Experimental study on wave-induced load on crest wall in North Indian Ocean

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Abstract. Wave-induced load is one of the most important aspects in the design of coastal engineering. It is well known that long period waves are very common along the coast of the Atlantic and India ocean, which is rather different from wind waves. Many coastal projects were designed by China Design Code and American Coastal Engineering Manual (CEM). Physical model test was carried out in this paper to study wave loading of crest wall under impulsive action by long-period wave. The result of test was compared with China Design Code and CEM. And then a verification test was also adopted to prove that there was obvious difference between them. It was indicated that China code and CEM had very close results but much smaller than that of model test, with ratio of 1:5. The long-period wave load on crest wall was much more than results by empirical formula. The isolated crest wall and rear unsupported was also taken up with wave action and it was destroyed easily. So impulsive action by long-period wave on crest wall should be paid more attention in project design. The scope of empirical formula is limited and physical model test is indispensable for the reliability of structure.

1. Introduction
Wave defending structures with crest wall is very common in the area of coastal engineering. Over the years, scholars at home and abroad have made a lot of research achievements on wave loads on crest walls. Many empirical formulas have been summarized, some of which have been adopted by national codes and design manuals. China's "Code of Hydrology for Harbor and Waterway" (Ministry of Transport, P.R.C., 2015) adopted the research results of China University, and Coastal Engineering Manual (U.S. Army Corps of Engineers, 2011) cited the empirical formula of the scholar Pedersen (U.S. Army Corps of Engineers, 1992). When wave acts on the slope surface of breakwater or revetment, the climbing water rises along the slope and breaks, turns back and rises high on the crest wall and superimposes with the traveling wave, which makes the action of wave more complex. It’s difficult to form a complete conclusion for the difference of crest wall shape, water depth and wave conditions. Traditional research results and empirical formulas cannot be simply copied and applied, and their applicable conditions should be carefully analysed (Lu, Jin and Zhao, 1993; Shu and Wang, 2003).

Especially in area with long-period wave, the climbing wave breaks sharply in front of crest wall, and the instantaneous impact force will be very large, which is not conducive to stability. This kinds of problems has caused widespread concern in project design. In the initial stage of design, the primary size of the crest wall can be determined according to the standard code or empirical formula. Then the
cross section is verified and optimized by physical model test. Sometimes there is obvious differences between the result of formula and model test.

The example project in this paper is located along the coast of India ocean. The perennial wave period is greater than 10 s, which belongs to the typical long period sea area. The water depth of breakwater is 8.7 m. The structure adopts slope type with armor block weight of 11 T, slope 1:1.5. Due to the need for belt conveyors and road functions, the overtopping requirement is high. In order to ensure safety, a vertical crest wall was set up at the top of breakwater, with top elevation of + 12.5 m, bottom elevation of + 5.5 m and the height of the breast wall of 7 M. The section is shown in Figure 1.

![Figure 1. Cross section of breakwater with crest wall](image1.png)

**2. Methods**

2D physical model was adopted to test the wave load and stability of crest wall in this paper. The model test was carried out in Tianjin Research Institute for Water Transport Engineering (TIWTE). The wave flume is 68m long, 1m wide and 1.5m wide, with poison-type wave maker. Irregular wave is adopted with JONSWAP spectrum. The model design follows the gravity similarity criterion with model scale 35. The cross section is shown in Figure 2.

![Figure 2. Photo of physical model for Cross section of breakwater](image2.png)

Press sensor was used to measure wave pressure on the crest wall and the position & number of sensor is shown in Figure 3 (left). There are seven sections of crest wall and the sensors are located in the third and fifth section, shown in Figure 3 (right). Wave process is 100 waves in the model. The wave condition used in model test is shown in Table 1.
3. Results

The statistical result of wave load, comparison of China code, CEM and model test, and stability of isolated wall were analysed. Generally, China code and CEM had very close results but much smaller than that of test, with ratio of 1:5. The long-period wave load on crest wall was much more than results by formula calculation. The isolated crest wall and rear unsupported was also taken up with wave action and it was destroyed easily.

3.1. Statistical Result of Wave Load

As shown in Figure 4, wave breaks up sharply in front of the wall after climbing along the slope. Obvious impact is formed on the wall and the high water crosses the top to form overtopping.

The horizontal and uplift force is calculated by summing the pressure of each sensor and the integral of representative area on the wall at each time of sampling. Then the time process of horizontal force per meter of the wall is obtained, as shown in Figure 5. The statistical result of maximum horizontal force are shown in Table 2.
Figure 5. Time process of horizontal force of wall.

Table 2. Statistical result of maximum horizontal force.

| Parameter     | values   |
|---------------|----------|
| Max force     | 378 kN/m |
| Max force     | 322 kN/m |
| Average       | 350 kN/m |
| Uplift force  | 40 kN/m  |

It is indicated that the results of two measurement sections are basically synchronous. The contribution of a few big waves is large during irregular wave process with many obvious peaks. From Table 2, the maximum horizontal forces of the two sections are 378 kN/m and 321 kN/m respectively, with an average of 350 kN/m, and the uplift force at the corresponding time is 40 kN/m.

The wave pressure of each sensor at time of max force is shown in Figure 6, with characteristics as following: (1) The height of pressure action basically covers the whole breast wall, and the average pressure is 50 kPa while the height of breast wall is 7 M. (2) Wave pressure in the upper and middle parts of the wall is relatively large, which accounts for about 2/3 of the height. (3) At the top and bottom of the wall, the pressure is relatively small because of overtopping and the shelter of blocks.

Figure 6. Wave pressure of each sensor at time of max force.

3.2. Comparison of Design Code and Model Test

According to the design code in China, wave pressure on crest wall is uniformly distributed along the height. After determining the average pressure $p$ and the wave action height $D1 + Z$, the total horizontal wave force is calculated by the formula $P = p \cdot (D1 + Z)$. Coastal Engineering Manual (CEM) also has adopted similar ideas. Comparison of result of design code and model test is shown in Table 3.

Table 3. Comparison of result of design code and model test.

| Calculated method     | values   |
|-----------------------|----------|
| China code            | 68 kN/m  |
| CEM                   | 70 kN/m  |
| Physical model test   | 350 kN/m |
The result of model test is much larger than that of formula calculation by design code, about five times. Such a big difference has aroused great attention of the designers and researchers. Then an assumption test with isolated wall was carried out to improve how much the wave force is.

### 3.3. Assumption Test of Isolated Wall

The assumption test is carried out with isolated wall, that is removing the stone behind of the wall. In another word, there is no support for the wall. The test phenomenon of isolated wall is very obvious. After action of about 10 waves, the isolated wall has an obvious movement from its original position, shown in Figure 7 (left). It continues to fall backwards under subsequent big waves. The final position is shown in Figure 7 (right).

![Figure 7. Movement of isolated wall (Left: first movement; Right: final placement).](image)

In this study, the weight of crest wall is 370kN/m. Considering of the uplift force 40kN/m and friction coefficient 0.6, the friction resistance \( F = (370-40)*0.6 = 198kN/m \). However, the wave load is 70kN/m, far less than force \( F \), that means, the wall would not move. From the obvious movement of isolated wall, the wave load on the wall is larger than \( F \) (198kN/m). From the aspect of time, the first large peak of force is about 250kN/m, which occurs the time of first move. That is to say, the peak of force and movement of wall corroborate each other. The result of model test is more reliable and practical.

### 4. Discussion

The research results of Chinese code originated in the 1980s. The research at that time mainly focused on the coastal areas of China, without considering the long wave (\( T > 10 \) s) situation, therefore, the applicability of the normative formula to the long-period wave area is not strong, and there is a big difference between model test results, which deserves special attention. According to the model test, wave pressure on crest wall is not uniformly distributed along the height, which is larger in middle. The average pressure and distribution height is compared between code and test in Table 4.

| Parameter         | Method       | values  |
|-------------------|--------------|---------|
| Average pressure  | China code   | 56.7 kN/m |
|                   | Model test   | 50.0 kN/m |
| Distribution height| China code   | 1.2 m    |
|                   | Model test   | 7.0 m    |

It is found that the average pressure from model test is close to that of Chinese code, but the distribution height is much higher. This is the main reason for the force of test five times of design code. The empirical formula does not consider the area of pressure attenuation, which results in a smaller total horizontal force. This finding is also consistent with other researchers (Jiang, Liu and Peng, 2015; Wang, 2007; Xu, Liu and Jia, 2015; Yu and Su, 2012).

### 5. Conclusions

This paper introduces a case study on wave load of crest wall under impulsive action by long-period wave. The empirical formula has a strong universality, but it also has certain limitations and applicable
conditions. In the case of near-breaking waves under long-period action, the wave force characteristics under this special condition are not fully reflected by either Chinese code or America CEM.

The empirical formula by China code and CEM is not applicable for the calculation of wave load in North Indian Ocean with long period wave. The difference may be out of imagination but assumption test of isolated wall will improve the reliability of model test. Physical model test was an effective measure to solve the problems in project design.

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