International Journal of Transportation Engineering and Technology
2023; 9(4): 86-95
http://www.sciencepublishinggroup.com/j/ijtet
doi: 10.11648/j.ijtet.20230904.13
ISSN: 2575-1743 (Print); ISSN: 2575-1751 (Online)

Methodology Article

Interpolation Analysis of Shipborne Hydrographic Survey Data Applied to the Discussion of Safe Navigation of Vessels -- Taking Zhoushan Tiaozhoumen Channel as an Example

Lixiong Chen[1, *], Junjie Zhou[2], Dongkui Wu[1]

[1]Merchant Marine College, Shanghai Maritime University, Shanghai, China
[2]Ningbo Dagang Pilotage Co., Ltd. Green Park Building, Ningbo, China

Email address:
chenlixiong2002@163.com (Lixiong Chen), chyo322@163.com (Junjie Zhou), wudk@shmtu.edu.cn (Dongkui Wu)
[*]Corresponding author

To cite this article:
Lixiong Chen, Junjie Zhou, Dongkui Wu. (2023). Interpolation Analysis of Shipborne Hydrographic Survey Data Applied to the Discussion of Safe Navigation of Vessels -- Taking Zhoushan Tiaozhoumen Channel as an Example. *International Journal of Transportation Engineering and Technology*, *9*(4), 86-95. https://doi.org/10.11648/j.ijtet.20230904.13

Received: November 15, 2023; **Accepted**: December 4, 2023; **Published**: December 18, 2023

Abstract: The development of Ningbo-Zhoushan Port requires the enhancement of navigation capacity of Tiaozhoumen Channel. However, the narrow section of the channel has strong and turbulent tidal currents, which poses great difficulties for pilots. Existing data is too simple to guide pilots in safe ship handling. Through shipborne hydrographic survey, the complex flow characteristics are displayed. Ningbo Dagang Pilotage Co., Ltd. hopes to display the flow field situation during the rising and falling tide periods, guide pilots to prepare for flow pressure difference angle, and ensure safe navigation. Interpolation analysis of shipborne hydrographic survey data is applied to display the regularities and characteristics of flow fields at different tide periods. The interpolation results show that the tide period conversion displayed is basically consistent with the tide period of Zhenhai Tide Station, which is referred by pilots in Ningbo Dagang Pilotage Co., Ltd.. The spatial distribution of the current is roughly consistent with the results calculated by pilots based on ship navigation data, which can also reasonably explain the pilot's many years of operating experience in the narrow section of Tiaozhoumen Channel. This indicates that using interpolation analysis of shipborne hydrographic survey data to calculate the flow distribution of the channel water area has a certain rationality. However, the actual flow field is affected by factors such as terrain and weather, and these factors need to be comprehensively considered in prediction to improve accuracy. This study provides important references for flow field analysis in the channel water area, but further research and verification of other related data are still needed to fully understand the changes and predictions of the flow field.

Keywords: Tiaozhoumen Channel, Shipborne Hydrographic Survey Data, Data Interpolation Processing, Distribution of Tidal Currents, Safe Navigation of the Channel

1. Introduction

Tiaozhoumen Channel is one of the important entrances to Ningbo-Zhoushan Port, with superior geographical location, deep waters, small waves, and stable seabed. The current navigation standard allows for fully loaded 150,000-ton bulk carriers and empty loaded 300,000-ton vessels. In order to meet the demand of building a world-class strong port in Ningbo-Zhoushan Port, a new round of development and construction will be carried out in the core port area, which requires upgrading Tiaozhoumen Channel to a 300,000-ton level channel [1]. The construction of Tiaozhoumen Channel can alleviate the navigation pressure of Xiazhi Channel, reduce navigation risks, and create a "dual channel" for ultra-large ships to enter the core port area, effectively guaranteeing the construction of a world-class strong port in Ningbo-Zhoushan Port.

However, as an alternative channel adjacent to the south and parallel to Xiazhi Channel (see Figure 1), Tiaozhoumen Channel has relatively poor navigation conditions, especially in the narrow section of Tiaozhoumen Channel (within one nautical mile before and after the Xiaohuangjiao lighthouse, see Figure 2). This narrow section is influenced by the surrounding island and reef terrain, with strong and turbulent tidal currents, complex flow field conditions, and variable tidal current directions, which bring difficulties in preparing for flow pressure difference angle [2]. Although the nautical chart information shows that the maximum flood and ebb currents in the Tiaozhoumen section are both 5.0 knots, it cannot accurately describe the complex flow field in the narrow section. Therefore, it is planned to use technical means to obtain the distribution of tidal currents in the narrow section.

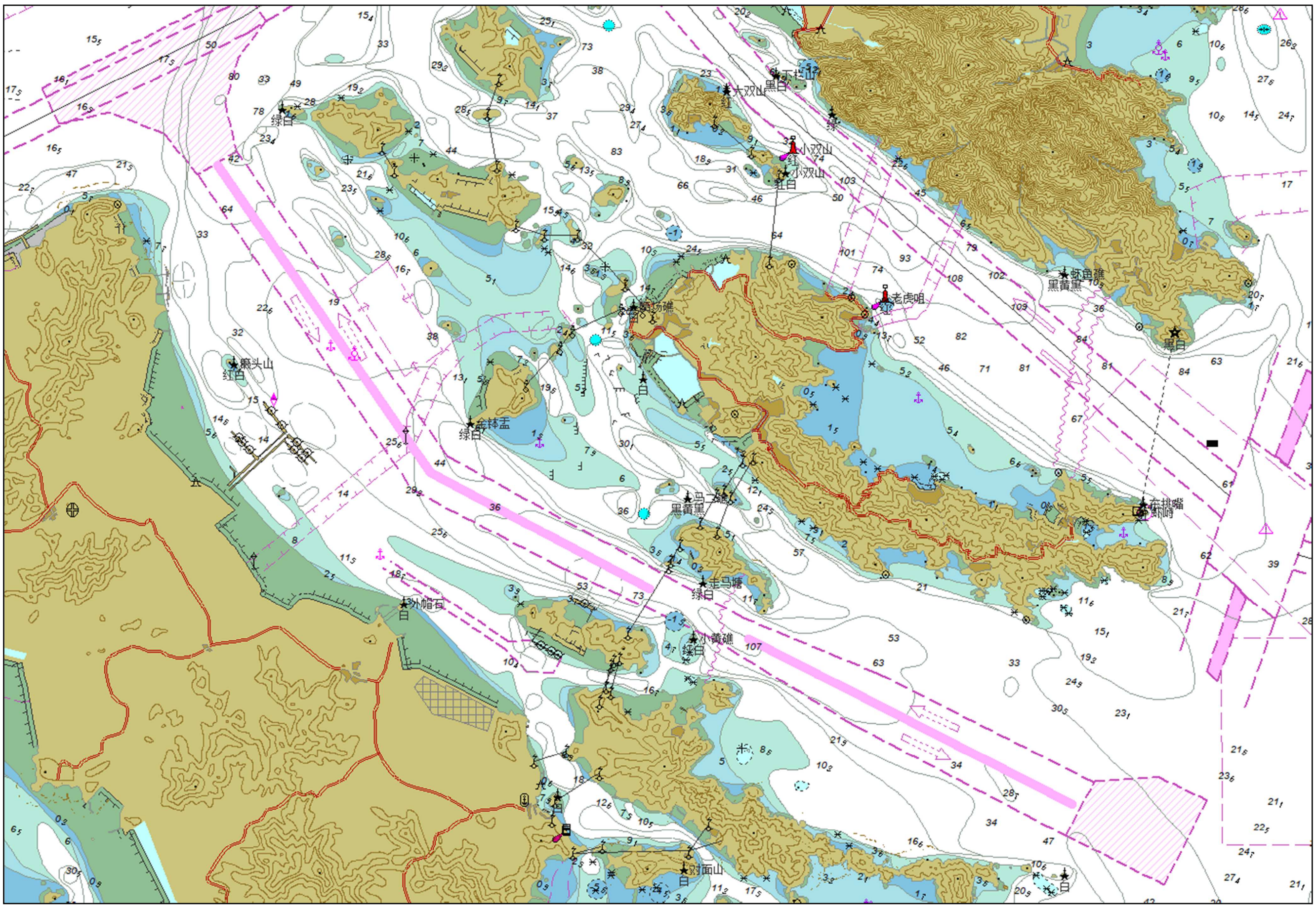

Figure 1. *Schematic map of the geographical location of Tiaozhoumen Channel.*

There are several methods to obtain the distribution of tidal currents [3]. These include direct observations, such as using buoys [4], measurement vessels, and underwater vehicles to conduct real-time monitoring and sampling in the ocean [5], recording parameters such as the speed, direction, and temperature of tidal currents [6]. In addition, remote sensing observations are also commonly used, utilizing radar, laser, and infrared sensors on satellites to monitor the sea surface and collect information on tidal currents [7]. These technologies enable the monitoring and distribution research of tidal currents in large-scale ocean areas, providing important data support for ocean circulation and climate change studies. Numerical simulation methods involve building ocean numerical models to simulate the dynamic processes of the ocean, including the interaction of tidal currents, winds, and tides, in order to infer the distribution of tidal currents [8]. Furthermore, indirect inference of tidal current distribution can be achieved through seabed topography and underwater imaging techniques, ocean buoy arrays, and hydrological methods [9].

To quickly and accurately obtain tidal current data in the narrow section of Tiaozhoumen Channel, we have adopted the shipborne hydrographic survey method [10]. This method utilizes shipborne current measurement instruments to record vessel speed and direction data, combined with GPS positioning technology, to calculate the flow velocity and direction of the water based on inertial navigation and fluid mechanics principles [11, 12]. According to our plan, we conducted 13 consecutive shipborne surveys in the narrow section of Tiaozhoumen Channel on days with different tidal conditions. However, there was a certain discrepancy between the compiled data and the specific flow requirements of Ningbo Dagang Pilotage Co., Ltd. Therefore, the focus of this study is how to compile the flow field at a specific moment using the existing shipborne survey data. We plan to use the 13 shipborne survey data obtained at each measurement point as a time series for interpolation analysis. Interpolation is a method used to handle missing or discontinuous data [13], which can estimate missing data, present a smooth trend in the data sequence, and more accurately analyze and predict the characteristics of water flow changes. Common interpolation methods include linear interpolation, polynomial interpolation, and spline interpolation [14, 15]. Through interpolation analysis, we can obtain continuous and complete flow field information and provide intuitive flow field information for navigating vessels, thereby providing safe navigation services.

2. Organization and Data Acquisition of Shipborne Hydrographic Survey Method for Tidal Currents

To observe the complex water characteristics in the narrow section of Tiaozhoumen Channel, we selected 4 cross-sections and 3 longitudinal points within the channel (as shown in Figure 2) for field measurements. The observation time was chosen during the rapid rise and fall of tides in both spring and neap tide periods. Shipborne surveys were conducted to obtain the basic tidal current data at the observation points. Based on tidal tables and tidal characteristics, we planned to conduct shipborne surveys during the rising and falling tide periods on a neap tide day (July 18, 2021, the ninth day of the lunar calendar) and a spring tide day (originally planned for July 25, but due to the impact of Typhoon "Fireworks" landing in Zhoushan, the survey was postponed to August 10, the third day of the lunar calendar).

During these surveys, we aimed to collect comprehensive data on tidal currents, including velocity, direction, and other relevant parameters. The selected observation points and survey timing were carefully chosen to capture the dynamic nature of tidal currents in the narrow section of Tiaozhoumen Channel.

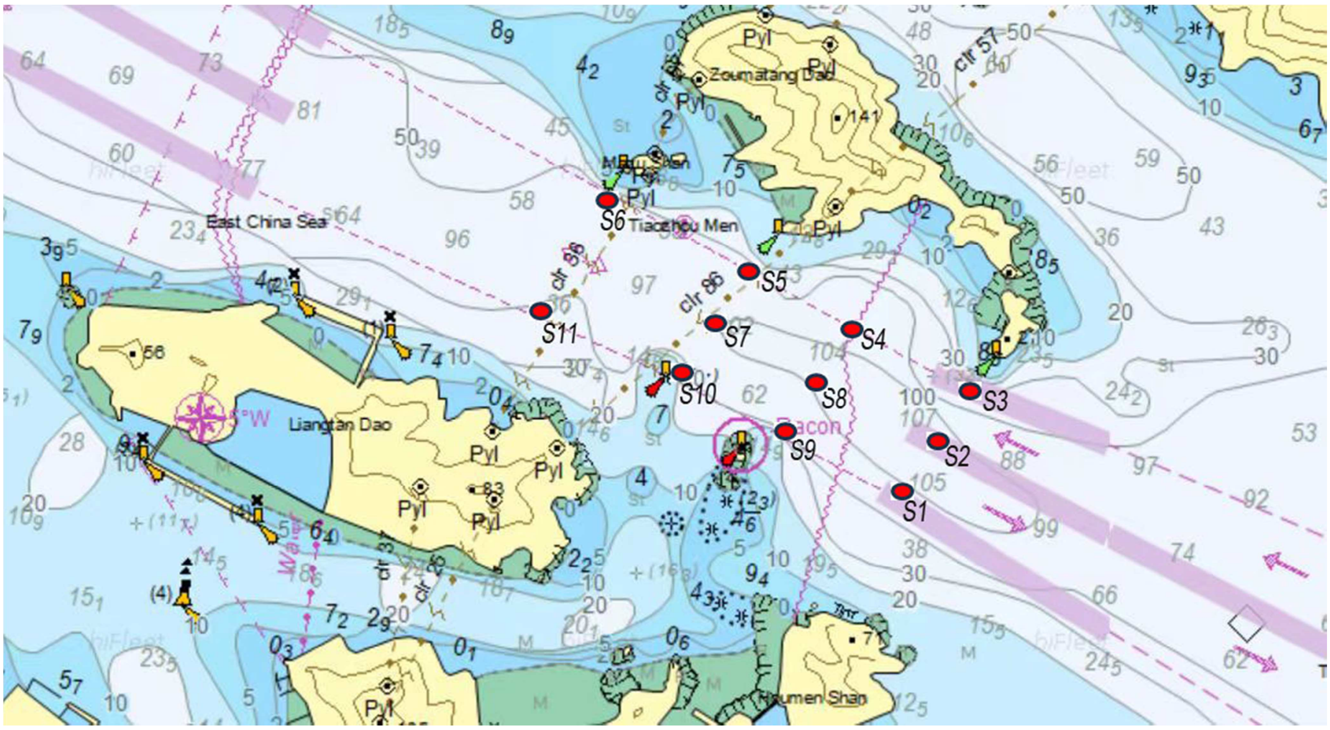

Figure 2. *Overview of the locations of tidal current measurement points in the narrow section of Tiaozhoumen Channel.*

We conducted hydrological data sampling in the narrow section of Tiaozhoumen Channel using an ADCP/TRDI300K and calibrated differential GPS fixed on the ship's side. The sampling was carried out in accordance with the specifications outlined in "Marine Survey Standards," "Channel Measurement Standards," "Water Transport Engineering Measurement Standards," and "Global Positioning System (GPS) Measurement Standards." According to the "Hydrological Data Compilation Standards," we processed the collected data at different layers: surface (the uppermost layer measured by ADCP), 0.2H, 0.4H, 0.6H, 0.8H, and bottom (the lowest layer measured by ADCP). We recorded the time intervals based on the actual arrival time at each station.

We conducted shipborne survey measurements every hour for a total of thirteen consecutive surveys. The measured data for each survey are shown in Figure 3. Subsequently, we extracted and organized the data for each of the thirteen measurement points. For example, the compiled values for measurement point S1 on August 10th are shown in Table 1.

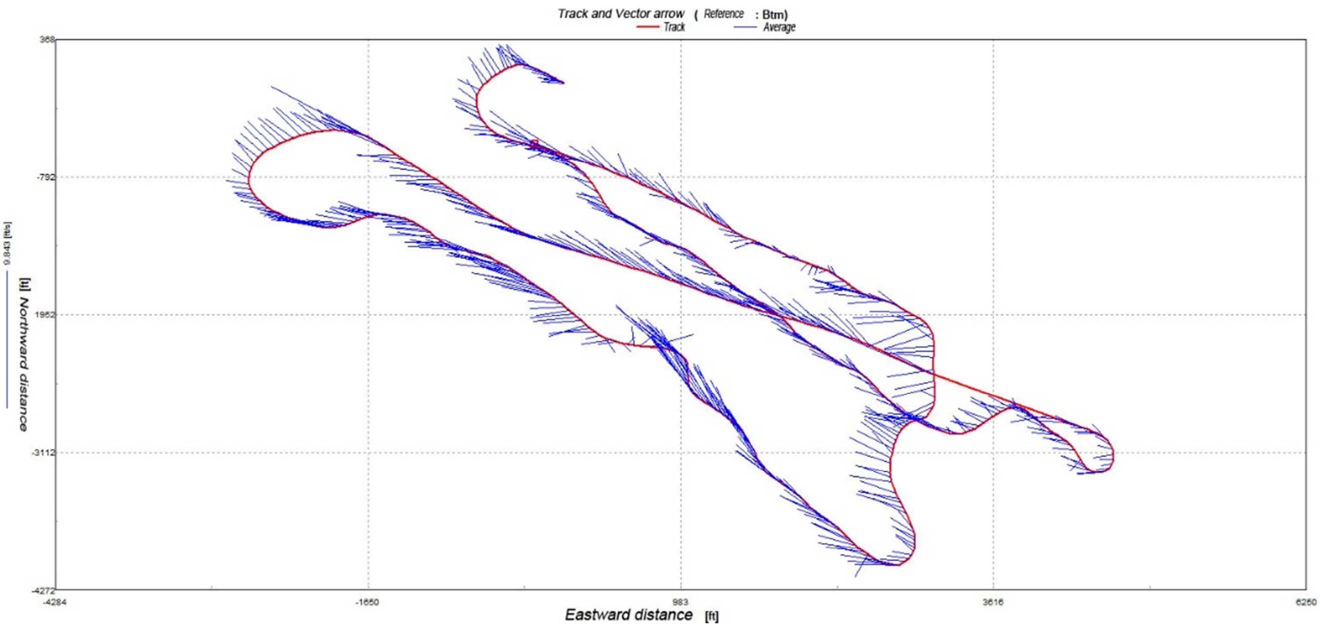

Figure 3. *Schematic diagram of the basic situation of tidal current observation data for each shipborne survey.*

Table 1. *Basic tidal current data for shipborne surveys at measurement point S1 during the spring tide on August 10th, after compilation.*

Area: Tiaozhoumen Channel; Tidal Phase: Spring Tide; Station Number: S1; Location: 29°43.364'N, 122°13.929'E; Instrument: RDI 300K (10681); Survey Vessel: Ningbo Pilot 35								
Serial Number	Date	Time	Surface		0.2H		0.4H	
			Flow Velocity	Flow Direction	Flow Velocity	Flow Direction	Flow Velocity	Flow Direction
			cm/s	(°)	cm/s	(°)	cm/s	(°)
1	2021/8/10	9:58	96	283	101	296	79	293
2	2021/8/10	11:13	91	238	80	241	48	252
3	2021/8/10	13:07	46	99	35	107	26	138
4	2021/8/10	13:20	58	138	59	129	44	145
5	2021/8/10	15:16	53	80	38	91	47	68
6	2021/8/10	16:07	87	75	79	80	76	64
7	2021/8/10	16:55	121	74	125	63	111	73
8	2021/8/10	17:47	102	82	94	74	94	92
9	2021/8/10	18:12	139	134	125	128	104	151
10	2021/8/10	19:19	48	291	46	293	55	290
11	2021/8/10	20:10	83	280	58	285	83	275
12	2021/8/10	21:18	114	281	120	277	116	268
13	2021/8/10	22:14	133	261	120	259	113	268

Table 1. *Continued.*

Area: Tiaozhoumen Channel; Tidal Phase: Spring Tide; Station Number: S1; Location: 29°43.364'N, 122°13.929'E; Instrument: RDI 300K (10681); Survey Vessel: Ningbo Pilot 35									
Serial Number	Date	Time	0.6H		0.8H		Bottom		Depth
			Flow Velocity	Flow Direction	Flow Velocity	Flow Direction	Flow Velocity	Flow Direction	
			cm/s	(°)	cm/s	(°)	cm/s	(°)	(m)
1	2021/8/10	9:58	86	290	83	282	74	271	95.0
2	2021/8/10	11:13	60	257	56	272	41	284	95.3
3	2021/8/10	13:07	24	157	40	126	41	120	95.2
4	2021/8/10	13:20	62	140	60	147	52	116	94.7
5	2021/8/10	15:16	50	113	51	94	42	61	94.1
6	2021/8/10	16:07	82	84	76	84	81	70	93.6
7	2021/8/10	16:55	110	79	105	79	126	65	93.2
8	2021/8/10	17:47	86	72	76	100	76	72	92.8
9	2021/8/10	18:12	123	134	116	127	91	129	92.6
10	2021/8/10	19:19	59	298	48	301	41	297	92.6
11	2021/8/10	20:10	59	266	67	284	53	296	93.2
12	2021/8/10	21:18	100	281	107	294	94	298	94.1
13	2021/8/10	22:14	107	278	105	297	98	260	94.8

3. Interpolation Processing of Measured Flow Vector

Shipborne survey is a method for observing multi-layered profile currents at different depths simultaneously. It has the advantages of time-saving, high efficiency, and wide observation range, and can obtain real-time ocean current data with high timeliness. In the shipborne survey method, the measured data is collected using a single Doppler current profiler on board a ship. To ensure the accuracy of the sampling data, the ship's speed is controlled to be less than 4 knots, and a stop of about 2 minutes is made when designing the sampling points. Therefore, it takes approximately 50 minutes to complete the shipborne survey for 11 measurement points, which cannot achieve synchronous sampling of all 11 points and it is difficult to form a flow distribution mapped by multiple current profilers at the same time.

However, the pilots of Ningbo Dagang Pilotage Co., Ltd. hope to present the flow conditions at a certain moment in the narrow section of Tiaozhoumen Channel, especially the surface tidal flow, in order to provide flow pressure difference for navigating vessels. Therefore, we plan to analyze the existing shipborne survey data and display the surface flow field at the same moment as a time series interpolation of each measurement point's 13 shipborne surveys. This can provide visual guidance for pilots to ensure safe navigation of vessels. However, as the measured ocean current data is a vector, there are certain difficulties in performing direct interpolation calculations. Therefore, we plan to decompose the ocean current data into scalar components and perform interpolation calculations separately before synthesizing them into vectors.

According to the principle of ADCP current measurement, assuming that the velocity of ocean currents can be considered constant within a certain range, ocean current velocity is defined as a three-dimensional velocity vector in the east-west direction, north-south direction, and vertical direction. To measure the velocity vectors in these three directions, ADCP typically emits pulse signals at angles of φ with respect to the vertical direction towards east, west, south, and north directions in seawater simultaneously, as shown in Figure 4 [13]. Taking surface ocean current data as an example, we can organize the shipborne survey data of each measurement point into surface water flow vectors, first decompose them into northward and eastward components, and then perform interpolation analysis on the time series of these components.

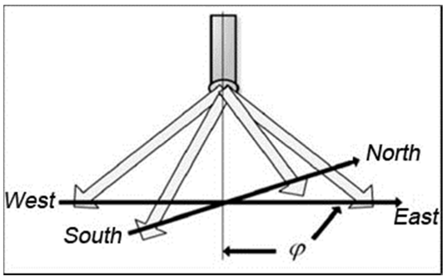

Figure 4. *JANUS structure of ADCP emitting acoustic signals.*

Perform time series interpolation analysis using Matlab software [16]. First, import the observation time, corresponding flow velocity, and flow direction of each measurement point into Matlab. Then, convert the flow velocity and flow direction into north and east components. Next, treat each component as a non-uniformly spaced time series and use interpolation algorithms such as Nearest, Linear, Spline, Pchip, etc. in Matlab to calculate the component values at the desired points and obtain the required time series [17]. Then, extract the values at whole-hour and half-hour time points for both the north and east components. Finally, reverse calculate the flow vectors for each point and compare them with nearby observed values, as well as analyze the values near the endpoints.

Map the 13 shipborne survey data of each measurement point to form a non-uniformly spaced time series. The "Nearest" interpolation yields a step-like fit, which does not match the continuous variation of tidal currents. The "Linear" interpolation yields a jagged fit, similar to "Nearest" interpolation, and does not match the actual tidal current variation. The "Spline" interpolation yields a relatively smooth curve fit, but the trends at the ends of the data series differ significantly from the actual variation. The "Pchip" interpolation yields a relatively smooth curve fit, with relatively smooth trends at the ends of the data series and smaller algorithmic errors. Therefore, "Pchip" piecewise cubic Hermite interpolation algorithm is chosen. Table 2 shows partial results of using the Pchip algorithm for interpolating surface flow velocity data during spring tide. At the same time, the flow vectors at the same moment are plotted to form a flow pattern map. Figure 5 shows the flow pattern map at 1000 hours during spring tide.

Table 2. *Partial interpolated values of surface flow velocity at various measurement points during spring tide. Unit: (cm/s; °).*

Station Number	Time	0930	1000	1030	1100	……	2100	2130	2200	2230
S1	Flow Velocity	108.9	95.4	92.3	93.3	……	106.8	118.0	127.0	141.5
	flow direction	304	281	257	241	……	281	279	268	254
S2	Flow Velocity	148.5	108.0	84.8	72.8	……	122.5	150.2	185.8	226.4
	flow direction	263	280	298	312	……	293	293	294	295
S3	Flow Velocity	204.0	130.6	73.1	39.8	……	140.4	144.1	128.0	126.3
	flow direction	252	249	240	223	……	257	252	265	297
S4	Flow Velocity	111.8	59.5	18.4	20.5	……	43.3	61.9	82.2	106.3
	flow direction	326	330	355	098	……	298	295	291	286
S5	Flow Velocity	169.7	114.4	68.0	38.2	……	64.0	73.9	86.0	107.6
	flow direction	277	280	287	303	……	281	294	284	266

Station Number	Time	0930	1000	1030	1100	……	2100	2130	2200	2230
S6	Flow Velocity	167.2	152.2	130.1	102.0	……	134.4	140.0	132.2	108.2
	flow direction	316	307	300	295	……	282	280	283	296
S7	Flow Velocity	257.3	203.9	154.0	107.8	……	171.6	191.3	198.7	187.0
	flow direction	310	309	308	306	……	286	292	301	314
S8	Flow Velocity	342.1	238.4	151.4	81.0	……	174.2	179.2	172.2	151.8
	flow direction	300	294	288	282	……	296	293	288	277
S9	Flow Velocity	258.2	207.4	156.3	107.8	……	136.9	141.9	145.6	145.0
	flow direction	338	333	327	320	……	280	269	262	261
S10	Flow Velocity	292.8	231.9	174.0	120.3	……	126.0	126.1	131.2	152.9
	flow direction	295	291	285	277	……	309	303	285	263
S11	Flow Velocity	102.1	77.2	47.3	21.3	……	88.7	89.2	110.7	169.6
	flow direction	305	310	318	348	……	312	292	258	234

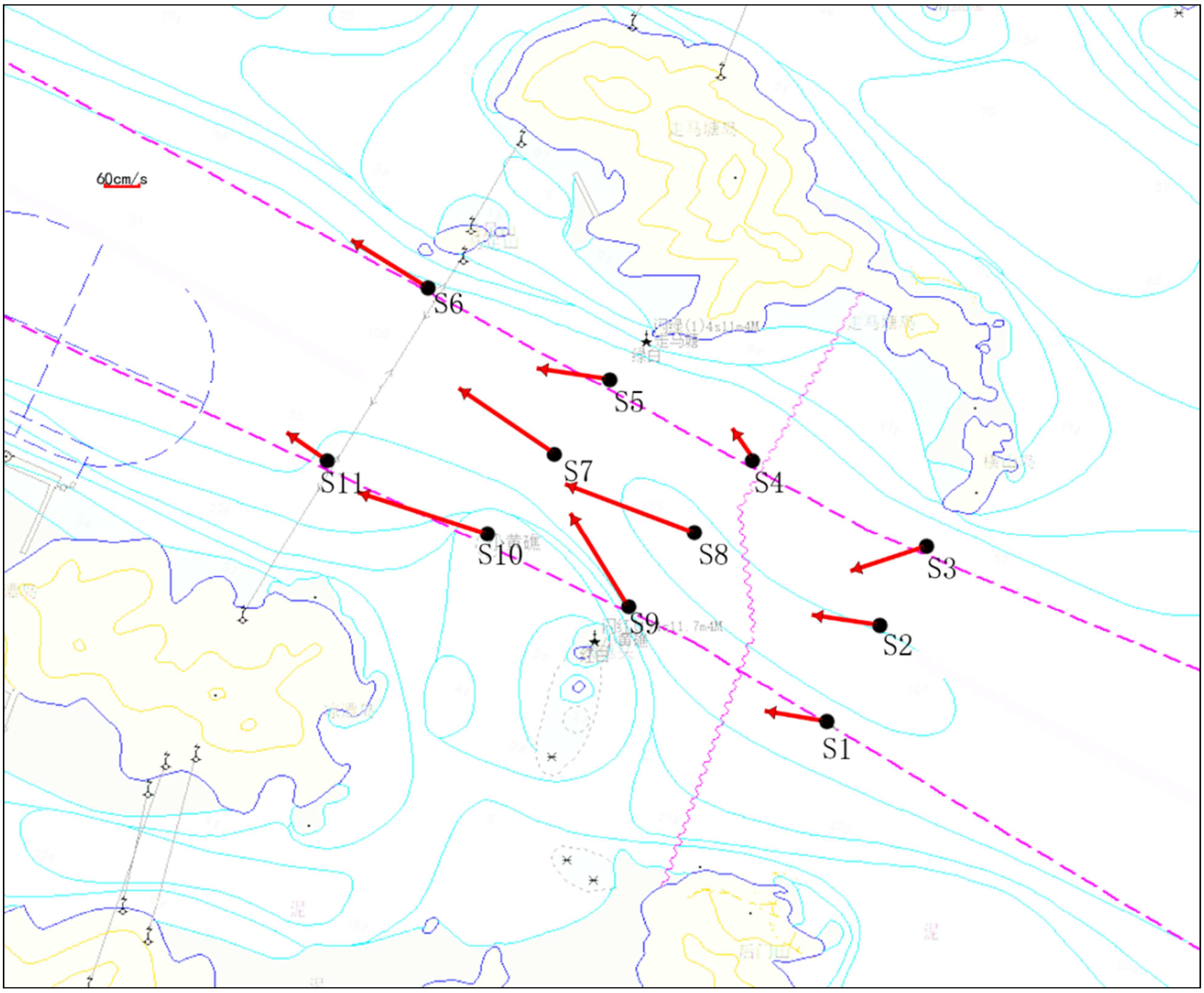

Figure 5. *Flow vector map of 11 measurement points at 1000 hours on August 10th.*

4. Discussion on Current Measurement and Interpolation Results and Reliability

4.1. Analysis of Flow Distribution Characteristics in Shipborne Survey (Surface Current as an Example)

Shipborne survey using ADCP allows for profiling observations of ocean currents in the navigation area, capturing multi-layer profiles of currents at different depths. However, the focus of attention for pilots is the surface flow field within the ship's draft range. Therefore, in shipborne survey data, we analyze the surface flow velocity and flow direction. By summarizing and processing the measured values at different times for each measurement point, we can obtain the distribution of flow vectors at different times for the same measurement point. The distribution of surface flow direction and velocity at the measurement points during neap tide and spring tide is shown in Figure 4 and Figure 5.

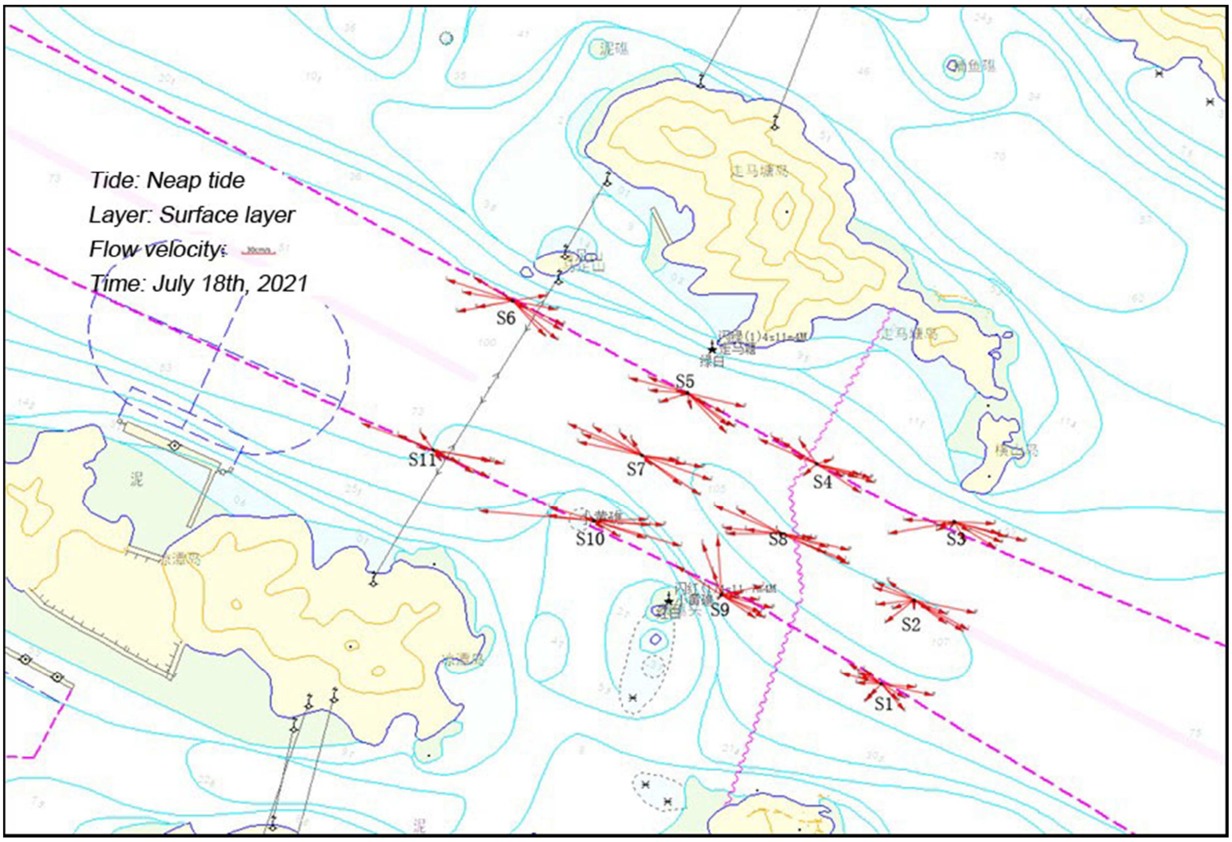

Figure 6. *Surface flow velocity and flow direction map during neap tide on July 18th.*

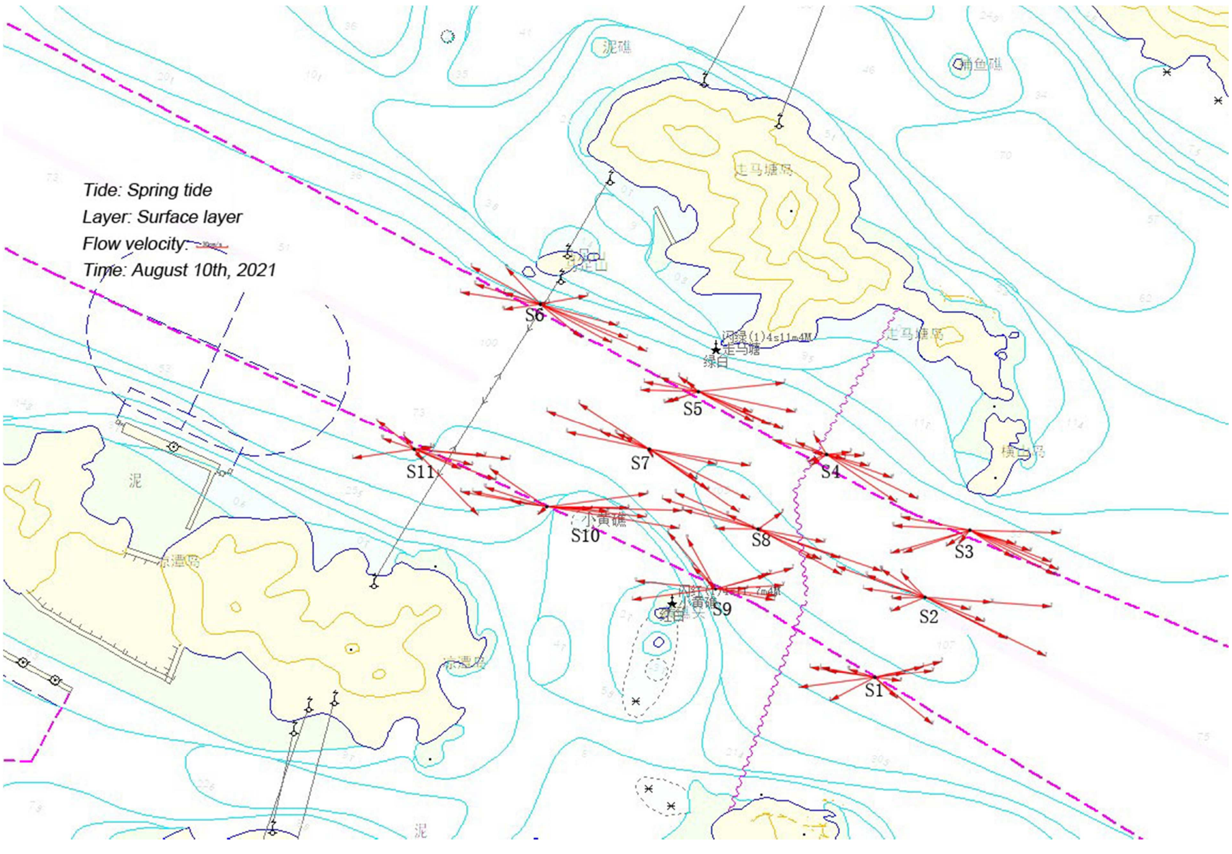

Figure 7. *Surface flow velocity and flow direction map during spring tide on August 10th.*

Based on the analysis results from Figure 6 and Figure 7, we can observe that the flow field at measurement points S1, S3, S4, S5, S6, S9, S10, and S11 is more complex. This is because these points are located near the edges of the channel and are greatly influenced by the terrain and reefs. Although the flow direction at measurement points S2, S7, and S8 near the center of the channel is divergent and the flow field is turbulent, they still exhibit a back-and-forth flow pattern overall. Data analysis shows that the maximum flood current velocity at the measurement points near the center of the channel ranges from 78 to 207 cm/s, while the maximum ebb current velocity ranges from 101 to 247 cm/s. The maximum flood current velocity occurs at measurement point S7 on spring tide days, while the maximum ebb current velocity occurs at measurement point S2 on spring tide days. Furthermore, by comparing the flow velocity values at the three measurement points near the center of the channel, it can be observed that the actual maximum flow velocity exhibits a trend where it is significantly higher than the neap tide flow velocity at the same measurement point on spring tide days. The flood current velocity at measurement point S2 is significantly lower than the ebb current velocity, while the difference in flood and ebb current velocities at measurement point S7 is not significant. On neap tide days, there is not much difference in flood and ebb current velocities at measurement point S8, but on spring tide days, the ebb current velocity is generally higher than the flood current velocity.

Regarding the vertical distribution of the maximum flow velocity near the center of the channel, it was found that there was no significant difference in flow velocity between layers during neap tide, but during spring tide, there was a general distribution pattern where the surface flow velocity was highest, followed by the middle layer, and the bottom layer had the lowest flow velocity. The vertical difference between the upper and lower layers was not significant.

Near the center of the channel in the narrow section, the flow direction of flood and ebb currents was generally stable and did not change much during neap and spring tides. The flow direction of flood current was between 273° and 316°, while the flow direction of ebb current was between 106° and 137°, which is roughly similar to the direction of the channel.

4.2. Characteristics of Whole-Hour and Half-Hour Surface Currents in Interpolated Time Series

Through interpolation processing of neap tide and spring tide data, it was found that the flow vectors at most measurement points in the narrow section of Tiaozhoumen Channel were at a certain angle to the direction of the channel for most of the time, showing a relatively turbulent flow pattern, especially during the transition period between flood and ebb tides. However, during rapid rising or falling stages with higher flow velocity, the flow direction at most measurement points tended to be consistent. Although not all measurement points had consistent flow directions, overall, some measurement points had flow directions that were either towards the center of the channel or towards the edge of the channel. The interpolation results intuitively displayed the flow pattern during the interpolation period in Tiaozhoumen Channel, providing pilots with a visual basis for predicting flow pressure differences for navigating ships. It should be noted that extrapolation at both ends of the numerical calculation may cause significant errors and deviation from actual observations, so further verification is needed to determine whether it can represent the actual tidal current conditions in Tiaozhoumen Channel.

4.3. Discussion on the Reliability of Sailing Current Measurement and Interpolation Results

According to literature and actual measurement data, the tidal current in Tiaozhoumen Channel exhibits a reciprocating flow pattern, with flood current flowing northwest and ebb current flowing southeast. The flow velocity can reach up to 5 knots in the narrow section (between Zoumatang Island and Liangtan Island), while the flow velocity is relatively small on the outer side of the reef [18]. Based on sailing measurement data, the maximum surface current velocity is 2.42 m/s, while the maximum surface current velocity calculated by interpolation is 3.42 m/s, which is consistent with observation data from around 2010.

The pilots at Ningbo Dagang Pilotage Co., Ltd. use the Zhenhai tidal forecast as a reference for the flood and ebb tides in Tiaozhoumen Channel. According to the tidal forecast for Zhenhai on July 18th, the ebb tide process is from 0440 to 1124, the flood tide process is from 1124 to 1744, and the ebb tide process is from 1744 to 2352. On August 10th, the tidal forecast is that the flood tide process is from 0625 to 1225, the ebb tide process is from 1225 to 1824, and the flood tide process is after 1824. Comparison shows that the flow data obtained by interpolation analysis completely matches the flood and ebb tides and transition periods predicted by Zhenhai tidal forecast. This indicates that interpolation analysis based on sailing current measurement data can reflect the flow pattern of the water at a certain moment.

Ningbo Dagang Pilotage Co., Ltd. conducted a shipboard trial in this area from May 16th to June 13th, 2021, and recorded relevant data. Through equipment installed on board, data from 100 ships were collected, including ship name, monitoring time, bow direction, track direction, relative water velocity, ground speed, wind-flow pressure difference angle, true wind direction, wind speed, pilot ladder side, wave height, pilot boat size, and difficulty of boarding and leaving. Through analysis of shipboard data and ship trajectories, the ebb current flow pattern obtained is basically similar to the flow pattern obtained by interpolation based on sailing current measurement.

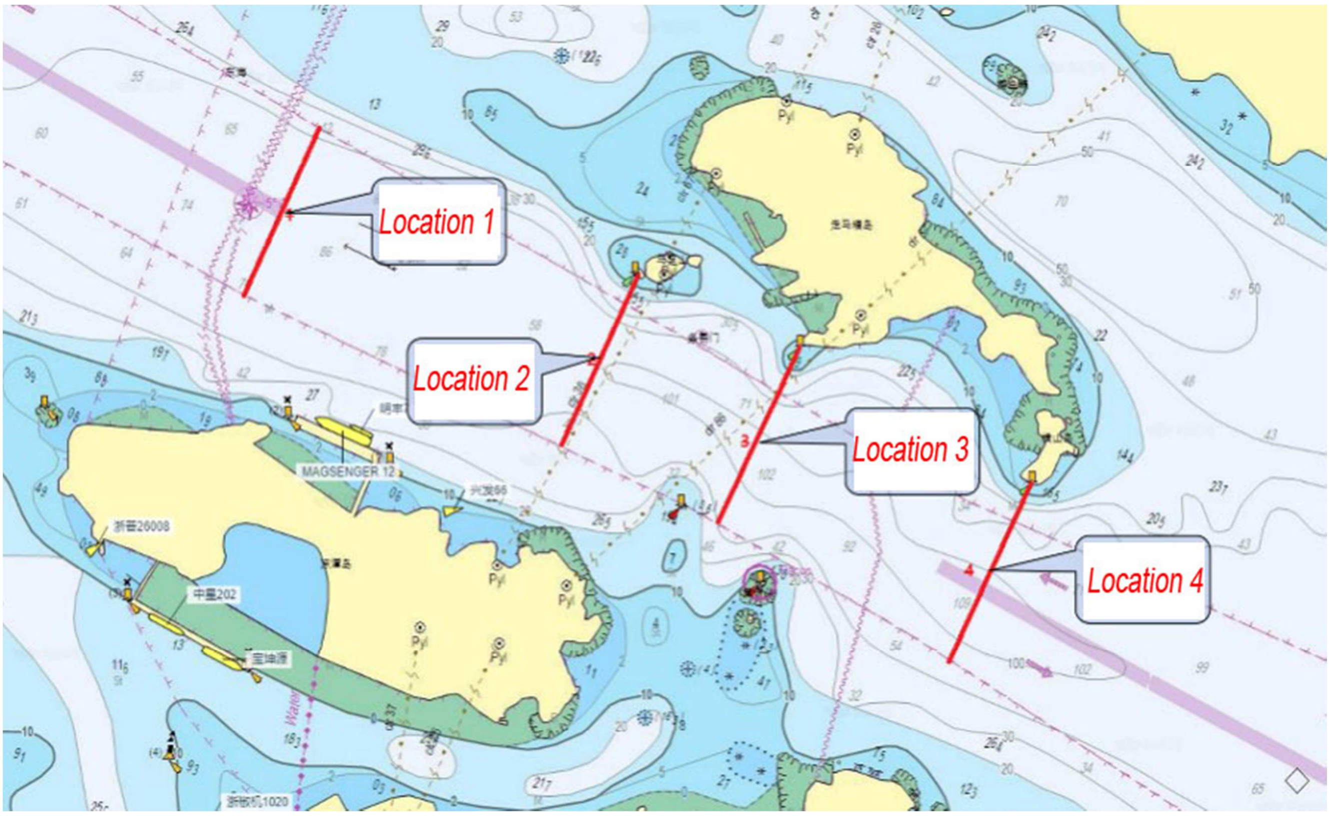

Figure 8. *Observation locations for shipboard trial.*

5. Conclusion and Outlook

The rapid development of Ningbo-Zhoushan Port has led to the saturation of Xiazhi Gate Channel, necessitating the enhancement of the navigational capacity of the adjacent Tiaozhou Strait Channel. However, the Tiaozhou Strait Channel, especially the narrow section, is characterized by turbulent and complex tidal currents, posing great challenges for ship navigation. The existing navigational chart information, which indicates a maximum flood and ebb current of 5 knots, is too simplistic and fails to accurately depict the complex flow patterns in the Tiaozhou Strait Channel. Therefore, sailing current measurement data was collected in the narrow section of the Tiaozhou Strait Channel, and the results showed that the surface flow pattern in the narrow section is generally aligned with the channel's central axis at an angle of 297-117°, while the flow on either side of the central axis is more chaotic. The flow is more turbulent and disorderly on the south side of the channel compared to the north side. Additionally, during spring tides, the maximum flow velocity can reach 2.5 m/s, and vortices are frequently observed near the channel boundaries.

Ship navigators need a visual representation of the distribution of surface flow patterns in the narrow section during flood and ebb tides. They also need to anticipate flow pressure difference angles based on tidal timing and the ship's position to guide safe navigation. The pilots at Ningbo Dagang Pilotage Co., Ltd. have summarized years of operational experience in the narrow section of the Tiaozhou Strait Channel as follows: during ebb tides, there is significant southwestward pressure west of Mazu Mountain, with a noticeable cross-flow pushing towards the channel between Xiaohuang Reef and Huang Reef Head, and mainly southward pressure between Huang Reef Head and Hengshan Island; during flood tides, the flow direction west of Mazu Mountain forms a certain angle with the channel, with slight northward pressure, flow between Xiaohuang Reef and Huang Reef Head diverges away from the channel, and flow between Huang Reef Head and Hengshan Island converges towards the channel. The time-series interpolation results provide a visual explanation for pilot operational experience and further demonstrate the practicality of interpolating sailing current measurement data.

However, with only 13 sailing current measurement data points, the interpolation results aligning with literature observations and pilot operational experience are limited. Sailing current measurement data interpolation is a relatively simple method, and the accuracy of the results is closely related to data quality and interpolation method selection. To obtain flow distribution in small areas like the narrow section, it is necessary to simultaneously measure with equipment such as buoys, multiple survey vessels, and submersibles. Therefore, interpolation algorithms are a remedial measure when existing sailing current measurement data cannot meet the requirements of Ningbo Dagang Pilotage Co., Ltd. and have certain limitations and deficiencies. Actual flow patterns are influenced by various factors such as topography and weather conditions, so these factors need to be considered comprehensively in practical applications to improve prediction accuracy. This study provides important references for analyzing flow patterns in navigational channels but further research and validation of other relevant data are needed to fully understand flow pattern variations and predictions. Future research can explore more accurate methods for current measurement to improve understanding of flow patterns in the Tiaozhou Strait Channel and provide more reliable guidance for safe ship navigation.

Conflicts of Interest

This research paper is based on the research task of the "Improvement of All-weather Navigation Capability in Taizhoumen Channel" conducted by the Port and Shipping Demonstration Research Group at Shanghai Maritime University. Authors Lixiong Chen and Dongkui Wu participated in the field measurements in Taizhoumen as members of the research group. Author Junjie Zhou, as a representative of Ningbo Dagang Pilots Co., Ltd., assisted in the field measurements in Taizhoumen. The research findings are based on objective and impartial analysis, and the study has been conducted independently and scientifically. No potential conflicts of interest have been identified.

References

[1] Editorial Department. Ningbo-Zhoushan Port: "Belt and Road" and the Path to Strong Port. China Ports, 2023, (10): 10-16.

[2] Zhou Xinwei, Tian Yanfei, Qi Weizhong, Zhang Ke, Chen Lijia. Risk Assessment of Navigation Environment in Zhoushan Port's Tiaozhumen Channel. Waterway Transportation, 2022, 44 (04): 27-30.

[3] Xiaodong Liu, Zheng Chen, Yulin Si, Peng Qian, He Wu, Lin Cui, Dahai Zhang. A Review of Tidal Current Energy Resource Assessment in China. Renewable and Sustainable Energy Reviews, Volume 145, 2021, 111012.

[4] Zhou Liangming, Mou Xiaoqian, Lv Jiaoyu, Li Xunxi, Huang Xiaobin, Lai Junrong, Ruan Fangwei, Liu Junquan. Analysis of Sea Current Characteristics Based on Single Buoy Observation in Yangjiang Sea Area of Western Guangdong. Journal of Hainan Tropical Ocean University, 2023, 30 (05): 118-122.

[5] Mou Yong, Liang Chujin, Lin Feilong, et al. Observation and Data Processing of Free-Falling Acoustic Doppler Current Profiler. Acta Oceanologica Sinica, 2023, 45 (04): 144-153.

[6] Elda Miramontes, Pierrick Penven, Ruth Fierens, Laurence Droz, Samuel Toucanne, Stephan J. Jorry, Gwenael Jouet, Lucie Pastor, Ricardo Silva Jacinto, Arnaud Gaillot, Jacques Giraudeau, François Raisson. The Influence of Bottom Currents on the Zambezi Valley Morphology (Mozambique Channel, SW Indian Ocean): In Situ Current Observations and Hydrodynamic Modelling. Marine Geology, Volume 410, 2019, Pages 42-55.

[7] He Yijun, Yang Xiaobo, Yi Na, et al. Research Progress on SAR Measurement of Ocean Current Field. Journal of Nanjing University of Information Science & Technology (Natural Science Edition), 2020, 12 (02): 181-190.

[8] Daejeong Kim, Tahsin Tezdogan, Atilla Incecik. A High-Fidelity CFD-Based Model for the Prediction of Ship Manoeuvrability in Currents. Ocean Engineering, Volume 256, 2022, 111492.

[9] Mingjun Liu, Wenyuan Li, Roy Billinton, Caisheng Wang, Juan Yu. Modeling Tidal Current Speed Using a Wakeby Distribution. Electric Power Systems Research, Volume 127, 2015, Pages 240-248.

[10] Qiao Zhengming, Sun Xia, Liu Xing, Zhong Qiuwen, Zhu Yi, Li Yuchao. Development and Application of Ocean Current Observation Methods. Marine Development and Management, 2022, 39 (05): 106-110.

[11] Feng Shuo. Design and Key Component Research of Ocean Current Observation System Based on Marine Platform [D]. Dalian: Dalian University of Technology, 2019.

[12] Wang Dewei, Hua Chen, Li Wei, Zhang Qiaoli. Research on Precision Control Measures of Sailing ADCP Flow Measurement. Jiangsu Water Resources, 2021, (02): 47-50.

[13] Dong Chao, Zhao Gengxing. Study on the Impact of Time Series Data Set Construction Quality on the Accuracy of Land Cover Classification. Remote Sensing Technology and Application, 2020, 35 (03): 558-566.

[14] Xuli Han. Direction-Consistent Tangent Vectors for Generating Interpolation Curves. Journal of Computational and Applied Mathematics, Volume 346, 2019, Pages 237-246.

[15] Mikhail Kudryavtsev, Sergio Palafox, Luis O. Silva. On a Linear Interpolation Problem for n-Dimensional Vector Polynomials. Journal of Approximation Theory, Volume 199, 2015, Pages 45-62.

[16] Kalani Rubasinghe, Guangming Yao, Jing Niu, Gantumur Tsogtgerel. Polyharmonic Splines Interpolation on Scattered Data in 2D and 3D with Applications. Engineering Analysis with Boundary Elements, Volume 156, 2023, Pages 240-250.

[17] Guo Rui, Li Sumin, Chen Yanan. Application Research of Multiple Interpolation Algorithms Based on MATLAB in Surface Time Series Monitoring. Software, 2019, 40 (04): 18-24.

[18] Wang Yibing, Wang Jie, Wang Zhijun. Tiaozhumen Channel of Ningbo-Zhoushan Port and Its Navigation Method. Navigation Technology, 2014, (03): 11-13.