Analysis of hydrodynamics and sediment conditions around East Coast Sea Area in Bay of Bengal

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Abstract. The bay of Bengal is an important sea area of the 21st century Maritime Silk Road. Systematic analysis of the hydrodynamic and sediment characteristics of the bay of Bengal is conducive to the development and implementation of offshore and coastal projects in the bay of Bengal. In this paper, based on the historical reanalysis data of ECMWF and the observed data of several hydrological stations along the east coast of Bangladesh, including wave, tide level, tidal current and sediment data are verified and assimilated, and the characteristics of wind wave, water level, tide and sediment along the east coast of Bengal are analysed. The hydrodynamic and sediment conditions in the bay of Bengal are generally characterized by "strong tide, strong wave and high suspended sediment concentration". The bay of Bengal is easily affected by cyclonic storms, which causes a great increase in storm surge. The above situation will lead to the complicated sediment erosion and deposition of storm surge, strong wave and strong tide and high suspended sediment concentration. At present, there has no deep-water port and coastal power plant located in the bay of Bengal. Whether to build a deep-water port or how to transfer at sea should be paid attention to or studied in depth.

1. Introduction

Hydrodynamic sediment environment is an important factor and key problem that restricts the construction and operation of coastal engineering and marine engineering. Offshore hydrodynamic factors mainly include tide, tidal current, wave and sediment transport, which are very important for the study and analysis of hydrodynamic sediment environment.

Bangladesh is close to the northern Bay of Bengal, with a coastline of about 550 km. Firstly, due to the narrowing effect of the bell mouth and the influence of the southwest monsoon, the tides and tidal currents entering the bay of Bengal gradually increase from the mouth to the upstream, which forms a strong tidal estuary and bay. Usually, this is a special kind of estuary, whose tidal wave deformation is severe, and the average tidal range is generally greater than 3.5m[1]. Secondly, most of the coastline of Bangladesh is directly facing the open sea area of the bay of Bengal, with frequent swell. Thirdly, the bay of Bengal is also a tropical cyclone prone area that is affected by storm surge every year. Fourthly, in the bay of Bengal, the Ganges and Brahmaputra estuary, a strong tidal estuary with abundant water and sediment, forms one of the largest deltas in the world calls Ganges delta. So far, due to the complex hydrodynamic and sediment conditions in the bay of Bengal, there is still no deep-water port along the coast of Bangladesh, which also limits the development of shipping and other industries in the bay of Bengal.

Wang Hui[2] etc. introduced the current situation of marine and meteorological disasters along the "21st century Maritime Silk Road", the monitoring and early warning status of countries along the route, and international cooperation organizations and mechanisms, and put forward key problems and
Countermeasures for disaster risk prevention. Chang Jinglong[3] analysed the overall characteristics and seasonal variation of mesoscale vortices in the bay of Bengal from 1993 to 2016 using the latest data set of mesoscale vortices provided by aviso. Xu Yanan[4] used the historical reanalysis data from ECMWF to statistically analyse the characteristics of wave field and sea surface wind field in the bay of Bengal for many years, indicating that the wave and wind conditions in the bay of Bengal have seasonal variation characteristics. Zhang Yajing[5] respectively used numerical simulation and physical model test methods to simulate the layout of wharf and water intake and drainage project for a power plant on the east coast of Bengal Bay, and analysed and studied the sediment erosion and deposition changes in the harbor basin, navigation channel and water intake open channel after the construction of the project. Luo Qiwei[6] carried out the parameter optimization and thermal discharge dispersion characteristics of the coal-fired power plant drainage diffuser in the bay of Bengal estuary by combining the CORMIX empirical model with the realizable $k$ - $\varepsilon$ turbulence model.

At present, the systematic analysis of hydrodynamic conditions along the east coast of the bay of Bengal is rare. This paper mainly introduces the hydrodynamic and sediment conditions of the east coast of the bay of Bengal from the aspects of water level, wind and wave, tidal current and sediment environment, so as to enrich the research on the natural conditions of the bay of Bengal, and provide scientific basis for the design of hydraulic structures for port construction and power plant construction along the coast of Bengal, which is conducive to promoting the development and implementation of offshore projects in the bay of Bengal.

2. Data sources and analysis methods

In order to understand the hydrodynamic and sediment conditions of the bay of Bengal, the reanalysis data of wind and wave from ECWMF, the tropical cyclone data provided by National Hurricane Center and Central Pacific Hurricane Center from National Oceanic and Atmospheric Administration, the observed data from different offshore and coastal projects along the east coast of Bengal Bay have been collected, assimilated, verified and analysed. For the wind and wave data, the selected areas from 0° N to 32.5° N and from 31.5° E to 102.5° E, including the bay of Bengal and the Arabian Sea were analysed statistically. For the tropical cyclones data, which occurred in the bay of Bengal from 1977 to 2017 was used. For the observed data, the locations of the observed hydrological stations are shown in Table 1.

| Name | Longitude | Latitude | Name | Longitude | Latitude |
|------|-----------|----------|------|-----------|----------|
| P1   | 91°27'39.88" | 22°45'58.07" | P4   | 91°53'25.14" | 21°58'1.74" |
| P2   | 91°31'20.07" | 22°42'7.93"  | P5   | 91°51'31.85" | 21°40'7.95" |
| P3   | 91°40'29.00" | 22°32'35.07" | P6   | 91°53'33.43" | 21°37'58.17" |

3. Analysis of hydrodynamic conditions in the bay of Bengal

3.1. Wave field distribution

In this paper, the distribution characteristics of significant wave height of the bay of Bengal from 1988 to 2017 are analysed. In the first quarter, the average significant wave height is from 0.95m to 1.55m. In the second quarter, the bay of Bengal is usually the season of monsoon transition, the monsoon changes from the northeast direction to the southwest direction, at this time, the average significant wave height is from 1.1m to 2m, and the isoline gradually rises from the low latitude to the middle and high latitude of the bay of Bengal, which can obviously show the phenomenon that the waves in the south of the Indian Ocean propagate northward. In the third quarter, under the influence of the southwest monsoon, the average significant wave height is from 1.6m to 2.4m. In the four seasons, the monsoon changes from southwest monsoon to northeast monsoon. Due to the influence of cold air, the significant wave height in the bay begins to decrease, with the average value varying between 0.8m and 1.8m.
Through the analysis of wave field in different seasons, it can be concluded that the wave condition of the bay of Bengal has seasonal variation characteristics, and the average significant wave height under the influence of the southwest monsoon is greater than that under the influence of the northeast monsoon, and greater than that in other quarters during the monsoon period (the third quarter). The seasonal characteristics of the wave field are shown in Figure 1.

3.2. Wind field distribution
In the first quarter, the northeast wind prevails in the Indian Ocean and the bay of Bengal is mainly affected by the monsoon. The average wind speed is from 4m/s to 5m/s, and the maximum average wind speed is about 5m/s. In the second quarter, the wind speed changed from northeast monsoon to southwest monsoon. Due to the change of monsoon wind direction, the change of wind speed in this season is not big, and the average wind speed is from 3.5m/s to 5m/s. In the third quarter, the southwest monsoon of the bay of Bengal developed strongly. Under the influence of the southwest monsoon, the wind direction is mainly in the southwest direction, with an average wind speed of 4m/s to 7m/s. The maximum average wind speed is distributed near the central sea area. In the four seasons, there is a transition of monsoon in the bay of Bengal which the monsoon changes from southwest monsoon to northeast monsoon. The wind direction is mainly in the northeast direction, with an average wind speed of 4m/s to 4.5m/s and little change in wind speed. The maximum wind speed is near the central sea area. The seasonal characteristics of the wind field are shown in Figure 3.

3.3. Tropical cyclones
From 1977 to 2017, 151 tropical cyclones were generated in the bay of Bengal, with an average of 3.68 tropical cyclones per year. The interannual variation characteristics of tropical cyclones are relatively large, of which the maximum number of tropical cyclones was 9 in 1992, but only one occurred in 1989, 1993, 2001, 2004 and 2015. The frequency of occurrence of depression is relatively small, only 1.32% of the total; the frequency of deep depression is 10, accounting for 6.62% of the total. The number of severe cyclonic storm is the most, up to 55, accounting for 36.4% of the total, with an annual average of 1.34 while the frequency of occurrence of severe cyclonic storm and very severe cyclonic storm is not much different, 38 and 36 respectively, accounting for 25.17% and 23.84% of the total.

In terms of seasonal distribution, the frequency of tropical cyclones in the bay of Bengal is the highest in autumn (September, October and November), during which the total frequency is 80,
accounting for 52.98% of the total, which is more than the total frequency of other tropical cyclones (71). The frequency of spring and winter season is almost the same, which is more than the frequency of tropical cyclones in summer. In terms of monthly distribution, the tropical cyclones in the bay of Bengal show obvious bimodal variation characteristics, with peaks in May and November respectively; the severe cyclonic storm, very severe cyclonic storm and super cyclonic storm are more frequent in April, May, October and November, with more super cyclonic storms, for example, the maximum wind speed of super cyclonic storm 4# in 1991 reached 140 kn in April of that year.

3.4. Storm surge
The shallow sea area on the delta continental shelf of the bay of Bengal and the low-lying coastal area of the triangle bell mouth bay are famous vulnerable zones of tropical cyclone that often lead to disasters such as storm surge and floods. During the tropical cyclone landing, the average water level can be increased by more than 5 meters in an instant. Because of the low pressure in the centre of the tropical cyclone, the tide rises in the process of movement, which causes great disasters and economic losses. For instance, the maximum storm surge height caused by tropical cyclone on the east coast of Bangladesh was 10 m in 1970 and 7.6m in 1991.

This paper analyses the influencing factors of severe storm surge on the east coast of Bangladesh, mainly including the following aspects. Firstly, the nearshore is shallow and the slope is gentle, which causes the storm surge to increase high water level along the coast. Secondly, the direction of Coriolis force is eastward in the northern hemisphere, which causes the storm surge in the bay of Bengal to move towards the east coast. Thirdly, under the influence of tide, the tidal range varies greatly in different seasons in the bay. The upstream rivers such as Feni and Meghna have large runoff, and the mixing of salt and fresh water in the estuarine area results in the increase of tidal range, which will increase from 60cm to 100cm in the annual flood monsoon period. Fourthly, there are many offshore islands near the shore, which leads to the reduction of the flow passage and the increase of water level.

3.5. Tidal characteristics
Tidal range is one of the important signs of tide in the sea area. Combined with the observed tidal level data of several tidal stations along the east coast and temporary hydrological stations (see Table 1), the tidal characteristic values of the east coast of the northern Bay of Bengal are statistically obtained, as shown in Table 2. The northern Bay is a typical strong tidal estuary. After the Indian Ocean tide wave is introduced into the bay of Bengal, the tidal range in the Bay increases gradually from the bay mouth to the top of the upstream, and then decreases gradually to the river at the top of the upstream, which conforms to the basic characteristics of the tidal range change of the strong tidal estuary. According to the statistical results, the maximum tidal range of the bay mouth is about 4.30m, while the maximum tidal range of the bay top is about 7.30m. From the harmonic analysis of the measured tide level data along the coast, the tide of the northern Bay of Bengal is mainly normal semidiurnal tide from the bay mouth to the bay top, that is, the tide level has two high tides and two low tides in a lunar day.

| Name                      | P2 | Chittagong | P4 | P5 | P6-1 | P6-2 |
|---------------------------|----|------------|----|----|------|------|
| Max. tidal range(m)      | 7.30 | 4.80 | 5.46 | 4.22 | 4.39 | 4.36 |
| Min. tidal range(m)      | 3.05 | 1.20 | 1.32 | 1.06 | 1.59 | 1.66 |
| Average tidal range(m)   | 5.53 | 3.00 | 4.00 | 2.69 | 2.78 | 2.92 |
| \((H_{01}+H_{11})/H_{M2}\) | 0.12 | -   | 0.15 | 0.20 |      |      |
| Average flood Duration(h:mm) | 5:00 | 5:30 | 5:54 | 6:19 | 6:17 | 6:28 |
| Average ebb duration(h:mm) | 7:30 | 6:54 | 6:28 | 6:13 | 6:07 | 5:56 |

3.6. Tidal current
According to the analysis of the tidal current data of the observed hydrological stations along the coast, the tidal current in the east coast of Bangladesh generally presents reciprocating flow, and the current direction is roughly the same as that of the coastline, mainly in the north-south direction. The tidal current moves from south to north at flood tide and from north to south at ebb tide.
The tidal current in the east coast of Bangladesh shows the phenomenon of time velocity asymmetry [7-8], that is, the duration and velocity of flood and ebb tides are unequal. From the Bay top to the estuary of Chittagong (Sandwip channel), the duration of flood tide is short and that of ebb tide is long. According to the conservation of the tidal water volume, the flood tidal velocity is greater than the ebb tidal velocity. For instance, the maximum current velocity at the surface layer during flood tide for P2 is 1.90m/s and that during ebb tide is 0.98m/s. From the Chittagong estuary to the bay mouth, the flood and ebb tides have the same duration and the current velocity. For instance, the maximum current velocity at the surface layer during flood tide and ebb tide for P4 located at the north side of Kutubdia Island are respectively 1.36m/s and 1.41m/s. While the maximum current velocity at the surface layer during flood tide and ebb tide for P6 located in a complex tidal channel are respectively 1.25m/s and 1.57m/s where the tidal current characteristics in the channel and in the open sea are quite different that the flood tide duration is longer than the ebb tide duration, and the ebb tide is dominant.

4. Sediment conditions along the east coast of the bay of Bengal

4.1. Sediment source
The Ganges and Brahmaputra estuary, which is rich in runoff and sediment, forms one of the largest deltas in the world. The total runoff of Ganges and Brahmaputra River estuary is 1310 billion m$^3$, and about 700 million tons of sediment are carried into the sea at the same time. When the runoff and sediment of Ganges Brahmaputra River and the Karnaphuli River diffuse to the open sea, a part of the sediment deposited in the sea area outside the estuary. Then the sediment is lifted, resuspended, and would be transported into the bay of Bengal along with the tidal current. In the bay of Bengal, the suspended sediment concentration is high in the west and low in the east, and the closer it is to the Meghna River, the greater the suspended sediment concentration.

4.2. Suspended sediment characteristics
The satellite images show that the overall suspended sediment concentration (SSC) in the bay of Bengal is high in the west and low in the east, and the closer to the Meghna River, the greater the suspended sediment concentration. In addition, from the analysis of the measured suspended sediment data (see Table 3 below), the characteristics of the suspended sediment concentration are as follows. Firstly, in terms of time distribution, SSC in the east coast of Bangladesh during the spring tide is large, followed by the medium tide, and less during the neap tide. Secondly, in terms of spatial distribution, SSC in the surface, middle and bottom layer of the sea area presents the general distribution law, namely SSC in the surface, middle and bottom layers increase in turn. Thirdly, from SSC and dynamic conditions, SSC is not only affected by the tides, but also by the waves. In the bay mouth area obviously affected by the wave, SSC during the period of spring and medium tide is positively correlated with the wave. In addition, the northern bay is distributed with the largest sedimentary Delta, with rich sediment sources, which directly forms the east coast of Bangladesh where the high suspended sediment environment of the sea area.

| Content        | P2     | P4     | P5     | P6-1   | P6-2   |
|----------------|--------|--------|--------|--------|--------|
| Spring tide    | -      | 0.75   | 0.40~1.03 | 0.40~0.83 | 0.31~1.15 |
| Medium tide    | -      | -      | -      | -      | 0.13~0.83 |
| Neap tide      | 0.40~0.64 | -      | 0.10~0.45 | -      | 0.13~0.39 |

4.3. Seabed bottom material
According to the measured data, the distribution of bottom material along the east coast of Bangladesh is quietly different from the bayhead to the bay mouth. The seabed bottom material near the bay mouth to Sandwip channel is muddy clay with fine particles. The median particle size of the seabed bottom material is about 0.01mm, which belongs to the category of fine sand, mainly composed of silt, clay
and sand. From the south of Chittagong estuary to the north of Kutubdia Island, due to the wave action, the seabed bottom material of the nearshore shoal is unevenly distributed, and the grain size is alternated between coarse and fine. The median grain size of the bottom material is between 0.02mm and 0.40mm. Sand dunes, sand beaches and mudflats are alternately distributed, mainly including coarse medium sand, medium sand, medium fine sand, fine sand, silty sand, sandy silt, silty sand and clay silt. From the south side of Kutubdia island to Cox's Bazar, under the action of swell and strong tidal current, the seabed bottom materials of nearshore shoal are mainly medium and fine sand, and the median grain size is between 0.15mm and 0.40mm. The difference of the distribution of the nearshore seabed bottom material along the east coast of Bangladesh is large, which may be caused by the difference of the wave dynamics from the bay mouth to the bay top.

5. Conclusion

Based on the observed data from several hydrological stations along the east coast of Bangladesh, including wave, tide, tidal current and sediment, this paper validates and assimilates the historical reanalysis data of ECMWF, and analyses the wind, wave, water level, tidal current and sediment characteristics of the east coast of the Bay of Bengal. The main conclusions are as follows.

1. The hydrodynamic and sediment conditions in the bay of Bengal are generally characterized by "strong tide, strong wave and high suspended sediment concentration". The wave and wind conditions in the bay of Bengal have seasonal variation characteristics, and the characteristic value of wind and wave during monsoon (the third quarter) is larger than other quarters. The bay of Bengal is easily affected by cyclonic storms, which causes a great increase in storm surge.

2. Based on the above-mentioned complex analysis of the hydrological and sediment conditions of the east coast of the bay of Bengal, the marine engineering of the east coast of the bay of Bengal needs to face the complex sediment erosion and deposition problems of storm surge, strong wave, strong tide and high sediment concentration, and whether to build a deep-water port or sea barge.

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