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COMPOSITE COASTAL PROTECTION METHODS USED AT CIJIN COAST, TAIWAN

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Key words: numerical simulation, submerged detached breakwaters, artificial nourishments, topographical evolution, physical model.

ABSTRACT

Cijin Coast has suffered from severe beach erosion and a consequent coastline retreat. To analyze the trend of topographic evolution of Cijin Coast, bathymetric data from field investigation were used and both numerical simulation and physical modeling were implemented in the wave basin to obtain the corresponding parameters that replicate similar phenomena. To protect Cijin Coast, composite coastal protection methods, such as submerged detached breakwaters accompanied with artificial nourishments, were proposed. Parameters used in previous studies were employed to test the proposed protection methods, and the results showed that the methods were effective in preventing the consequent retreat of the coastline. Thus, field construction of the proposed methods was initiated and completed in August 2013. Recent aerial photographs showed that the beach erosion was eliminated, proving the validity of the composite methods.

I. INTRODUCTION

Cijin Coast lies to the west of Kaohsiung City, located in the southwest of Taiwan (Fig. 1). It is located between the two entrances of Kaohsiung Harbor. There are numerous recreational facilities, such as the Cijin lido (CL), coastal park (CP), sightseeing deck (SD), softball field (SF), and windmill park (WP) that have been constructed by the Kaohsiung City government (KCG) for developing a superior marine environment. In recent years, significant erosion around Cijin Coast has resulted in the retreat of the coastline and the endangerment of structures in the surrounding areas (e.g., toe scouring in front of the CL) (Fig. 2). Through comparison with the previous

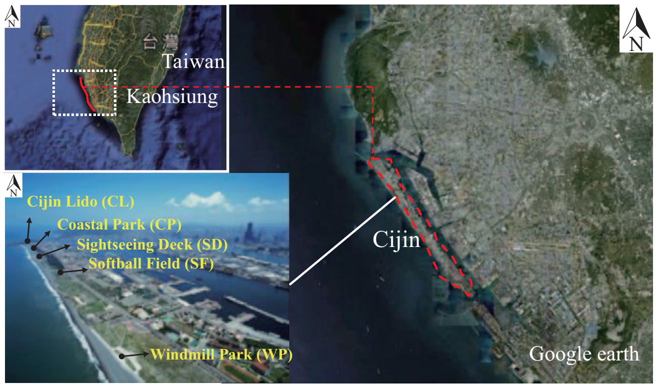

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Fig. 1. Location map of Cijin Coast.

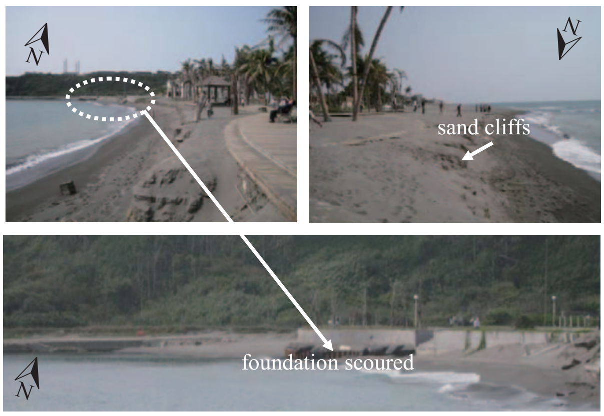

Fig. 2. Photographs of Cijin Lido.

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Fig. 3. Comparison of historical photographs near Softball Field.

Fig. 4. Comparison of historical photographs near Windmill Park.

photographs (Figs. 3 and 4), we observed that the platform near the SF had collapsed and the stone cage in front of the WP was damaged. Although the beach in the coastal area near WP was strengthened by vertical steel piles, beach erosion was worsening. Thus, the KCG started conducting a series of projects to protect Cijin Coast.

Submerged detached breakwaters might be one of the optimal choices for reducing the negative impact on the amenities and aesthetic values of the beach. Consequently, community pressure on coastal management authorities and government agencies to consider submerged structures for beach protection has increased (Ranasinghe and Turner, 2006; Ranasinghe et al., 2006). Several studies have been conducted on the feasibility of submerged coastal structures, such as those by Deguchi and Sawaragi (1986), Douglass and Weggel (1987), Lamberti and Mancinelli (1996), Tomassicchio (1996), Dean et al. (1997), Jackson et al. (2002), and Liou et al. (2009). Using appropriate design parameters of the submerged structures, such as their position with respect to the shore, their toe depth, toe width, toe length, toe height, and the gap between pairs of structures, the wave impact might be reduced and a salient might be formed in the lee of the submerged structures. Researchers believe that artificial nourishments behind a submerged breakwater might also alter the wave height and wave period and result in a more stable coast enlargement (Zhang et al., 2010; Wu et al., 2012). Implementation of beach nourishments in E.U. countries has been discussed with respect to the general situation, project type and objectives, design and evaluation procedures, legal framework, and financial aspects

Table 1. Bathymetry survey data near Cijin Coast.

Survey time	Remark
2005 summer	Survey range: Cijin coastline, from the Kaohsiung First Harbor to the Kaohsiung Second Harbor, about 7.5 km in length.
2005 winter	
2006 winter	
2007 summer	
2007 winter	
2008 summer	
2008 winter	
2009 summer	
2009 winter	
2010 summer	

Data is courtesy of the KCG and integrated by this study.

(Hamm et al., 2002; Hanson et al., 2002). Shoreline evolution caused by beach nourishments has also been investigated using various approaches (Dean, 2005; Kuang et al., 2010; Kuang et al., 2011). Beach nourishments are regarded as an effective means of coastline preservation and are expected to continue over the foreseeable future.

The purpose of this study was to verify the adoptability of the aforementioned engineering methods at Cijin Coast. Historical variations in bathymetry near Cijin Coast were quantified and a series of numerical and physical modeling tests were adopted to investigate the topographic response to submerged structures. Furthermore, field bathymetric profiles before and after the implementation of the protection plan were characterized.

II. SEDIMENT TRANSPORT IN THE CIJIN COAST AREA

1. Evolution of the Cijin Coastline

Because of the complex phenomena of sediment transport, a series of investigations on the evolution of the Cijin coastline over time was completed prior to the improvement planning. From 2005, the KCG has started a regular project for monitoring bathymetry near the Cijin coastal area. Bathymetric surveys were conducted biannually, during the summer (June to August) and winter (October to December) seasons. In this study, data of 10 bathymetric surveys, spanning a period of six years, were used (Table 1), and the reference height was the local mean water level.

Fig. 5 depicts the planar bathymetric deviation indicated by the subtraction of the bottom elevation at the reference period (2005 summer) from that at subsequent times, within a depth of 20.0 m, where the color represents the quantities of bathymetric deviation, the positive values denote beach accretion, and the negative values denote beach erosion. During the summer, monsoon, and typhoon periods, a majority of the nearshore areas of the Cijin beach were gradually eroded. The tendency of coastline retreat was evident near the CP and SF, and the amount of erosion near the north of the WP increased

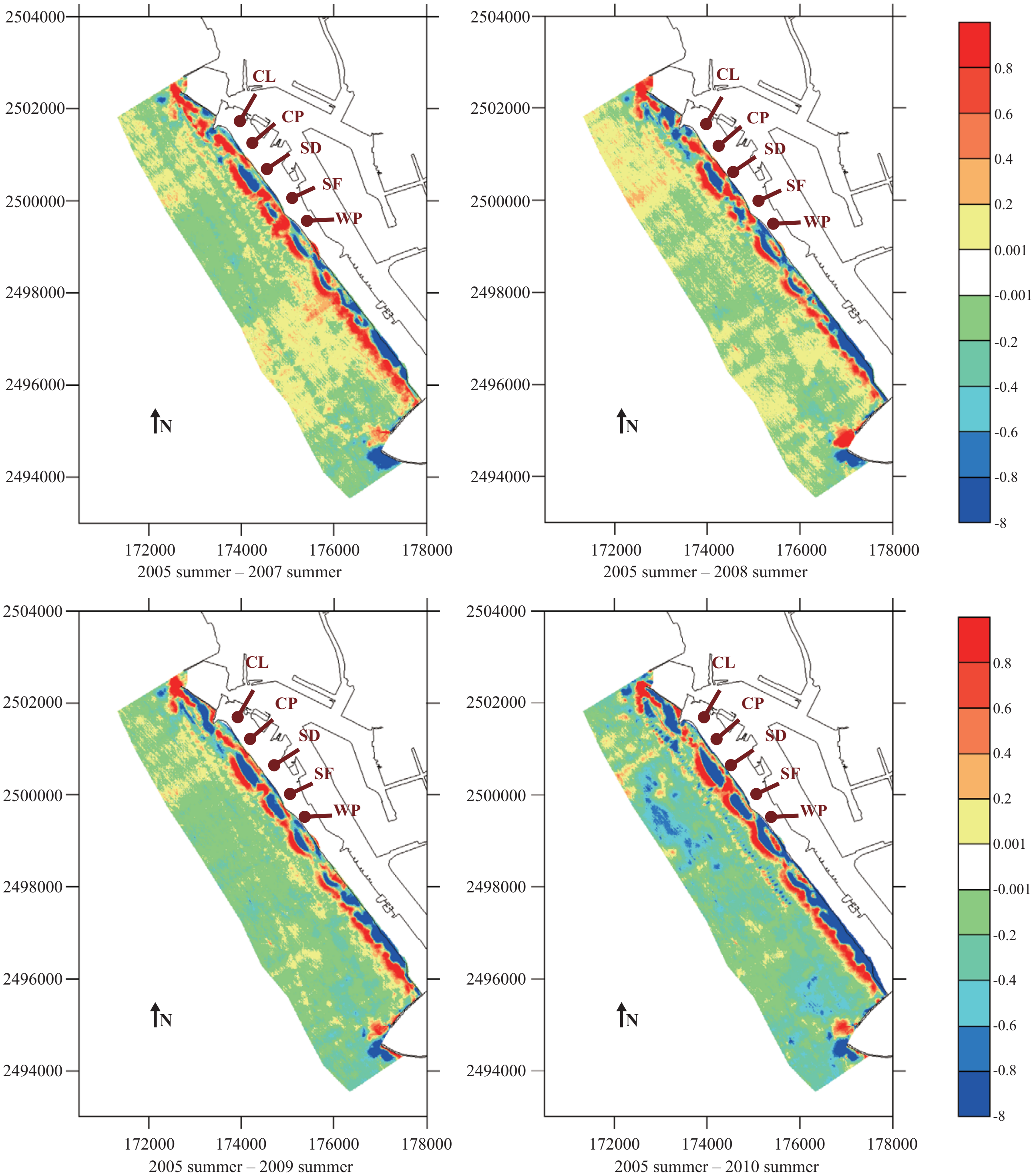

Fig. 5. Planar variation of bathymetry near Cijin Coast (reference time: 2005 summer).

annually. Accretion of sand in the region from −1.0 to −3.0 m showed that the sediment transport was in the offshore direction. This accretion of sediment in the offshore area and erosion in the nearshore area, particularly from the CP to the SD, SF, and WP, worsened over time.

For calculating the accumulative volumetric evolution of bathymetry over time, the offshore region from the CP to the WP was divided into four subregions (Fig. 6), with −10.0 m as the outer limit and −5.0 m as the delimiter for the nearshore and offshore subregions. The accumulative volumetric evolution of bathymetry over time (2005-2010) for each subregion per unit area is shown in Figs. 7 and 8. For both regions

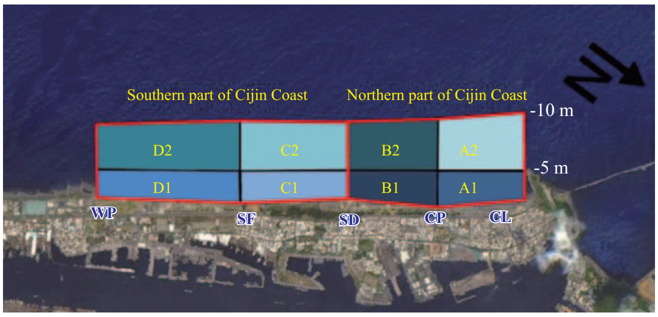

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Fig. 6. Sub-regions used in calculation of the accumulative volumetric evolution of the bathymetry over the years.

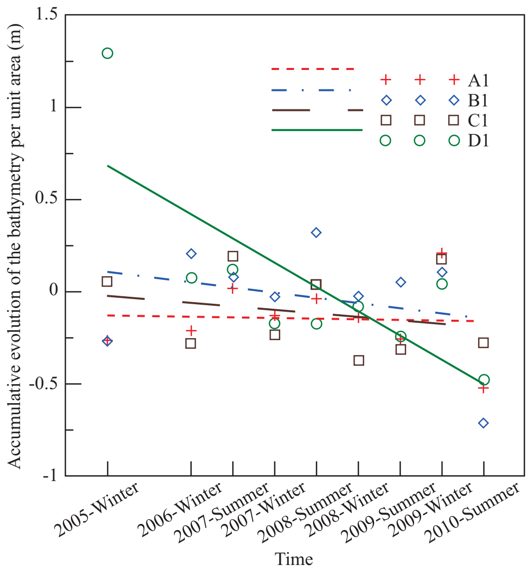

Fig. 7. Accumulative evolution of the bathymetry per unit area within -5 m.

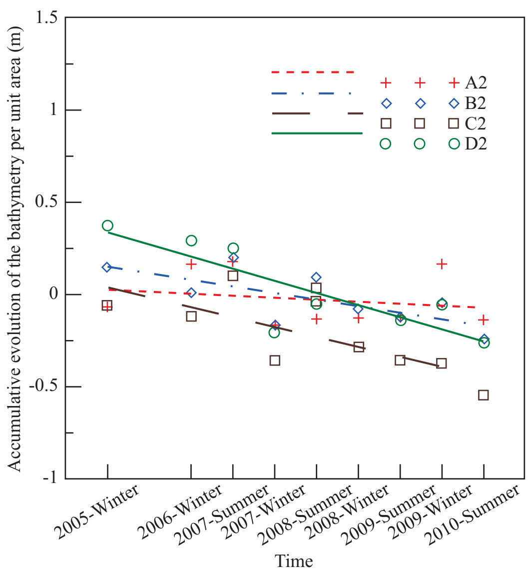

Fig. 8. Accumulative evolution of the bathymetry per unit area between -5 m to -10 m.

Table 2. Wave parameters used in model simulation.

type	direction	period Ts (sec)	Significant wave height Hs (m)
Winter monsoon	W	6.20	0.77
Summer monsoon	S	6.91	1.11
10-year return period typhoon	W	8.80	4.40
	S	11.10	7.00

within −5.0 m (A1-D1) and between −5.0 m and −10.0 m (A2-D2), the long-term trend for the volumetric evolution of bathymetry was erosion, with the worst situation in the region within −5.0 m. A remarkable increase in the amount of erosion was observed after 2008, and this might have resulted from severe weather, such as a typhoon. Bathymetry in this area did not attain equilibrium.

2. Numerical Model Simulation

To elucidate the mechanics of topographic evolution near Cijin Coast, numerical simulation methods were used, and the bathymetric data facilitated the model validation. DHI software MIKE21 (ST module) was implemented in this study to simulate the dynamics of sediment transport, and the results were adopted for evaluating the morphological evolution. Based on the description of MIKE21, the transported materials were divided into coarse particles (D50 > 0.125 mm) and fine particles (D50 < 0.125 mm). The coarse particles comprised only sand, whereas the fine particles could be further divided into clay, silt, and fine sand. According to the investigation on the diameters of the bed materials, the D50 of the materials in the nearshore region was > 0.125 mm, which indicated that the transported materials in the nearshore region are mainly coarse particles. Consequently, ST module, which mainly analyzes sand transport, was selected as the analysis module of sediment transport in our study. The wave parameters used in the model simulation are listed in Table 2. For monsoon waves, the dominant direction was west (W) for winter and south (S) for summer. Both W and S directions were calculated for a 10-year return period of the typhoon waves. The range of the typhoon wave evaluation for beach nourishments recommended by CEM is from a frequent 5-year return period to a rare 100-year return period. Every year, this region of Cijin experiences 1.4 typhoons on an average, which is a high incidence. In addition, considering the safety of general structures, the extreme external condition—a 50-year return period—was considered in the design concepts. Large-scale sediment transport occurs over a long period. The frequency of the external conditions influencing sediment transport should be lower than that of the structural safety analysis. Therefore, the 10-year return period was considered as the wave condition for the simulation.

The mean water level (EL + 0.19 m) was used for the simulation of the monsoon waves, and the mean high water level (EL + 0.38 m) was used for the simulation of the typhoon

Table 3. Driving forces and their weighting factors for monsoon and typhoon waves.

Driving forces	Simulation time	Weight factors
Winter monsoon (W)	One month	× 6
Summer monsoon (S)	One month	× 6
Typhoon (W)	Half day	× 3
Typhoon (S)	Half day	× 3

Table 4. Rate of erosion or accretion in calibration area.

		northern part of Cijin Coast	southern part of Cijin Coast	Total
Calibration area (Ha)		90.5	117.8	208.3
Net erosion/ accretion (ten thousand m^3/yr)	Bathymetry	-20.1	-16.7	-36.8
	Model	-21.0	-17.2	-38.2
averaged erosion/ accretion depth (cm/yr)	Bathymetry	-22.2	-14.2	-17.7
	Model	-23.2	-14.6	18.3
Error		4.5%	3.0%	3.8%

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Fig. 9. Calibration area for model simulation.

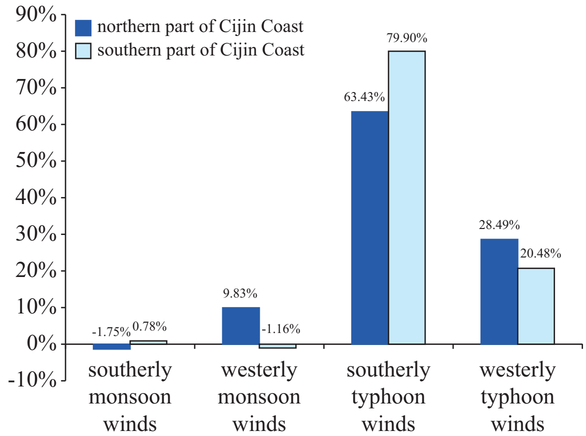

Fig. 10. Percentage of the amounts of erosion or accretion in calibration area.

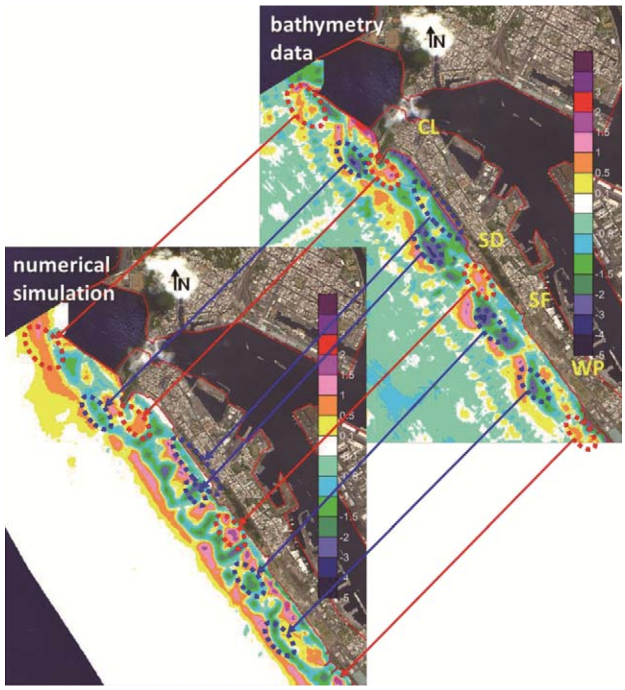

Fig. 11. Comparison of the numerical model results and bathymetry data for topographic evolution from 2008 to 2010.

waves. Model calibration was performed using the 2008 and 2010 bathymetric data and the calibration area is shown in Fig. 9. Various combinations of the monsoon and typhoon waves with various weighting factors were tested in the model simulation until the calibration data exhibited the least difference. The most suitable weighting factors and the various durations of the external forces are listed in Table 3. The results that were closest to the actual 2008 to 2010 bathymetric data are listed in Table 4. Based on these combinations of external forces, the errors between the model simulations and the bathymetric data were below 5% both in the northern and the southern parts of Cijin Coast.

Fig. 10 shows the corresponding percentages of the total amount of erosion caused by the various external forces along with their weighting factors. The southerly typhoon waves had remarkable influences on the topographic evolution of the Cijin region. This is consistent with the field situation whereby plenty of sand was lost after typhoons landed in recent years. A 2-year model simulation, from 2008 to 2010, using the combined external forces, is shown in Fig. 11, and the corresponding variation in the bathymetric data was calculated. Reasonable agreements can be concluded from the comparison of the model results with the bathymetric data, and the parameters are suitable for further assessment of the sediment transport.

3. Physical Model Test

The physical model domain is shown in Fig. 12, with 5.8 km in the alongshore direction and 2.9 km in the offshore

Table 5. Wave parameters used in physical modelling.

wave parameters		offshore			near wave paddle		
		Hs (m)	Ts (sec)	MWD	max. Hs (m)	mean Hs (m)	MWD
10-year return period typhoon waves	S	7.00	11.10	180	5.69	5.52	193
	W	4.40	8.80	270	4.36	4.30	270
summer monsoon	S	1.11	6.91	180	1.09	1.07	182
winter monsoon	W	0.77	6.20	270	0.77	0.77	270
depth		-192.45 m			Southern side: -12~-39 m western side: -30~-62 m		

Table 6. Wave parameters for physical model validation tests.

	Monsoon waves				Typhoon waves				Typhoon waves				Monsoon waves			
	direction	height (cm)	period (sec)	duration	direction	height (cm)	period (sec)	duration	direction	height (cm)	period (sec)	duration	direction	height (cm)	period (sec)	duration
Test 1	W (270°)	1.67	0.91	1 hr 30 min	S (193°)	11.96	1.63	1 hr 25 min	W (270°)	9.32	1.3	1 hr 20 min	S (182°)	2.32	1.02	1 hr 30 min
Test 2	W (270°)	1.67	0.91	1 hr 30 min	W (270°)	9.32	1.3	1 hr 20 min	S (193°)	11.96	1.63	1 hr 25 min	S (182°)	2.32	1.02	1 hr 30 min
Test 3	W (270°)	1.67	0.91	1 hr 30 min	W (270°)	9.32	1.3	1 hr 20 min	S (187°)	11.96	1.63	1 hr 25 min 1 more hr	S (182°)	2.32	1.02	1 hr 30 min
Test 4	W (270°)	1.67	0.91	1 hr 30 min	W (270°)	9.32	1.3	1 hr 20 min	S (182°)	11.96	1.63	1 hr 25 min	S (182°)	2.32	1.02	1 hr 30 min

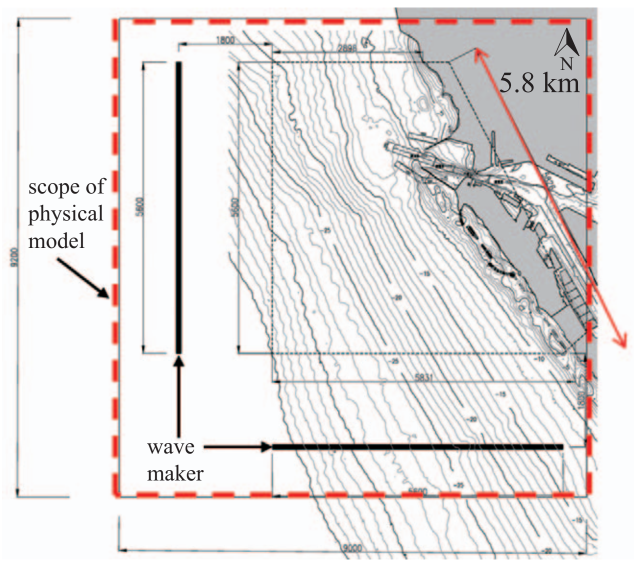

Fig. 12. Scope and bathymetry of physical model (scale: 1/200).

direction. After the simulation range was determined, laboratory scale and functionality of the wave maker were considered, and the test was implemented within 1/200 horizontal and 1/100 vertical scale factors. The wave parameters used in the model simulation are listed in Table 5. For the monsoon waves, the dominant direction was W for winter and S for summer. Both W and S directions were calculated for the 10-year return period typhoon waves. The mean water level (EL + 0.19 m) was used for the simulation of the monsoon waves, and the mean high water level (EL + 0.38 m) was used for the simulation of the typhoon waves. The deployed bathymetry for the physical model test used the 2012 bathymetric data. The 2008 summer bathymetric data were used for the validation test, and 2010 summer was the target bathymetry for the physical model test.

The wave direction, height, and period for both monsoon and typhoon waves were determined through numerical analysis, and the duration of wave generation was determined through regression analysis of the typhoon events. Parameters used in the physical model tests are listed in Table 6. Test 1 was an initial trial test, and the others were used for validation by adjusting the wave parameters. Bottom bathymetry was repaved in each test case. In all test cases, similar erosion and accretion areas were observed after comparison with the bathymetric data for the topographic evolution from 2008 to 2010, particularly in Test 3. The results are diagrammatically represented in Fig. 13. The average erosion and accretion depths were calculated for two areas (Table 7). Similar to that in the numerical simulation, the northern and southern parts of

Table 7. Comparison of averaged erosion/accretion depth between the bathymetry data and physical model results.

	averaged erosion/accretion depth (cm)		
	Northern part	southern part	Deviation from bathymetry data
2008 to 2010 data	-44.4	-28.4	-
Test 1	-88.9	-82.8	50.3
Test 2	-60.7	-55.3	22.5
Test 3	-49.1	-48.7	13.5
Test 4	-54.8	-63.1	24.1

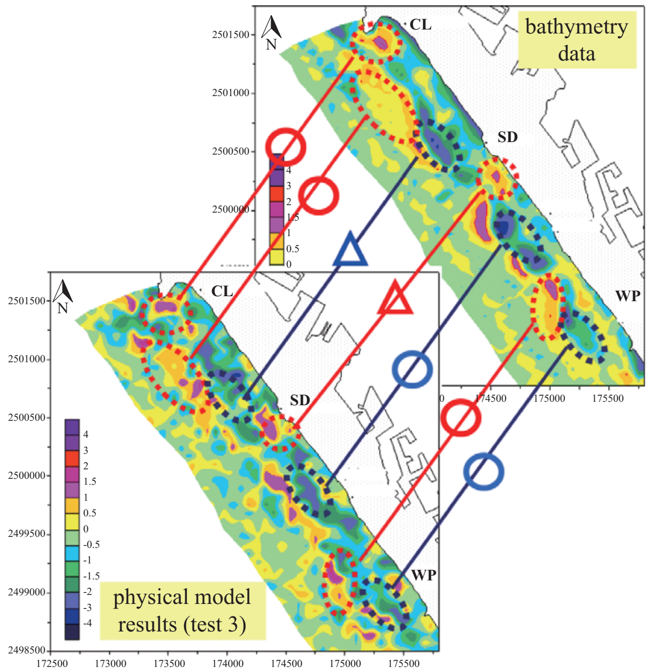

Fig. 13. Comparison of topographic evolution between the bathymetry data and physical model results (test 3).

the Cijin coastal area were used to calculate the difference between the bathymetric data and model results. The least difference was observed in Test 3, and thus, all the parameters used in this case dominated the mechanics of the process of topographic evolution. Thus, the same parameters as used in Test 3 were used in additional experiments assessing the protection plans.

III. BEACH PROTECTION PLANNING

To reduce the negative impact on the amenities and aesthetic values of the beach, an increase in the seawall height and armor units as not considered while developing the Cijin beach protection plan. A beach protection plan consisting of various engineering methods was proposed (Fig. 14), considering the financial budget and environmental concerns. From the SD to the CL, the total breakwater length is 1400 m, consisting of two submerged artificial bays in the northern and southern parts with lengths 500 m and 300 m, respectively, a 300-m submerged detached breakwater, and a 150-m submerged detached breakwater connected to a 150-m emerged detached breakwater. The volume of artificial nourishments for this area is 640,000 m^3. Regarding the part from the SD to the WP, the total breakwater length is 900 m consisting of six 150-m and a 90-m submerged detached breakwater, and the volume of artificial nourishments for this area is 480,000 m^3. A circular bulkhead with a diameter of 40 m was designed to repel the northerly current and served as a navigation caution outside the SD. For designing the cross section, the depth at the toe of the submerged breakwater was maintained between −3.0 m and −9.0 m, and because the mean low water level was −0.17 m, the breakwater height was set between −0.5 m and 0.5 m. The width of the breakwater was set at 20.0 m for a maximum wave height of 6.46 m at its toe. Highly porous armor units or quarried stones and filter cloths were used as a breakwater body (Fig. 15).

1. Numerical Simulation of Protection Configuration

Numerical modeling was adopted to elucidate the evolution of bathymetry with the deployment of the designed protection plan. The model depth used the 2012 bathymetric data, and no artificial nourishments were implemented during the numerical simulation. A 2-year modeling of the topographic evolution caused by the interaction with typhoons and summer and winter monsoon waves is shown in Fig. 16. Accretion of sand was observed in the shallow water region (within −5.0 m), and both accretion and erosion occurred between −5.0 m and −10.0 m. However, most regions near the intertidal zone were eroded. The numerical simulation showed that the retreat of the 0-m shoreline cannot be prevented without artificial nourishments, although the loss of sand can be retarded after the deployment of the protection plan.

2. Physical Modeling of Protection Configuration

The numerical results showed that the proposed protection configuration might not be successful without additional artificial nourishments. Thus, artificial nourishments were included in the physical modeling tests. A 2-year modeling of the topographic evolution caused by interactions with typhoons and summer and winter monsoon waves is shown in Fig. 17. Accretion of sand behind the submerged breakwaters and a reduction in the retreat of the 0-m shoreline were observed. This shows that the proposed plan is suitable for protecting and preserving the beach environment and its amenities.

3. Comprehensive Assessment and Field Application

The average erosion/accretion depth before and after the deployment of the protection plan was calculated (Figs. 18 and 19) using bathymetric data from 2005 to 2010, numerical simulation, and physical modeling tests. The calculation was performed for an area within −5.0 m that was divided into the

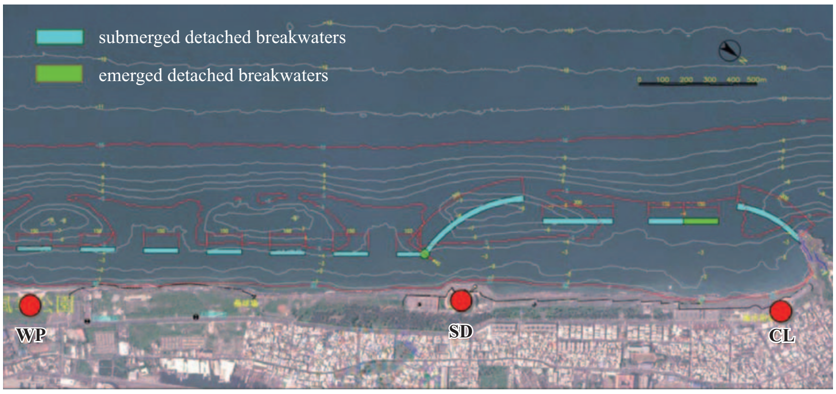

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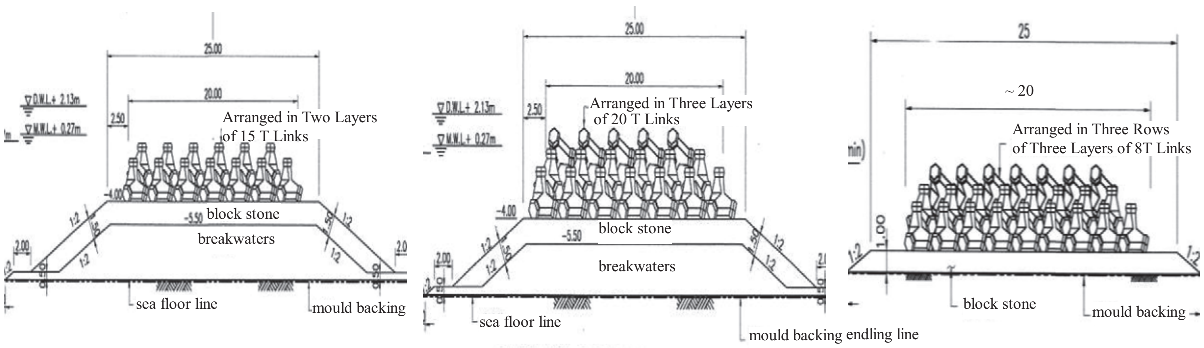
Fig. 14. Configuration of the protection plan.



Standard Cross Section of Manmade Submerged Breakwater in the South (EL-8.00 m~9.00 m)

Standard Cross Section of the Offshore Submerged Breakwaters in South (EL-7.00 m~8.00 m)

Cross Section of the Submerged Breakwaters #2, 3, and 4

Fig. 15. Cross-Section design of submerged breakwaters.

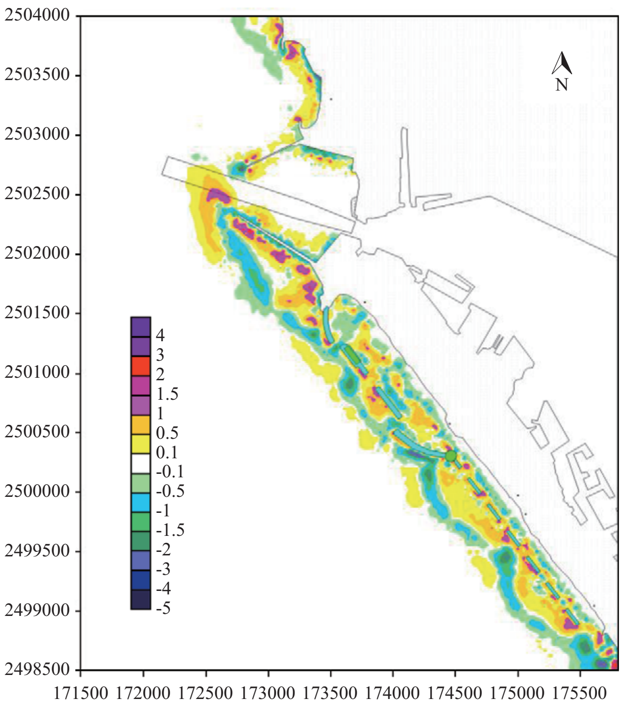


Fig. 16. Numerical simulation of topographic evolution.

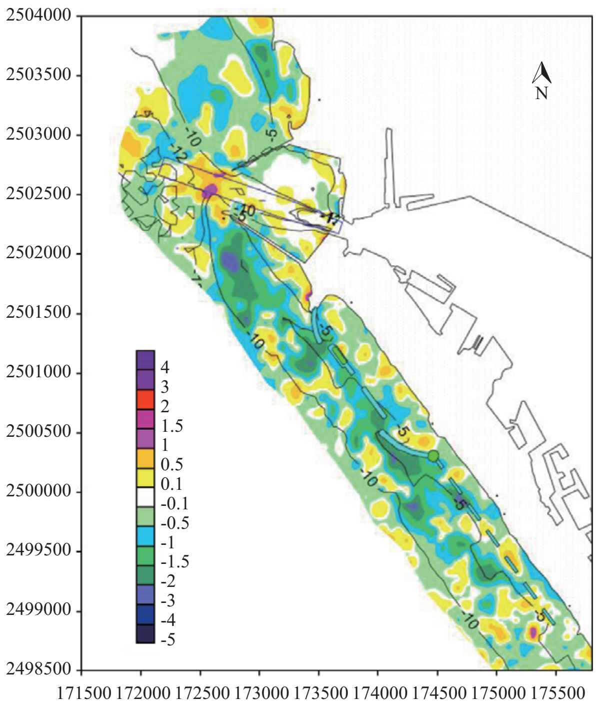


Fig. 17. Results of physical modelling of topographic evolution.

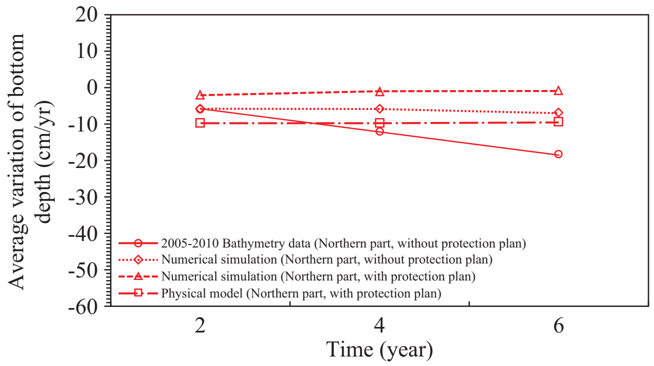


Fig. 18. Tendencies of averaged variation of bottom depth with/without protection plan (Northern Part of Cijin).

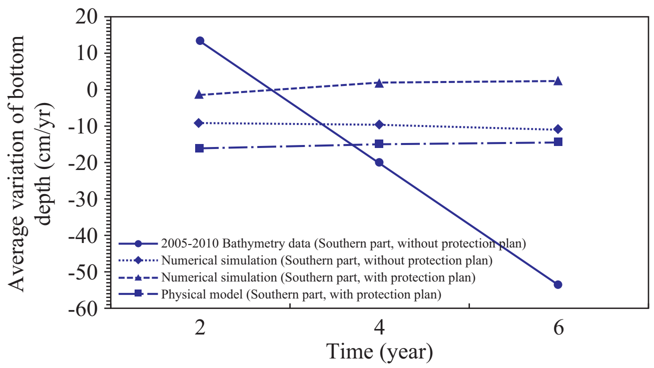


Fig. 19. Tendencies of averaged variation of bottom depth with/without protection plan (Southern Part of Cijin).

Image is courtesy of the KCG.

Fig. 20. Aerial photograph of Cijin Coast after construction.

Image is courtesy of the KCG

Fig. 21. Comparison of the Cijin coastal area before and after the protection plan.

northern and southern parts (Figs. 18 and 19). Unlike the steep negative slope of the bathymetric data, both numerical and physical model results exhibited a mild positive slope. Based on the results of the protection plan simulations, the tendencies of the average erosion and accretion depth showed that the net sediment transport maintained an equilibrium state in both parts of Cijin Coast. Moreover, the southern part of the coast exerted a stronger effect in balancing the sediment transport.

Both the numerical simulation and physical modeling results showed that the design of the protection plan was effective at Cijin Coast. Thus, the KCG started the construction in October 2011 and completed it in August 2013 (Fig. 20). Through comparison of the aerial photographs taken before and after the implementation of the protection plan, a large number of sand strips were observed to be retained (Fig. 21). The protection plan was thus proven to be useful in trapping sand and reducing coastal hazards.

IV. CONCLUSION

In this paper, the adoptability of the proposed engineering methods at Cijin Coast was studied. Historical variations in bathymetry near Cijin Coast were quantified and a series of numerical and physical modeling tests were adopted to investigate the topographic response to submerged structures. The average annual erosion and accretion heights obtained from the numerical simulation and physical modeling tests revealed that, compared with the previously observed gradually aggravating erosion, the completion of beach protection planning was effective in reducing the erosion and maintaining the sand. The use of the proposed protection configuration and additional artificial nourishments was found to be an effective engineering method. Negative impacts on beach amenities were thus reduced, and the beach was gradually restored. Water accessibility to the residents and tourists also increased.

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