

Study on Disaster Prevention and Reduction under large-scale human activities: A case of CiXi Coastal area in Zhejiang Province

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Abstract The city of CiXi is typical Estuary of Zhejiang Province which has been influenced by human activity. The coastline has been dramatically modified by human activity of large-scale land reclamation projects in CiXi from 1997 to 2015. This study aims to develop and implement storm surge model and hydrodynamic model for river networks. The idea is to investigate the response to disaster prevention and reduction considering the change rate of storm surge, water level and discharge of flood. Due to cluster land reclamation, the change rate of storm surge is about 5-9% and the maximum storm surge has decreased by 8cm. The duration time of storm surge above 50cm has decreased by 1-3h. Besides, the average of the highest water level has dropped by 18cm and the discharge of flood has increased by 38m³/s. The findings of the study will be used to influence the management, development, and usage of coastal.

Index Terms human activities, cluster land reclamation, CiXi city, disaster prevention and reduction

I. Introduction

In China, coastal areas are economically advanced and densely populated. Due to land shortage, coastal mudflat is considered an important marine resource. Tideland reclamation is a common approach to promote economic development, alleviate population pressure and maintain the dynamic equilibrium of cultivated land in coastal areas.

In general, tideland reclamation is prone to marine disasters such as storm surges. Many existing studies have investigated tideland reclamation projects from different perspectives (e.g., disaster risk, coastal power and environment, ecological environment and risk assessment). However, limited studies have examined many other important issues, such as comparing the new and old tideland reclamation plans; emphasizing reasonable and appropriate tideland reclamation area; monitoring marine environment for preventing marine disasters, surface subsidence and earthquake disasters; and conducting orderly tideland reclamation tolerated by the marine ecological environment [1]. Besides, economic and reasonable safety monitoring projects, early warning standards and evaluation systems should be put forward for the new-type reclamation and embankment projects [2]. After implementing the Bohai Bay Reclamation Project, the tidal level has increased or exceeded the threshold level for storm-surge-prevention of surrounding ports during storm surges, resulting in potential disaster risks in coastal ports [3]. This has accelerated the advance of the coastline to the sea [4], leading to a sharp change in current flow near the reclamation area. The changes in hydrodynamics have caused some environmental problems, including coastal erosion, sediment movement and pollutant diffusion [5]. The large-scale reclamation of tidal flats at the Sanmen Bay is anticipated to adversely affect natural coastal wetlands, offshore marine and coastal ecosystems, and nearshore biological resources [6], and the risk of disasters is expected to rise due to the increase in the highest tidal level at the bay head [7]. The reclamation project at the Meizhou Bay has influenced its hydrodynamics and sediment transport. The suspended sediment in the main areas of the bay has reduced, and erosion risk has increased in the eastern coast of the bay [8]. In developed countries (e.g., the Netherlands), the seawall flood protection system has been analyzed through tidal flat reclamation and seawall risk assessment using probabilistic design principles, entropy theory and mathematical-statistical models [9], [10].

After long-term and large-scale cluster land reclamation along the coast, on the one hand, original embankments of the reclamation area become the first-line seawalls. Whether the new embankments can defend against typhoons and tides remains unknown. On the other hand, the response of the reclamation area to the upstream flood control and discharge before and after reclamation is unclear. Moreover, there are no in-depth studies on the cumulative effect of reclamation on the disaster prevention and reduction capacity of the reclamation area and its surrounding

areas. By taking the coast of CiXiof Zhejiang Province as an example, this paper investigates the ability of the CiXi reclamation area to respondto disaster prevention and reduction under cluster land reclamation.

II. Study regions

CiXi is a typical reclaimed city located at the south bank of Hangzhou Bay, where 85% of the ground was formed by reclamation. There are many mountains, less sea and long coasts, as well as insufficient water resources and frequent storm surges in CiXi. Besides, CiXi has relatively poor drainage conditions because of its terrain of high outside and low inside. Therefore, it is often affected by natural disasters, e.g., droughts, waterlogging and storm surges. The impacts from frontal attacks of frequent typhoon surges and periodic force tides have seriously threatened and damaged marine projects (e.g., seawalls and embankments) in the city. Meanwhile, the destructive power of storm surges is also affected by large-scale cluster land reclamation.

In 1997-2015, the Longshan Reclamation Project, Dan shui hong Reclamation Project, West Si zao pu Reclamation Project, Bilateral Xujiapu Reclamation Project and Bilateral Lu zhong wan Reclamation Project had been successively carried out along the coast of CiXi, with a total reclamation area of nearly 300,000 mu. The changes of the coast and computational domains of the CiXi reclamation area after the long-term and large-scale reclamation in 1997-2015 are shown in Figure 1.

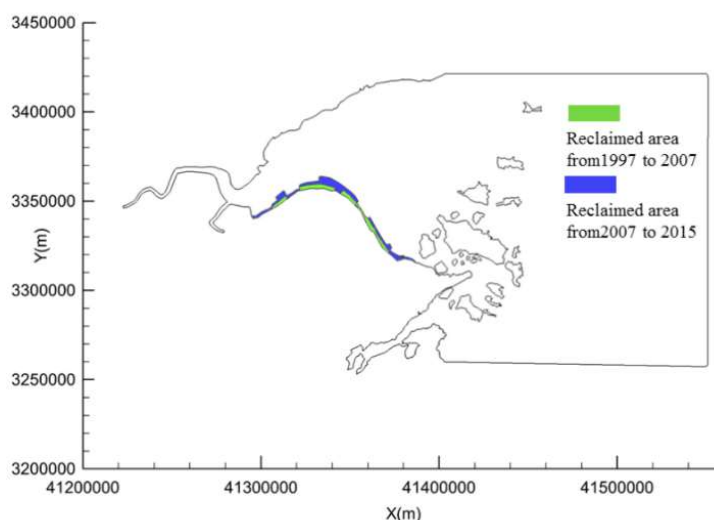


Figure 1: Coastline changes and computational domains of the CiXi reclamation area before and after cluster land reclamation

After implementing the cluster land reclamation project, the original substandard 10-year return period of first-line seawall outside the CiXi reclamation area became the second-line seawall, and some new standard seawalls were also constructed. The standard seawalls of key bank sections reached the flood and tide control standard of 50-year return period. Among them, the built 20- and 50-year return period of seawalls were extended by 16.03 km and 61.08 km, respectively (Table 1).

Table 1: Newly built embankments in CiXi during cluster land reclamation

Flood (tide) control standard/return period (year)	1997-2007	2007-2015	1997-2015
	Length of newly-built embankment (km)		
20-year return period	7.84	8.19	16.03
50-year return period	34.74	26.34	61.08

III. Research methods and analysis

III. A. Mathematical model of storm surges

In this paper, the typical Typhoon 9711 is selected for demonstration purpose. The marine mathematical model of the terrain and coastline in 1997, 2007 and 2015 is constructed to study and analyze the changes in storm surges before and after the implementation of the cluster land reclamationproject. Based on the change rate of water level

fluctuations caused by storm surges, the impact of the cluster land reclamation project on the bearing capacity to storm surges is analyzed. The analysis indicates that the greater the change rate of water level fluctuations of the cluster land reclamations, the greater the impact on disaster prevention and reduction will be.

III. A. 1) Basic equations

In the FVCOM model, three-dimensional unstructured grids, primitive equations and finite-volume coastal ocean models are utilized to simulate and calculate the storm surge tidal level in the estuary and adjacent areas for the target domain. The continuity equation and momentum equation are as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - f v = -\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \left(K_m \frac{\partial u}{\partial z} \right) + F_u \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + f u = -\frac{1}{\rho_0} \frac{\partial p}{\partial y} + \frac{\partial}{\partial z} \left(K_m \frac{\partial v}{\partial z} \right) + F_v \quad (3)$$

where u, v and w are the speed components in x, y and z directions, respectively; p is the pressure; ρ_0 is the density; f is the coefficient of formula; K_m is the vertical rotational viscosity coefficient; F_u and F_v are the horizontal momentum diffusion term.

Boundary conditions of the model are:

Free surface ($\sigma \rightarrow 0$):

$$\rho_0 \frac{k_m}{d} \left(\frac{\partial u}{\partial \sigma}, \frac{\partial v}{\partial \sigma} \right) = (\tau_{0x}, \tau_{0y}) \quad (4)$$

Water bottom ($\sigma \rightarrow -1$):

$$\rho_0 \frac{k_m}{d} \left(\frac{\partial u}{\partial \sigma}, \frac{\partial v}{\partial \sigma} \right) = (\tau_{bx}, \tau_{by}) \quad (5)$$

Under the initial conditions, the flow velocity and surface water level are both 0, $u = v = 0$.

The solid boundary is set to 0, and the boundary tide level at the open boundary is calculated using the harmonic analysis method.

$$\xi = \frac{P_b - P_0}{\rho g} + \sum f_i H_i \cos [w_i t + (u + v)_i - g_i] \quad (6)$$

where P_b and P_0 are the pressures at the open boundary and the center of the typhoon, respectively, w_i is the angular frequency of tidal components; H_i and g_i are the harmonic constant of tidal components; and $(u + v)_i$ is the argument of tidal components. In this model, eight major tidal components, namely $K_1, O_1, P_1, Q_1, M_2, S_2, N_2$ and K_2 are used.

III. A. 2) Scope of the model

The calculation range of the model is 120.13°E-123.48°E, and 29.39°N-30.89°N. The grids of the coast of CiXi in 1997, 2007 and 2015 are plotted, respectively; followed by simulation and calculation. The numbers of grids and nodes in the model in 1997, 2007 and 2015 are 184,677 and 94,249, 154,854 and 79,183, and 142,901 and 69,270, respectively. After running and validating the model, the tidal level information in front of the embankment in the CiXi reclamation area can be extracted from the calculation. Hydrodynamic model bathymetry of Zhejiang coast in 2015 is displayed in Figure 2.

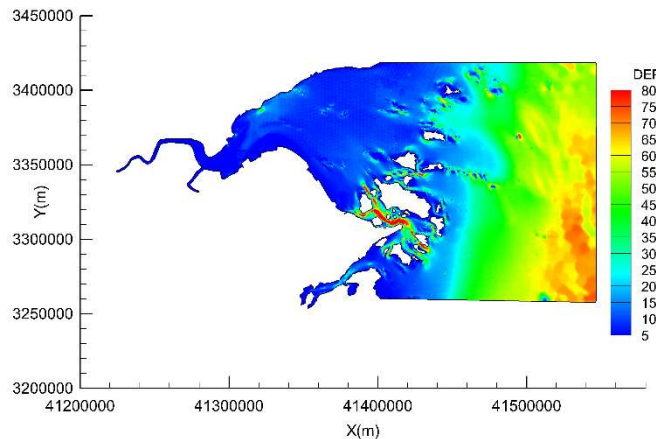


Figure 2: Hydrodynamic model bathymetry of Zhejiang coast in 2015

III. A. 3) Model validation

By comparing the simulated and observed values of storm surges in Dinghai during Typhoon 9711 (Figure 3), we can see that the calculated values of storm surges in the model sufficiently captured the process of the typhoon storm surge rarely seen in history. Besides, the simulated result of the typhoon tidal level is acceptable. In particular, the goodness of fit terms of the high tidal level. Moreover, the simulated and observed values during the entire typhoon process are quite consistent in terms of time-validity.

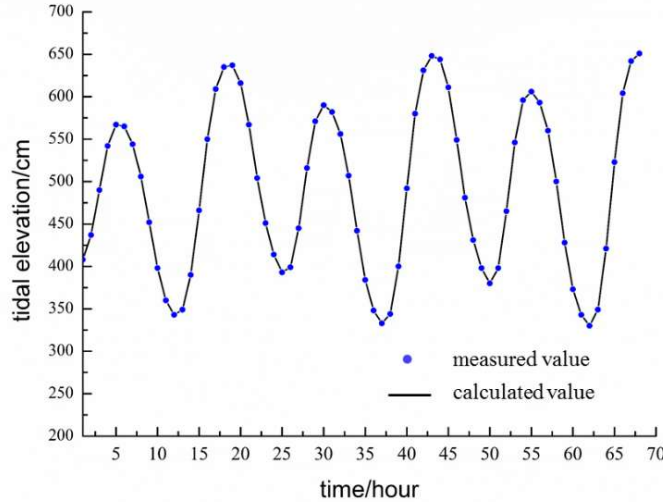


Figure 3: Comparison of simulated and observed tidal levels of storm surges in Dinghai during Typhoon 9711 (start time of the simulation: 4 o'clock on Aug. 17, 1997)

III. A. 4) Water level elevation in front of the embankment in the CiXi reclamation area

With the proceeding of reclamation, 85 points are set at the bank of CiXi from west to east by the three changes of the coast, and 85 tidal levels in front of the embankment are extracted from the typhoon storm surges in three terrain-based simulations. Besides, the regional astronomical tidal level in front of the embankment is extracted in the three terrain-based simulations. Then, the influences of reclamation on the change rate of water level elevation in front of the embankment and high tide level at control points are analyzed (Figure 4).

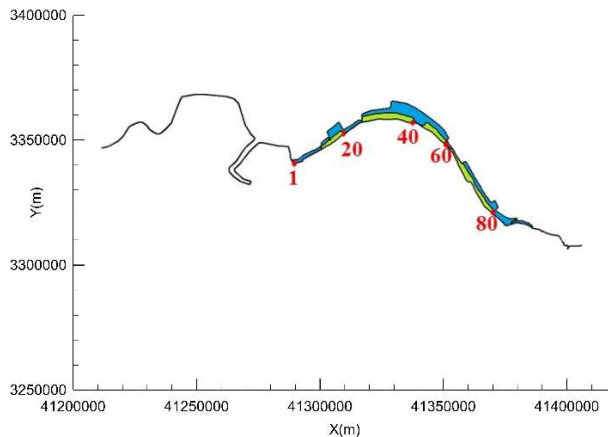


Figure 4: Location of control points

The storm-induced water level elevation in front of the embankment is obtained by calculating the difference between the tide level in front of the embankment and the astronomical tide level in front of the embankment during the landing of the typhoon. When the change rate of coastal water level fluctuations in front of the embankment exceeds 10%, the original storm surge level in the sea area is expected to be severely affected by sea reclamation projects [11]. The impact of reclamation on regional disaster prevention and reduction is determined based on the

change rate of storm-induced water level elevation at control points. The change rate of storm-induced water level elevation is calculated as follows:

$$\Delta h_k = \frac{\Delta h_b - \Delta h_a}{\Delta h_a} \times 100\% \quad (7)$$

where Δh_k is the change rate of the maximum water level elevation in the front of the embankment(%), Δh_a is the maximum water level elevation in the front of the embankment(m), and Δh_b is the maximum water level elevation after reclamation(m).

The maximum storm-induced water level elevation in front of the embankment in the CiXi reclamation area gradually declined after cluster land reclamation, with a maximum decrease of 0.13 m and a mean decrease of 0.08 m (Table 2). After the implementation of the three-stage reclamation projects, the change rate of storm-induced water level elevation in the CiXi reclamation area has dropped, with an overall reduction of 5-9%. Since the original storm surge level in the sea area has not changed, the existing embankment should be able to withstand storm surge disasters.

Table 2: Change rate of the maximum storm-induced water level elevation in front of the embankment in the reclamation area

Control point	Maximum water level elevation in front of the embankment in 1997 (m)	Maximum water level elevation in front of the embankment in 2007 (m)	Maximum water level elevation in front of the embankment in 2015 (m)	Change rate of water level elevation in 1997-2007 (%)	Change rate of water level elevation in 2007-2015 (%)	Change rate of water level elevation in 1997-2015 (%)
1	1.55	1.53	1.42	1.3	7.2	8.4
20	1.52	1.49	1.39	2	6.7	8.6
40	0.6	0.57	0.56	5	1.8	6.7
60	0.57	0.55	0.54	3.5	1.8	5.2
80	0.58	0.56	0.53	3.4	5.4	8.6
Mean				3	4.6	7.5

During the landing of a typhoon, affected dams and coastal lands would be flooded by seawater if the strong storm surge is longstanding and persistent on coastal seawalls. This can seriously threaten the lives and properties in coastal areas and cause heavy economic damages. In this paper, the action time of great water level elevation in front of the embankment is employed as a consideration factor of the capacity of the cluster reclamation projects to respond to disaster prevention and reduction.

Table 3: Action time of water level elevation at the embankment

Characteristic point	Water level elevation (m)	Action time in front of the embankment in 1997 (h)	Action time in front of the embankment in 2007 (h)	Action time in front of the embankment in 2015 (h)
1	>0.5 m	8	7	6
20		7	6	6
40		3	2	2
60		3	2	0
80		3	2	0

As shown in Table 3 (action time of great water level elevation in front of the embankment in the CiXi reclamation area in 1997-2015), the action time of water level elevation >0.5 m in front of the embankment can be shortened by 2 h on average with the extrapolation of the coastline after reclamation. After conducting the cluster land reclamation project, the ability of the embankment in the CiXi area to withstand off-sea typhoon disasters can be improved to some extent.

III. B. Numerical model of river network

The rivers in the east, middle, west and northwest river districts of CiXi City are crisscrossed (Figure 5) with interconnected water flows. Therefore, the actual drainage conditions can be better characterized using the unsteady flow calculation method.

In MIKE11 HD, a one-dimensional hydrodynamic model based on the matter equation and momentum conservation equation of the vertical integration, the water flow and hydrodynamic state of rivers are simulated using

the one-dimensional unsteady flow Saint-Venant equations established by the French scholar Saint-Venant in 1871. The specific Saint-Venant equations are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{8}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial(Q^2/A)}{\partial x} + gA \frac{\partial h}{\partial x} + g \frac{Q|Q|}{c^2 AR} = 0 \tag{9}$$

where t is time, x is the distance coordinate, A is the area of river cross section, Q is the cross section flow, h is the water level, q is the lateral inflow flow and c is the Chezy coefficient.

In the case of free discharge (the flood discharge form of sluices),

$$Q = mB\sqrt{2g}H^{3/2} \tag{10}$$

In the case of submerged discharge (the flood discharge form of sluices),

$$Q = \varphi mBH_s\sqrt{2g(Z_u - Z_d)} \tag{11}$$

where m is the flow coefficient in the case of free discharge of the sluice opening, φ is the flow coefficient in the case of submerged discharge of the opening, Z_u is the water level in front of sluices, Z_d is the water level behind sluices, H is the water head in front of sluices, H_s is the water head behind sluices and B is the width of the sluice opening.

According to the survey on the river network rate of each town in each river district of CiXi, flood-discharge channels connected in the basin are generalized with a total generalized channel of 1797.5 km. Cross sections are set every 300-600m on average. The floodgate, flood discharge gate are check gate were all considered as control buildings in the model. During the calculation, the bottom sill elevation, opening size and control strategy are set. The appropriate flow coefficient, opening speed of sluices, maximum opening height and other parameters are taken into account. The generalized river network in the mathematical model of flood discharge is shown in Figure 5.

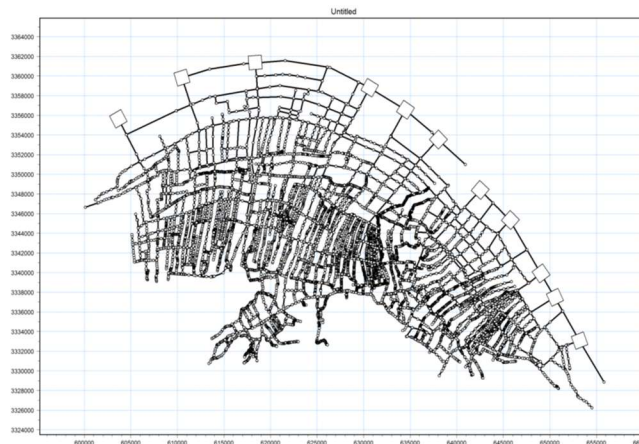


Figure 5: Division of inland river network in CiXi and generalization of river network in the mathematical model of flood discharge

Considering the water conservancy construction in the CiXi basin, for the upper boundary, the rainstorm of 20-year return period in the Yaojiang River Basin, i.e., the Rainstorm "620831", is used as a typical rainstorm by following the Atlas of Short-Duration Rainstorms in Zhejiang Province (2003). For the lower boundary, the high tide level of 5-year return period in flood season is adopted as the designed flood discharge tidal stencils.

The flood discharge processes of the inland river network before and after cluster land reclamation are separately subjected to the numerical simulation study. The changes in the flood level of the backbone river network are calculated and compared, and the effects of the coastal reclamation on the flood control and discharge in CiXi City are analyzed. Table 4 - Table 5 show the calculated water levels of the river network in the CiXi basin before and after cluster land reclamation.

Table 4: Flood level in front of the gate in the main flood discharge channels before cluster land reclamation

River district	Basin area (km ²)	Name of flood discharge gate	Highest flood level in front of the gate (m)	Maximum flood discharge flow (m ³ /s)	Total flood discharge volume (m ³)
Northwest river district	84.88	Jiantang River-Jiutang Gate	3.42	168.93	519.67

		Sanba River-Jiutang Gate	3.52	281.12	837.07
West river district	134.87	Luzhongwan-Jiutang Gate	3.61	300.33	1134.84
Middle river district	371.54	Sizaopu-Shitang Gate	3.29	370.48	1758.46
		Shuiyunpu-Shitang Gate	3.44	389.78	1671.55
		Banjuepu-Shitang Gate	3.47	344.65	1570.55
East river district	347.29	Xujiapu-Jiutang Gate	3.44	309.99	1274.41
		Gaobeipu-Jiutang Gate	3.34	358.27	1590.80
		Songpu-Jiutang Gate	3.31	355.18	1405.47
		Danshuihong-Jiutang Gate	3.44	340.78	1276.20
		Zhenlongpu-Jiutang Gate	3.20	171.71	586.63

Table 5: Flood level in front of the gate in main flood discharge channels after cluster land reclamation

River district	Basin area (km ²)	Name of flood discharge gate	Highest flood level in front of the gate (m)	Maximum flood discharge flow (m ³ /s)	Total flood discharge volume (0,000 m ³)
Northwest river district	118.89	Jiantang River Gate	3.05	270.68	618.16
		Sanba River-Shiyitang Gate	3.25	339.26	893.81
West river district	198.69	Luzhongwan-Shiyitang Gate	3.30	333.80	927.03
Middle river district	409.89	Sizaopu-Shiyitang Gate	3.28	404.63	2499.62
		Shuiyunpu-Shiyitang Gate	3.27	434.42	2302.59
		Banjuepu-Shiyitang Gate	3.26	379.68	1848.18
East river district	412.74	Xujiapu-Shitang Gate	3.26	319.23	1447.26
		Gaobeipu-Shitang Gate	3.25	377.15	1656.43
		Songpu-Shitang Gate	3.20	371.26	1719.37
		Danshuihong-Shitang Gate	3.17	367.53	1497.23
		Zhenlongpu-Shitang Gate	3.18	221.57	926.38

After the implementation of the cluster land reclamation project, the runoff-producing and confluence areas in the plain has increased, resulting in higher total flood discharge volume and flood discharge pressure. At the same time, however, the major flood discharge sluices were moved toward the sea and had an expanded scale, so the width of backbone river cross-section has generally increased by 10-60 m, thereby reducing the flood level in front of the gate in main flood discharge channels, and increasing the maximum flood discharge flow during flood discharge. Generally, it brought a positive impact on the flood discharge of heavy rain in CiXi.

By comparing the highest flood level in front of the gate, it is found that the water level in front of the gate in main flood discharge channels after cluster land reclamation is lower than that before reclamation, with a reduction of 18 cm on average. In terms of flood discharge flow, the maximum flood discharge flow after reclamation is greater than that before reclamation, with a mean increase of 38 m³/s. After the implementation of reclamation projects, the total flood discharge flow has increased by 2,710.4 m³.

IV. Conclusion

After the implementation of large-scale reclamation projects in CiXi City in 1997-2015, the cumulative effect of disaster prevention and reduction capability includes these aspects:

(1) There are more high-standard seawalls. The total length of first-line seawalls in the CiXi reclamation area is 77.1 km. Besides, the 20- and 50-year return period of seawalls built were extended by 16.03 km and 61.08 km, respectively (Table 1).

(2) The capacity of built seawalls to withstand extreme weather typhoon storms has improved. The maximum storm-induced water level elevation in front of the embankment has increased by 8 cm on average; the mean change rate of water level elevation is less than 10%; and the storm surge level is unaffected. In addition, the action time of water level elevation >0.5 m in front of the embankment has shortened by 2 h on average, hence less risk of storm disasters.

(3) The major flood discharge sluices have been expanded. These have reduced the flood level in front of the gate in major flood discharge channels by 18 cm on average; and increased the maximum flood discharge flow during flood discharge by 38 m³/s on average. These have positive effects on the flood discharge of heavy rain in the reclamation area.

Author Contributions

Conceptualization and methodology, Hui Nie.; software, Hao Chen.; validation, Hui Nie.; formal analysis, Hao Chen.; writing—original draft preparation, Hui Nie.; writing—review and editing, Sai-hua Huang, Hao Chen; funding acquisition, Hui Nie. All authors have read and agreed to the published version of the manuscript.

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