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Comparison and investigation on tidal levels designed for the coastal embankments in Guangdong-Hong Kong-Macao Greater Bay Area

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Comparison and investigation on tidal levels designed for the coastal embankments in Guangdong-Hong Kong-Macao Greater Bay Area

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Abstract. Tidal levels designed for coastal levee in Pearl River estuary have been provided by Department of water resources of Guangdong Province in 2002 and played important role in ensuring the security of coastal cities in recent decades. However, big changes have taken place in the hydrological regime of the estuary as the sea water level rise and Frequent storm surges in recent years. The proportions of the coastal levee lengths in Guangzhou and Zhuhai city occupied a large part of the portion in the Bay Area, about 30% and 23% respectively, while the shortest in Shenzhen city, accounting for only 5%. The designed tidal levels used for coastal levees in the past were compared with those proposed by PRWRC in the year 2011, showing lower about 0.2~0.5m totally in the mouths and open waters including Shiziyang of the estuary. It would reach to about 0.6~0.7m lower in the waters around Nansha district after considering the influence of the typhoon Mangkhut and Hato, while there was little variation in the net river area upstream in any case. The controlled tidal levels designed for coastal levees were analyzed for its applicability and it showed that those used in Guangzhou, Shenzhen and Jiangmen city meet the requirements and were somewhat lower in Dongguan, Zhuhai and Zhongshan city under variation of hydrological regime recently.

1. Introduction

Guangdong-Hong Kong-Macao Greater Bay Area (GBA), as one area with the largest degree of openness and the most dynamic economy, has strategic significance in the overall development layout of China. Coastal levees are the key to the protection of the GBA from the tide. Design of the levees is based on the standards specified in *Design Guide for Coastal Levee Project of Guangdong Province (DB44 T182-2004)*[1]; the tide level for design was based on the research result achieved in 2000 [2,3]; the crest elevation of levees was determined according to *Code for Design of Levee Project* (GBT 51015-2014)[4] and *Code for Design of Sea Dike Project* (SL435-2008)[5] by adding the design highest tide level, the design wave runup and safety freeboard together. In addition, there are another two calculation methods: one is by calculating the wave overtopping rate, and the other is by adding up the highest tide level with safety freeboard [6]. However, along with the global climate changes in recent years, extreme weather has occurred more frequently at the Pearl River Estuary, with more and more typhoons hitting the GBA in the last decade [7]. The water level increased remarkably during the storm tide. For example, during Typhoon Hato (No.1713) and Super Typhoon Mangkhut (No. 1822), the maximum and minimum amplitude of surge at Sanzao Station of Modaomen Outlet were up to 1.86 m and 2.84 m, respectively[8]; when Typhoon Hagupit (No.0814) hit the Pearl River Estuary, the amplitude of surge at Chiwan Station was 1.46 m[9], and was 2.0 m[10] at Zhapo Station in the west of the Pearl River Estuary. The combination of storm tide and astronomical tide will result in severe flood disaster loss at the Pearl River Estuary [11]; according to relevant studies[12], in combination of the influence of Typhoon Hagupit, the amplitude of surge of design tide level at 6 control stations of the Pearl River Estuary, compared with that in the year about 2000 and under the same frequency, was up to 0.2-0.5 m, which means that the original design achievements are significantly low; if taking the influence of Typhoon Hato (No. 1713) and Super Typhoon Mangkhut (No. 1822) into further consideration, the amplitude of surge will be more considerable. Therefore, this paper summarized, analyzed and compared the existing tide level design achievements at the main control stations of the Pearl River Estuary, and further discussed the safety of design tide level of coastal levees at main cities of GBA.

2. Distribution and Design Tide Level of Coastal Levees

2.1. Distribution of coastal levees

In Flood-Control Planning Report in Pearl River Basin [14] and Pearl River Basin Comprehensive Plan (2012-2030)[13], Guangdong-Hong Kong-Macao Greater Bay Area is classified into the flood-protected area of Pearl River Downstream Delta and coastal flood/tide control protected area of the Pearl River Delta, and GBA's flood/tide control mainly relies on the levees and reservoirs at the middle and lower reaches of Xijiang River, Beijiang River and Dongjiang River in combination of flood-control engineering system and coastal levees. Till now, the coastal levees built in GBA are 1723.2 km long, wherein, the existing and planned Level I coastal levees are 781.8km long, with the tide-control standard being one-in-100-200-year tide; others are mainly Level II coastal levees, with the existing and planned tide-control standards for big storms that would occur once in half a century. The main cities under protection include Guangzhou, Dongguan, Shenzhen, Zhongshan, Zhuhai and Jiangmen, and the distribution of coastal levees is shown in Figure 1.

(1) From the perspective of the tide-control standards, the existing and planned tide-control standards for coastal levees at GBA are one-in-50-year tide at least. The standards for construction of coastal levees in Wherein, Guangzhou, Shenzhen, as key cities in China, are to resist big storms that occur once in a century; while those in other cities are to resist big storms that will occur once every 50 to 100 years.

(2) From the perspective of the length distribution of coastal levees, GBA coastal levees are mainly distributed at Lingdingyang Estuary, Shiziyang Estuary, Huangmaohai Estuary and Eight Major Outlets of Pearl River; since the coastline of Guangzhou city and Zhuhai city is relatively long, the length of coastal levees at these two cities accounts 30% and 23% respectively of the total length of coastal levees of GBA; following Guangzhou city and Zhuhai city are Zhongshan city, Dongguan city and Jiangmen city, with the length respectively being 17%, 14% and 12%, and the length in Shenzhen city is the least, only accounting for 5%;

(3) From the perspective of cross-section morphology of the coastal levees, GBA coastal levees mainly consist of four structural section forms, namely, up-straight retaining wall type, ladder-shaped embankment type, mixed type and super levee, all of which take the crest elevation of the retention part of wave walls or anti-flood walls as the crest elevation of levees; the up-straight retaining wall type is mainly applied in cities and towns, while ladder-shaped embankment type, mixed type in the suburbs or the farming area; "super levees" refer to those built in combination of ecological, landscape and afforestation demands on the basis of "the principle of replacing width with height", and are mainly applied in the existing coastal levee plans carried out in Shenzhen;

(4) From the perspective of existing problems related to coastal levees, most GBA coastal levees fail to meet the construction standards, the flood-control function of coastal levees does not shut down, the adopted design tide level is relatively low, the crest elevation of coastal levees fails to meet the requirements, the soft foundation sinks, the protection degree of coastal levees is weak, and there is eco-friendly design for protecting natural ecology is absent.

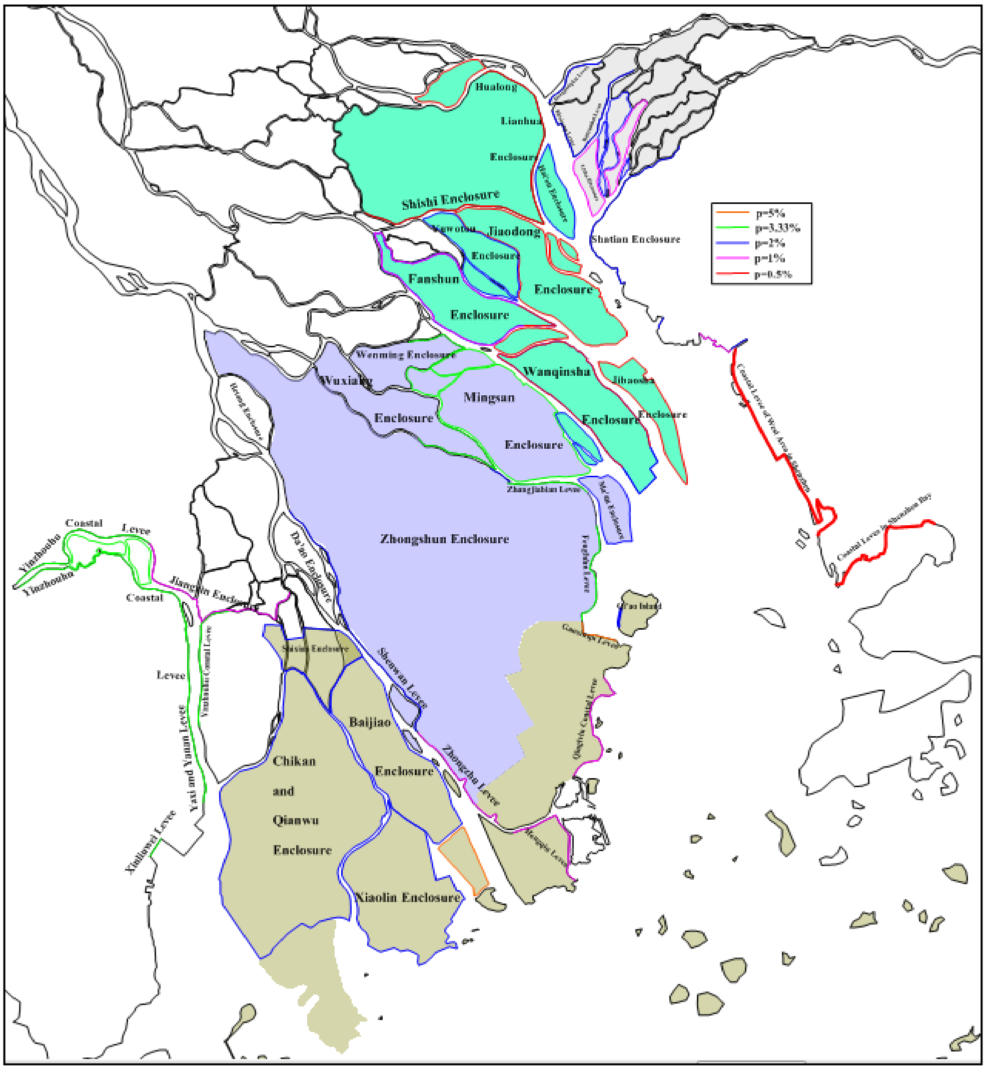

Figure 1. GBA Coastal Levees Distribution Diagram.

2.2. Design tide level achievementss

Main tide stations distributed at the Pearl River Estuary include: Shizui Station and Guanchong Station at Yamen Channel, Hengshan Station and Xipaotai Station at Hutiaomen Channel, Huangjin Station and Baijiao Station at Jitimen Channel, Sanzao Station, Denglongshan Station and Dahengqin Station at Modaomen Channel, Hengmen Station at Hengmen Channel, Wanqingsha West Station and Banshawei Station at Hongqimen Channel, Nansha Station at Jiaomen Channel, Dahu Station, Sanshakou Station, Dasheng Station and Sishengwei Station at Shiziyang Estuary, Huangpu Station at Pearl River Channel, and Chiwan Station at Lingdingyang Estuary. In order to guide the construction of coastal levees at the Pearl River Estuary, since 1995, Water Resources Department of Guangdong Province and the Pearl River Water Resources Commission; Ministry of Water Resources have been successively issued the design achievements for main tide stations, as shown in Table 1. In the table, the review result by the Pearl River Water Resources Commission; Ministry of Water Resources in 2016 is generally the same as in 2011.

Table 1. GBA Tide Level Achievements.

Time	Issued by	Name of Achievement	Description
May, 1995	Water Resources and Hydropower	Calculation Results of the Annual Highest Tide Level Frequency in	Wherein, 18 stations are distributed in the Pearl

	Department of Guangdong Province	Guangdong Province ("1995 Provincial Result" in short)	River Delta.
May, 1999	Survey and Designing Institute of the Pearl River Water Resources Commission	Review Report on Design Flood, Design Tide Level and the Relation between Water Level and Flow at Main Hydrological Stations in the Pearl River Basin ("1999 Annual Review Report" in short)	Put forward 34 tide station achievements.
June, 2002	Water Resources Department of Guangdong Province	Design Flood/Tide Waterline for Rivercourse at River Network Area of Lower Reaches of Xijiang River and Beijiang River and Their Deltas (Trial)	Position of control stations and river course waterline at Xijiang River Delta and Beijiang River Delta inside of the eight major outlets of the Pearl River Estuary.
September, 2004	Water Resources Department of Guangdong Province	Calculation Report of Design Flood/Tide Waterline for the Main Stream and Delta Section of Dongjiang River	Position of control stations and river course waterline at Dongjiang River Delta.
March, 2005	China Water Resources Pearl River Planning Surveying & Designing Co., Ltd.	Hydrological Analysis Report on Flood Control Planning in the Pearl River Basin	On the basis of 1999 results, two stations: Dasheng Station and Sishengwei Station are added.
June, 2011	The Pearl River Water Resources Commission; Ministry of Water Resources	Preparation of the Review Report on Design Tide Level of Main Observation Stations in the Pearl River Delta Based on Pearl River Basin Comprehensive Plan (June, 2011) ("2011 Annual Pearl River Basin Planning Results" in short)	On the basis of 1999 Annual Review Report, the measured length of the series by each station is extended from the year of 1998 to the year of 2008.
July, 2016	The Pearl River Water Resources Commission	Review on Main hydrological Design Achievements in the Pearl River Basin- Review Report on Design Tide Level of Main Observation Stations in the Pearl River Delta	On the basis of 2011 Annual Pearl River Basin Planning Results, the length of the series is extended to 2010, with 4 tide station achievements added.
April, 2020	The Pearl River Water Resources Commission	2020 Flood Control Safety Support Scheme for Guangdong-Hong Kong-Macao Greater Bay Area	Still continue to adopt the 2016 achievements

3. Analysis on Design Tide Level Achievements

3.1. Comparison of design tide level

The coastal levees at the Pearl River Estuary are designed by referring to 2002 Design Flood/Tide Waterline for Rivercourse at River Network Area of Lower Reaches of Xijiang River and Beijiang River and Their Deltas (Trial). In April 2020, the Pearl River Water Resources Commission, Ministry of Water Resources issued 2020 Flood Control Safety Support Scheme for Guangdong-Hong Kong-Macao Greater Bay Area, of which the design tide level achievements continue to adopt the 2016 achievements, and takes the influence of surge caused by Typhoon Hagupit (No.0814), thus being with more feasibility and authority. Through comparison, we can find that:

Compared with the tide level design result in 2002, there is no significant change in the design water level at Guanchong Station of Yamen Channel, the amplitude of surge of design tide level under different frequency at Huangjin Station of Jitimen Channel, Xipaotai Station of Hutiaomen Channel and Denglongshan Station of Modaomen Channel is 0.3-0.45 m, 0.15-0.35 m and 0.1-0.3 m, respectively. The design tide level at Zhuyin Station slightly increases, with the surge no more than 0.1 m; there is no significant change in the design tide level at Hengmen Station of Hengmen Channel, Wanqingsha West Station of Hongqimen Channel, and Nansha Station of Jiaomen Channel; the amplitude of surge at Humen Station and Sanshakou Station of Shiziyang Estuary is 0.15-0.25 m and 0.12-0.17 m respectively; there is a slight change at Huangpu Station, Banshawei Station and Sanshanjiao Station, river network area of Delta; the amplitude of surge of design tide level at Dasheng Station of Shiziyang Estuary, north mainstream of Dongjiang River and at Sishengwei Station of Shiziyang Estuary where the south branch flows into is 0.14-0.27 m and 0.19-0.25 m respectively. In conclusion, the higher the design frequency is, the larger the amplitude of surge of tide level is.

The implementation of the GBA strategic plans in recent years means there is a large space for improving the planned tide control standards for coastal levees at the estuary. The design specification against big storms that would occur once every two centuries, the adoption of 2002 design tide level achievements may result in significant lower in the crest elevation of coastal levees. For example, the lowering amplitude of crest elevation at Jitimen, Hutiaomen, Modaomen, Lingdingyang Bay and Shiziyang Bay of Outlet Area Channel is 0.15-0.45 m, and water areas with lower design tide level are mainly located at those directly facing the open seas or open area, and the design tide level at river network area of Delta in the upstream is generally the same.

3.2. Influence of Super Typhoon Mangkhut and Typhoon Hato on tide level

Super Typhoon Mangkhut landed on the west side of Huangmao Sea at 17:00 of September 16, 2018 (the seventh day of the eighth lunar month), and all control stations at Outlet Area of the Pearl River Estuary were at the stage of falling tide of a lower high water during the neap season of astronomical tide at the moment when the typhoon landed, with the astronomical tide level of all control stations under the maximum storm surge elevation influence being between -0.25m and 0.25m. Typhoon Hato grew to be a severe typhoon (Level 14, 42m/s) on the morning of August 23, 2017, and then landed at Zhuhai at 12:50 (Severe typhoon, Level 14, 45m/s), at which moment, the Four Eastern Outlets in the Pearl River Estuary were at the beginning of falling tide, while Four Western Outlets were at the lower low water.

During Typhoon Hato (No.1713) and Super Typhoon Mangkhut (No.1822), the measured tide level of each station was on record-breaking runs. During Super Typhoon Mangkhut, the maximum tide level at Dahu Station, Nansha Station, Wanqingsha Station, Hengmen Station, Huangjin Station and Sanzao Station was up to 3.15m, 3.20m, 3.23m, 3.22m, 3.13m and 3.44m respectively; while during Typhoon Hato, the measured tide level at Dahu Station, Nansha Station, Wanqingsha Station and Hengmen Station was 3.11m, 3.12m, 2.86m and 2.87m accordingly. The main control stations at the Outlet Area suffering these two storm tides were designed with one-in-200-year tide level standards. As a result, on the basis of the foregoing hydrological design achievements, the author has further collected the tide level data in the Pearl River Delta till 2018, reviewed the design tide level of control stations at Lingdingyang Bay of the Pearl River Estuary, and validated the recurrence interval of maximum tide level during the typhoon to be 120 years, with the review results as shown in Table 2[15].

As the result shows, after taking the surge influence of storm tide caused by Super Typhoon Mangkhut and Typhoon Hato, the design tide level of control stations at Lingdingyang Bay and Shiziyang Bay was remarkably increased in comparison to the result achieved in 2016. The amplitude of surge in one-in-1000-year design tide level at Wanqingsha West Station, Sanshakou Station,

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Nansha Station, Dahu Station, Chiwan Station was about 1.0m, and the amplitude of set up in one-in-200-year design tide level was 0.6-0.7 m; there is almost no change in the design tide level at Banshawei Station, Hongqimen Channel, river network area and Sanshanjiao Station. In conclusion, those with significant change in the design tide level are mainly concentrated at the open water area facing the open seas.

Table 2. Comparison of Tidal Level Achievements

Station	Source of Achievements	0.10%	0.50%	1%	2%	5%
Wanqingsha West	Pearl River Basin Planning Achievements	3.07	2.78	2.65	2.52	2.34
	Considering the storm surge elevation	4.0	3.41	3.16	2.91	2.58
Sanshakou	Pearl River Basin Planning Achievements	3.0	2.74	2.62	2.51	2.34
	Considering the storm surge elevation	3.88	3.36	3.13	2.9	2.6
Nansha	Pearl River Basin Planning Achievements	3.12	2.83	2.69	2.56	2.38
	Considering the storm surge elevation	4.04	3.46	3.21	2.96	2.63
Dahu	Pearl River Basin Planning Achievements	3.03	2.75	2.62	2.49	2.32
	Considering the storm surge elevation	4.01	3.43	3.18	2.93	2.61
Sanshanjiao	Pearl River Basin Planning Achievements	4.83	4.26	4.01	3.75	3.4
	Considering the storm surge elevation	4.85	4.28	4.03	3.77	3.42
Banshawei	Pearl River Basin Planning Achievements	3.83	3.49	3.34	3.18	2.95
	Considering the storm surge elevation	3.85	3.51	3.36	3.2	2.97
Chiwan	Pearl River Basin Planning Achievements	2.65	2.7	2.6	2.5	2.37
	Considering the storm surge elevation	3.73	3.33	3.16	2.98	2.74

4. Discussion on Value of Design Tide Level of Coastal Levees

The design tide level of control hydrological stations at GBA Estuary is an external control boundary condition for calculating 2002 flood/tide waterline of river network area of Delta, and the reference basis of design tide level of coastal levees at the coastal area. According to the comparison and analysis, changes of design tide level in recent years are focused at the Outlet Area and open seas. In combination of the coastal levee planning achievements of main coastal cities in GBA, it shows that:

(1) Guangzhou coastal levees are mainly distributed in Nansha District and Panyu District, and Pearl River Basin Planning Achievements have been adopted for the design tide level; coastal levees at Panyu District are mainly distributed along Shiziyang water area, while coastal levees at Nansha District are mainly facing towards Shiziyang Bay and Lingdingyang Bay; for the reinforcement standards for coastal levees in Nansha District, Achievements of Design Level at Waijiang River, Nansha District[15] issued in 2020 is proposed to be adopted, the tide level of main control stations with one-in-200-year design frequency is increased by 0.6-0.7m compared with that specified in Pearl River Basin Planning Achievements, while, the tide level at the river network area remains almost the same; in conclusion, the tide level adopted for elevation design of coastal levees in Guangzhou city can basically meet the current flood/tide control requirements;

(2) Shenzhen coastal levees are mainly distributed in the east of Lingdingyang Bay, Dapeng Bay and Daya Bay, and the design tide level of coastal levees can be available by calculating that at Shanbanzhou Station, Chiwan Station and Port Station; under the frequency of one-in-200-year flood/tide, the design tide level adopted for planning the coastal levees in 2014 is 0.4-0.5m lower than that in Pearl River Basin Planning Achievements, in the ongoing revision of plans, the storm surge elevation in 2017 and 2018 has been taken into consideration, the design tide level of Chiwan Station

and Shanbanzhou Station is increased by 0.8-0.9m compared with the original plan, the design tide level at the Port Station increases about 0.6m, thus meeting the design flood/tide control requirements;

(3) Dongguan city's existing coastal levees are distributed along Shiziyang Bay and Lingdingyang Bay, and 1995 provincial tide level design achievements have been adopted for designing the elevation, with Dasheng Station and Sishengwei Station as examples, the one-in-100-year design tide level of which is 0.36m and 0.44m respectively lower than that in Pearl River Basin Planning Achievements, namely, it fails to meet the new flood/tide control requirements, and measures are urgently needed to correct the design tide level achievements;

(4) Zhuhai city's coastal levees are arranged along Lingdingyang Bay, South China Sea and Huangmao Sea, which are significantly affected by the storm tide. The design tide level of existing coastal levees still adopts 2002 provincial achievements, which are lower than the Pearl River Basin Planning Achievements as a whole; under the one-in-100-year design tide level, the tide level is 0.1-0.7m lower, and the closer to the Outlet Station is, the larger the lowering amplitude is;

(5) Zhongshan city's coastal levees are disposed at the left bank of Modaomen Station upstream and right side of Lingdingyang Bay, and the design tide level of existing coastal levees still adopts 2002 provincial achievements; under the one-in-100-year design tide level, the tide level of Denglongshan Station and Maan Station is respectively 0.22m and 0.19 lower than that specified in Pearl River Basin Plans.

(6) Jiangmen city's coastal levees are laid out along both side of Yinzhou Lake and Yamen Channel, and the design tide level of existing coastal levees still adopts 2002 provincial achievement; this achievement is basically identical to Pearl River Basin Planning Achievements, thus meeting the basic design requirements.

Therefore, compared with the Pearl River Water Resources Commission achievements in 2016, the design tide level adopted for elevation of coastal levees in Guangzhou city, Shenzhen city and Jiangmen city is basically in line with the requirements; while that in Dongguan city, Zhuhai city and Zhongshan city is low to different degree. After taking the storm surge elevation influence caused by Super Typhoon Mangkhut (No.1822) and Typhoon Hato (No.1713), such lowering amplitude will be further enlarged. Under the general background of imposing higher safety guarantee of waters during the implementation of existing GBA strategic plans, it's urgent to proceed more demonstrations and analysis on design tide level achievements of existing control station in GBA.

5. Conclusion

GBA coastal levees are mainly laid out in six coastal cities, namely, Guangzhou, Dongguan, Shenzhen, Zhongshan, Zhuhai and Jiangmen. Wherein, the length of levees in Guangdong city and Zhuhai city accounts for more than half of the total length of levees in GBA, being 30% and 23% of the total length, respectively, while Shenzhen has the shortest levees, which take up only 5% of the total length. Comparison of the different design tide level achievements made in these years show that the design tide level in Jitimen Channel, Hutiaomen Channel, Modaomen Channel, Humen Channel, Shawan Channel, north main stream of Dongjiang River and South Branch Estuary is remarkably lower, with the lowering amplitude being 0.2-0.5 m, while that at the control stations of Yinzhou Lake, Hengmen Station, Wanqingsha Station, Jiaomen Channel, Pearl River Channel Lower Reaches and upstream river network area remain largely unchanged; after considering the impact of Super Typhoon Mangkhut and Typhoon Hato, the tide level at Lingdingyang Outlet increases by 0.6-0.7 m, but these storms mainly affected the outlet and the open seas, with slight impacts on upstream river networks. The design tide level adopted for elevation of coastal levees in Guangzhou city, Shenzhen city and Jiangmen city has met the standard, but that adopted in Dongguan city, Zhuhai city and Zhongshan city is below the standard.

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