Field Observation and Experimental Study on the Interaction Between Ship Waves And Vertical Wave Dissipation Revetment

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Abstract. With China's economic development, many inland waterways adopt vertical revetment structure to save land resources, but this structure is not conducive to wave attenuation. According to the measurement results of the ship wave data of typical ship types in Sunan Canal sailing at different speeds collected in field observation, the maximum wave height in front of the vertical revetment wall was less than 1.0 m under normal navigation conditions, while the navigation administration boats can form a wave height of nearly 1.8 m in front of the vertical revetment wall at the maximum speed. In channels with heavy freight and fast ship speed, the ship waves formed by ships, superposed with the reflected waves by vertical impervious revetment, would result in severe water surface fluctuation, affecting the safety of ship navigation and the stability of revetment structure. Based on the regulation project of Sunan Canal, this paper put forward two types of vertical wave dissipation revetment, namely round-hole caisson structure and grid-type structure. And their wave dissipation effects are compared and optimized through 2-D wave test. Finally, the 3-D physical model tests of ship wave and revetment were carried out, and the effects of reducing ship wave height of round-hole caisson structure and grid structure are compared. The results show that these two vertical wave dissipation structures can reduce the maximum ship wave height in front of the revetment wall by about 20–25%. The relevant research results of this paper can serve as a reference for similar projects.

Keywords: Wave dissipation revetment · Ship wave · Field observation · Physical model test

1 Introduction

Jiangsu Province boosts abundant canals and developed water transportation since ancient times (Sun 2007), occupying about one fourth of China's shipping mileage, tonnage of transportation vessels, annual cargo transportation volume and turnover. In response to the economic development and shipping needs in recent years, many canals have carried out waterway regulation by dredging channels and building revetments to improve the efficiency of canals.

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The interaction between ship waves and revetment is a traditional hydrodynamic issue. Revetment structure is one of the important facilities of inland waterway engineering, which can alleviate the scouring of bank slope by water flow and ship waves, thus playing an important role in ensuring the stable and unobstructed waterways. Choosing an appropriate revetment structure is the primary task of revetment engineering design. The revetment structures are generally divided into slope type and vertical type. Slope revetment structure is more commonly used and has a long history, which tends to be more ecological and diversified in recent years (Li et al. 2019). Compared with the slope structure, the vertical revetment requires less land resources but has weaker ability of dissipating ship waves. In order to reduce wave reflection and dissipate waves, people set holes in vertical structures on the wave-ward side, often with perforated caissons. The caisson type breakwaters was first proposed by Jarlan in the 1960s. Subsequently, many domestic and foreign scholars have carried out a lot of experimental research and theoretical analysis on the wave dissipation effect and mechanical characteristics of perforated caissons, and achieved fruitful results (Chen et al. 2001; Shi et al. 2011) while the researchers are focusing more numerical simulation in recent years (Cai et al. 2022). The main mechanism of wave dissipation by using perforated caissons is to introduce part of the wave energy into the caissons through the holes opened on the wave-ward side of the vertical structure, and weaken the reflected waves through the dissipation of waves in the caisson and the influence of phase difference, so as to realize the wave dissipation effect.

The main hydrodynamic force in the canal is ship waves. Throughout the long history of studies on ship waves, many achievements have been made in theoretical research on Kelvin's ship-wave pattern (Ursell 1959) and empirical formulas have been developed through field observation and experiments (Blaauw et al. 1984; Pilarczyk 1984; Robert and Sorensen 1986; Zhou and Chen 1995). In recent years, the research on ship waves mostly focuses on numerical simulation (Zhou et al. 2013).

Relying on the regulation project of Sunan Canal, the field observation was carried out to collect the ship wave under different conditions. Then, 2-D wave tests were carried out to explore different vertical revetment wave dissipation structures and propose the reasonable types of structure accordingly. Finally, 3-D tests of ship waves and different wave dissipation revetments were carried out to verify the effect of vertical revetment on dissipating ship waves.

2 Field Observation of Ship Waves

2.1 Basic Information About Field Observation of Ship Waves

The field observation on the ship waves in Sunan Canal was mainly conducted at two sites: ① Zhenjiang section of Sunan Canal. The revetment spacing on both sides of the channel is 90 m, and the water level during observation was 2.3 m; ② Yixing beltway section of Wushen Line. The revetment spacing on both sides of the channel is 70 m, and the water level during observation was 2.1 m. The upstream and downstream shorelines of the two observation locations are straight. The canal section of the ship wave field observation sites is shown in Fig. 1.

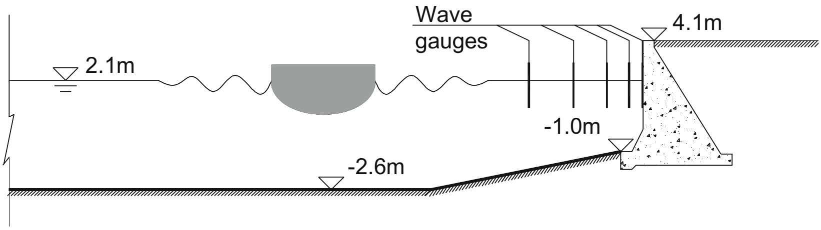

Fig. 1. Schematic diagram of ship wave field observation

The wave gauges which adopted for field ship wave surface measuring are 2 m high. During wave surface measuring, the computer-controlled acquisition system was used, the data collection frequency is 20 20 Hz. The layout of wave height gauges is shown in Fig. 2. The distance between the ship and the shoreline was measured by infrared rangefinder.

Ship types at two sites: 500 ton–1000 ton cargo ships, navigation administration boats.

Ship waves were measured mainly in two scenarios: ① when the canal is under temporary control, and individual vessels pass the canal separately at a constant speed, record the water surface fluctuation process when the vessel passes through the observation points; ② when the canal is open for normal navigation without control measures, record the water surface fluctuation process for a period of time (0.5 hours).

2.2 Main Results of Ship Wave Field Observation

Figure 2 shows the typical water surface fluctuation process in field under normal navigation conditions, while Fig. 3 shows the same process when the navigation administration boat (NA boat) passes through at high speed. Among them, wave gauge 1# was deployed adjacent to the revetment wall, while the distance between wave gauges 2#, 3#, 4# and 5# and the revetment wall were 0.6 m, 1.6 m, 3.1 m and 5.1 m, respectively. The results of the maximum wave height and the maximum runup on the revetment wall measured by wave gauges under normal navigation conditions are shown in Table 1, while those obtained when the NA boat passes through are shown in Table 2.

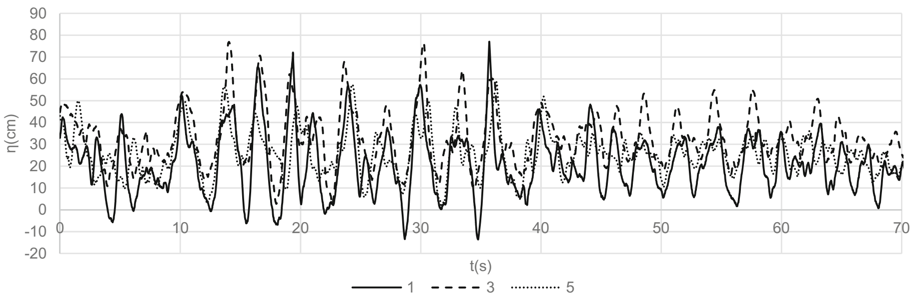

Fig. 2. Typical water surface fluctuation process under normal navigation condition

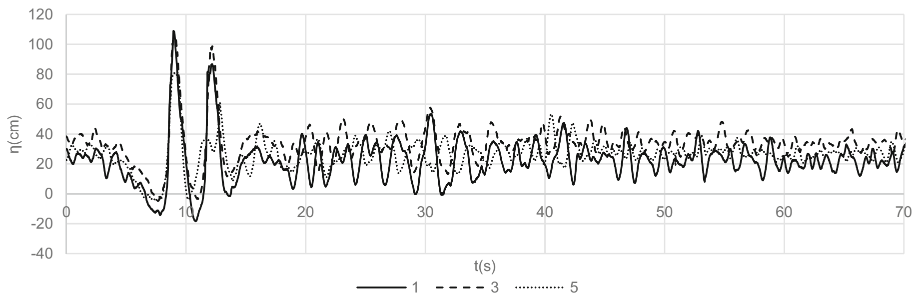

Fig. 3. Typical water surface fluctuation process when the NA boat passes through at a high speed

Table 1. Maximum wave height and runup on the revetment wall measured at two sites (normal navigation)

Measurement no.	Maximum wave height, Hmax (m)					Max runup on the revetment wall (m)	Period (s)
	Gauge 1#	Gauge 2#	Gauge 3#	Gauge 4#	Gauge 5#		
1	0.34	0.29	0.25	0.28	0.33	0.21	1.36
2	0.72	0.70	0.68	0.54	0.54	0.46	1.52
3	0.43	0.31	0.25	0.24	0.32	0.27	1.54
4	0.44	0.40	0.33	0.26	0.32	0.22	1.88
5	0.36	0.29	0.22	0.27	0.27	0.24	2.00
6	0.38	0.35	0.27	0.31	0.32	0.24	1.72
7	0.47	0.33	0.36	0.27	0.31	0.25	1.60
8	0.84	0.73	0.68	0.55	0.50	0.53	2.64

Table 2. Maximum wave height and runup on the revetment wall measured at two sites (NA boat)

Measurement no.	Offshore distance s (m)	Average speed v (m/s)	Hmax (m)					Max runup on the revetment wall (m) (m)	Period (s)
			Gauge 1#	Gauge 2#	Gauge 3#	Gauge 4#	Gauge 5#		
1	15	4.0	0.71	0.64	0.67	0.60	0.65	0.45	2.85
2	17	3.8	0.57	0.50	0.46	0.41	0.35	0.37	2.00
3	15	5.3	1.73	1.61	1.11	0.53	0.84	1.17	3.60
4	15	4.6	1.27	1.14	1.11	1.01	0.89	0.87	3.02

Under normal navigation conditions, the average value of the maximum wave height of different measurement times at the measuring points on the revetment wall was 0.49 m and the maximum wave height was 0.84 m; the average runup of wave on the revetment wall was 0.30 m, and the maximum runup was 0.53 m. The wave height formed by a single cargo ship passing through the observation point was small due to its small speed; when the NA boat passed through the observation point at a high speed, the wave was much higher. The maximum wave height of the observation points on the revetment wall was 1.73 m and the maximum runup height of the wave surface was 1.17 m.

3 2-D Test of Vertical Wave Dissipation Revetment

3.1 Section of Vertical Revetment Wave Dissipation Structure

According to the hydrological, geological and topographic data of the regulated channel, two types of vertical wave dissipation structures were adopted: round-hole caisson structure and grid-type structure. See Fig. 4 for the section and front of the round-hole caisson wave dissipation structure (the elevation unit in the drawing is m, and other marked units are mm). The top elevation of round-hole caisson structure was +4.1 m and the bottom elevation was −1.9 m. The circular holes were 150 mm in diameter, arranged in three rows, with a transverse spacing of 800 mm and a longitudinal spacing of 1000 mm. The elevation of the center point of the top row was +2.6 m and that of the bottom row was +0.6 m. See Fig. 5 for the section and front of the grid-type wave dissipation structure. The upper and lower elevations of grid openings were 3.7 m and 1.3 m respectively, the grid width was 400 mm, and the column width between grids was 600 mm.

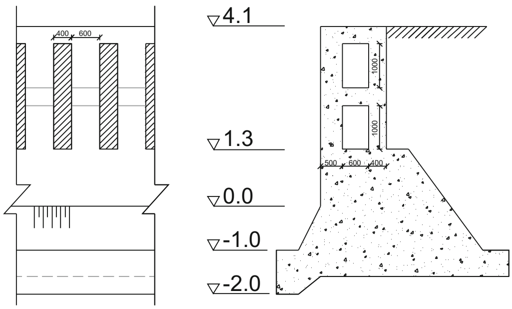

Fig. 4. Round-hole caisson wave dissipation structure

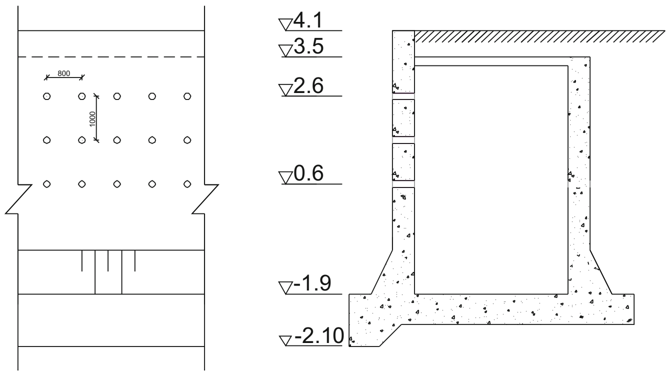

Fig. 5. Grid-type wave dissipation structure

3.2 Test Conditions

The physical model test of wave section was carried out in the wave tank, which was 170 m long, 1.2 m wide and 1.6 m deep. One end of the flume was equipped with a wave maker and the other end a wave dissipation slope. The test was designed according to Froude's law of similarity, and the geometric scale of the model was 1:5. Regular wave is adopted for the section test wave, with the test wave period including 2.0 s and 3.0 s, and the test wave height including 0.3 m and 0.5 m. During the test, capacitive sensors were adopted to measure the wave surface, which was automatically collected by computer control at the sampling frequency of 40 Hz; the reflection coefficient was analyzed by multipoint method.

3.3 Test Results and Analysis

(1) Test results of round-hole caisson wave dissipation structure

The opening ratio of round-hole caisson wave dissipation structure has a great influence on its wave dissipation effect. In the section test, the reflection coefficients of perforated caisson under different opening ratio were measured to analyze the influence of opening ratio on the reflection coefficient. The caisson opening ratio (n) is equal to the ratio of the hole area in the opening area to the total area. When n = 0.15, the transverse spacing of holes was 40 cm, the longitudinal spacing was 30 cm and the hole diameter was 15 cm. When n = 0.22, the transverse spacing of holes was 40 cm, the longitudinal spacing was 20 cm and the hole diameter was 15 cm. When n = 0.26, the transverse spacing of holes was 40 cm, the longitudinal spacing was 30 cm and the hole diameter was 20 cm. When n = 0.39, the transverse spacing of holes was 40 cm, the longitudinal spacing was 20 cm and the hole diameter was 20 cm. See Fig. 6 for comparison of reflection coefficient test results of wave dissipation structure with different opening ratio.

The results show that when the water level is 2.5 m, the wave period is 2 s and the wave height is 0.3 m, the reflection coefficients of the round-hole caisson revetment wave dissipation structure are 0.94, 0.71, 0.61, 0.59 and 0.57 respectively under opening ratio of 0.02, 0.15, 0.22, 0.26 and 0.39, indicating that the decreasing trend of reflection coefficient slows down when the opening ratio is greater than 0.26.

(2) Test results of grid-type wave dissipation structure

Considering the structural design of the grid-type structure, the test was made with two kinds of opening structures. One structure was with an opening ratio of about 0.40, grid width of 90 cm (solid part), grid spacing of 60 cm (cavity part), while the other was with an opening ratio of about 0.33, grid width of 100 cm (solid part) and grid spacing of 50 cm (cavity part). The top and bottom elevations of the grid structure are shown in Fig. 5. The test results of reflection coefficients of the two grid-type structures under the action of different waves with the water level of 2.5 m are shown in Table 3.

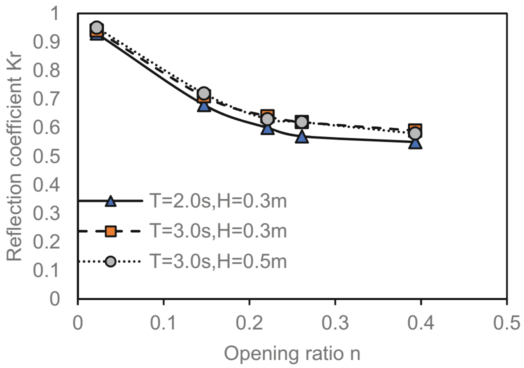

Fig. 6. Variation of wave reflection coefficient of round-hole caisson under different opening ratio

Table 3. Test results of wave reflection coefficient of different grid-type structures

Period (s)	Incident wave height (m)	n = 0.40	n = 0.33
2.0	0.3	0.75	0.78
3.0	0.3	0.74	0.77
	0.5	0.66	0.67

The test results show that the two grid structures have similar wave dissipation effects. Under the action of forward waves, the wave reflection coefficient of the grid-type wave dissipation structure was larger than that of the round-hole caisson wave dissipation structure.

4 3-D Test of Ship Waves and Revetment

4.1 Test Conditions

The bottom width of the test channel is 46 m, and the spacing of the fronts of the revetment wall is 90 m. See Fig. 7 for the section. The test water level is the average navigable water level, i.e. +2.5 m.

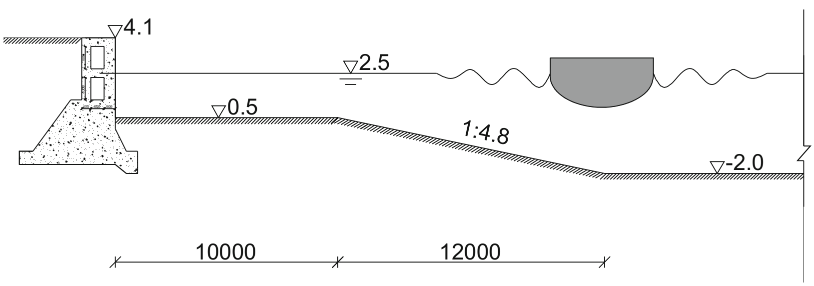

Fig. 7. Channel section of the 3-D test of ship waves and revetment

The test ship includes 1000 t cargo ship and 500 t cargo ship. See Table 4 for the type and size of ship for the 3-D test.

Table 4. Ship type and size for the 3-D test of ship waves and revetment

Ship type	Length (m)	Width (m)	Draft depth (m)
500 t cargo ship	41.6	8.3	3.0
1000 t cargo ship	44.6	8.8	3.4

Five types of different revetment structures were tested, including:

REVETMENT 1: vertical impervious structure;
REVETMENT 2: round-hole caisson structure (opening ratio n = 0.02);
REVETMENT 3: round- hole caisson structure (opening ratio n = 0.26);
REVETMENT 4: grid-type structure (opening ratio n = 0.4);
REVETMENT 5: riprap slope structure (slope gradient 1:2).

4.2 Model Test Design

The test was carried out in a water tank with a length of 50 m, a width of 6.0 m and a height of 0.8 m. The revetment structure is simulated within a 20 m section in the middle. The ends of the water tank are the acceleration and deceleration areas of the test ship, as shown in Fig. 8. The geometric scale of the 3-D ship waves and revetment wave dissipation test model is 1:20.

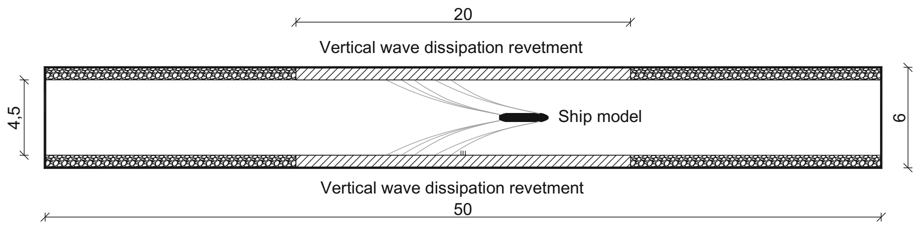

Fig. 8. Layout of the 3-D ship wave and revetment test model

The model ship is self-propelled with remote control, with the designed maximum speed of 2.5 m/s.

The wave height is measured by using capacitive wave surface sensors, and sample collection is controlled by computer at the sampling frequency of 40 Hz. The layout position of wave gauge is the same as that in the field observation.

Particle imaging analysis technology is adopted for the measurement of ship speed trajectory: install position identification devices on the ship model, erect high-definition camera devices above the water tank, and calculate the motion trajectory and speed of the ship through video analysis software.

During the test, accelerate the model ship to a certain speed before the test section and stabilize it, and then drive it into the model test section at a uniform speed. Measure the ship speed by using the particle imaging system and collect the wave surface process of each measuring point by the wave surface acquisition system. See Fig. 9 for test photos.

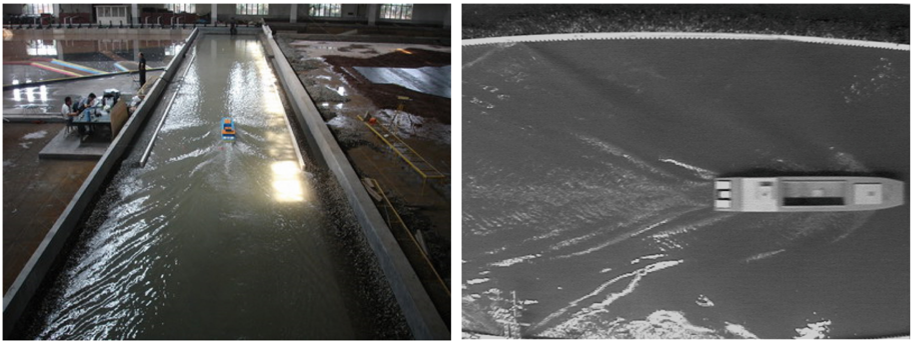

Fig. 9. Photos of 3-D ship wave and revetment test

4.3 Model Test Results

(1) Comparison between the test results and field observation results
The fourth condition of field observation of NA boats in Table 5 was re-demonstrated in the 3-D test. During the ship wave re-demonstration test, the revetment wall is a vertical impervious structure. See Fig. 10 for the comparison between the waveform change at the revetment wall measured in the laboratory and the field observation results. In general, the waveform changes of the ship waves were basically identical, from the larger "bow waves" caused by the ship to the "stern waves" with relatively small wave height. The peak shape and interval of the "bow waves" simulated in the laboratory were basically consistent with those measured during field observation. However, the water reduction phenomenon of the bow wave front was greater than that in the field observation, which was mainly due to the difference between the near shore terrain of the channel at the field observation site and the simulated terrain in that the water at the field was deeper while that in the near shore of the laboratory was shallow. The comparison between the maximum wave height at the revetment wall generated by 1000 t cargo and 500 t cargo ship sailing at different speeds in the laboratory and the field observation results is shown in Fig. 11 (22 m from the center line along the edge of the channel). It can be seen that the trend of maximum wave height is close to the speed variation.

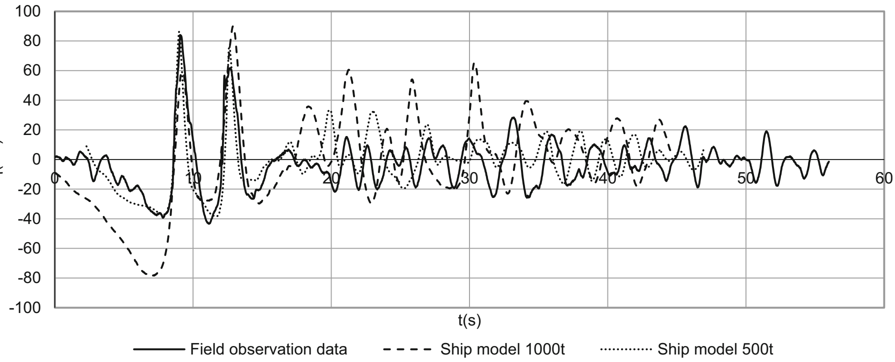

Fig. 10. Comparison of wave surface fluctuation process between field observation and test

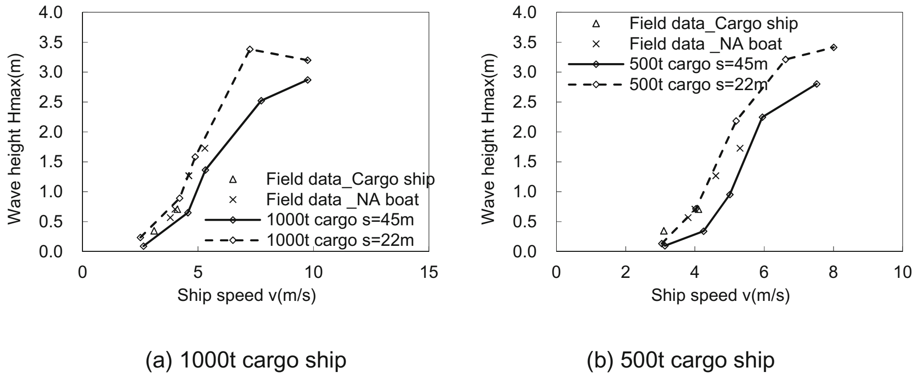

Fig. 11. Comparison of ship wave height between test and field observation

(2) Comparison of wave dissipating effect of different revetment structures
In the test, the wave height in front of the revetment wall was measured under different ship speeds and offshore distance. The comparison of the maximum wave height in front of the revetment wall in different routes is shown in Fig. 12

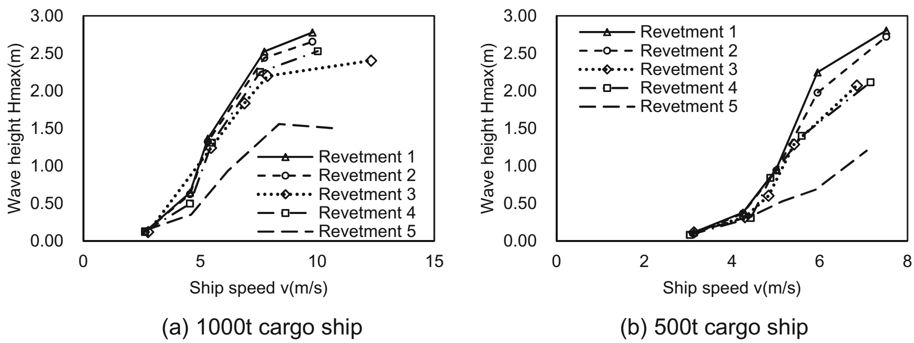

Fig. 12. Comparison of the maximum ship wave height in front of the revetment wall of different revetment structures when the vessel is sailing in the middle of the channel

The test results show that the maximum wave height was similar in the case of vertical impervious revetment structure and round-hole caisson structure (opening ratio n = 0.02), followed by grid-type structure (opening ratio n = 0.4) and round-hole caisson structure (opening ratio n = 0.26), and the smallest height was generated with riprap slope structure. The maximum wave height in front of the revetment wall of the round-hole caisson structure (opening ratio n = 0.26) and the grid-type structure (opening ratio n = 0.4) was reduced by about 20–25%, while that of the riprap slope structure was reduced by about 40%.

5 Main Conclusions

Vertical revetment is a structure that saves land resources, but it can hardly reduce the wave reflection. In the waterway with busy shipping and fast vessel speed, the interaction between vertical impervious revetment structure and ship waves often leads to severe water surface fluctuation, which will affect navigation safety. In addition, the larger wave height is also unfavorable to the stability and safety of revetment. Through field observation, 2-D wave test and 3-D ship wave and revetment test, this study came to the following conclusions:

(1) The field observation on ship waves in Sunan Canal shows that under normal navigation conditions, the maximum ship wave height formed by cargo ships on the canal was less than 1.0 m, but the maximum height of the waves formed in front of the vertical revetment wall can reach 1.73 m when the NA boats sail at the maximum speed.
(2) The 2-D wave test results show that the wave dissipation effect of the round-hole caisson structure was continuously improved with the increased opening ratio of the wave-ward side. When the water level was 2.5 m, the wave period was 2 s, the wave height was 0.3 m, and the opening ratio of the round-hole caisson wave dissipation structure were 0.02, 0.15, 0.22, 0.26 and 0.39, the wave reflection coefficients were 0.94, 0.71, 0.61, 0.59 and 0.57, respectively.
(3) The 3-D test of the interaction between ship waves and revetment shows that the round-hole caisson structure (opening ratio n = 0.26) and grid-type structure (opening ratio n = 0.4) could effectively reduce the front wave height of the revetment wall by about 20–25%.

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