Research on the Mechanism of Breakwater Damaged by Typhoon Waves under the Background of Climate Change

Yingni Luan¹, Zegao Yin¹ and Hanbao Chen²*

¹ College of Engineering, Ocean University of China, Qingdao, Shandong, 266100, China
² Key Laboratory of Engineering Sediment of Ministry of Communications, Tianjin Research Institute for Water Transport Engineering, Tianjin, 300456, China
*Corresponding author’s e-mail: chenhanbao@tiwte.ac.cn

Abstract. Typhoons are violent storms that occur in the tropical oceans of the Northwest Pacific and South China Sea. The waves caused by typhoons are often the strongest dynamic on the coast. The south-eastern coast of China and Japan is in the most frequent and severe area affected by typhoons, and typhoon waves often reach more than 10m. Based on many years’ coastal wave survey data in Japan, it was shown that typhoon waves have been continuously strengthened in the past 100 years, and typhoon tracks and duration have also changed. During the “Mangkhut ” typhoon, many projects along the south China coast were damaged by typhoon waves. Simulation result of the typhoon waves caused by the typhoon showed that the designed wave conditions were exceeded. The physical model is used to reproduce the situation of the breakwater being destroyed by typhoon waves, and analyses the failure mechanism.

1. Introduction
The typhoon waves generated when a typhoon passes by will threaten human life and property and coastal structures and cause harm. Li S[1] studied the characteristics of wave disasters in China from 2002 to 2015 for a total 15 years, and conducted a separate analysis of typhoon wave disasters; Peng J[2] found that typhoon waves are the biggest factor in the loss of wave disasters by analyzing the wave disaster data in the past 10 years from 2002 to 2011. Over the years, many scholars have conducted in-depth studies on the simulation of typhoon waves. Among them, Wang N[3] simulated the waves generated during the 36 typhoons transited from 1979 to 2018, and calculated the intensity and duration of the typhoons; Han S Z[4] used the CMA-STI data set to calculate the wind field of 92 typhoons from 1981 to 2020 when the typhoon passed through the typhoon formula, and then used the SWAN model to calculate the typhoon waves, then the distribution characteristics of the effective wave height of typhoon waves in the East China Sea were analyzed. The above researches show that the study of typhoon waves is very necessary, and the SWAN model verified by survey data can achieve more accurate typhoon wave results.

Since there are many parameters expressing the characteristics of typhoon waves, this article mainly uses the typhoon wave data on the coast of Japan in the past 50 years to analyze the following five aspects: the wave height of the typhoon wave, the relationship between the wave period and the wave height, the relationship between the maximum wave height and the effective wave height, the inter-annual change of wave height and the duration of typhoon waves. Firstly, analyze the trend of typhoon waves under climate change, and then perform numerical simulations on the typhoon waves generated by the super typhoon "Mangkhut" in 2018, and use the physical model to test and reproduce the
breakwaters destroyed when the typhoon "Mangkhut" passed by. Finally, the damage mechanism is further analyzed.

2. Typhoon wave changes under the background of climate change

2.1 Data sources of typhoon waves on the coast of Japan

In the past 50 years, Japan’s National Harbor Ocean Wave Information Network has set up nearly 70 wave observation stations around the coast of Japan. The southeast coast is most frequently hit by typhoon waves. From northeast to southwest, 10 stations on the southeast coast of Japan are selected for statistics. The stations are shown in Figure 1 (Tokachi, Mutsu-ogawara Port, Kamaishi, Kashima, Shimoda, Shionomisaki, Muotsu, Hososhima, Shibushi Bay, Nakagusuku Bay).

![Figure 1. Schematic diagram of the distribution of Japanese wave stations](image)

2.2 Analysis of typhoon wave intensity

A statistical analysis of the strongest waves affected by typhoons in the 40 years from 1971 to 2010 at 10 observing stations was done. Count the average value of the maximum significant wave height and the annual maximum significant wave height of each station in 10 years at intervals of 10 years. From the statistical results, it can be seen that the maximum wave heights of Shionomisaki, Muotsu, Hososhima in the middle and Shibushi Bay, Nakagusuku Bay in the south are all above 10m, and the waves are stronger than those in the north. The average maximum wave in Nakagusuku Bay from 2001 to 2010 exceeded 8m, which means that the area has a wave of over 8m once every two years, and it is an area with strong typhoon waves. During the 10 years from 1971 to 1980, the maximum typhoon wave at the 7 effective observation stations was 8.46 m, and the average annual maximum wave was 5.36 m; during the 10 years from 1981 to 1990, the maximum typhoon wave at the 8 effective observation stations was 8.77 m. The maximum wave average value is 5.86m; during the 10 years from 1991 to 2000, the maximum typhoon wave of 9 effective observation stations was 10.63m, and the annual maximum wave average value was 6.09m; during the 10 years from 2001 to 2010, there were 10 effective observation stations. The largest typhoon wave is 13.61m, and the average annual maximum wave is 6.58m. There was a relatively obvious increasing trend. Taking the four 10-year maximum wave
height averages of the Kamaishi station are 4.08m, 4.62m, 4.94m, and 5.01m respectively; the four 10-year maximum wave height averages of the Nakagusuku Bay station are 5.86m, 7.14m, and 7.35 respectively m, 8.11m; also presents the characteristics of continuous enhancement. In order to avoid the difference caused by the measurement reasons, the measuring instrument and the position of the measuring point have been checked, which shows that there is no difference in 40 years.

Table 1. The depth of the station and the maximum wave height every 10 years

| Station | Depth (m) | Max Wave height (m) | Average wave height (m) | Max Wave height (m) | Average wave height (m) | Max Wave height (m) | Average wave height (m) | Max Wave height (m) | Average wave height (m) |
|---------|-----------|---------------------|------------------------|---------------------|------------------------|---------------------|------------------------|---------------------|------------------------|
| Tokachi | -23.0     | 6.1                 | 4.8                    | —                   | —                      | 5.14                | 4.67                   | 7.82                | 5.96                   |
| Mutsu   | -43.8     | 6.5                 | 5.22                   | 7.91                | 5.98                   | 9.56                | 6.58                   | 8.79                | 7.06                   |
| Kamaishi| -49.8     | 5.15                | 4.08                   | 5.3                 | 4.62                   | 6.13                | 4.94                   | 7.22                | 5.01                   |
| Kashima | -24.0     | 7.4                 | 5.69                   | 7.4                 | 6.43                   | 7.09                | 5.71                   | 7.5                 | 6.07                   |
| Shimoda | -51.1     | —                   | —                      | 6.08                | 4.78                   | 6.71                | 4.83                   | 8.49                | 5.43                   |
| Shionomisaki | -54.7 | 5.43                | 4.49                   | 8.77                | 6.69                   | 9.07                | 7.33                   | 11.2                | 7.89                   |
| Murotsu | -27.7     | —                   | —                      | 5.63                | 5.63                   | 9.48                | 6.91                   | 13.55               | 7.01                   |
| Hososhima| -48.3     | —                   | —                      | —                   | —                      | —                   | —                      | 11.88               | 7.93                   |
| Shibushi Bay | -35.0 | 7.39                | 7.39                   | 7.88                | 5.6                    | 8.3                 | 6.44                   | 10.3                | 5.28                   |
| Nakagusuku Bay | -39.6 | 8.46                | 5.86                   | 8.46                | 7.14                   | 10.63               | 7.35                   | 13.61               | 8.11                   |
| Total   | -54.7     | 8.46                | 5.36                   | 8.77                | 5.86                   | 10.63               | 6.09                   | 13.61               | 6.58                   |

Out of concerns about the aggravation of disasters caused by global climate change and the increasing occurrence of low-probability marine disasters, the inter-annual changes of waves have received more attention. Facts are needed to prove whether disasters are aggravated and how much they are intensified. Here we select the annual maximum data of all wave stations along the coast of Japan, statistically analyze the annual arithmetic average, and fit the average annual wave height. The result is very clear. The average wave height increases by 2.4cm per year and 24cm in 10 years. It has increased by nearly 1m in 40 years.

Figure 2. Interannual variation of typhoon wave height

These figures cannot directly explain the degree of wave increase. According to traditional methods, we can use 20-year historical data to calculate wave conditions in different return periods. The results show that by 2010, the 50yrs return period wave (9.6m) in 1990 was between the 10yrs return period
wave (9.8m) and the 2yrs return period wave (9.2m). The 50yrs return period wave (10.6m) in 2000 was lower than the 25yrs return period wave (10.8m) in 2010.

2.3 Analysis of the duration of typhoon waves
The duration of the peak typhoon wave is often also related to the stability of the structure. The longer the duration, the greater the impact on the threat of damage to the wave-prevention structures and the degree of damage. Here we analyze typhoons in 2011, 2012, 2013, and 2014. The selection of typhoons is based on the principle of the greatest impact. In 2011, the 15th and 16th typhoons were selected, and the typhoon paths are shown in the figure 3. The biggest wave appears in Yamashige Tail, and the time when the significant wave height exceeds 10m is 6 hours.

In 2012, when the No. 16 typhoon passed by, the largest wave appeared in Kochi, and the significant wave height exceeded 6m for 4 hours. In 2013, on the 26th typhoon, the largest wave occurred in Shizuoka Omaezaki. The significant wave height exceeded 8m for 6 hours. In 2014, No. 18th typhoon, the largest wave occurred in the west of Kochi, and the significant wave height exceeded 10m for 4 hours. Judging from the 4 typhoons in the 4 years from 2011 to 2014, the maximum wave lasted about 4 hours for the typhoon path after landing or landing, and the maximum wave lasted for about 6 hours for the typhoon advancing along the coast. By analyzing the duration of more typhoon waves, it is found that the law is basically the same. It can be concluded that when controlled by typhoon waves, the frequency of occurrence of 1/1200~1/1800 should be considered for the largest wave. In the Chinese standard, the duration is two hours. The largest wave considers the frequency of 1/100, which is obviously underestimated.

3. Simulation Analysis of Typhoon "Mangkhut"
Typhoon "Mangkhut" originated in the Northwest Pacific on September 8, 2018. It passed through the Philippine Islands and entered the South China Sea on September 15. The path diagram is shown in Figure 4. The study uses the typhoon model and the wave model SWAN to study the typhoon and typhoon waves in the engineering sea area. The process is repeated. Use the collected wave process near Dongsha Island to verify the Mangkhut Typhoon process, as shown in Figure 5 below, the calculated maximum H1/3% is 12.3m, the measured maximum H1/3% is 12.2m, the correlation coefficient between the two curves is 0.95, and the trend fit is good. Using the above calculation results, extract the wave height process of the 20m isobath in Shantou, the maximum H1/3% is 8.9m, the average period is 12.8s, the wave direction is the SE direction, and the time of occurrence is September 16, 2018. The results of the wave elements calculated to the top of the embankment in the project area are shown in Table 3, which has exceeded the designed value of the once-in-50-year wave. What is particularly striking is that from September 15 to September 16, the big wave lasted for 16 hours, resulting in significant cumulative damage to the breakwater. The H1/3% distribution of the typhoon wave on September 16, 2018 is shown in Figure 7.
Table 2. Calculation results of wave elements at the head of the breakwater

| Position          | Wave direction | $H_1$(m) | $H_4$(m) | $H_5$(m) | $H_{13%}$(m) | $\bar{H}$(m) | $\bar{T}$(s) |
|------------------|----------------|----------|----------|----------|-------------|-------------|-------------|
| Head of breakwater(F1) | SE             | 9.18     | 8.15     | 7.97     | 7.03        | 4.92        | 12.80       |

Figure 4. Track of Typhoon "Mangkhut"

Figure 5. Wave Height Verification of Typhoon "Mangkhut"

Figure 6. $H_{13%}$ distribution at 16:00 on September 16, 2018

Figure 7. The completed model (outside the port)

4. Replay test study of physical model of breakwater typhoon damage

4.1. Making physical model of damaged breakwater

A physical model with a length scale of 1:43 was used to simulate according to the gravity similarity criterion. The model includes two parts: a caisson-type vertical dike and a slope dike. The head of the caisson-type vertical dike is 56m long, and the one connected to the vertical dike is Slope breakwater, the slope protection surface is a 24t twisted king block, as shown in Figure 7.
4.2. Model test and results
The replay test started from the wave elements at 0:00 on September 16, and then proceeded according to the averaged wave elements and observed the test phenomena under the action of each wave element. The test results are shown in Figure 8, which is similar to the on-site damage pattern.

(1) Breakwater damage diagram after the test (2) Breakwater diagram on site
Figure 8. Comparison of the breakwater damage in test and on-site

It was found in the test that the connecting section of the vertical and the slope breakwater is a weak position [5-8]. Due to the reflection of the vertical section and propagation along the breakwater, the wave energy concentration occurs at the connecting section, and the damage starts from this section. Due to the typhoon “Mangkhut” and the strong waves lasted for a long time, the damage continued to develop, the scrubbing intensified, and the parapet wall collapsed.

5. Conclusions
- The waves caused by typhoons on the southeastern coast of Japan have continued to increase in the past 40 years, and the wave height has increased by about 2.4cm every year.
- The waves caused by typhoon "Mangkhut" in Shantou exceeded the once-in-50-year level in the area and lasted more than 16 hours.
- The 1:43 model was used to reproduce the process of typhoon waves, and at the same time, the damage process of the breakwater was reproduced, indicating that the converging part of the vertical section and the slope section is the wave energy concentration area, and the damage starts from this part. Typhoon Mangkhut lasted for a long time and the damage continued to increase.

References
[1] Li S, Tao A F. Analysis of the characteristics of China's ocean wave disasters in the past 15 years. Proceedings of the 18th China Ocean (Shore) Engineering Symposium (Part 1):195-197.
[2] Peng J, Tao A F. Analysis of the characteristics of China's ocean wave disasters in the past ten years. Collection of Essays on the 16th China Maritime (Shore) Engineering Science Conference (Part 1):805-808
[3] WANG N, HOU Y J. Numerical simulation of the Hazard distribution of typhoon waves in 1979-2018[J]. Oceanologia et limnologia sinica, 2020(51):861-868.
[4] HAN S Z, SHI Y J. The Distributional Character of Typhoon Waves in the East China Sea [J]. Periodical of Ocean University of china, 2013, v.43; No.222 (10):1-7.
[5] WU Y Q, LI Y B. Discussion on the Research and Reasons of Breakwater Failures[J]. Port Engineering technology, 2008(02):8-11.
[6] HU X G, YU D Y. Failure Cause Analysis and Renovating Plan Study on Deepwater Mound Breakwaters[J]. Coastal Engineering,2014,33(03):47-54.
[7] HUA M M. Kammen Fishing Port Breakwater Renovating Plan[J]. China Water Tansport, 2016, 16(06):286-288,292.
[8] WANG Y D, HUANG X J, LI J H. Stability test study on repair section of west breakwater in Bohe port area of Maoming Port[J]. China Harbour Engineering, 2018,38(06):51-54.