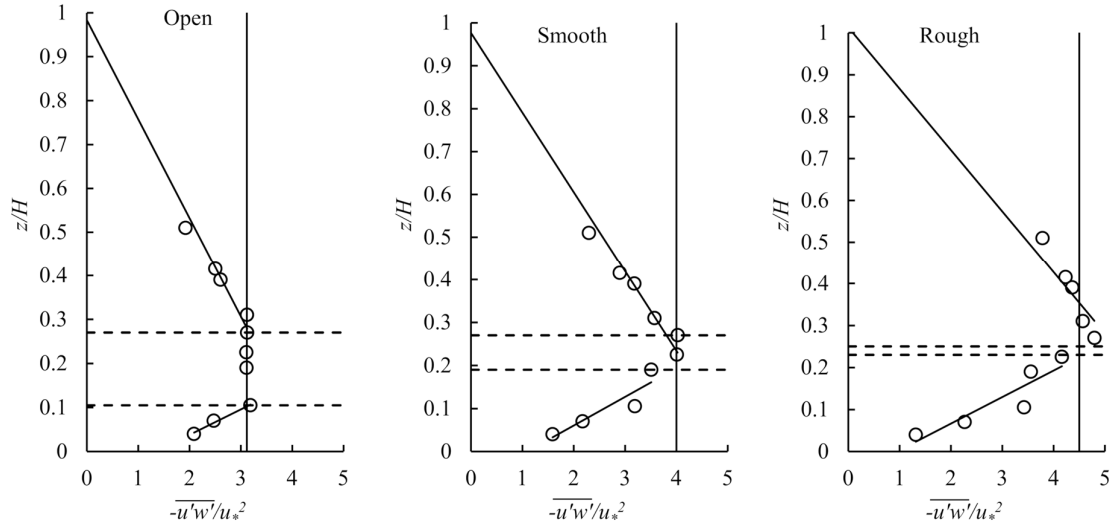


Fig. 13. Reynolds shear stress distribution in the RSS-increasing, RSS-damping, and RSS-decreasing zones

Table 3. Comparison of the RSS-increasing, RSS-damping, and RSS-decreasing zones under open, smooth, and rough ice-covered flow conditions.

Variable	Water surface cover conditions		
	Open	Smooth	Rough
z_1/H	0.11	0.19	0.23
z_2/H	0.27	0.26	0.26
% change of $ z_2/H - z_1/H $	N/A	-37.50	-81.25

^a z_1 and z_2 represent the lower and upper boundaries of the damping zone. The percentage change refers to results compared to that under open-channel flow, and negative values indicate decreasing trends. N/A refers to not applicable.

Spatial variations in Reynolds stress components are influenced by factors beyond mean velocity gradients, such as coordinate axis rotation and diffusion. This spatial inhomogeneity in velocity and Reynolds stresses leads to wake production, where excess kinetic energy is generated as the mean flow interacts with form drag. Wake phenomena can erode riverbeds, induce local scour, and suspend sediment, transporting bed materials downstream through eddies protected by hydraulic structures (Keshavarzi et al., 2018). Analyzing Reynolds shear stress is essential for understanding fluid dynamics in the near-wall region of boundary layers, where solid surface influences are the most pronounced.

3.3 Analysis of dominant turbulent events

The spatial variability of flow fields, both laterally and vertically, contributes to shaping the turbulent structure in channels (Yang et al., 2023). Quadrant analysis is an effective method for processing turbulence data, especially in studying turbulent shear flows, as it accounts for spatial variability. However, selecting the threshold hole size (H_t) introduces uncertainties, with no clear consensus on an optimal value in the literature (Wan Mohtar et al., 2020).

Velocity and Reynolds shear stress analyses show that a 90° dike alignment produces the largest velocity field variations, with minimal influence from flow separation at the dike top. This study investigated different H_t values (0, 0.1, 0.2, and 0.3) using data from experimental setups with a 90° dike alignment, a 50 cm dike length, and a dike height approximating the flow depth.

Figure 14 presents the percentage of dominant turbulent events at the dike tip across the flow depth under open channel, smooth, and rough ice-covered conditions.

The case of $H_t = 0$ is analyzed in this section, as it includes all Reynolds stress values in the four quadrants without exclusion. With $H_t = 0$, all recorded events are incorporated into burst analysis, and results indicate that sweep events (Q_4) dominate under all flow conditions. As H_t increases, the proportion of ejection events (Q_2) rises, becoming the most frequent event at $H_t = 0.3$ in both open channel and ice-covered flows. Sweep and ejection events play a crucial role in transverse momentum exchange.

Under ice-covered conditions, the sweep events remain dominant, but ejection events follow closely, resulting in higher momentum flux and increased shear compared to open-channel flow. As ice cover roughness increases, the distribution of inward (Q_1) and outward (Q_3) events becomes more balanced, reducing the likelihood of these events disappearing and indicating more complex turbulence with rougher ice cover.

Figure 15 shows the absolute contributions of each quadrant ($|S_i|$, per Equation 8) across various dike alignment angles under open channel and ice-covered conditions for $H_t = 0$, measured at different depths. In both smooth and rough ice-covered flows, ejection (Q_2) and sweep (Q_4) events dominate Reynolds stress contributions. In open-channel conditions, sweep events (Q_4) are the primary contributors. As the dike alignment angle increases beyond 90°, the dike's blockage ratio decreases, leading to reduced contributions from ejection and sweep events. Additionally, increasing the alignment angle diminishes the difference between dominant ($|S_2|$ and $|S_4|$) and marginal ($|S_1|$ and $|S_3|$) contributions.

Spur dikes with a 90° alignment are widely adopted in both submerged and non-submerged configurations (Zhang et al., 2018). Therefore, burst events around the 90° dike are analyzed in greater detail. Results from laboratory experiments, shown in Figure 16, depict burst events at three cross-sectional positions at the lowest measuring depth ($z/H = 0.04$), highlighting turbulence in the scoured bed. Upstream of the spur dike, burst events concentrate in the second and fourth quadrants, while they are evenly distributed across all four quadrants downstream of the spur dike. The dominance of upstream sweep (Q_4) and ejection (Q_2) events suggests their critical role in mobilizing sediment within the scour hole. Under ice-covered conditions,

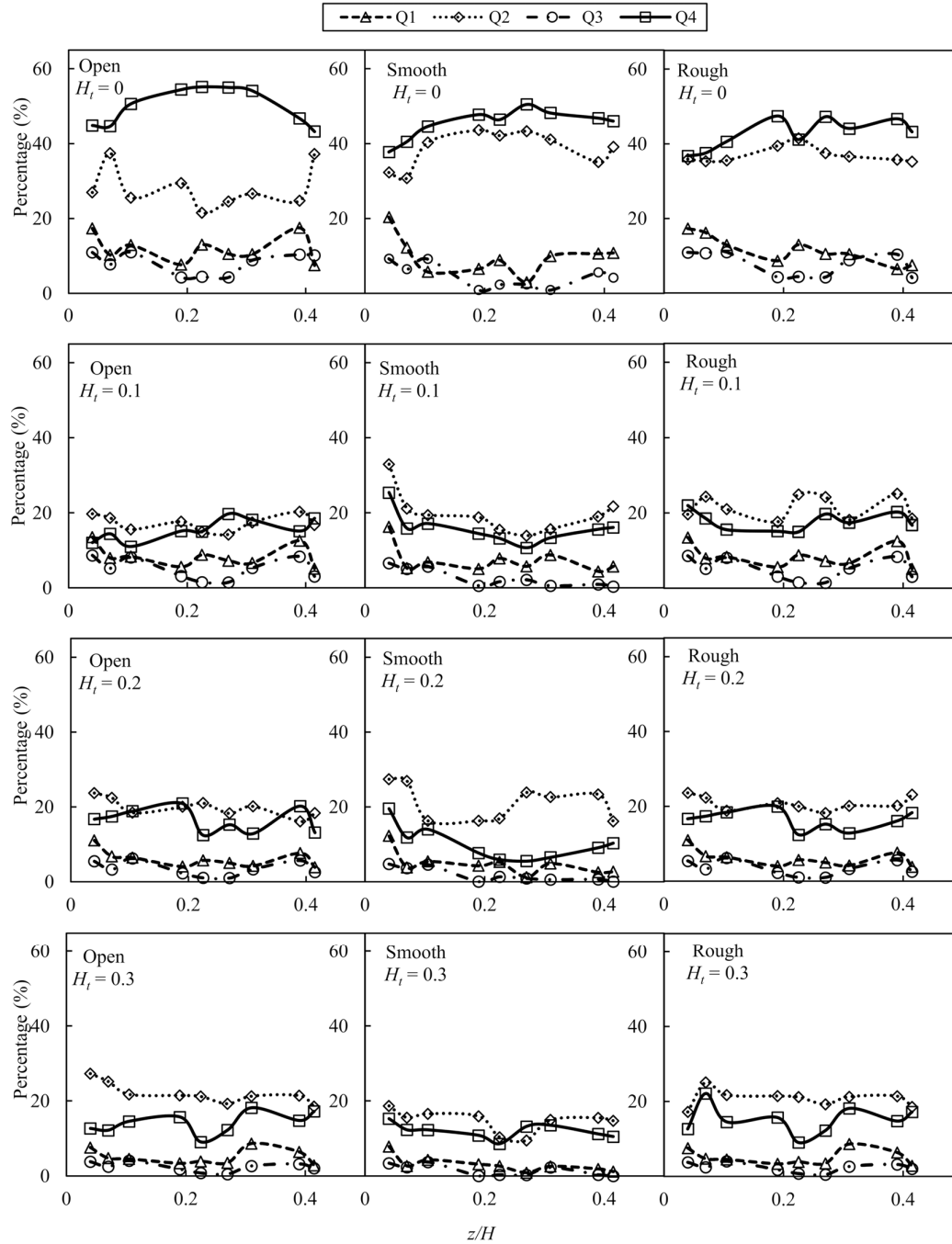


Fig. 14. Percentage of the dominating turbulent events at the dike tip across the measured flow depth with different hole size values (H_t) ($\alpha = 90^\circ$, $L = 50$ cm, $T = 25$ cm).

the difference between sweep and ejection event contributions decreases, while increased ice-cover roughness leads to higher contributions from inward (Q_1) and outward (Q_3) interactions, reducing the prominence of the sweep and ejection events. Near the dike tip, increased noise reduces the amount of valid data, as filtered by WinADV software.

4 LIMITATIONS AND RECOMMENDATIONS

This study is limited by its constrained spatial coverage and reliance on Acoustic Doppler Velocimeter (ADV) measurements

at specific points around the spur dike. While the ADV provides valuable velocity data, its use at discrete locations may miss the broader flow dynamics influenced by the dike's alignment angle and submergence. The technique may overlook subtle variations in flow patterns and the full complexity of turbulent structures. Additionally, using a single ADV restricts the ability to fully capture the temporal and spatial characteristics of recirculation zones and vortices, leading to an incomplete characterization of the flow field.

Future research should expand spatial data collection beyond the current measuring points. Employing multiple ADVs

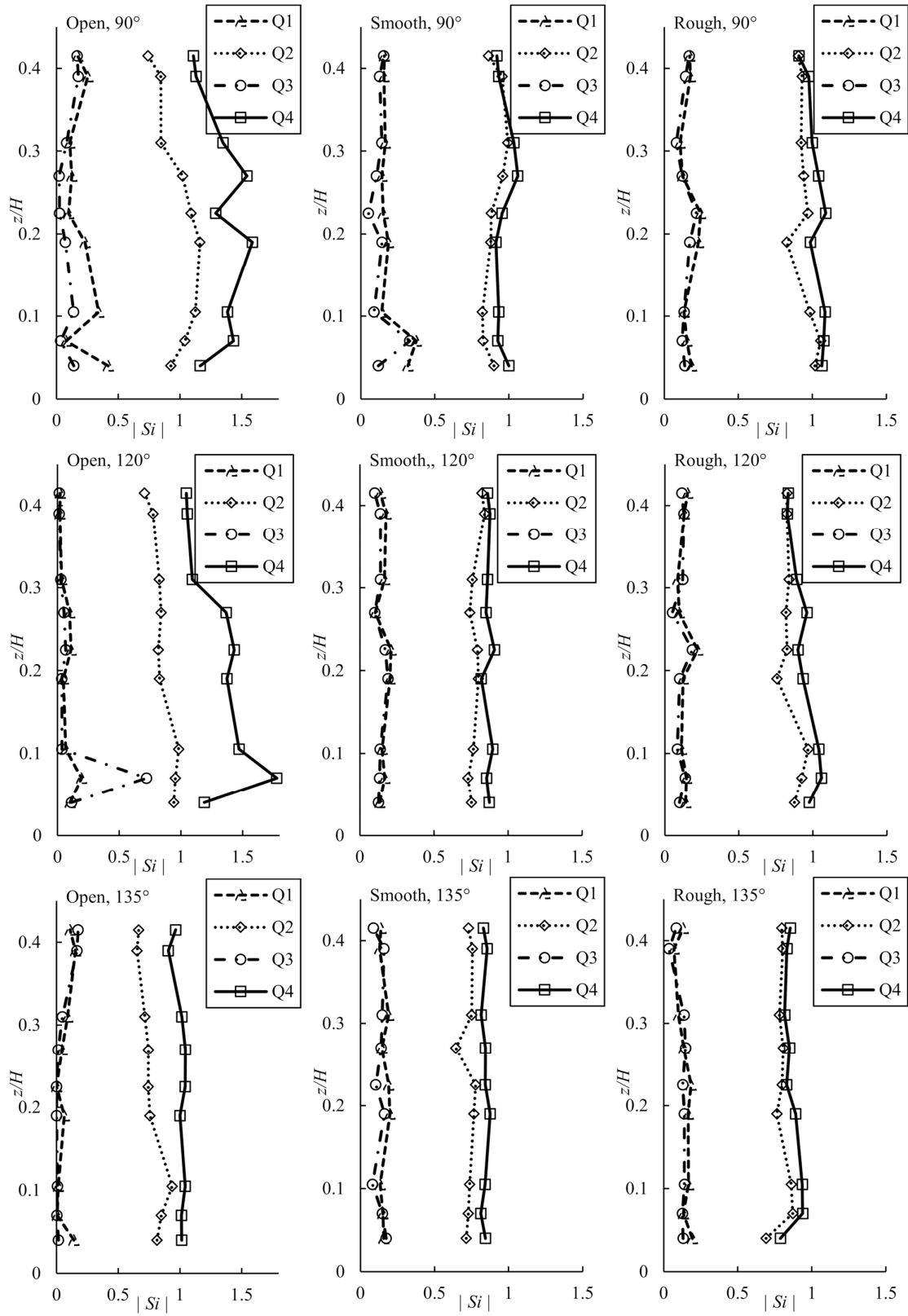


Fig. 15. Variation of the absolute values of contributions $|S_i|$ along the measured results around spur dikes for the case of $H_t = 0$.

or integrating other measurement technologies, such as imaging or numerical simulations, could provide a more comprehensive understanding of turbulent flow structures around spur dikes.

Combining these methods would improve the accuracy and depth of analysis, particularly for submerged dikes and ice-covered flows.

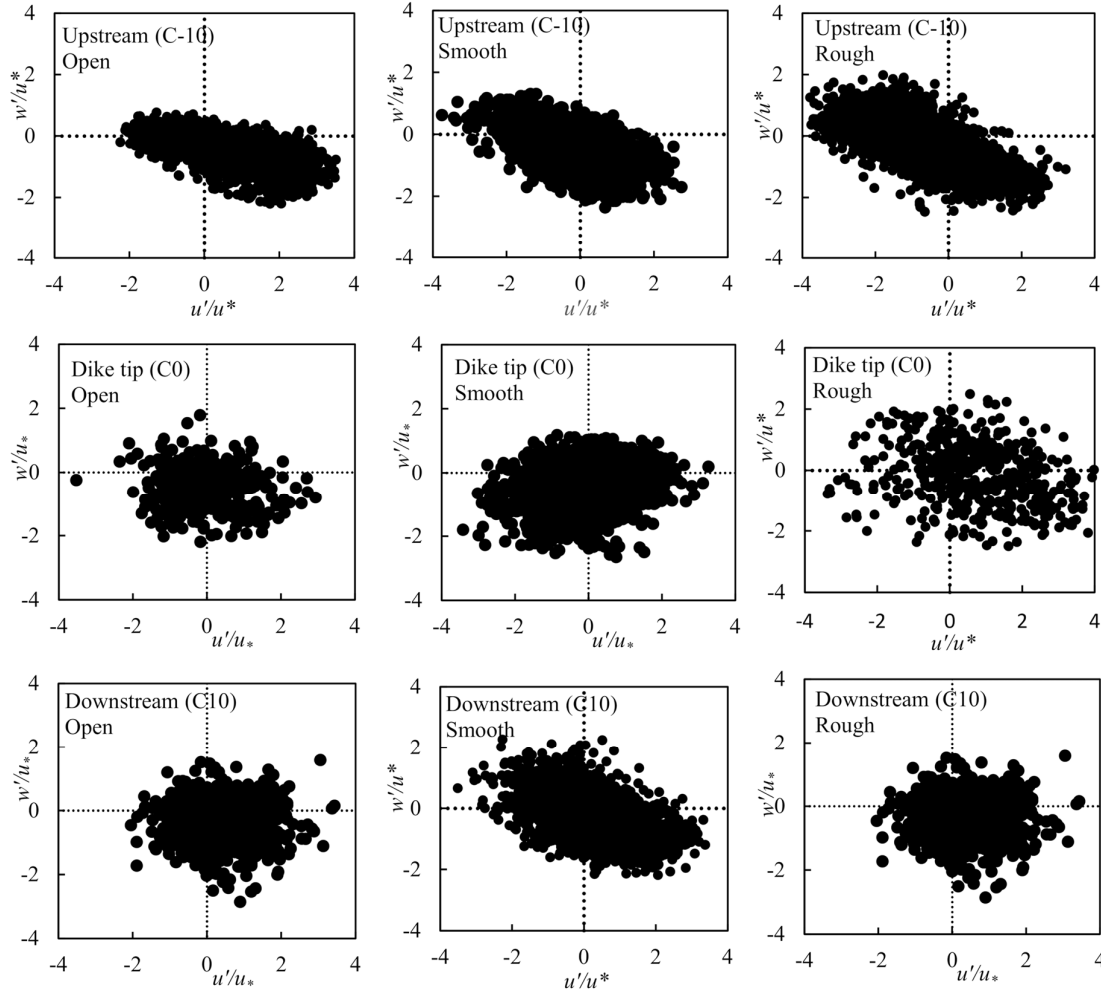


Fig. 16. Probability distributions of u'/u_* and w'/u_* at $z/H = 0.04$ when $H_t = 0$ ($\alpha = 90^\circ$, $L = 50$ cm, $S = 1$).

Additionally, this study focuses on a single dike configuration, using submergence level and alignment angles to represent dike geometry. Future studies should explore multiple dike configurations and additional geometric factors, such as dike head inclination and body slopes, to increase the transferability of the findings. Moreover, while this study controlled bed roughness and sediment mobility to simulate clear-water scour, natural environments feature dynamic sediment movement and evolving scour holes. Future research should incorporate these factors to better simulate natural processes and their influence on local flow dynamics.

5 CONCLUSIONS

This large-scale flume study investigates the turbulence dynamics around submerged spur dikes under various ice-cover conditions, focusing on three-dimensional velocity components, Reynolds shear stress (RSS), and turbulent burst events. It provides insights into the hydrodynamic behavior influenced by dike geometry, flow conditions, and ice cover. Key findings include:

1) Despite the flume's aspect ratio being greater than 5.0, hydrodynamic instabilities were observed due to the boundary layer created by the spur dike. Time-averaged velocity components (u/U , v/U , w/U) at the dike-tip cross-section (Y-Z plane) suggest that as submergence increases, flow over the dike

reduces the recirculation zone's reverse flow. Near the dike front, streamwise (u/U) and lateral (v/U) velocities exhibit negative values near the bed, while vertical (w/U) negative flow occurs higher in the flow region.

2) Ice cover increases maximum streamwise velocity by 12% under smooth ice and 20% under rough ice conditions. Increasing the dike alignment angle from 90° to 135° reduces flow velocity ($u/u_{avg.}$) and increases velocity amplitudes at the dike front, irrespective of surface cover. Streamwise velocity trends align with logarithmic laws for both open-channel and ice-covered flows.

3) Downstream of submerged spur dikes, RSS varies due to recirculation caused by flow separation behind the dike. RSS decreases steadily along the streamwise direction, with more pronounced reductions in moderate submergence due to a larger separation zone. RSS distribution across the flow depth shows increasing, damping, and decreasing zones, with the RSS-decreasing zone extending to zero at the water surface. As ice cover roughness increases, the RSS-increasing and RSS-decreasing zones expand, while the RSS-damping zone contracts.

4) Quadrant analysis shows that ejection and sweep events dominate RSS in both smooth and rough ice-covered conditions, while only sweep events dominate in open-channel flow. Increasing the dike alignment angle from 90° to 135° reduces ejection and sweep contributions due to a lower blockage ratio,

and the difference between dominant (sweep and ejection) and marginal (inward and outward) events diminishes.

This study enhances the understanding of turbulent flow around submerged spur dikes under ice-covered conditions and highlights the effects of dike geometry and ice cover on flow dynamics. Further research should expand the spatial and methodological scope to better capture the interactions between hydraulic structures and environmental factors, incorporating advanced measurement techniques and numerical simulations for a more comprehensive understanding of natural river systems.

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NOMENCLATURE

- B/h – aspect ratio
 B – channel width
 d_{50} – 50th percentile particle diameter (mm)
 h – approaching flow depth
 H_t – threshold hole size
 I – indicator function in quadrant analysis
 k_e – equivalent sand grain roughness (or Nikuradse roughness)
 k_s – average roughness height at the bottom of the ice cover
 L' – projected normal dike length, calculated as $L_d \sin \alpha$
 L_c – flume characteristic length
 L_d – spur dike design length
 l_e – entrance length for fully developed flow
 n_b – channel bed Manning's coefficient
 n_i – Manning's coefficient for ice cover
 n – number of events
 Re – flow Reynolds number
 S_i – proportion of stress for quadrant i
 t_0 – first zero-crossing time
 T – dike height above the initial sand bed
 T_i – integral time scale
 T_t – total turbulent burst time
 u_{*b}, u_{*i} – shear velocity in the lower bed and upper ice cover layer
 u^* – streamwise shear velocity
 u, v, w – WinADV post processed velocity in x, y, z direction
 u', v', w' – velocity fluctuation for u, v, w
 $\overline{u'w'_z}$ – proportion of turbulent bursts that surpass the threshold
 $u'_j w'_j$ – conditional Reynolds stresses
 U – average magnitude of the velocity vector
 $u_{avg}(t)$ – time-averaged streamwise velocity
 u_{avg} – depth-averaged streamwise velocity
 $u_i(t)$ – instantaneous velocity component in x, y, z direction indicated by i
 u_{max} – maximum streamwise velocity component
 W – coefficient of adjustment
 α – spur dike alignment angle
 κ – von Karman constant
 τ_{ij} – Reynolds stress
 τ – lag between two points in time series data