Study on the Characteristics of Tides and Storm Surge in Dongji Islands

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Abstract. Storm surge has posed a great threat to the safe development of marine ranch in Dongji Islands. Research on the tidal dynamics and storm surge of Dongji Islands is more and more urgent. For this reason, based on measured data of tidal level in 2012, this paper conducts research on the variations of tidal level and storm surge in Dongji Islands. Main conclusions are: Affected by the topography and tidal waves in the East China Sea, temporal and spatial distribution of tidal level and storm surge is asymmetric. Tidal intensity is strong in the eastern sea and weak in the western. The amplitudes of main semi-diurnal tides (M2, S2, N2) in the western sea have a significant attenuation, with the average tidal range decreased by about 16%. Cycle of the practical storm surge is consistent with the tidal constituents, for the cycle at Daishan station was close to 24 h, while Miaozihu station was about 12 h.

1. Introduction
Tidal dynamics in archipelagic waters have always attracted much concern. For Zhoushan Archipelago, one of the most interesting areas for oceanographers, numerical models along with limited measured data are widely used in previous studies on large-scale flow fields in Zhoushan Archipelago Sea [1]–[4]. With the development of coastal engineering in recent years, researchers mainly focus on some specific channels, such as Jintang Channel, Cezi Channel, Luotou Channel, etc. [5]–[8]. Since then, hydrodynamics of wide-range flow fields and partial channels in Zhoushan Archipelago have been deeply studied. However, due to the restriction of traffic and basic survey data, few studies on the far-shore sea area of Zhoushan Archipelago are published, such as Dongji Islands Sea [9]. As the "gateway" between Hangzhou Bay and the East China Sea, local tidal dynamics differ a lot from the east to west in this sea area, where scientific research is urgently needed. Therefore, based on the tidal observation data in 2012, this paper analysed and discussed the characteristics of tidal level and storm surge in Dongji Islands. The research focuses on the generation mechanism of tidal dynamics and storm surge, with an aim to providing a scientific basis for the disaster prevention and mitigation for marine ranch and Green Petrochemical Base in Zhoushan Islands.

2. Data and methodology

2.1. Study area
Dongji Islands (figure 1, 30°05’-30°15’ N, 120°15’-130°05’ E), an islands chain at the easternmost end of the Zhoushan Islands centre, where differs a lot from the Zhejiang coastal areas in hydrodynamic processes. The islands chain spans 70 km from east to west, and is composed of 118 islands and 174 reefs. The water depth increases gradually from west to east, ranging from 8 to 70m. The waterways generally show the trend of NNE-SSW, and the water depth of each is above 30 m.
2.2. Data sources
Tidal level data are provided by two temporary stations that last for 31 days——Miaozihu temporary tide station and Daishan temporary tide station (hereinafter referred to as Miaozihu station and Daishan station). Observation time was from 0:00:00 on July 18, 2012 to 23:00:00 on August 17, 2012 (UTC+8, the same below), with the time interval of 1h. Miaozihu station is located near the Miaozihu Island, the easternmost part of Dongji Islands sea area. Daishan station is located near the Daishan Island, the westernmost part of sea area. Basic information of stations is shown in table 1. Geographical location of stations is shown in figure 1.

| Station   | Latitude °N | Longitude °E | Observation Time               |
|-----------|-------------|--------------|--------------------------------|
| Daishan   | 30.2408     | 122.1958     | 2012.07.18 0:00:00 — 2012.08.17 23:00:00 |
| Miaozihu  | 30.1917     | 122.6833     | 2012.07.18 0:00:00 — 2012.08.17 23:00:00 |

2.3. Methodology
Variations of the tidal level of the eastern and western sea area in Dongji Islands are summarized by the comparative analysis of three parameters: main tidal constituents, tidal form and tidal range. Based on the measured tidal level data of 31 consecutive days in 2012 at the Miaozihu and Daishan stations, main tidal constituents are obtained by method of harmonic analysis [10] after eliminating outliers of the tidal level during typhoons. Characteristics of the storm surge under extreme weather conditions are mainly based on the curves of the practical storm surge. The practical storm surges are calculated by the differential method, which is obtained by subtracting the predicted tide level from the measured tide level.
3. Characteristics of tidal level

3.1. Main tidal constituents
Table 2 lists the amplitudes and phase lags of 8 main tidal constituents of the Miaozihu station and Daishan station. It can be seen that the main tidal constituents of Dongji sea area are M2, S2, K1 and O1. The M2 tidal constituent is dominant, with its amplitude 96cm in Daishan station and 120cm in Miaozihu station, two to three times the amplitude of S2 respectively. The amplitudes of S2 and K1 are second, and the O1 are smaller. Shallow water tides M4 and MS4 are smallest (3~5 cm), indicating that the nonlinear distortion caused by shallow water effect is small when offshore tidal waves pass through the islands, rather than a prominent nonlinear distortion due to the decreasing water depth from east to west. This suggests that, though from east to west, decrease in depth of the water contributes to the enhancement of shallow effects [11], the topography of islands make it differs from the estuary or harbour area. Due to the moderate changes in water depth when tides passing through, with numerous islands, unclosed sea area and strong current, the friction effect is enhanced. In this case, the nonlinear characteristics of tidal waves are not significant and thus shallow water tides are not prominent.

Table 2. Results of tidal level harmonic analysis.

| Category          | Constituent | Miaozihu | Daishan | Growth Rate | Average |
|-------------------|-------------|----------|---------|-------------|---------|
| Semi-diurnal tides| M2          | amplitude/cm | 120.44  | 95.55 | -21% | Amplitude: -23.3%; Phase lag: +40.21° |
|                   |             | phase lag/° | 32.31   | 73.38  | +41.07° |
|                   | S2          | amplitude/cm | 51.70   | 37.20  | -28% |
|                   |             | phase lag/° | 75.21   | 116.65 | +41.44° |
|                   | N2          | amplitude/cm | 15.72   | 11.39  | -28% |
|                   |             | phase lag/° | 3.07    | 41.18  | +38.11° |
| Diurnal tides     | K1          | amplitude/cm | 37.25   | 43.34  | +16% |
|                   |             | phase lag/° | 102.19  | 112.59 | +10.4° |
|                   | O1          | amplitude/cm | 24.82   | 27.32  | +10% |
|                   |             | phase lag/° | 35.37   | 22.70  | -12.67° |
|                   | Q1          | amplitude/cm | 3.16    | 5.18   | +64% |
|                   |             | phase lag/° | 320.13  | 230.27 | -89.86° |
| Shallow tides     | M4          | amplitude/cm | 4.23    | 3.89   | -8% |
|                   |             | phase lag/° | 314.85  | 344.01 | +29.16° |
|                   | MS4         | amplitude/cm | 3.17    | 3.16   | 0% |
|                   |             | phase lag/° | 13.04   | 54.30  | +41.26° |

According to table 2, changes in the main tidal amplitudes of Daishan station compared to Miaozihu station is analysed below. (1) The main semi-diurnal tidal constituents (M2, S2 and N2) decreased significantly. Compared with Miaozihu station, amplitudes of the M2, S2 and N2 tidal constituents of Daishan station decreased by 21%, 28% and 28%, respectively. (2) The main diurnal tidal constituents (K1, O1 and Q1) increased by 16%, 10% and 64%, respectively. (3) The main shallow tidal constituents (M4 and MS4) decreased slightly, within 8%.

According to the tidal form criterion, judging the tidal form by $F = (H_{K1} + H_{O1})/H_{M2}$. Thus, the tidal form number of Miaozihu station is 0.52, and that of Daishan station is 0.74. It indicates that both stations are irregular semi-diurnal mixed tides, and the tidal ratio of Daishan station is significantly increased by 42.3%. According to the shallow water tide criterion $G = H_{M4}/H_{M2}$, it can be calculated that Miaozihu station is 0.035, while Daishan station is 0.041, with an increase of 16.3%. The results
show that the shallow water constituents are slightly enhanced when it is propagated to the shallow sea, however the nonlinearity is still small generally. It is encouraging to compare this result with that found by Wu et al. [4] who found that the tidal form of Zhoushan Archipelagos was related to the concentration of islands distribution. Wu et al. [4] studied through numerical simulations and concluded that the islands-intensive sea area was dominated by irregular semi-diurnal tides, while the islands-sparse sea area was regular semi-diurnal tides. The results of this paper are consistent with this conclusion. As shown in figure 1a, the denseness in the distribution of islands from east to west is larger in Dongji sea area, which is related to the formation and evolution process of continental islands, indicating the feature of irregular semi-diurnal mixed tides from east to west in Dongji Sea is enhanced. This is also consistent with the attenuation in the diurnal tidal constituents. According to the results of the two stations, when tide waves pass through the western part of Dongji islands, the amplitudes of the main semi-diurnal tides (M2, S2, N2) decrease significantly. Meanwhile, the amplitudes of the main diurnal tides (K1, O1, Q1) increase slightly, thus the tidal form number increases significantly. This phenomenon has been found in other channels in Zhoushan Archipelagos [12]–[13]. To date, several studies have investigated it in the deep-water channels in Zhoushan. Chen [12] found that the amplitude of the M2 tidal constituent decreased pronouncedly when the tidal waves passed into the sea area near the Jintang channel, while the M2 tidal constituent gradually increased and resumed after the tidal wave came into the mouth of Hangzhou Bay. Ren and Yang [13] also found that the amplitude of the main semi-diurnal constituent tide significantly decreased when it passed through the Guanmen channel in the north of Zhoushan. Hence, it could conceivably be hypothesized that the attenuation of the main semi-diurnal tidal amplitudes exists in large area of Zhoushan sea area. There are several possible explanations for this phenomenon. In this paper, the area which we studied is located in an open islands sea, Dongji archipelagos sea, which proved that this phenomenon can also take place in open sea area, in addition to the case of channels. Apart from the influence of bottom friction and conversion of potential energy to kinetic energy in complex islands environment [13], there may still exist two reasons. First, for open and unclosed sea areas, compared with semi-closed estuaries and bays, it is not conducive to the water level to rise when the depth is deep. Second, it is related to the crisscrossed water channels in islands sea. For example, there are no less than ten tidal channels that are approximately parallel between Miaozihu Station and Daishan Station. Circulation around the islands and complicated flow paths are not conducive to backwater. Of course, whether there are other reasons remains to be further explored.

3.2. Tidal range

As shown in table 3, characteristic values of the tidal levels of Daishan station have several changes relative to those of Miaozihu station. (1) Average tidal ranges of both stations are small. In contrast, all tidal range values of the Daishan station are smaller than those of Miaozihu station, with the average tidal range decreased by 16%. (2) The duration of ebb tide is longer than that of flood tide, and the difference at Daishan station is slightly shortened. Previous studies have suggested that the coastal sea areas of Zhejiang province were strong-current and dominated by the semi-diurnal tides [3], [12]. Except near the Zhenhai, tidal form number of the wide sea area of Hangzhou Bay and Zhejiang north coastal water is less than 0.5. Meanwhile, average tidal range is basically larger than 2.5 m and the maximum tidal range is larger than 4.0 m [12]. Thus, the changes show a decrease in the tidal range from east to west in Dongji sea area. Due to the dense islands and crisscrossed channels, it reflects that the tidal intensity in the western margin of Dongji islands is decreasing gradually, while the eastern margin is still strong-current sea area.

| Station    | Maximum tidal range /m | Minimum tidal range /m | Average tidal range /m | Maximum possible tidal range /m | Average duration of flood tide /h:m | Average duration of ebb tide /h:m |
|------------|------------------------|------------------------|------------------------|----------------------------------|-------------------------------------|----------------------------------|
| Miaozihu   | 4.17                   | 0.58                   | 2.59                   | 5.25                             | 5.56                                | 6:28                             |
| Daishan    | 3.49                   | 0.40                   | 2.17                   | 4.37                             | 6:00                                | 6:25                             |

Table 3. Characteristic values of tidal levels.
4. Characteristics of storm surge

Taking into account the typhoon path, intensity and tide conditions, we select two types of typhoon processes: affected type (No.1209 and No.1210) and landing type (No.1211). According to table 4 and figure 2, the characteristics of the storm surge at two stations are analysed respectively for the two typical typhoon processes.

**Table 4.** Statistics of the maximum storm surge of typhoons at two stations.

| Typhoon Process | No.1209 and No.1210 | No.1211 |
|-----------------|---------------------|---------|
|                 | Daishan             | Miaozihu| Daishan | Miaozihu |
| High tide level (cm) | 240                | 264     | 254     | 278     |
| High tide moment  | 22:00, August 1     | 22:00, August 3 | 02:00, August 8 | 00:00, August 8 |
| Maximum storm surge (cm) | 121             | 152     | 140     | 141     |
| Maximum storm surge moment | 14:00, August 3   | 14:00, August 3 | 14:00, August 7 | 22:00, August 7 |
| Tide moment of maximum storm surge | 3h behind the ebb tide | 4h behind the ebb tide | astronomical high tide | 4h behind the flood tide |
| Tide of maximum storm surge | spring tide | spring tide | neap tide | neap tide |

**Figure 2.** Curves of the water level and practical storm surge of two stations during three typhoons. The blue lines mean the measured tidal levels. The red dotted lines mean the predicted tidal levels after harmonic analysis. The black solid lines mean the practical storm surges.

**Figure 3.** Curves of the practical storm surge during the affected and landing typhoon respectively. The left panel shows the curves of the practical storm surge of two stations during the affected
typhoon process (No.1209 and No.1210). The right panel shows the curves of the practical storm surge during the landing typhoon process (No.1211).

4.1. Two types of typhoon processes

4.1.1. Affected typhoon process. Double typhoons (1209 and 1210) affected the Dongji sea area from July 31 to August 4, which was coincided with the spring tide. According to table 4, high tide level at Daishan station and Miaozihu station reached 240 cm and 264 cm, respectively, and the maximum practical storm surge reached 121 cm and 152 cm. According to figure 3, due to the tide-surge interactions, the curves of the practical storm surge at both stations are fluctuated over a 12-hour cycle. At 14:00 on August 3, both stations arrive their maximum surge values at the same time. Due to the generation and westward movement of Typhoon 1211 on the Northwest Pacific on August 5, the surge values of both stations decreased slightly on August 4, and then increased to a certain extent on August 5.

4.1.2. Landing typhoon process. Strong typhoon No. 1211 landed at Zhejiang Province and hit the Dongji sea area from August 5 to August 10, which was coincided with the neap tide. As shown in table 4, high tide level at Daishan Station and Miaozihu Station reached 254 cm and 278 cm, respectively, and the maximum storm surge reached 140 cm. According to figure 3, on the eve of the typhoon landing (from 00:00 on August 5th to 00:00 on August 7), the fluctuations of the curves at both stations were significant, which may be affected by the previous double typhoons. The cycle of the fluctuations at Daishan Station shows a long period of about 24 hours, while that at Miaozihu Station is about 12 hours. The main body of storm surge of both stations had no single peak, but lasted for a long time (1 to 2 days). During the extinction stage (after 00:00 on August 9), the surge values turned to decrease rapidly. In this case, the residual fluctuations at Daishan station was very smooth, while that at Miaozihu station was significant with a period of several hours.

4.2. Mechanism of the island effect of storm surge

Similar to tidal waves, storm surges can also be regarded as long waves that propagate to the shore as shallow water waves. During the propagation, storm surges are subjected to seabed friction, Earth’s rotation (Coriolis force), and local enhancements due to resonance producing large surges [14]. For shallow coastal areas, the tide-surge interactions will greatly affect the magnitude of storm surge and its fluctuations pattern.

4.2.1. The relationship between tidal wave and storm surge. According to figure 2, period of precursor surge fluctuations is related to local tidal constituents. In the cases of two types of typical typhoons, the precursory surge at both stations showed pronounced fluctuations, but the periods are quite different: the precursory period at Daishan station was close to 24 h, showing a diurnal cycle, while at Miaozihu station was 12 h, showing a semi-diurnal cycle. This phenomenon is consistent with the feature of tidal constituents found in previous harmonic analysis. Due to the attenuation in amplitudes of main semi-diurnal constituents, the influence of diurnal tidal constituents in the western Dongji Islands Sea has increased, causing the period of storm surge fluctuations longer. However, in the eastern Dongji Islands Sea, the semi-diurnal constituents are still dominant and thus the fluctuations show a significant semi-diurnal cycle. Ding and Che [15] extracted the practical storm surge based on the measured data and found that the period of the practical storm surge is similar to the astronomical tide, which is consistent with the viewpoint of this paper. This periodicity feature is very useful for the prediction and forecast of storm surge. According to the fluctuations of precursory surge, the surge pattern in the following period can be predicted to some extent.

4.2.2. The relationship between terrain and storm surge. It has been observed for a long time that the storm surge peak usually occurs on the rising tide or falling tide period rather than at the high water, which is due to the tide-surge interactions [16]–[19]. Rossiter [20] suggested that a key mechanism of the tide-surge interactions is one of mutual phase alteration. Horsburgh and Wilson [19] confirmed
this conclusion and proposed that the interactions will lead to an increase in the difference of the phase. Analysing the phase of maximum surge, it can be found that the time difference between the maximum surge and high water was significant with more than 10 hours at Daishan Station, while that at Miaozihu Station was within 10 hours. It reveals that the tide-surge interactions at Daishan Station are greater than that of Miaozihu Station. This phenomenon is related to the shallow water depth and islands effect in western Dongji Islands Sea. Studies have suggested that the magnitude of various interactions (including sea level rise, tides, waves, etc.) that influence storm surges are directly related to local water depth [21]. In deeper areas, interactions have smaller magnitudes and can thus be considered as negligible in some locations; conversely, these interactions can be strengthened in shallow areas. For the archipelagos, islands groups are irregular and water depth are complicated. Generally, the water depth decreases when waves propagate to the coast, while the channel effect causes strong tide currents and deep-water depth. At this time, the influence of local tidal current and water depth on the tide-surge interactions needs to be considered comprehensively. For the Dongji Islands Sea, the variations in water depth of the whole field is significant, decreasing from east to west (70–8 m). Moreover, the western islands in group distribution are denser than the eastern. In this case, tidal currents are complex and the islands effect is enhanced in the western sea, thus causing tide-surge interactions have larger magnitudes in the western Dongji Islands Sea to some extent.

5. Conclusions

Based on multi-space-time tidal observation data, combined with coastal dynamics theory, the temporal and spatial distribution characteristics and generation mechanism of tidal dynamics and storm surge in Dongji Islands are analysed. With a view to providing basis knowledge for disaster prevention and mitigation for marine ranch and Green Petrochemical Base in Zhoushan Islands. Main conclusions are as follows.

(1) Affected by the topography and tidal waves in the East China Sea, the spatial and temporal distribution of tidal level is asymmetric. Tidal intensity in Dongji Islands Sea is strong in the eastern sea and weak in the western. Compared with the eastern sea, the amplitudes of main semi-diurnal tidal constituents (M2, S2 and N2) in the western Dongji Islands Sea have a significant attenuation phenomenon, with the average tidal range decreased by about 16%.

(2) Affected by the topography and tidal dynamic characteristics, the temporal and spatial distribution of storm surge is uneven. Due to the large differences in tidal dynamics between the eastern and western sea, the cycle of the practical storm surge is consistent with the dominant tidal constituents. The cycle of precursory storm surge at Daishan station was close to 24 h, while at Miaozihu station was 12 h. Due to the local water depth, the tide-surge interactions tend to have larger magnitudes in the western Dongji Islands Sea than the eastern to some extent.

6. References

[1] Cao X, Tang L and Zhang Y 1996 J. Mar. Sci. 14 1–9
[2] Shou W, Wu J, Hu R and Zhu L 2009 Mar. Geol. Front. 25 1–9
[3] Huangfu K, He Z and Li L 2016 Bull. Sci. Technol. 32 102–6
[4] Wu R, Jiang Z and Li C 2018 Ocean Modell. 132 139–56
[5] Chen B 1997 Port Waterw. Eng. 9 1–4
[6] Jiang G, Jin R, Gu J and Shen B 2001 Mar. Sci. Bull. 20 15–22
[7] Lu J, Lou H and Hu J 2015 Zhejiang Hydrotech. 5 54–94-75
[8] Hou Q, Wang Z, Lu Y and Mo S 2017 Int. J. Sediment Res. 32 351–63
[9] Fei Y, Shi J, Du P and Chen X 2013 Mar. Sci. Bull. 32 648–56
[10] Pawlowicz R, Beardsley B and Lentz S 2002 Comput. Geosci. 28 929–37
[11] Qian L, Du Y and Yu G 1995 Oceanol. Limnol. Sin. 26 32–9
[12] Chen G 1989 Mar. Sci. Bull. 8 1–9
[13] Ren J and Yang T 2008 Ocean Eng. 26 77-82+97
[14] Déborah I, Xavier B, Philip T and Mark D P 2019 Surv. Geophys. 40 1603–30
[15] Ding J and Che Z 2003 Mar. Forecasts 20 5–14
[16] Doodson A T 1929 Geophys. Mem. Lond. 47 1–26
[17] Proudman J 1955 Proc. R. Soc. Lond. A 231 8–24
[18] Wolf J 1981 Academic 75–94
[19] Horsburgh K J and Wilson C 2007 J. Geophys. Res. 112 C08003 1–13
[20] Rossiter J R 1961 Geophys. J. R. Astron. Soc. 6 29–53
[21] Idier D, Dumas F and Muller H 2012 Nat. Hazards Earth Syst. Sci. 12 3709–18