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The effects of long-time strong wave condition on breakwater construction

S. Chen[a], G. Liang[b], H. Chen[a]*, R. Zhou[a]

[a]*Tianjin Research Institute of Water Transport Engineering, Jianjin, 30045, China*
[b] *Second Engineering Company of China Fourth Harbour Engineering Co., Ltd., Guangzhou, 510300, China*

Abstract

In this paper, long-time strong wave condition is defined according to the comparison between the China's Ocean and the Indian Ocean, as well the characteristic of long-time strong wave condition is described. Combined with practical works, the effects of long-time strong wave condition on breakwater construction are analyzed. Some specific construction measures, including placement of rock material, wave prediction and breakwater head protection during construction period, are introduced. Some valuable references are provided for similar projects in the future.

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Keywords: long-time strong wave; Indian ocean; breakwater; breakwater head protection

1. Introduction

As the development of Chinese port construction technology, more and more countries employ Chinese company to build wharfs and breakwaters. Most of the projects are located around the Indian Ocean, such as Indonesia, Malaysia and Sri Lanka etc. The wave dynamic condition in such project sites is main long period swell, which is significantly different from the wind wave in the China's Ocean. Therefore the traditional breakwater construction technology and test method which were successfully used for China's Ocean is no longer applicable in the Indian Ocean. Some specific construction measures should be developed in order to conform with the long-time strong wave condition.

* Corresponding author. Tel.: +86-22-5980-5205; fax: +86-22-5980-5205.
E-mail address: chenhanbao@163.com

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This paper is organized as followed. In the second section, the definition of long-time strong wave condition is given by comparing the China's Ocean wave with the Indian Ocean wave. The effects of long-time strong wave condition on breakwater construction are analyzed in the next section, and some specific measures are proposed. Finally some conclusions are given.

2. Wave comparisons between China's Ocean and Indian Ocean

2.1. The wave characteristics in China

In China, the coastline is 18000 kilometers long from south to north, crossing the tropic, subtropics and temperate zone. But generally speaking, the wave is mainly induced by wind in China's sea. The main dynamic of the wind wave are monsoon, gale and typhoon. The key influence factors in different areas are different. For example, in the Bohai Sea and the Yellow Sea, gale (monsoon) is considered commonly, and in the South China Sea typhoon is the key factor, while typhoon and gale (monsoon) are both focused in the East China Sea.

The average wave heights in Chinese nearshore are listed in Table 1. It can be seen that the average wave heights in Chinese nearshore are all fairly small, and most of them are below 1.0 meter. The wave in Bohai Sea is smallest, while the ones in East Sea and South Sea are much larger. The reason why the wave heights are such small is that the wave in Chinese sea is controlled by monsoon. In winter the prevailing northerly wind is offshore but with a short fetch. Although in summer the prevailing southerly onshore wind has a long fetch, the frequency of the strong wind which is faster than 13.8m/s is very low (less than 5% in Bohai Area and the north of Yellow Sea, 5%~10% in the south of Yellow Sea and East China Sea, 5%~20% in South China Sea). The largest wave is often generated by tropical cyclone (typhoon) and cold wave. However the occurrencefrequency of the extreme weather is very low per year. Therefore the strong wave weather would not last for a long time(Chen and Zhang, 2005).

Table 1. The average wave height (Ha) of China's coast in different sites(m)

Station	H_a	Station	H_a	Station	H_a	Station	H_a
Da lu island	0.56	Qing ji island	0.83	Zha pu	0.23	Nao zhou island	0.96
Xiao chang shan	0.5	Cheng shan jiao	0.66	Nan ji	0.96	Bai sha men	0.54
Lao hu tan	0.54	Shi island	0.59	Tai shan	1.26	Yu bao	0.61
Chang xing island	0.8	Qian li yan	0.97	Ping tan	0.91	Dong fang	0.75
Ba yu quan	0.44	Xiao mai island	0.7	Chong wu	1.18	Ying ge hai	0.72
Hu lu island	0.58	Shi jiu suo	0.59	Yun ao	1.03	Yu lin	0.49
Zhi mao wan	0.67	Lian yun gang	0.66	Biao jiao	1.07	Lang wang ya	0.51
Qin huangisland	0.57	Gao qiao	0.31	Zhe lang	1.18	Tong peng ling	0.9
Tang gu	0.72	Yin shui chuan	1.02	Da ya wan	0.75	Wei zhou island	0.64
Bei huang cheng	1.06	Da ji shan	1.04	He bao island	1.13	Bei hai	0.32
Qi mu island	0.95	Sheng shan	1.07	Chuan island	0.7	Bai long wei	0.61
Zhi fu island	1.44	Tan hu	0.59	Shui dong	0.78		

2.2. The wave characteristics in south coast of Java Island, Indonesia

Indonesia facing the northern Indian Ocean has lots of wave related issues. Java Island is the most important regions in Indonesia, not only concentrates 60% of the population, but also the location of the capital Jakarta , special economic zone Yogyakarta and the main economic cities Surabaya , Bandung , Semarang. Therefore, there are more and more port projects being under construction in south coast of Indonesia's Java island facing the Indian Ocean. In order to guide design and construction, the wave characteristic should to be studied.

Three typical regions along south coast of Java island, including Adipala, Gama and Pacitan are selected to analyze the characteristics of the waves(Zhu, 2010 and Liu, 2010). Their latitudes, longitudes, and locations are shown in Table 2 and Fig. 1(Chen, 2010 and Zhang, 2014). Based on lots of measuring datum in the North Indian Ocean, it can be concluded that northeast monsoon prevails from November to next March, while southwest monsoon prevails from May to September, and the monsoon changes direction in April and October. Southwest monsoon is shorter in the duration than northeast monsoon, but stronger and wider in range(Liu, 1998). The occurring frequency when wave heights are higher than 1.3m and 2.0m in these three regions are shown in Fig.2. As is seen in this Fig, large waves higher than 2m appeared every month in these regions, and the wave directions are almost South-South-West(SSW). This wave condition is especially obvious under the effect of southwest monsoon from May to September, and the days when 2 to 3m high wave appears accounted for about 70%. In other months, the days when 2 to 3m high wave appears still accounted for 20% to 30%. Such large proportion means that the breakwater would be attacked by strong waves higher than 2m in every month during the construction period, and will bring great difficulties and challenges for the breakwater’s continuous construction .

Fig. 1. The locations of the three typical areas in Google earth

Table 2. The latitude and longitude coordinates of the three typical regions

Location	Longitude	Latitude
L#1(Gama)	106°46'28.32"east	7°26'54.44"south
L#2(Adipala)	109°13'5.25"east	7°41'59.11"south
L#3(Pacitan)	111°16'7.98"east	8°15'18.29"soutn

Besides the wave height, the wave period in the south coast of Java island is significantly different from the one in China's coast. The strong waves in China's coast are mainly produced by wind, such as tropical cyclone (typhoon) and cold wave. And the wave period is usually less than 10s, with a relatively short wave length. On the contrary, the strong waves in the Indian Ocean coast is composed by the swell with longer period swell. As is seen in Table 3, the average swell period is generally longer than 13s, and the maximum period can reach to 20s. The main reason why the long-period strong wave appears frequently in the south coast of Java island is because it faces the broad Indian Ocean whose area is approximately half of the earth, crossing all wind band in the southern hemisphere. Waves can fully grow into large waves in such a long fetch. Moreover, the energy dissipation is weak in the propagation process because the sea water depth is up to several kilometers. Before arriving at the south coast of Java island, waves has traveled thousands of kilometers away. In such a long distance, the low-frequency part of long waves are gradually stripped out due to the effects of diffusion and angular dispersion, and on the other hand, high-frequency parts of waves are dissipated constantly by the internal friction. Therefore the wave period becomes quite long when reach the south coast of Java island.

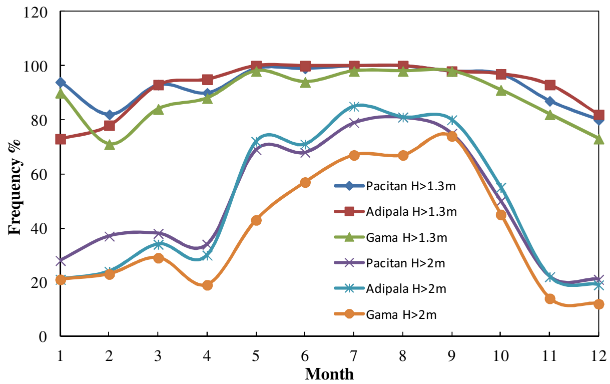

Fig. 2. The frequency of the waves higher than 1.3m and 2.0m in three regions

Table 3 The observation data in Adipala project from April, 2012 to March, 2013

Wave characteristics	2012									2013		
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
The maximum period(s)	20	19	18	20	20	19	18	19	17	18	17	17
The maximum height(m)	3.5	2.4	2.2	2.5	3	3	2.2	2.2	2.3	2.5	3.5	2.5
The average period(s)	14.2	13.2	15	15.3	14.7	14.5	14.1	13.5	13.3	12.6	13.1	13.1

2.3. *The definition of long-time strong wave*

The strong wave is defined as the wave whose significant height exceeds the maximum wave height which is allowed in some construction process. For example, for the blocks stability, the maximum significant wave height allowed in breakwater construction can be calculated according to the formula in the 'Specification for design and construction of breakwaters ' (JTS 154-1-2011 in China):

$$H = \sqrt{\frac{10WN_D^3\left(\gamma_b - \gamma\right)^3}{\gamma_b L_p \gamma^3}} \tag{1}$$

Where H is the significant wave height, W is the block weight, N_D is the stability coefficient, L_p is the wave length corresponding to peak spectral period, γ_b and γ is the density of block and sea water. It can be known from the above formula that, the block less than 1 ton can not meet the stability requirements when wave height exceeds 1.3m. Consequently, the waves of height larger than 1.3m can be considered as strong waves for breakwater construction.

Comparing China's coastal waves with those in southern coast of Java island, it can be obviously found that the wave conditions in southern coast of Java island are much stronger. Waves higher than 2.0m appear in every month, and the number of month when the probability of large wave occurring exceeds 50% is more than 6. Moreover the wave period is always longer than 10s. Hence the long-time strong wave is defined as follows: the wave whose average period is more than 10s, and occurring days of whose height larger than 1.3m accounts for 70%, and whose composition is mainly swell. The above wave condition is defined as long-time strong wave condition. Under the long-time strong wave condition, some specific construction measures for breakwater construction should be applied.

3. The effects of long-time strong wave condition on breakwater construction

The construction process of sloping breakwater mainly includes rock placement on the water and on the shore. The period of waves during the breakwater construction in China is usually less than 10s, expect 15~18s when typhoon comes. Therefore the construction conditions are good enough in most time. By contrast, there is a bad wave condition in the south coast of Indonesia's Java island with a 10 to 20s long wave period and 2 to 3.5m high wave height attacking the breakwater 1 to 3 times per month. Therefore challenges to the traditional breakwater construction technology are posed under such long-time strong wave condition, performance in two aspects. The first is that rock placement ships and machines on the water which used to be in traditional breakwater construction is no longer applicable, and large-scale construction ships and machines can not be used because of serious swing; the second is that the breakwater head is always subjected to the strong wave attacking(as shown in Fig.3), as a result the breakwater head needs to be protected timely and effectively.

Fig. 3. The breakwater head is badly destroyed by strong waves (left: before the destruction; right: after the destruction)

3.1. Rock placement on the water

Conventional rock placement on the water mainly includes the following processes(Dai, 2014): preparing and loading blocks, fixing positioning vessels, body-open barges approaching the positioning vessel to riprap, body-open barges returning to the port for loading, relocating positioning vessels, and checking and accepting. But under the long-time strong wave condition, large-scale construction ships are no longer applicable. An alternative construction process on the water is adopted, which is the measure combining the positioning buoy with the small body-open barges.

The positioning buoy is mainly composed of a concrete pier, nylon ropes, and bamboo pole. Different colours flags are hung at the top of bamboo pole in order to show different positions. Because the area of thrust surface of bamboo pole is quite small, the position will be relatively fixed even if attacked by the extremely large wave. This kind of positioning buoy is durable, and can keep workable for 2 months in the natural state. Besides, propellers of small body-open barges will not be impacted adversely when passing over the buoy. A high safety factor is provided during the construction period. It also has advantages of low cost and convenient arrangement is convenient and simple. For these reasons it can be widely used under the long-time strong wave condition. The positioning buoy system of breakwater rock placement on the water in the project in Adipala is shown in Fig.4(Zhou, 2013).

The small body-open barges which is used in the harbour has advantages of flexibility and good adaptability. They can work normally when the wave height is less than 1.8m(working days account for more than 70% per month). Although the volume of small body-open barge is only 45m³, the maximum rock placement capacity of 4 small body-open barges can reach 4000 m^3 every a day. As is shown in Fig.5, the small body-open barge sails to the designated area to unload positioned rocks by the buoy after completing the loading in the port. The unloading position should be adjusted according to the sea condition and barge's speed in order to ensure rocks filled into the designated area.

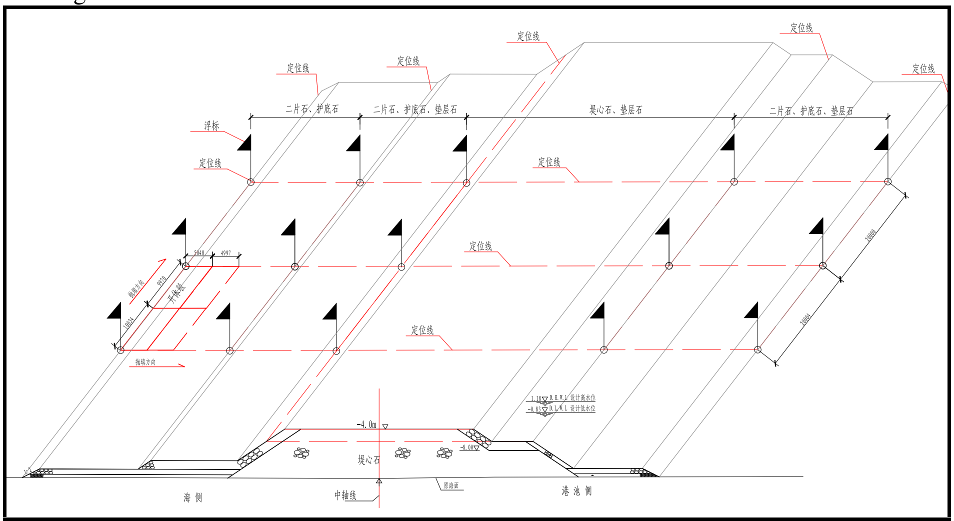

Fig. 4. The buoy positioning system

The construction mode of combining the positioning buoy with the small body-open barge can be used to throw and fill core rocks, two flaky stones and bottom protection rocks. Under the long-time strong wave condition, this construction mode were successfully applied in the project of Adipala and Gama. It has been proven that this measure can speed up the advance speed of breakwater, and reduce the pressure of construction on land greatly.

3.2. Wave prediction

Under the long-time strong wave condition in the south coast of Java island, the long-period waves appear randomly, having no direct or reciprocal relationship with tidal chart, therefore they can not be predicted accurately. The wave period in such project sites changes suddenly, increasing from 10s to 20s in 24 hours, and the wave height that comes along changes from 1m to 3.5m. When such long-period strong wave containing high energy attacks breakwaters, it is very easy to cause the breakwaters' destruction and destabilization. Because project sites are usually located in the undeveloped areas, no effective wave prediction system exists. Then a convenient and effective wave prediction measure is desired so as to provide enough time to take actions to protect the breakwater in advance, and reduce the breakwaters' failure losses.

According to the field monitoring, it has been found that waves in the south coast of Java island always change more acutely on the day before or after the first and middle day of the lunar calendar each month, and during this period strong waves appear more likely. Before the arrival of strong waves, period always changes prior to height. And more greatly the period changes, more acutely the wave height changes. Though the wave prediction data is lacked in project sites, the wave prediction data far away from project sites can be found in some international web www.surf-forecast.com. Therefore, by comparing the monitoring data of project sites with the Web's data (as shown in Fig.6), some relationships between them can be established. Combined with the recognition on variation of the waves in the south coast of Java island, strong waves could be predicted and prevented in time, and the site construction and protection measures could also be guided by above data directly. This measure has been used to predict waves successfully during breakwater construction period in Adipala and Gama. Strong waves are failed to be predicted less than 2 times in one year. It has been proven that this measure is applicable for wave prediction in the south coast of Java island, and can effectively reduce damages and losses for the breakwater construction.

Fig. 5. The work mode of small open body barge

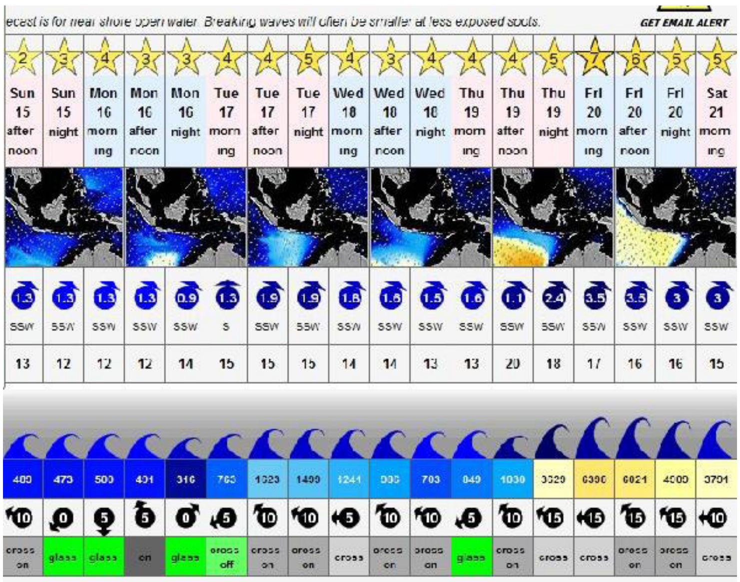

Fig. 6. The changes of wave period and height when one big wave coming

3.3. Breakwater head protection during construction period

In the south coast of Java island, breakwaters are attacked 1 to 3 times each month when wave height is from 2.5m to 3.5m and period is between 18s and 21s. By contrast breakwaters construction in China are affected by typhoon only 1 to 3 times each year. Therefore breakwater head protection under the long-time strong wave condition is needed more frequently during construction period(Zhou, 2014).

In view of the fact that breakwater head is impacted by strong waves with normalization and high frequency, if breakwater heads are all protected by artificial armours, the cost will be too high and also the time of assembly and disassembly will cost too much. Different breakwater head protection measures, such as block protection, breakwater head rubble grouting, protection of steel truss cover and wire mesh gabion etc, are compared from views of construction process, construction period, cost, practicability and other characteristics. Finally the measure combining wire mesh gabions with artificial armours is chosen to protect the breakwater head, as is shown in Fig.7.

Fig. 7. The measure combining wire mesh gabions with artificial armours for breakwater head protection during construction period

Wire mesh gabions have good permeability, flexibility, strong anti-scour and anti-wave ability(Fu, 2010). Good permeability reduces the scouring erosion to gabions by strong waves, meanwhile reduces the jacking and vacuum suction of the water flow to protective structure. Good flexibility makes gabions would adapt themselves to reach a new equilibrium to the wave action, even though blocks have produced great displacement after scouring by water flow. After field practice, wire mesh gabions have good performance in strong anti-scour and anti-wave ability. At the same time, lots of advantages, such as simple process, easy installation, and convenient recover, make wire mesh gabions suitable to protect the breakwater head temporarily under the high-frequency strong waves condition.

According to the project experiences(Cao, 2014), breakwater head temporary protection measure are divided to four different cases on the basis of prediction wave height using the measure in chapter 3.2. Details are shown in Table 4.

Table 4 Four different cases of breakwater head protection measures

Item	Wave Height	Breakwater head temporary protection measures
Case1	1.5m≤H＜2.0m	Use not less than 1000kg cushion block stone to protect the outer slope and breakwater head, slope trimming height is -5.0m to +3.5m, protect the breakwater head while promote it.
Case 2	2.0 m≤H＜2.5m	Use CAT385 large excavator to build the carriage way of -5.0m height on breakwater head and outer slope, use wire mesh gabion of $4m \times 1m \times 1m$ to protect the breakwater head slope, regularly check and complement.
Case 3	2.5 m≤H＜3.0m	Use CAT385 large excavator to build the carriage way of -5.0m height on breakwater head and outer slope, install the wire mesh gabion and set the block pressure foot below the water, set 22T accropode armours to protect the slope above the water.
Case 4	H＞3.0m	Use CAT385 large excavator to build the carriage way of -5.0m height on breakwater head and outer slope, set 22T accropode armours on all slopes.

Based on the prediction wave condition, breakwater head temporary protection measure is classified clearly. In this way, the cost of breakwater head protection could be reduced maximally, and the efficiency of construction could be enhanced significantly. It has been proven in the practice that the measure combining wire mesh gabions with artificial armours is effective to solve the technical problem of breakwater head temporary protection under the high-frequency strong waves condition.

4. Conclusions

In this paper, the definition of long-time strong wave condition is given by comparing the China's Ocean wave with the Indian Ocean wave—the wave whose average period is more than 10s, and occurring days of whose height larger than 1.3m accounts for 70%, and whose composition is mainly swell. The effects of long-time strong wave condition on sloping breakwater construction are discussed, including placement of rock material on the water, wave prediction and breakwater head protection during construction period. Some specific construction measures are summarized to be suitable for the long-time strong wave condition. The measure combining positioning buoys with small body-open barges in placement of rock material effectively overcomes the problem that large construction ships can not be used under the long-time strong wave condition; By comparing the monitoring data of project sites with the Web's data, some relationships can be established to predict the wave change in project sea area, and provide enough time to take breakwater head protection actions during construction period; The measure combining wire mesh gabions with artificial armours can solve the technical problems of breakwater head temporary protection under the high-frequency strong waves condition. By these methods, the breakwater construction speed is enhanced, the risk of breakwater damage is lowered and the cost of breakwater protection during construction period is reduced significantly. In addition, some valuable references are provided for the similar projects in the future.

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